OCEAN Challenge

Volume 16, No. 1, 2006
(published Autumn 2008)

The views expressed in *Ocean Challenge* are those of the authors and do not necessarily reflect those of the Challenger Society or the Editor.

ISSN 0959-0161

SCOPE AND AIMS

Ocean Challenge aims to keep its readers up to date with what is happening in oceanography in the UK and the rest of Europe. By covering the whole range of marine-related sciences in an accessible style it should be valuable both to specialist oceanographers who wish to broaden their knowledge of marine sciences, and to informed lay persons who are concerned about the oceanic environment.

***Ocean Challenge* is sent automatically to members of the Challenger Society.**
For more information about the Society, or for queries concerning individual subscriptions to *Ocean Challenge*, please see the Challenger Society website (www.challenger-society.org.uk) or contact the Executive Secretary of the Society (see inside back cover).

INDUSTRIAL CORPORATE MEMBERSHIP

For information about corporate membership, please contact the Executive Secretary of the Society (see inside back cover).

ADVERTISING

For information about advertising, please contact the Editor (see inside back cover).

AVAILABILITY OF BACK ISSUES OF OCEAN CHALLENGE

For information about back issues, please contact the Editor (see inside back cover).

INSTITUTIONAL SUBSCRIPTIONS

Ocean Challenge is published three times a year. The subscription (including postage by surface mail) is £80.00 per year for libraries and other institutions. New subscriptions, renewals and information about changes of address should be sent to:

Angela Hatton, Scottish Association for Marine Science, Dunstaffnage Marine Laboratory, Oban, Argyll, PA37 1QA

DATA PROTECTION ACT, 1984 (UK)

Under the terms of this Act, you are informed that this magazine is sent to you through the use of a computer-based mailing list.

Printed by Halstan Ideal, Amersham.

OCEAN Challenge

The Magazine of the Challenger Society for Marine Science

SOME INFORMATION ABOUT THE CHALLENGER SOCIETY

The Society's objectives are:

To advance the study of Marine Science through research and education.

To disseminate knowledge of Marine Science with a view to encouraging a wider interest in the study of the seas and an awareness of the need for their proper management.

To contribute to public debate on the development of Marine Science.

The Society aims to achieve these objectives through a range of activities:

Holding regular scientific meetings covering all aspects of Marine Science.

Supporting specialist groups to provide a forum for discussion.

Publication of a range of documents dealing with aspects of Marine Science and the programme of meetings of the Society.

Membership provides the following benefits:

An opportunity to attend, at reduced rates, the biennial five-day UK Marine Science Conference and a range of other scientific meetings supported by the Society.

An electronic newsletter (*Challenger Wave*) which carries topical marine science news, and information about jobs, conferences, meetings, courses and seminars.

The Challenger Society Website is
www.challenger-society.org.uk

MEMBERSHIP SUBSCRIPTIONS

The subscription for 2008 costs £40 (£20.00 for students in the UK only). If you would like to join the Society or obtain further information, contact the Executive Secretary, Challenger Society for Marine Science, Room 251/20, National Oceanography Centre, Waterfront Campus, Empress Dock, Southampton SO14 3ZH, UK;
Fax: +44(0)23-80-596149; Email: jxj@noc.soton.ac.uk

ADVICE TO AUTHORS

Articles for *Ocean Challenge* can be on any aspect of oceanography. They should be written in an accessible style with a minimum of jargon and avoiding the use of references. If at all possible, they should be well illustrated. Copy may be sent electronically.

For further information (including our 'Information for Authors') please contact the Editor:
Angela Colling, Aurora Lodge, The Level, Dittisham, Devon, TQ6 0ES, UK.
Tel. +44-(0)1803-722513

Email: A.M.Colling@open.ac.uk

CONTENTS

CONTENTS

Most of the maps and diagrams were drawn by The ArtWorks. The cover was designed by Ann Aldred Associates. The photograph at top-right was taken by Phil Williamson, and won the President's Photographic Prize ar the 2008 Challenger Society Conference in Bangor.

Message from the Editor

We begin this *Ocean Challenge* with a report of one of the workshops held at the UK Marine Science Conference in Bangor, because it relates directly to matters covered by Peter Liss in his 'Message from the President' at the start of the last issue. Reports of other conference events will be covered in Vol.16, No. 2.

We are delighted that one of this issue's feature articles comes from the newly elected President, Carol Robinson, while our Honorary Secretary, Rachael Shreeve, is one of the authors of the article on tall ships and science. The third feature article, on the problems associated with the mining of minerals from hydrothermal vent sites, is co-authored by a Challenger Fellow, and previous President, Christopher German.

The issue also contains appreciations of David Cushing and Mike Fasham, who died earlier in 2008. Both were pioneers in their fields, and active members of the Challenger Society over many years.

Angela.

Progress towards a UK marine science strategy

Report on discussion at the Challenger Conference for Marine Science, September 2008

Trevor Guymer and Peter Liss

About 60 people attended the workshop 'Why we need a Marine Science Strategy', which was chaired by Peter Liss and Trevor Guymer. The meeting began with a brief presentation by Trevor Guymer summarizing the history of UK marine science coordination over the last 20 years – in particular the recent inquiry by the House of Commons Science and Technology Committee.

As described by Peter Liss at the start of the last issue of *Ocean Challenge,* the government has decided to set up a new body, the Marine Science Coordination Committee (MSCC), which will report to ministers. One of its first tasks will be to develop a UK marine science strategy, and a commitment has been made by the Secretary of State for Defra that this will be ready during the second half of 2009. The Strategy document is intended to be concise and focussed, and to build on existing departmental strategies within an overarching framework; it should also have wide influence and make a difference to the way that things are done.

The MSCC will not be a Defra committee. It will be composed of all the government departments (including devolved administrations) that fund marine science. It will not include Treasury representation. It was noted that while the Department for Innovation, Universities and Skills see NERC as representing their interests, marine science is also funded by HEFCE and other research councils.

In the discussion on the Marine Science Coordination Committee, and the proposed Strategy, the main points to emerge were as follows:

- The geographical reach of the MSCC must extend beyond UK waters because UK marine science interests are global. This breadth would need to be reflected in the Strategy which should specifically identify links to the global change programmes being undertaken by the international community.
- The MSCC is likely to include up to three independent members appointed via open competition and filling a non-executive role. The wider UK marine community should therefore ensure that it is ready to suggest appropriate people.
- A crucial test of the success of MSCC will be whether it is able to produce the funding required to sustain long-term observations.
- Although the Strategy should have clear links to policy, its scope has to be wider than that of the Marine Bill.
- The Strategy should aim to focus on a small number of key issues. Suggestions made at the meeting as to what should be covered included:
  - How best to generate information relating to climate, energy and environment, required by government;
  - Highlighting crucial issues where progress is achievable;
  - Training (a topic in which the Challenger Society has a particular interest).
- It was emphasized that having a Strategy will help with resources being allocated to the right priorities and strengthen arguments for increased funding.
- Maintenance of scientific excellence should be a given.
- The Strategy should place particular emphasis on those activities that cut across agencies.

Other points covered included:

- Monitoring had featured prominently in the Select Committee inquiry and the Secretary of State has promised that the MSCC would give this close attention. Funding of sustained observations should be one of the key issues in the Strategy.
- The training afforded by marine science should be seen as a way of bringing people into maths and natural sciences and of benefitting UK industry. Future policy needs should be borne in mind when developing the Strategy and it would be useful to identify the skills required and the time-scales involved.
- As found by the Inter-Agency Committee on Marine Science and Technology, maintaining the engagement of key government departments over a long period is difficult – but it is vital.
- The balance between directed research and research led by Principal Investigators, and the relationship of the Strategy to other cross-governmental programmes such as Living With Environmental Change, were both discussed. It was recognized that many of the science strategies produced by departments and agencies are cross-disciplinary so it would be necessary to separate out the marine science components.

The MSCC intends to set up mechanisms for engagement with stakeholders, and the Challenger Society should play a role in developing and contributing ideas.

Note: Mechanisms for consultation with stakeholders are not yet in place, but in the interim, suggestions from individuals may be sent to Trevor Guymer (email: thg@noc.soton.ac.uk).

Message from the Editor

We begin this *Ocean Challenge* with a report of one of the workshops held at the UK Marine Science Conference in Bangor, because it relates directly to matters covered by Peter Liss in his 'Message from the President' at the start of the last issue. Reports of other conference events will be covered in Vol.16, No. 2.

We are delighted that one of this issue's feature articles comes from the newly elected President, Carol Robinson, while our Honorary Secretary, Rachael Shreeve, is one of the authors of the article on tall ships and science. The third feature article, on the problems associated with the mining of minerals from hydrothermal vent sites, is co-authored by a Challenger Fellow, and previous President, Christopher German.

The issue also contains appreciations of David Cushing and Mike Fasham, who died earlier in 2008. Both were pioneers in their fields, and active members of the Challenger Society over many years.

Progress towards a UK marine science strategy

Report on discussion at the Challenger Conference for Marine Science, September 2008

Trevor Guymer and Peter Liss

About 60 people attended the workshop 'Why we need a Marine Science Strategy', which was chaired by Peter Liss and Trevor Guymer. The meeting began with a brief presentation by Trevor Guymer summarizing the history of UK marine science coordination over the last 20 years – in particular the recent inquiry by the House of Commons Science and Technology Committee.

As described by Peter Liss at the start of the last issue of *Ocean Challenge,* the government has decided to set up a new body, the Marine Science Coordination Committee (MSCC), which will report to ministers. One of its first tasks will be to develop a UK marine science strategy, and a commitment has been made by the Secretary of State for Defra that this will be ready during the second half of 2009. The Strategy document is intended to be concise and focussed, and to build on existing departmental strategies within an overarching framework; it should also have wide influence and make a difference to the way that things are done.

The MSCC will not be a Defra committee. It will be composed of all the government departments (including devolved administrations) that fund marine science. It will not include Treasury representation. It was noted that while the Department for Innovation, Universities and Skills see NERC as representing their interests, marine science is also funded by HEFCE and other research councils.

In the discussion on the Marine Science Coordination Committee, and the proposed Strategy, the main points to emerge were as follows:

- The geographical reach of the MSCC must extend beyond UK waters because UK marine science interests are global. This breadth would need to be reflected in the Strategy which should specifically identify links to the global change programmes being undertaken by the international community.
- The MSCC is likely to include up to three independent members appointed via open competition and filling a non-executive role. The wider UK marine community should therefore ensure that it is ready to suggest appropriate people.
- A crucial test of the success of MSCC will be whether it is able to produce the funding required to sustain long-term observations.
- Although the Strategy should have clear links to policy, its scope has to be wider than that of the Marine Bill.
- The Strategy should aim to focus on a small number of key issues. Suggestions made at the meeting as to what should be covered included:
  - How best to generate information relating to climate, energy and environment, required by government;
  - Highlighting crucial issues where progress is achievable;
  - Training (a topic in which the Challenger Society has a particular interest).
- It was emphasized that having a Strategy will help with resources being allocated to the right priorities and strengthen arguments for increased funding.
- Maintenance of scientific excellence should be a given.
- The Strategy should place particular emphasis on those activities that cut across agencies.

Other points covered included:

- Monitoring had featured prominently in the Select Committee inquiry and the Secretary of State has promised that the MSCC would give this close attention. Funding of sustained observations should be one of the key issues in the Strategy.
- The training afforded by marine science should be seen as a way of bringing people into maths and natural sciences and of benefitting UK industry. Future policy needs should be borne in mind when developing the Strategy and it would be useful to identify the skills required and the time-scales involved.
- As found by the Inter-Agency Committee on Marine Science and Technology, maintaining the engagement of key government departments over a long period is difficult – but it is vital.
- The balance between directed research and research led by Principal Investigators, and the relationship of the Strategy to other cross-governmental programmes such as Living With Environmental Change, were both discussed. It was recognized that many of the science strategies produced by departments and agencies are cross-disciplinary so it would be necessary to separate out the marine science components.

The MSCC intends to set up mechanisms for engagement with stakeholders, and the Challenger Society should play a role in developing and contributing ideas.

Note: Mechanisms for consultation with stakeholders are not yet in place, but in the interim, suggestions from individuals may be sent to Trevor Guymer (email: thg@noc.soton.ac.uk).

News and Views

Oceanographers cannot ignore groundwater!

The chemistry of the coastal ocean may be much more influenced by the addition of groundwater than many marine scientists realize. Water entering the ocean from the sea-bed at continental margins is not freshwater. As terrestrial groundwater (possibly polluted) flows seawards it flows up over denser, salty water intruding from the ocean, and mixing occurs along the interface in a situation sometimes described as a 'subterranean estuary'. The mixture of water then enters the ocean having passed through coastal sediments.

Because of its history, this groundwater must enrich coastal waters in a wide range of constituents, including nutrients, metals and organic material. In the case of the Atlantic, the total volume of submarine groundwater discharged annually has been estimated at $2\text{–}4 \times 10^{13}\,\text{m}^3$ – 80–160% of the volume of freshwater entering the Atlantic Ocean from rivers (including the Amazon). This means that the addition of nutrients from submarine groundwater could be more important than river flow, and that groundwater plays a significant role in the global carbon cycle.

This estimate (reported in *Nature Geoscience,* **1**, No.5) was made by constructing a budget for the radium isotope ^{228}Ra in the upper Atlantic. 12% of this radium is lost each year by radioactive decay (plus a small loss by scavenging). To maintain steady state, there must be an equivalent flux from continental margins, as ^{228}Ra released from deep-sea sediments does not enter the uppermost 1000 m of the ocean. It was calculated that only 46% of the loss in ^{228}Ra from radioactive decay is replenished by input from dust, rivers and coastal sediments, so the remainder must come from submarine groundwater discharge.

How the Gulf Stream affects the entire troposphere

The Gulf Stream transports large amounts of heat from the tropics to higher latitudes, and it is well known that it affects the overlying atmosphere though large fluxes of heat and water vapour, and is associated with the generation of cyclonic weather systems and low cloud. However, detailed research using a combination of operational weather analyses, satellite observations and an atmospheric general circulation model show that the Gulf Stream influences not only the air/sea boundary layer, but the entire thickness of the free troposphere (*Nature*, **452**, No. 7184).

A narrow band of precipitation along the Gulf Stream is the result of surface wind convergence, resulting from atmospheric pressure adjustments to the marked sea-surface temperature gradients associated with the current. Confirmation that the convection and cloud formation associated with this rain band extend into the upper troposphere is provided by very low cloud-top temperatures, and frequent lightning which indicates cold ice clouds. This means that the Gulf Stream can affect the entire atmosphere locally, and by forcing planetary (Rossby) waves, possibly also influence remote regions.

The authors suggest that this discovery may contribute to our understanding of the processes involved in climate change, because the Gulf Stream is the upper limb of the Atlantic meridional overturning circulation, which is predicted to weaken in response to global warming.

Hurricanes really are getting stronger – or perhaps not ...

It has been generally assumed that global warming is inevitably leading to an increase in the intensity and/or frequency of tropical cyclones because they are powered by energy from the sea-surface. Actually demonstrating this has been proving tricky, but the evidence is accumulating.

For example, a study published in 2007 by Holland and Webster found that over the past century, long-period variations in the frequency of tropical cyclones in the North Atlantic have occurred as three relatively stable phases separated by sharp transitions. Each phase saw 50% more hurricanes than the previous one, and was associated with a distinct range of sea-surface temperatures (SSTs) in the eastern Atlantic. Overall, there appears to have been a marked 100-year trend with increases of > 0.7 °C in SST and of >100% in hurricane numbers. The authors conclude that the overall trend in SSTs and hurricane numbers is strongly influenced by greenhouse warming.

Research published in September 2008 (*Nature,* **455**, 92–5) involved using an archive of satellite records to determine the maximum intensities that cyclones achieve during their lifetimes. It was found that for the top 30%, there has been a significant upward trend in wind speed, as much as $\sim 0.3\,\text{m}\,\text{s}^{-1}\,\text{yr}^{-1}$ for the strongest cyclones. The most marked increases occurred in the North Atlantic. Over much of the tropics, it has been hard to determine trends in cyclone intensity, partly because of the unreliability/patchiness of the observational record. A study of cyclone frequency published in 2005, using data from 1877–1998 for tropical cyclones developing over the northern Indian Ocean, found that in months when cyclones are most common, their frequency over the Bay of Bengal increases, whereas in transitional monsoon months their frequency decreases. More generally, the study found an increase in the frequency of the most intense cyclones, and identified, for various months of the year, a number of multi-decadal cycles in cyclone frequency, and a strong link with the El Niño–Southern Oscillation cycle.

As far as the western North Pacific is concerned, there is disagreement as to whether an increase in the frequency of intense typhoons is a trend, or reflects large interdecadal atmospheric cycles which influence the frequency of intense typhoons.

Since Hurricane Katrina, there has been a focus on a cyclone's potential for destruction. Research has shown that – because of longer lasting storms and greater intensities – the total dissipation of power over a cyclone's lifetime has increased markedly since the mid-1970s. Power dissipation is highly correlated with tropical SSTs and is believed to reflect well-documented multi-decadal oscillations in the North Atlantic and North Pacific, as well as global warming.

However, if hurricanes are indeed becoming more powerful over time, then this trend should manifest itself in more destruction. An analysis of a long-term dataset of hurricane damage in the United States shows no upward trend once the data had been adjusted to remove the effects of increase in population densities near the coast.

Finally, the results of modelling studies reported in a recent *Nature Geoscience* (Vol.1, No.6) indicate that greenhouse warming *per se* is not necessarily going to lead to many more hurricanes in the Atlantic, and may lead to a reduction. The researchers conclude that increases in hurricane activity in the Atlantic do not result simply from raised SSTs, but from the fact that the tropical Atlantic has been warming more quickly than the other tropical oceans, which favours northward displacement of the Intertropical Convergence Zone in the Atlantic, and other conditions that encourage cyclone development.

Kelp, clouds and anti-oxidants

It seems that the typically cloudy British holiday weather could, at least in part, be caused by stressed seaweed! When under stress, kelps release large quantities of iodine into the coastal atmosphere, where it may contribute to cloud formation. During low tide, when kelp is exposed, it may be stressed by high light levels, desiccation and the presence of atmospheric ozone.

Recent research* using X-ray absorption spectroscopy has shown that kelps store iodine in the form of iodide, which detoxifies aqueous oxidants and ozone. The reactions with ozone result in the release of high levels of molecular iodine and the consequent formation of hygroscopic iodine oxides, which result in small particles which are the precursors to cloud condensation nuclei. Increased production of cloud condensation nuclei is believed to lead to more small cloud droplets, and result in clouds that reflect more sunlight and last longer than clouds made up of fewer, larger droplets.

Kelps also release iodide into the sea in response to attacks by pathogens such as bacteria, viruses and fungi, and large amounts of iodine oxide and volatile halocarbons can be detected in the atmosphere above kelp beds.

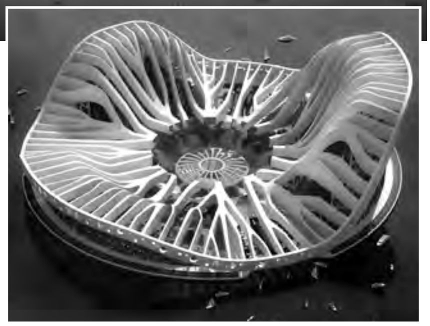
Kelps accumulate iodine more efficiently than any other living organism, and for a long time were the only source of the iodide widely used as an antiseptic. Now, kelp's production of iodide in response to oxidative stress is the first production of an inorganic oxidant to be observed in a living system. In experiments complementary to the fieldwork, iodide was found to effectively scavenge reactive oxygen species in human blood cells.

Proceedings of the National Academy of Science, May 13, 2008, **105**, No.19, 6957.

'Energy islands'

Inspired by the work of Jacques-Arsène d'Arsonoval (a 19th-century French physicist) a team of British architects, including Dominic and Alex Michaelis and Trevor Cooper-Chadwick, are aiming to build a network of 'energy islands'. These will be floating hexagonal platforms of reinforced concrete and corrosion-resistant metals that would support wind turbines, wave-energy converters and solar panels. The islands would also carry OTEC plants (ocean thermal energy converters) which, at low latitudes, exploit the temperature difference between warm surface waters and cold waters below the permanent thermocline. It's estimated that each island complex could produce about 250 MW, and that 50 000 energy islands could meet the world's energy requirements.

Life on lilypads



Above *Ecopolis seen from below.*
Inset *The underlying structure, inspired by the waterlily* Victoria amazonica.
Below *An artist's impression of lilypads floating off a city at night.*

As sea-level continues to rise over coming decades, there will undoubtably be millions of displaced people, especially as many of the world's most populous cities are coastal and low-lying, and some are even sinking (*Ocean Challenge*, Vol.15, No.1, 13–17).

Perhaps the most ambitious solution proposed to date is the vision of the Belgian architect Vincent Callebaut – populated islands, which will float around the oceans. The structure of an 'Ecopolis' is directly inspired by the 3-metre leaves of the giant Amazonian waterlily. According to Vincent Callebaut's website, one 750 m-diameter 'lilypad' should be able to support 50 000 people.

The vision is that by employing every kind of renewable energy available (wind, solar, photovoltaic, hydraulic, tidal, osmotic, biomass ...) each lilypad will be carbon-neutral. Food will be produced in aquaculture and 'biotic corridors' on and under the island; CO_2, water and waste will all be recycled.

Increasing biodiversity is encouraged by a central lagoon, which collects and purifies rainwater and, being below sea-level, acts as ballast.

Perhaps one day such structures will be built, and may benefit the displaced poulations of large cities like Tokyo but it seems doubtful that they will be populated by the homeless millions from Bangladesh and the mid-ocean islands. *Ed.*

Pioneer of marine fisheries ecology, David Henry Cushing FRS (1920–2008)

Challenger Society members will be sorry to hear that David Cushing died on 14 March, on his 88th birthday. He was Britain's foremost marine fisheries ecologist, and in a career of more than 50 years, he did much to make the subject a science in its own right.

He was born in Alnwick, Northumberland on 14 March 1920, the son of a schoolmaster. He was educated at the Duke's School, Alnwick, and the Newcastle-upon-Tyne Royal Grammar School, before going up to Balliol College, Oxford, where he gained his MA, and also in 1950 his D Phil., on the subject of 'Vertical migration of the zooplankton'. After war service in the Army from 1940 to 1946, he joined the Fisheries Laboratory, Lowestoft (now CEFAS) as a Scientific Officer. He eventually became Deputy Director and Head of the Fish Population Dynamics Division from 1974 until his retirement in 1980. He was also active in ICES, serving on both the Advisory Committees on Fisheries Management and on Marine Pollution, as well as on the Biological Oceanography Committee and the Herring Working Group. His achievements in fisheries science were widely recognized, through his election as a Fellow of the Royal Society in 1977, and numerous international prizes and medals.

His early scientific work in the late 1940s was on the development of acoustic methods for the study of both fish and zooplankton. Using small boats and primitive equipment (including condoms and ping-pong balls) he and his co-workers began grappling with the perennial problems of calibration, target strength estimation and species identification from their acoustic return. Later, he continued his work on zooplankton, by conducting plankton surveys at sea, including no fewer than 13 cruises between March and June 1954 off the north-east coast of England. In those days he was able to obtain the use of two ships for three months, merely by asking the question and getting approval from his Director, Michael Graham in only 10 minutes! The results of this work, 'Studies on a *Calanus* patch', were published in the *Journal of the Marine Biological Association* in 1963, and demonstrated the great importance of grazing by zooplankton, as well as nutrient-limitation, in marine planktonic ecosystem dynamics.

Soon after this he began research into the decline of North Sea herring, following the first great crash of the East Anglian herring fishery in 1955, which had devastating effects on the East Anglian and Dutch economies. This led to a major series of meetings convened by ICES, with Cushing pressing the Herring Working Group to obtain estimates of abundance *independent of* catch and effort data. To determine separately the fishing mortality on the adult stock and on the juvenile stock, a programme of tagging the adults on the Downs spawning fishery and the juveniles on the Bløden Ground was established. These tagging experiments were later successfully complemented by a large-scale programme, initiated by Cushing, in which high-speed plankton samplers were used to catch herring larvae directly and quantitatively.

This work on fish population dynamics stimulated his abiding interest in the fundamental relationship between parent stock size and the abundance of their offspring (the stock–recruitment relationship). David introduced the concept of 'recruitment overfishing' by which the parent stock is reduced to a degree that the entry of young fish to the fishery (i.e. recruitment) suffers, complementary to the Beverton and Holt concept of 'growth overfishing' (reducing the potential of the fishery by taking animals that are still growing). However, even around a constant stock size, recruitment is often extremely variable, leading David into the study of climate and its possible effects, which became his fourth and most enduring research focus. In 1973, he proposed the 'Match–Mismatch hypothesis' to explain the natural regulation and variation of fish populations in terms of the timing of larval production relative to that of their food. This is perhaps his finest and most famous construct, one of those simple ideas which seem obvious only after they have been proposed. He was delighted when he recently heard (some 35 years later, and within one month of his death) that the complexities of his Match–Mismatch mechanism had been convincingly demonstrated in a detailed model study by a young Ph.D student at Imperial College, London.

Cushing published many books, including *Marine Ecology and Fisheries* (CUP, 1975), *The Provident Sea* (CUP, 1988) and *Population Production and Regulation in the Sea: A Fisheries Perspective* (CUP, 1995). In these, the whole of fisheries science – the observation and modelling of primary and secondary production, the identity and the population dynamics of fish stocks, the temporal changes in their physical and chemical environments, and thus the regulation of fish populations by both nature and by man – are laid out in a modern and unified way. He would have regarded the ecosystem approach to fisheries management as being obviously necessary, having done so much to lay the scientific foundations on which it is based.

David Cushing was always determined to test the accepted wisdom for himself, however 'well-established' it might be. He had an unerring ability to identify the obstacles that were hindering progress, and was positively fizzing with energy and determination to sweep these away. His enthusiasm, his iconoclasm, and his mischievous sense of humour made him an inspiration to several generations of younger colleagues. His official retirement merely ushered in a new and equally productive phase of his long career, as he established the new *Journal of Plankton Research* in 1979, and then for 22 years acted as its Executive Editor until stepping down in 2001. It would be widely acknowledged that *JPR*, now one of the leading international marine science journals, was largely the result of this one man's vision and drive.

David is survived by his wife Diana and their daughter Camilla.

Bob Dickson
CEFAS

John Shepherd
National Oceanography Centre Southampton

John Woods
Imperial College, London

Keith Brander
DTU Aqua

Modelling the marine biota: A tribute to Mike Fasham (1942–2008)

The field of marine ecosystem modelling has proliferated rapidly over recent decades, with ever more sophisticated models being developed to study the role of the marine biota in global biogeochemistry. Nobody has made a greater contribution to this progress than Mike Fasham who will be especially remembered for his famous 'Fasham–Ducklow' model, published under the title 'A nitrogen-based model of plankton dynamics in the oceanic mixed layer' (Fasham, Ducklow and McKelvie, *Journal of Marine Research*, 1990). With nearly 500 citations, it is the single most important paper in the marine biogeochemical modelling literature, and its continuing high citation rate is testament to its importance in laying the foundations for the ongoing study of marine ecosystems and their interactions with the physicochemical environment.

This paper was, however, but one of the many articles of the highest quality that Mike wrote over the years. He also set up the Biological Modelling Group at the Southampton Oceanography Centre, which has gone from strength to strength ever since. Mike is also remembered for the leading role that he played in the Joint Global Ocean Flux Study (JGOFS) programme, with his appointment of chair of the JGOFS International Committee from 1998 to 2000. Fittingly, he edited the book *Ocean Biogeochemistry – The role of the Ocean Carbon Cycle in Global Change* (Springer, 2003) which provided a synthesis of the tremendous successes achieved by JGOFS in monitoring the state of the ocean and predicting its future course in the face of climate change. In recognition of his many outstanding achievements, Mike was elected a Fellow of the Royal Society in 2000 and awarded the Challenger Medal – the Challenger Society's most prestigious award – in 2002.

Mike first set his sights on being a scientist during his school days in London in the 1950s. Enjoying the intellectual challenge of academic life, he progressed to Birmingham University where he cultivated interests such as relativity and quantum mechanics (heady topics for a budding biogeochemical modeller!), graduating in physics in 1963, and being awarded a Ph.D in geophysics in 1968. Soon afterwards he joined the National Institute of Oceanography, where two remarkable changes came about that were to shape his career. First, Mike was immediately transfixed by the then-new world of computers, enthused by Jim Crease, a physical oceanographer who was in charge of the newly formed computer department at the NIO. Mike was soon a regular sea-goer, playing an important role in setting up shipboard computer systems with which to log and analyse data. Second, he was introduced by Martin Angel to the bewildering yet fascinating world of marine biology, and indeed he was to join the Marine Biology group. Working with Martin, Mike applied statistical methods to investigate the spatial patterns of zooplankton in the North Atlantic as measured by the Longhurst–Hardy plankton recorder. The work demonstrated that animals such as ostracods and copepods are patchily distributed, leaving Mike to ponder as to possible causes, such as predation, social attraction, turbulence and the physico-chemical environment.

While very much enjoying his time at sea, it was the application of mathematical theory to analyse the resulting data that was nevertheless Mike's primary scientific focus. In 1976 he met John Steele, one of the pioneers of marine ecosystem models. Steele, and Gordon Riley before him, had developed simple models incorporating phytoplankton and/or zooplankton, and shown how the use of differential equations could be used to study the seasonal succession of plankton in marine waters. Up until this time Mike had been using statistical methods and steady state flow analyses, but he was soon to focus his attention on the use of differential equations and master the art of simulation modelling.

The Joint Global Ocean Flux Study, starting in the late 1980s, captured Mike's imagination and provided the perfect opportunity to demonstrate his modelling acumen. The stated aims of JGOFS were to determine and understand the dynamics of carbon and associated nutrient elements in the ocean, and to develop a capability to predict on a global scale the response of ocean biogeochemistry to anthropogenic perturbations, in particular those related to climate change. This was Big Science, involving internationally coordinated field programmes and, of course, modelling. With his background in going to

Mike Fasham – pioneer in modelling the role of marine ecosystems in global biogeochemistry

sea and working directly with those collecting the data, as well as his modelling skills, Mike was ideally placed to take the initiative. Always happy to share his ideas with others, he epitomized the spirit of cooperation between scientists of different nationalities and disciplines, and in particular between field oceanographers and modellers, that was to make JGOFS such a success.

Mike repeatedly emphasized that, in order for modelling to be successful in advancing our understanding of marine systems, careful parameterization of key processes was necessary, along with robust validation through model–data comparison. Addressing these issues effectively is much more easily said than done, yet Mike's work throughout his career is a shining example of how to pay attention to detail, adopt appropriate mechanistic formulations, and use objective optimization methods to permit robust and meaningful conclusions to be drawn. His work is pervaded by immense creativity and depth of insight, qualities that are all too often lost in today's hustle-bustle 'publish or perish' world. JGOFS set him up perfectly. Whereas the ultimate aim of the programme was to make predictions at global scale, a major component was intensive sampling at chosen stations, in order to study particular processes and build up time-series. Mike realized the importance of using the resulting high-quality datasets to constrain models, and much of his work throughout his career was focussed on modelling time-series stations. He applied the Fasham–Ducklow model to address nutrient cycling at the Bermuda time-series site and then moved on to look at other sites in the North Atlantic, as well as elsewhere in the world ocean.

Mike also led the way when it came to incorporating ecosystem models into three-dimensional general circulation models (GCMs) with a view to studying basin-scale or global-scale plankton dynamics. The Fasham–Ducklow model was, for example, incorporated into the Princeton North Atlantic GCM, one of the first such projects of its kind. Fasham-type models are still used today in global ocean biogeochemical models, an example being the Hadley Ocean Carbon Cycle model (HadOCC) that is run by the UK Meteorological Office in both operational and climate simulations. Mike always had in mind the goal 'to construct a reasonably simple model that can be calibrated by observations and will be geographically robust, in the sense that the same model with fixed parameters will give reasonably accurate predictions of biological production in all the major parts of the world ocean' (quoted from Mike's chapter 'Modelling the Marine Biota' in the NATO ASI volume, *The Global Carbon Cycle*, published by Springer-Verlag in 1993). Mike made enormous progress in tackling this most difficult of tasks – modellers today would do well to study and learn from the approaches that he adopted.

Modelling marine ecosystems is as much a social exercise as it is a scientific discipline. Success is achieved through interacting with experts in all manner of fields of study – physics, chemistry, biology, oceanography, mathematics, etc. The very fact that Mike was such a likeable, kind and considerate character gave him a great advantage in this respect. He was always willing to engage in conversation about the latest thinking on marine ecosystem dynamics, or perhaps recent developments in rugby and cricket (or whatever else England were losing at the time!). He enjoyed fruitful collaborations with scientists across the globe – Hugh Ducklow, Vladimir Ryabchenko, Jorge Sarmiento, Kevin Flynn and John Brindley, to name but a few – as well as being an inspirational leader for the modelling group in Southampton. He will be fondly remembered by those who knew him, not just as an ambassador for his profession but for his modesty, enthusiasm, cheerful optimism and humour.

Mike Fasham was born in Edgware, Middlesex, on 29 May 1942. He died on 7 June 2008 after a courageous and dignified battle with cancer over many years. Mike is survived by his wife, Jos, and son Matthew.

Tom Anderson
National Oceanography Centre
University of Southampton

Wave power from two very different sea-serpents

In September, the world's first wave farm was officially inaugurated off the Atlantic coast of Portugal, north of Oporto. Manuel Pinho, Portugal's Minister of Economy and Innovation, travelled by naval frigate to the site, 5 km offshore from Aguçadora, and a Portuguese flag was raised on one of the wave-energy converters.

The Scottish company that built the devices, previously called Ocean Power delivery, has renamed itself Pelamis Wave Power – *Pelamis* is a sea-snake. The individual wave-energy converters float semi-submerged, and indeed resemble large metal sea-snakes (See various video clips on YouTube.)

Each 'snake' consists of several cylindrical sections, 140 m long, linked by compact power conversion modules. Motion of the hinged joints between the cylindrical sections and the power conversion module caused by the passage of waves is resisted by hydraulic rams which extend into the power conversion module, and the motion of the rams pumps high-pressure oil through hydraulic motors, which drive generators which produce electricity. The device is flexibly moored so as to swing head-on to incoming waves.

The project was delayed by more than a year because of problems with floats forming part of the tether to the sea-bed. Installation off Portugal in water slightly deeper than that off Orkney, where trials had taken place, meant that the foam in the floats was damaged by the extra pressure.

Four similar wave-energy converters are being installed off Orkney next year, with seven more due to be deployed off north Cornwall the year after, and there are further projects planned for Norway, Spain, France, South Africa and North America. It is estimated that a 30 MW wave farm (sufficient power for > 20 000 homes) would occupy 1 km^2 of ocean.

Meanwhile, a very different snake-like wave-energy converter is also being developed in the UK. Using a completely different principle from other wave-energy converters, 'Anaconda' is essentially a giant rubber tube, and dispenses with the need for hydraulic rams, hinges and articulated joints. This reduces capital and maintenance costs and the likelihood of breakdowns.

Anaconda is closed at both ends and completely filled with water. It is designed to be tethered so that it lies just below the sea-surface, with one end facing the oncoming waves. As each wave passes it squeezes the tube, causing a 'bulge wave' to travel along just ahead of it (similar to the pressure pulse that travels along arteries). As the wave runs along the outside of the tube, it and the resulting bulge are travelling at the same speed; there is therefore a resonant interaction between the two, and the size of the bulge grows linearly with distance, as it takes energy from the wave. The bulge wave turns a turbine at the far end of the device, and the power produced is fed to shore via a cable.

The Anaconda concept is still at an early stage of development and has only been demonstrated at a very small scale in the laboratory. In collaboration with the Anaconda's inventors and its developer (Checkmate SeaEnergy), a team led by John Chaplin of the University of Southampton is taking the project further. Experiments using tubes with diameters of 0.25 and 0.5 m will be used to assess the device's behaviour in regular, irregular and extreme waves. As well as providing insights into the device's hydrodynamic behaviour, the data will form the basis of a mathematical model to estimate the power that would be generated by a full-scale Anaconda.

A one-third scale model could be built for testing at sea next year, and in about five years' time the first full-size Anaconda could be deployed off the UK coast, in water depths of 40–100 m. Each would be 200 m long and 7 m in diameter. The capital cost per MW is likely to be about £2–3 million, much less than existing wave power converters.

The Anaconda was invented by Francis Farley (an experimental physicist) and Rod Rainey (of Atkins Oil and Gas). Their website on the Anaconda is at www.bulgewave.com. An animation of the Anaconda in action can also be seen at www.checkmateuk.com/seaenergy/links.html *Eds* was focussed on modelling time-series stations. He applied the Fasham–Ducklow model to address nutrient cycling at the Bermuda time-series site and then moved on to look at other sites in the North Atlantic, as well as elsewhere in the world ocean.

Mike also led the way when it came to incorporating ecosystem models into three-dimensional general circulation models (GCMs) with a view to studying basin-scale or global-scale plankton dynamics. The Fasham–Ducklow model was, for example, incorporated into the Princeton North Atlantic GCM, one of the first such projects of its kind. Fasham-type models are still used today in global ocean biogeochemical models, an example being the Hadley Ocean Carbon Cycle model (HadOCC) that is run by the UK Meteorological Office in both operational and climate simulations. Mike always had in mind the goal 'to construct a reasonably simple model that can be calibrated by observations and will be geographically robust, in the sense that the same model with fixed parameters will give reasonably accurate predictions of biological production in all the major parts of the world ocean' (quoted from Mike's chapter 'Modelling the Marine Biota' in the NATO ASI volume, *The Global Carbon Cycle*, published by Springer-Verlag in 1993). Mike made enormous progress in tackling this most difficult of tasks – modellers today would do well to study and learn from the approaches that he adopted.

Modelling marine ecosystems is as much a social exercise as it is a scientific discipline. Success is achieved through interacting with experts in all manner of fields of study – physics, chemistry, biology, oceanography, mathematics, etc. The very fact that Mike was such a likeable, kind and considerate character gave him a great advantage in this respect. He was always willing to engage in conversation about the latest thinking on marine ecosystem dynamics, or perhaps recent developments in rugby and cricket (or whatever else England were losing at the time!). He enjoyed fruitful collaborations with scientists across the globe – Hugh Ducklow, Vladimir Ryabchenko, Jorge Sarmiento, Kevin Flynn and John Brindley, to name but a few – as well as being an inspirational leader for the modelling group in Southampton. He will be fondly remembered by those who knew him, not just as an ambassador for his profession but for his modesty, enthusiasm, cheerful optimism and humour.

Mike Fasham was born in Edgware, Middlesex, on 29 May 1942. He died on 7 June 2008 after a courageous and dignified battle with cancer over many years. Mike is survived by his wife, Jos, and son Matthew.

Tom Anderson
National Oceanography Centre
University of Southampton

Wave power from two very different sea-serpents

In September, the world's first wave farm was officially inaugurated off the Atlantic coast of Portugal, north of Oporto. Manuel Pinho, Portugal's Minister of Economy and Innovation, travelled by naval frigate to the site, 5 km offshore from Aguçadora, and a Portuguese flag was raised on one of the wave-energy converters.

The Scottish company that built the devices, previously called Ocean Power delivery, has renamed itself Pelamis Wave Power – *Pelamis* is a sea-snake. The individual wave-energy converters float semi-submerged, and indeed resemble large metal sea-snakes (See various video clips on YouTube.)

Each 'snake' consists of several cylindrical sections, 140 m long, linked by compact power conversion modules. Motion of the hinged joints between the cylindrical sections and the power conversion module caused by the passage of waves is resisted by hydraulic rams which extend into the power conversion module, and the motion of the rams pumps high-pressure oil through hydraulic motors, which drive generators which produce electricity. The device is flexibly moored so as to swing head-on to incoming waves.

The project was delayed by more than a year because of problems with floats forming part of the tether to the sea-bed. Installation off Portugal in water slightly deeper than that off Orkney, where trials had taken place, meant that the foam in the floats was damaged by the extra pressure.

Four similar wave-energy converters are being installed off Orkney next year, with seven more due to be deployed off north Cornwall the year after, and there are further projects planned for Norway, Spain, France, South Africa and North America. It is estimated that a 30 MW wave farm (sufficient power for > 20 000 homes) would occupy 1 km^2 of ocean.

Meanwhile, a very different snake-like wave-energy converter is also being developed in the UK. Using a completely different principle from other wave-energy converters, 'Anaconda' is essentially a giant rubber tube, and dispenses with the need for hydraulic rams, hinges and articulated joints. This reduces capital and maintenance costs and the likelihood of breakdowns.

Anaconda is closed at both ends and completely filled with water. It is designed to be tethered so that it lies just below the sea-surface, with one end facing the oncoming waves. As each wave passes it squeezes the tube, causing a 'bulge wave' to travel along just ahead of it (similar to the pressure pulse that travels along arteries). As the wave runs along the outside of the tube, it and the resulting bulge are travelling at the same speed; there is therefore a resonant interaction between the two, and the size of the bulge grows linearly with distance, as it takes energy from the wave. The bulge wave turns a turbine at the far end of the device, and the power produced is fed to shore via a cable.

The Anaconda concept is still at an early stage of development and has only been demonstrated at a very small scale in the laboratory. In collaboration with the Anaconda's inventors and its developer (Checkmate SeaEnergy), a team led by John Chaplin of the University of Southampton is taking the project further. Experiments using tubes with diameters of 0.25 and 0.5 m will be used to assess the device's behaviour in regular, irregular and extreme waves. As well as providing insights into the device's hydrodynamic behaviour, the data will form the basis of a mathematical model to estimate the power that would be generated by a full-scale Anaconda.

A one-third scale model could be built for testing at sea next year, and in about five years' time the first full-size Anaconda could be deployed off the UK coast, in water depths of 40–100 m. Each would be 200 m long and 7 m in diameter. The capital cost per MW is likely to be about £2–3 million, much less than existing wave power converters.

The Anaconda was invented by Francis Farley (an experimental physicist) and Rod Rainey (of Atkins Oil and Gas). Their website on the Anaconda is at www.bulgewave.com. An animation of the Anaconda in action can also be seen at www.checkmateuk.com/seaenergy/links.html *Eds*

Sherkin Island Marine Station – a jewel of the Emerald Isle

Gary Caldwell

With a coastline stretching for almost 1500 km, it is perhaps unsurprising that the Irish have a deep rooted maritime heritage. Ireland, whilst offering a wealth of marine habitats for the biologist to study, has historically been poorly served by the necessary research infrastructure. Thankfully, with the growth of the Irish economy, significant inward investment and the drive for science-based knowledge and management, this situation has reversed. Attention is understandably drawn to large, superbly equipped facilities such as the Martin Ryan and the Irish Marine Institutes; however, such developments tend to distract from some of the more established yet perhaps less well known resources that Ireland has to offer. One such unsung stalwart of Irish marine biological activity has been the Sherkin Island Marine Station (SIMS), situated in the spectacular setting of Roaringwater Bay, Co. Cork (Figure 1).

The marine station was established in 1975 by the charismatic and passionate partnership of Matt Murphy and his late wife Eileen. Neither individual hailed from a scientific background, but their burning desire to study and understand the marine life of Roaringwater Bay inspired them to invite a small band of budding young biologists to stay with the Murphy family and begin what would prove to be a successful monitoring programme.

Subsequently many of the UK and Ireland's biologists have passed through SIMS at some point in their careers. Following Eileen's death in 1979, Matt, with the unflinching support of his seven children, continued with the daunting challenge of not just maintaining the station, but expanding and improving its profile both regionally and nationally. This arduous task was made all the more difficult as the station received no state funding, and remains to this day entirely privately run and funded.

The station's life-blood is the eclectic group of students who brave the treacherous North Atlantic weather to undertake detailed monitoring programmes of the flora and fauna of Roaringwater Bay. The surveys are inclusive of, but not restricted to, the plankton, rocky shore

Figure 1 ***Above*** *The setting of Sherkin Island in Roaringwater Bay off south-western Ireland. The star indicates the position of the Marine Station.* ***Below*** *Aerial view of the Marine Station.*

Figure 2 *It's a bod's life: collecting water samples in Roaringwater Bay using the Marine Station's boat.*

intertidal communities, soft sediment communities and otter populations. The terrestrial biology of the Bay's numerous islands is also covered by botanical and entomological surveys. The students, affectionately referred to as Sherkin 'bods', give freely of their time and energy in exchange for meagre bursaries (which invariably bolster the takings of the island's two pubs), all the root vegetables they can eat, and some less than luxurious accommodation surrounded on all sides by cattle. Such spartan board and lodgings might sound decidedly unappealing, but the hardships pale into insignificance when compared with the priceless experience of several months' survey work in some of the most beautiful surroundings that Europe has to offer – a season spent at SIMS will always be indelibly ingrained on every bod's heart.

Life as a Sherkin bod was always challenging. Aside from the restricted range of culinary ingredients, the limited cash flow and the ever-present essence of cow, one could not claim that Matt was an easy Director to work under. A forceful personality, coupled with a clear and rigid view of what each bod should be doing, put many a bod on a collision course with the Matt Murphy style of directorship. Many bods have crossed swords with Matt during their tenure, often because they wanted to do things differently, but we all learned very early on that it was the 'Murphy way or the highway'. Such obstinacy was often difficult for we bods to take, but the prospect of having to leave the station was normally a sufficient threat to force even the most ardent critic to bite his tongue and get on with the job.

One of the true strengths of SIMS has been the focus on the collection and maintenance of detailed long-term datasets (see for example www.sherkinmarine.ie/survey.htm). The 'snapshot' nature of scientific funding in the UK and Ireland generally precludes support for long-term datasets, with the result that subtle yet significant shifts within ecosystems may be overlooked. As the nature and composition of life in our oceans appears to be changing rapidly, the intrinsic value of long-term datasets becomes even more apparent.

Of the Sherkin observations, the rocky shore and phytoplankton datasets are the longest established, and both contain a wealth of vitally important information. Despite the laudable goal of SIMS to collect and archive these data, a major criticism that has been levelled at the Sherkin Island operation is the issue of access to, and availability of, data. For whatever reason, Matt has been resolute in his refusal to publish in the scientific mainstream, and as a result the wealth of information contained within the Sherkin archives is greatly under-used and undervalued.

As Matt approaches a well deserved retirement, he accepts fewer bods into the marine station. Perhaps he too now sees the need to publish the Sherkin data while he still has the energy. 2003 saw the publication of *The Ecology of the Rocky Shores of Sherkin Island – a Twenty-Year Perspective*, by Gillian Bishop. Gillian was one of the initial cohort of Sherkin bods and accepted the daunting challenge of collating and published the rocky shore intertidal data from 60 sites around the Co. Cork coastline. The book brings together the Sherkin data in an easily digested species-by-species format. The analysis, while rather rudimentary, is still intellectually valuable and would be amenable to more robust analyses in the future. The book, which also combines elements of the history of the station and some general aspects of rocky shore ecology, makes a useful contribution to temperate rocky shore ecology and finally begins to demonstrate the intrinsic value of the Sherkin datasets.

As the time approaches when Matt will finally relinquish his hold on the Sherkin tiller, we must wonder what the long-term future of the station will be. Will one or more of the Murphy children assume directorship or will SIMS simply pass into memory? What will be the ultimate fate of the extensive Sherkin data? Will we see publication of the plankton and other datasets? I believe that one thing is for certain, if SIMS is to survive it must actively seek to engage with other marine institutes and universities in the region and nationally. Perhaps SIMS should look to encourage final-year undergraduates to conduct their research projects there, thereby allowing continuity of the Sherkin datasets. These are all important questions to be addressed if there is to be a future for SIMS. Personally speaking, I would mourn the passing of a marine station with a colourful history and equally colourful Director. I fervently hope that we will see a smooth transition from one Murphy generation to the next, but who can tell.

Gary Caldwell is a Lecturer in Marine Biology, Newcastle University. He was a Sherkin Island zooplankton bod in 1999.

Going for Gold!

Who will win the race to exploit ores from the deep?

Maria Baker and Christopher German

Gold, copper, zinc, lead, silver, barium, nickel and cobalt are just some of the metals whose ores deep within the ocean are becoming economically ripe for exploitation. Three decades ago, it was generally thought that the primary activity for the mining industry in the deep sea would be recovery of manganese nodules for their commercially valuable trace constituents, notably nickel, copper and cobalt. Between 1974 and 1982, more than 1 billion US dollars was spent by private companies and governments on manganese nodule investigations, but none of these endeavours resulted in commercial success, owing in large part to overestimates of the potential resource, high extraction costs, political intervention and collapsing metal prices, particularly in the case of nickel. However, today, renewed efforts in deep-sea metal extraction are underway as a result of soaring metal prices (notably for gold and copper) in response to demands from fast-growing 'new' economies such as India, China and Brazil.

In international waters, oversight of the deep sea floor outside any national jurisdiction is provided by the International Seabed Authority (ISA) – an autonomous international body established when the UN Law of the Sea Convention came into force in 1994 (see Box on p.13). There are currently eight groups from around the globe with contracts with the ISA for sea-bed exploration of manganese nodules in international waters. During the last few years, another extremely viable commodity found in the marine environment has begun to be pursued – sea-floor massive sulphide (or 'SMS') deposits formed by submarine hydrothermal venting. SMS deposits are more or less homogeneous masses of metal sulphide, which when fresh are dark metallic greys and golds, and age to rusty oranges and browns. They contain significant concentrations of base metals such as cadmium, lead and copper as well as more precious metals such as platinum, silver and gold. Although at a very early stage of exploration, the SMS industry is already extremely active, with the potential to eclipse manganese nodule mining in the race to extract minerals from the deep marine environment.

Mining in the marine environment is certainly not a new pursuit. Throughout much of the past century and in some cases even earlier, there has been mining of alluvial deposits for heavy metals (gold, tin, titanium, zirconium and others), and of diamonds and aggregates, from beaches and from shallow waters. Advanced marine technologies are currently in use on the sea-bed off the Atlantic coast of southern Africa to recover gem-quality diamonds, down to depths of 250 m. Deeper waters (down to ~4000 m) have recently become a standard operating environment for the offshore hydrocarbon industry, and with the infrastructure that has resulted – not least the worldwide availability of deep-diving remotely operated vehicles (ROVs) – the sea-floor mining industry is poised to follow suit.

Formation and occurrence of SMS deposits

Massive sulphide deposits can be formed at the sea-floor wherever cold seawater comes into contact with hot, fresh, volcanic or magmatic rocks – at mid-ocean ridges, at ocean islands and seamounts, in the flanks of island arcs and at back-arc spreading centres.* The very first hydrothermal deposits to be discovered were in the deep axial basins of the Red Sea in the mid-1960s, but it was in the late 1970s that the first actively circulating hydrothermal systems were discovered on the Galápagos Spreading Centre in the eastern Pacific. Not only did these hydrothermal systems have massive sulphides associated with them,

*At mid-ocean ridges basaltic magma rises to the sea-bed and erupts to form new ocean floor. Oceanic islands and seamounts are also formed by volcanic activity; back-arc spreading centres are special forms of mid-ocean ridge that arise, as their name suggests, landward of the island arcs that are formed whenever the ocean floor of one tectonic plate is thrust (subducted) beneath the ocean floor of another. The most famous examples of such arcs (e.g. the Marianas Arc) occur in the western Pacific.

The photograph in the title artwork is used by courtesy of the University of Bremen.

but they were also teeming with life previously unknown to science: this discovery has recently been recognized as one of the top 30 scientific discoveries of the entire 20th century!

The common basics to all hydrothermal circulation are as follows: as cold oxygenated seawater penetrates downward into young crust it becomes progressively warmer and undergoes a series of chemical exchange reactions with the rocks with which it is in contact (Figure 1(a)). As oxygen and other relatively oxidized chemical species are consumed (e.g. by iron(II) oxidation), the circulating fluids become anoxic as well as acidic, and acquire high concentrations of numerous metals dissolved from the host rock – notably iron, manganese, copper, zinc and lead, but also precious *trace* metals including silver, platinum and gold. Eventually, a point is reached at which this chemically laden fluid is heated to such an extent that it becomes buoyant and begins to rise back toward the sea floor. It is the delivery of this ore-forming fluid from below, followed, as it reaches the sea bed, by mixing with overlying cold oxygenated seawater, that gives rise to the formation of massive sulphides, both at the sea floor (often in the form of chimneys 10s of metres tall) (Figure 1(b)), and in the underlying 'stockwork' – the network of fluid-flow channels that feed an active vent system at the sea floor (cf. Figure 1(a)).

These massive suphide deposits range in size from several thousand tonnes to around 100 million tonnes and are highly enriched in copper, zinc, lead and cadmium, in addition to gold and silver. The ore bodies are made up of loose material such as fallen chimneys, along with recrystallized sulphides. They are very similar to ores that are being mined on land, which formed in ancient oceans almost 3000 million years ago. In the past 30 years, many more deposits of this type have been discovered around the globe at both active and inactive vent sites. Most vents found to date are located at depths between 1500 and 3500 m, although a few have been discovered in far shallower waters.

The biology of hydrothermal vents

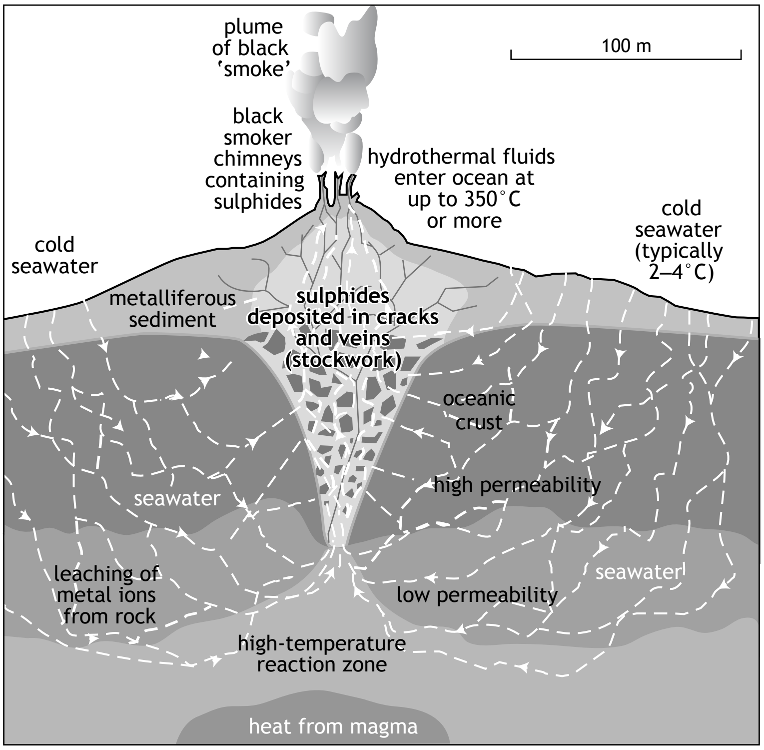
Close investigation of hydrothermal vent sites has revealed a remarkable way of life for many of the local inhabitants. These environments are extreme for life owing to the ever-changing gradients of chemistry and temperature of the fluids emanating from vents, and the ephemeral nature of the vent fields. Nevertheless, most active (established) vent sites studied to date are characterized by dense communities of exotic fauna which are sustained by the process of chemosynthesis, relying on chemo-autotrophic microbes which use chemicals such as hydrogen sulphide or methane supplied by the hydrothermal vent as their energy source. More than 500 species new to science have been discovered in the first 30 years of vent research, making an average rate of one new species every two weeks.

These animals are specially adapted for life at the vents and are different from the fauna in the surrounding deep sea. Some of the key inhabitants associated with hydrothermal venting are tubeworms, large bivalves, shrimp, gastropods

Figure 1 ***(a)*** *Schematic diagram to illustrate the environment in which massive sulphide deposits are formed within the ocean crust and at the sea-bed. Black smoker chimneys result when the metal-rich fluid reaches the sea-bed without having mixed with cold seawater in the upper part of the crust; when significant mixing occurs, the resultant fluids can be substantially cooler and are typically much less chemically enriched as they enter the ocean, having deposited much of their mineral content within the crust (these fluids are often also those most preferred by chemosynthetic organisms).*

(b) *The black smoker chimney 'Candelabra', formed at one of a number of hydrothermal vents located within the Logatchev hydrothermal field at ~15°N, at around 3000 m depth on the Mid-Atlantic Ridge. The black 'smoke' is mainly metal sulphide particles, but also oxides and hydroxides.*

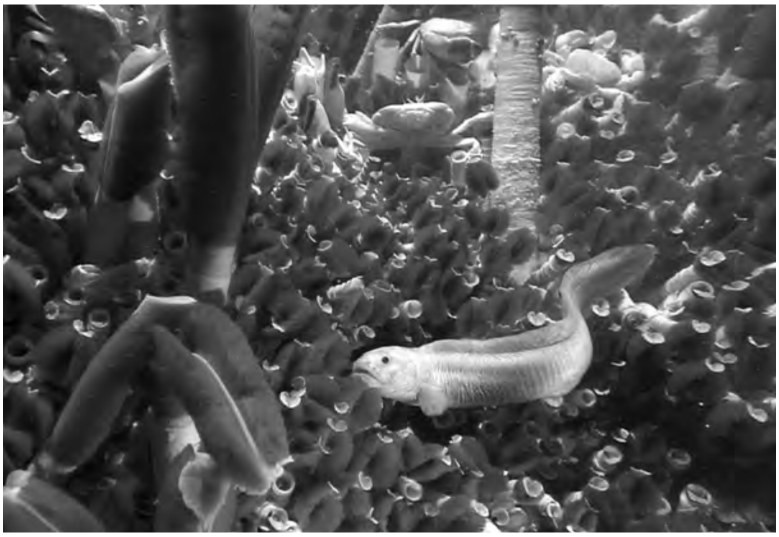
Photo courtesy of MARUM, University of Bremen



(a)

(b)

SMS deposits are found at the sea bed in the form of chimneys, and within the stockwork at shallow depths within the ocean crust



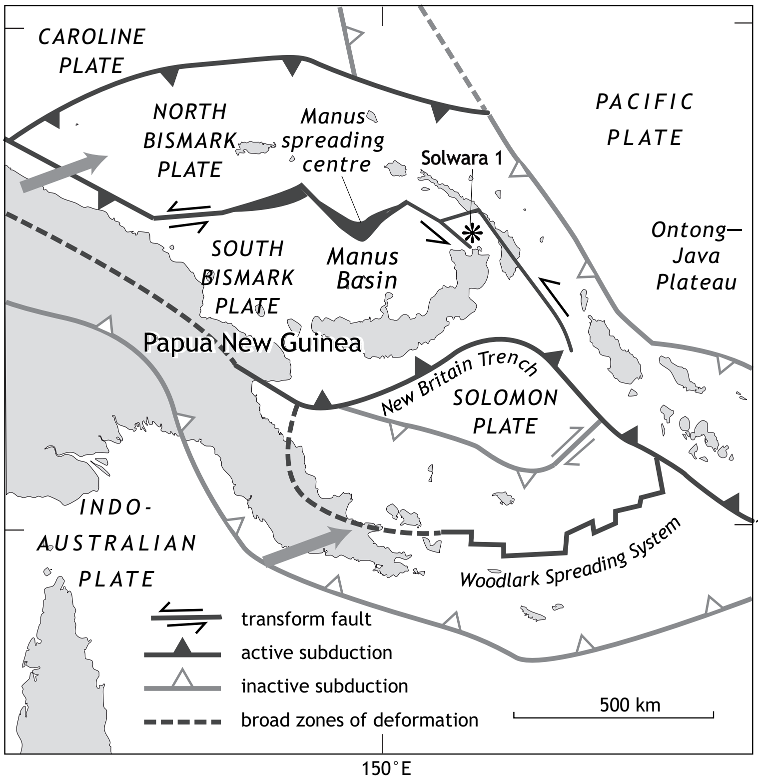
Active vent sites support flourishing communities of unique animals that could be adversely affected by mining of SMS deposits

Figure 2 *Giant tubeworms,* Riftia pachyptilla*, with zoarcid fish (commonly known as eelpouts) and galatheid crabs (also known as squat lobsters) inhabit an active vent at 2600 m depth on the East Pacific Rise (to the west of Mexico). The tubeworms are distinct from those found at vent sites on the Juan da Fuca Ridge in the north-east Pacific, as are the invertebrates and fish that live in association with them.*

Courtesy of Emory Kristof

Nautilus's Solwara 1 site is on a volcanic mound in a zone of rifting between two transform faults

Figure 3 *Tectonic map of the area around Papua New Guinea, showing the position of the Solwara 1 site at the eastern end of the Manus back-arc spreading centre system. This is just one area under investigation by sea-bed mining companies; for the positions of prospecting areas (both granted and under application) in the vicinity of Papua New Guinea, see Figure 4. (Grey arrows indicate relative plate motions.)*



and crabs (Figure 2). In addition, the chemosynthetic bacteria can grow into thick mats which can attract grazing animals from the surrounding waters and sea-bed.

Scientific investigations have only just begun to unravel the potential for exciting discoveries in these environments. Currently, there are major gaps in our knowledge of life at vents in terms of the adaptation of animals to long-range dispersal and (often rapid) colonization processes, and of genetic diversity and variability at vents among and between different ocean basins. In particular, there is a lack of knowledge about what fauna might inhabit extinct/inactive sulphide deposits which, inevitably, will be far more attractive to future economic exploitation than the active sites, spewing hot acidic fluids, that have attracted most scientific attention to date. There are likely to be hundreds, if not thousands, of undiscovered vents around the globe, in all ocean basins.

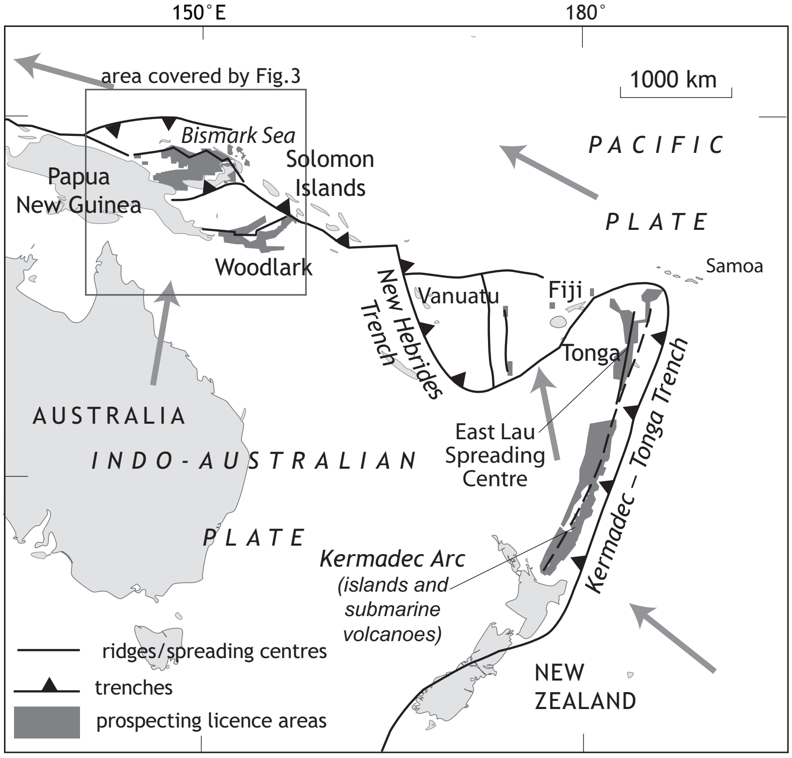
Over 200 active vent sites have been discovered to date and only a small number of these have been studied in any detail in terms of their fauna. Nevertheless, six discrete biogeographic provinces of hydrothermal vent fauna are already evident and are distributed around the Pacific, Atlantic and Indian Oceans, indicating the isolated nature of vent communities. Figure 2 shows a group of animals typical of active vents on the East Pacific Rise.

It is inevitable that additional biogeographic provinces will be distinguished as more vent systems are discovered. These discoveries will bring increased understanding of the ecology of vent fauna and the limits to life, as well as great potential for fundamental discoveries for biotechnology and biomedical applications.

Current SMS mining pursuits

Thus far, commercial interest in the mining of deep-water massive sulphides has been restricted to the deep waters of individual nation states' exclusive economic zones (cf. Box, p.13) and, in this regard, two companies have been particularly prominent in the past few years – Nautilus Minerals Inc. (www.nautilusminerals.com) and Neptune Minerals (www.neptuneminerals.com). Both are now listed on the London stock exchange, with Nautilus also listed on the Toronto stock exchange.

In recent years, Nautilus Minerals Inc. has undertaken exploratory investigations and environmental baseline assessments incorporating sampling, drilling, side-scan sonar and ROV-based studies, in the eastern Manus Basin of the Bismarck Sea, Papua New Guinea, at depths of around 1500 m. In total, however, Nautilus has already licensed a cumulative area of > 521 000 km^2 (more than twice the area of the UK) in a combination of tenement licenses (i.e. leases) and exploration applications in waters off Papua New Guinea, Fiji, Tonga, the Solomon Islands and New Zealand – including much of the axis of the East Lau Spreading Centre, the focus of much international back-arc basin/mid-ocean ridge and hydrothermal research (cf. Figure 4). Nautilus Minerals Inc. is aiming to bring their first site (Solwara 1, in the territorial waters of Papua New Guinea; Figure 3)



A tectonically active region with extensive zones of hydrothermal activity, the south-western Pacific is a focus of interest for the SMS industry

Figure 4 *Map of the south-western Pacific, showing sites of prospecting areas (licences both granted and under application) in relation to active plate boundaries and various tectonic features. Grey arrows indicate relative plate motions. The boxed area is that covered by Figure 3.*

into full production by 2010, subject to the granting of appropriate permits.

Neptune Minerals have also been establishing extensive exploration programmes across the western/south-western Pacific with, in their case, a particular initial focus on New Zealand waters. Their recent success includes the discovery of two hydrothermally inactive massive sulphide zones along the Kermadec Arc region offshore North Island (Figure 4). Their currently granted exploration license areas in the EEZs of New Zealand, Papua New Guinea, Vanuatu and the Federated States of Micronesia, total >278 000 km^2. They also have pending exploration applications covering 436 000 km^2 in the territorial waters of New Zealand, Japan, Palau, the Commonwealth of Northern Mariana Islands and, closer to home, in the Mediterranean, off Italy. Ultimately, Neptune is seeking to undertake extensive sampling operations and assessment of the characteristics and extents of the SMS deposits within these territorial waters, as part of a 'staged' commercialization process. At present, they have committed to focus upon massive sulphide deposits from inactive hydrothermal sites, in an attempt to minimize impacts on chemosynthetic fauna. Pilot mining operations, in which systems and equipment are to be fully trialled and tested on a reduced scale, are planned for the end of 2010, followed by full-scale mining thereafter.

It seems highly likely, therefore, that economically viable extraction of sulphides from the deep sea floor may begin within the next few years, and become established within the next decade, providing markets with metals for which the demand seems destined only to grow.

Marine minerals and the Law of the Sea

The legal instrument that covers exploration for, and exploitation of, marine mineral resources is the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which came into force in 1994 and is binding on those states that have ratified or acceeded to it.

Under UNCLOS, coastal states have complete control over exploitation of sea-bed resources (and living resources) in their territorial seas, which are typically 12 nautical miles (n.m.) wide.

Within their exclusive economic zones (EEZs), which extend out to 200 n.m., coastal states have sovereign rights over sea-bed resources and can lease exploration/exploitation rights to foreign companies as they see fit. UNCLOS places special emphasis on coastal states' responsibility for protecting and preserving the marine environment within their EEZs.

Areas of ocean beyond EEZs, i.e. international waters (also known as the high seas), are underlain by the International SeaBed Area (or the 'Area'), which is defined as 'the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction'. All activities in the Area are organized and controlled by the International Seabed Authority (ISA). The ISA acts on the principle that the Area and its resources are the common heritage of all mankind (including people in developing countries and landlocked states), but by the time UNCLOS came into force in 1994 its approach to managing sea-bed resources had become more commercial. Environmental protection has nevertheless remained one of the ISA's highest priorities.

The ISA's Mining Code regulates prospecting, exploration and exploitation of marine minerals in the International Seabed Area and sets out standard terms for exploration contracts. Environmental provisions are a major part of the obligations that the Authority placed on itself and on sea-bed contractors in its regulations. In 2000, the ISA adopted regulations governing prospecting and exploration for polymetallic nodules (i.e. manganese nodules). In August 2002, work began on regulations covering polymetallic sulphides (i.e. SMS deposits) and cobalt-rich ferromanganese crusts. Contentious issues still remaining include the definition and configuration of areas to be allocated to contractors for exploration, the fees to be paid to the ISA, and the question of how to deal with overlapping claims.

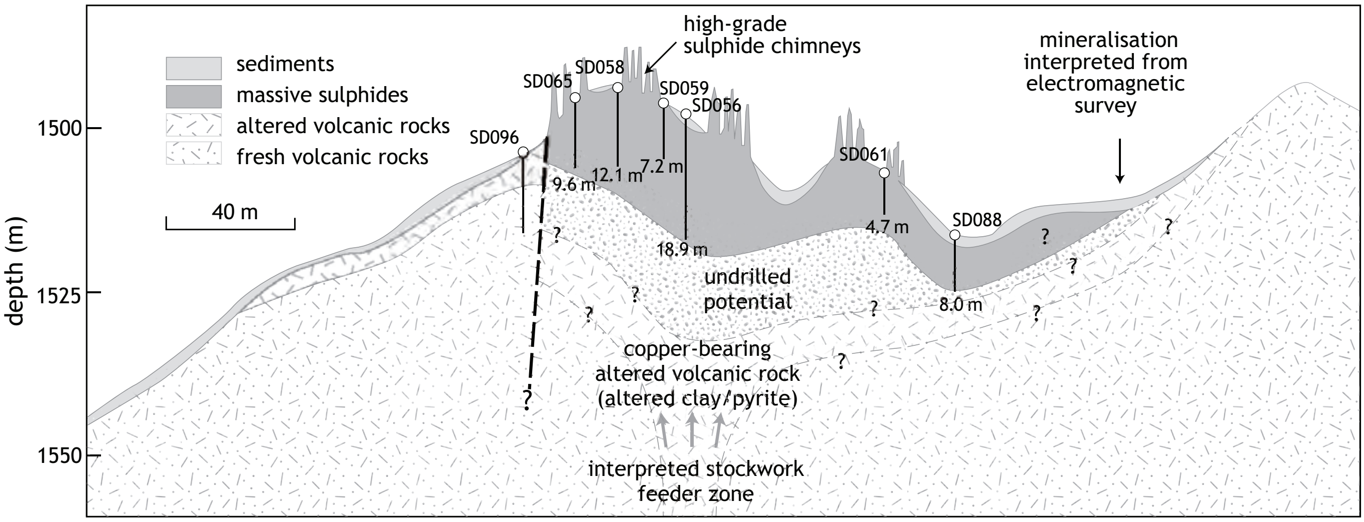


Figure 5 *Cross-section of an area of hydrothermal chimneys being explored by Nautilus, providing an example of typical spacings and depths of drill cores. (Note the exaggerated vertical scale.)*

Courtesy of Nautilus Minerals Inc.

Geophysical surveys and grid-drilling are used to assess the average ore grade of a massive sulphide deposit and predict its extent and volume

Technology for SMS mining

Much of the technology that will be used for sea-floor mining of massive sulphides will undoubtedly be adapted from that already developed for the offshore hydrocarbon industry. For example, technologies are required to explore for and locate deposits (mapping, sub-sea-floor geophysics), for sample-collection (e.g. for resource characterization and site-evaluation; Figures 5 and 6), and for transportation and processing. One of the key challenges that designers of deep-sea mining equipment might face, especially if they need to be

Collecting hydrothermal sulphide samples from the deep sea floor has become much easier since the widespread availability of deep-water ROVs

Figure 6 ***(a)*** *A hydrothermal massive sulphide deposit, being sampled by means of an ROV. The deposit is rusty gold in colour, and the snails (*Ifremeria *sp., which prefer waters of ~ 6 °C) are a few centimetres across.*

(b) *The Senior Geologist of Teck Cominco Ltd (under secondment to Nautilus) with a sample of massive sulphide (part of a chimney) recovered from the Solwara 1 site, at ~1500 m depth in the Bismark Sea, off Papua New Guinea (cf. Figure 3).*

(c) *High-grade Solwara 1 copper/gold chimney sample ~ 0.5 m across. The voids are the 'pathways' that the metal-rich fluids rise up through.*

Courtesy of Nautilus Minerals Inc.

(a)

(b)

(c)

prepared to work at active hydrothermal sites, will be to develop technology that can operate safely and efficiently, and with minimal environmental impact, in extreme environments where extraordinarily steep chemical and thermal gradients may be encountered under conditions of immense pressure, amongst extremely rugged topography.

Exploratory techniques for locating deep-sea vent sites have recently been revolutionized with the recognition that AUVs (autonomous underwater vehicles) can be used for this purpose. Active vents can be located from their plumes, which can disperse some 10s of kilometres through the water column but can be tracked back to their vent-source. In essence, pin-pointing the position of a vent can be conducted in three discrete phases. First, dispersing hydrothermal plumes can be traced over several kilometres, using both chemical and physical sensors, and the cores of these plumes located to within less than 1 km. Next, using a combination of high resolution multibeam mapping and/or sonar imaging, coupled with continued use of *in situ* physical and chemical sensors, individual sites of venting and their geological setting can be determined to within length-scales less than 100 m. Finally, AUV- or ROV-based photographic surveys can be used to fully characterize the lateral extent of individual sites and the ecosystems that they host.

While inactive and active vents can often be found in close proximity, locating inactive vents away from sites of active venting remains a challenge. For this reason, very little is yet known about the geology, chemistry and biology of inactive deep-sea hydrothermal systems – and yet such understanding will be fundamental to the baseline survey of any inactive hydrothermal site selected for commercial exploitation. Consequently, we would argue that multidisciplinary investigations of both active *and* inactive SMS systems should be an urgent target for future international research.

Once located, more detailed investigation of a massive sulphide deposit is required using a combination of geophysical surveys and geochemical analyses of samples recovered from the deposit. This work is conducted to determine the massive sulphide ore-grade (i.e. the concentrations of valuable metals that it contains) and the tonnage of the deposit. If initial samples from the surface of the deposit combined with sonar investigations and mapping of its areal extent indicate a potentially high-grade ore, of commercially exploitable size, then coring ± further geophysical surveys are required to determine its three-dimensional form and, hence, full extent. Grid-drilling, for example, can be used to determine the average ore grade throughout the body of a deposit and to determine its volume (cf. Figure 5). Such drilling operations may be carried out by drill ship or using dedicated sea-floor ROVs and instruments.

If positive results are obtained from the coring process, trial mining may begin and this requires new extractive technologies based upon previous crust and nodule mining systems, themselves modified from terrestrial coal and ocean diamond mining methods. Progress in this field is swift – large mining machines are already being used to dig pipe trenches for moving oil and gas to shore from deep-sea wells. In December 2007, Nautilus Minerals Inc. awarded a contract worth around £33 million to Soil Machine Dynamics (based in the UK) for the design and build of two Seafloor Mining Tools (SMTs). A second contract with a $116 million target price was awarded to Technip USA Inc. in April 2008 to develop the Riser and Lifting System (RALS) components (Figure 7). In June 2008, a third contract was awarded to North Sea Shipping Holding AS to provide a specialist Mining Support Vessel (MSV).

The SMTs – gigantic crab-like mining robots with multiple claws – are capable of digging out 100 cubic metres of rock per hour at SMS deposit sites. The crushed material will then be pumped to the surface as slurry through the steel riser pipe onto the MSV. It is envisaged that the commercially valuable cargo will then be dewatered onboard ship before being transported to a nearby port facility by barges. The waste water will be filtered and released at a predetermined depth in the water column to be ascertained through impact assessment.

The extractive technologies being developed to exploit SMS deposits are based on systems developed to exploit manganese nodules and crusts

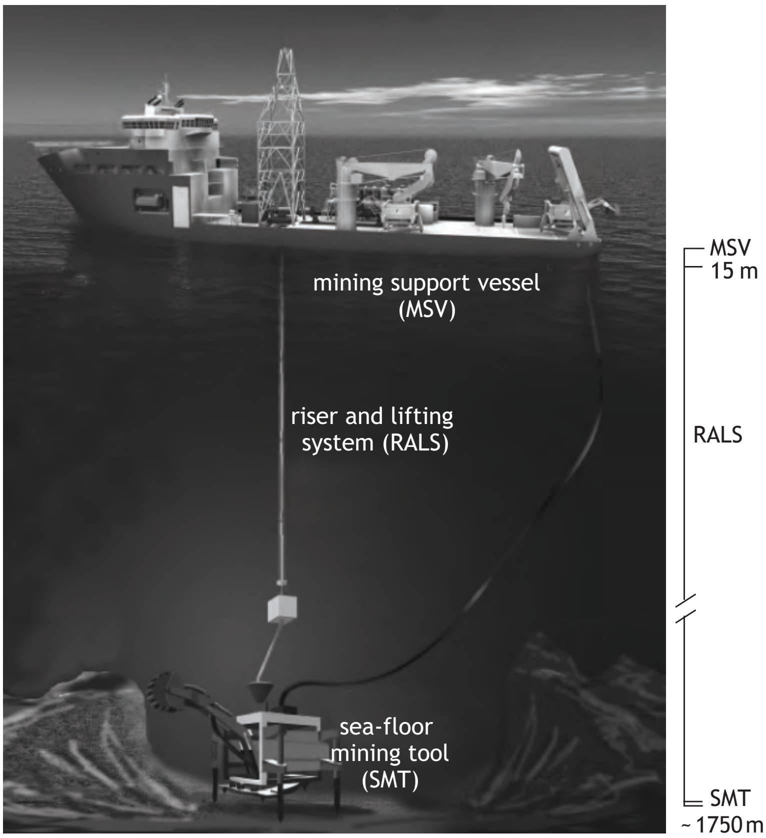
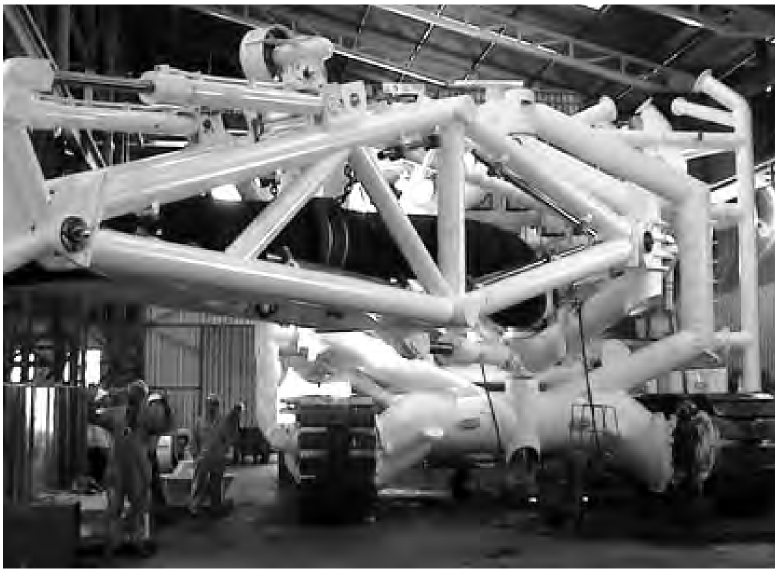


Figure 7 *Artist's impression of Nautilus's planned sea-floor mining system (see text). The first step in the mining process involves cutting the massive sulphide and drawing it into the suction mouth of the Seafloor Mining Tool as slurry. The slurry is then transported to a pumping module and lifted up a steel riser pipe to the Mining Support Vessel on the surface, where the material is dewatered.*

Adapted from an image supplied by Nautilus Minerals Inc.



Gigantic mining robots known as 'crawlers' are capable of digging out 100 cubic metres of rock per hour

Figure 8 *Marine and Mineral Projects of South Africa are currently adapting this deep-sea 'crawler' (which moves on tracks, visible here) for the mining of SMS deposits. It is linked to the mining support vessel by an 'umbilical' that provides power and allows it to be remotely controlled from above (cf. Figure 7). Material which is sucked from the sea-bed takes just 25 seconds to travel up the 'riser' to the vessel at the surface.*

By courtesy of Nautilus Inc.

Potential environmental impacts

The true nature of the environmental impacts of massive sulphide mining will remain uncertain prior to the onset of commercial deep-sea mining activity or at least the trial-mining stage. However, attempts may be made to try to minimize any impacts prior to the proposed new industry commencing in 2010. The design and application of the technology to be used in deep-sea mining, and the standards adopted by both regulators (where appropriate) and the industry itself, will largely determine the impacts on the environment. There are a number of potential environmental effects of mining that are of concern to some stakeholders. These include: direct physical damage to the sea-bed at the operation site and the surrounding area; production of sediment plumes and deposition of sediment, which will affect marine life by smothering or inhibiting filter-feeders; alteration of fluid-flow paths at the vent, on which the benthic (often sessile, i.e. permanently attached to the substrate) vent fauna rely; noise pollution; waste water disposal; and equipment failure which may result in leakage.

It is very difficult to assess the impacts of such disturbances. Whereas some effects will be obvious and inevitable (e.g. the detrimental short-term effects on fauna living at or close to the mining site), other consequences are not so clear. For example, increased concentrations of nutrients in the upper water column could occur as a result of water pumped up during the mining process being released after dewatering of the mined rock. This could lead to localized eutrophication, an increase in primary productivity, and consequent changes in structures of biological communities. The rate of recovery of the local marine community post-mining operations, and knock-on effects with respect to neighbouring vent communities, are difficult to predict. To be able to predict impacts, one first has to thoroughly understand the functioning of the unperturbed system. But we still know so little about the dispersal mechanisms of animals from one vent to another and about recolonization and recovery processes, that attempts to gauge such impacts are severely impaired. There is uncertainty about the degree of endemism at particular vent sites (the extent to which organisms are uniquely found there), especially in the case of active sites. Baseline studies of the first SMS mining sites are therefore crucial if we are to enhance our knowledge of these matters, and so help in the development of regulatory mechanisms for the industry.

To date, there have been very few impact studies of potential SMS mining sites. However, some information may be gleaned by looking at the extensive array of studies that have been conducted relating to the mining of deep-sea nodules (see Further Reading). Although many factors differ greatly between between the two habitat types (such as depth, topography and thickness of overlying sediments) some overlaps may be evident, such as the generation and effects of sediment plumes.

Both Nautilus Minerals and Neptune Minerals are currently supporting biological studies to determine the level of biological activity at their potential mining sites. Neptune is undertaking detailed baseline assessments of their sites, which are cold inactive sites. Preliminary research indicates that these inactive sites are colonized by animals from the surrounding area, once venting ceases. Neptune state that their sites of study do not appear to have high levels of biomass or endemism but are composed of cosmopolitan species from the surrounding deep sea. Nautilus is undertaking baseline assessments of both active and inactive sites in their proposed mining area. In collaboration with vent scientists they are currently developing an Environmental Impact Statement for their planned ocean mining operation off Papua New Guinea. These baseline studies of the local habitat and biodiversity will help to inform the scientific community, and will provide information to allow comparison of pre- and post-mined sites and hence define the course of action needed to avoid any long-term damage to sea-floor communities.

Some industrialists and scientists argue that sea-floor mining will be better for the environment than terrestrial mining. Only 30% of our planet is land and, as we know, mining on land leaves a substantial footprint in terms of scarring of the land, polluted waterways, carbon emissions from heavy machinery, and huge amounts of dumped waste rock. The high levels of enrichment of sulphide ore deposits found in the ocean mean that far smaller amounts may be mined profitably, and with far less waste. It may well be easier to plunge through a few hundred or thousand metres of water than it is to drill through a few thousand metres of rock.

Science and policy involvement

This new and exciting frontier of deep-sea exploration and mining of base and precious metal sulphides raises a significant number of questions about potential environmental impacts and the sustainable use of ocean resources. It is therefore imperative that, without delay, all stakeholders, including industry and scientists, come together to discuss the national and international regulations governing marine exploration and mining activities in order to achieve transparency for all interested parties, and in particular the public who are increasingly concerned about the state of our oceans. It is crucial that updated guidelines are established and followed by the emerging SMS mining industry.

At the time of writing, some guidelines have begun to be developed, relating to activities at hydrothermal vent sites. In terms of scientific input, InterRidge has established a statement of commitment to responsible research practices at deep-sea hydrothermal vents (www.interridge.org/en/IRstatement), which has been signed by many vent scientists and endorsed by the Census of Marine Life's ChEss Project (www.noc.soton.ac.uk/chess; see also Further Reading). This signatory process is ongoing via the InterRidge website. In the case of industry, a Code for Environmental Management of Marine Mining was established by the International Marine Minerals Society in 2001 and is due to be updated shortly (www.immsoc.org/IMMS downloads/codefeb2002.pdf).

Discussions initiated in 2004, at the 10th anniversary celebrations of the International Seabed Authority, led to a meeting among various stakeholders, hosted by the ISA, in October of that year. While the ISA had previously focussed its attention much more upon policies relating to manganese nodule mining from the deep ocean floor, increasingly it has been turning its attention to SMS deposits and, in 2007, published its first draft regulations on this topic (www.isa.org.jm/en/documents).

Building on this momentum, the offices of ChEss and InterRidge joined forces in early 2008 to propose, in collaboration with the ISA, a joint scientific and policy discussion meeting to be held in spring 2009. This meeting will comprise two parts: together, ChEss and InterRidge will organize a meeting, targeted predominantly at scientists, to discuss key recent findings and future directions of sea-floor hydrothermal research. Nested within this, in April 2009, a Morss Colloquium will be held in Woods Hole, USA, on the socio-economic and societal impacts of future SMS mining. This will include representatives of the industrial and (national and international) regulatory communities as well as numerous other interested parties, alongside key international scientists. In concert, the aim of these activities will be to identify the highest priorities for future international research, and develop implementation plans to ensure that we bridge serious gaps in understanding.

Concluding remarks

It seems likely that the marine massive sulphide industry will win out over the manganese nodule industry in the race for exploiting ores from the deep, at least in territorial waters. These are exciting times for both marine mining and hydrothermal research. There is increasing recognition that hydrothermal vents may be much more widespread than was initially apparent, especially along slow-spreading ridges, such as the Mid-Atlantic Ridge. Further, at least some slow-ridge hydrothermal systems (e.g. TAG and Rainbow) are now known to be longer lived and hence to give rise to much larger sea-floor deposits at any one site than is typical along faster spreading ridges such as the East Pacific Rise.

With increasingly positive news regarding the existence of sizeable massive sulphide deposits of high grade, it is perhaps inevitable that we will soon see metals extracted from the sea floor of ocean island states now entering the global economy – not least to sustain the growth of various rapidly emerging manufacturing-based 'new' economies. Exactly what the environmental impacts will be, and what lessons can be learned to steer regulation in international waters, remain to be seen. But this is clearly a field where deep ocean scientists have much opportunity – and a responsibility – to participate, to investigate previously overlooked aspects of deep-sea hydrothermal systems, and to provide national and international regulatory bodies with the best possible advice on how to proceed.

Further Reading

Herzig, P.M., R. Holroyd, R. Hardman, M. Osmaston, J.A. Karson, R.S. White and K. Rohr (1999) Economic potential of sea-floor massive sulphide deposits: ancient and modern (and Discussion) *Phil. Trans. Roy. Soc.: Mathematical, Physical and Engineering Sciences*, **357**, No. 1753 (Apr. 15), Response of the Earth's lithosphere to extension, 861–75.

Hilbig, Brigitte (2006) Europe's role within the Census of Marine Life (CoML), *Ocean Challenge*, Vol. 15, No.1, 8–11. (Includes a description of ChEss.)

Raloff, Janet (2006) Venting concerns: exploring and protecting deep-sea communities, *Science News,* **170**, No.15 (7 Oct.), 232–4 (also online).

Schrope, Mark (2007) Digging deep, *Nature*, **447**, No. 7142, 17 May, 246–7 (also online).

Thiel, H., H. Bluhm, C. Borowski, C. Bussau, A.J. Gooday, C. Maybury, and G. Schriever (1992) The impact of mining on deep-sea organisms: the DISCOL Project, *Ocean Challenge,* Vol. 3, No.1, 40–46.

See also:

www.isa.org.jm/files/documents/EN/Brochures/ENG8.pdf

www.isa.org.jm/files/documents/EN/13Sess/Cncl/ISBA-13C-WPL.pdf

www.underwatermining.org

Maria Baker* is a benthic biologist and a Project Manager for the Census of Marine Life ChEss Programme, concerned with improving knowledge of the diversity, abundance and distribution of species from chemosynthetic habitats at a global scale, and understanding the biogeographic forcings involved.

Christopher German† is a marine geochemist interested in the global distribution of sea-floor hydrothermal vents and their impact on ocean chemistry. He is currently the Chief Scientist for Deep Submergence at WHOI in the USA where he co-Chairs both the ChEss and InterRidge Programmes. He is a Fellow and former President of the Challenger Society.

*National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK

†Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA

Investigating the links between plankton and climate

The Atlantic Meridional Transect Programme 1995–2012

Carol Robinson

Understanding how climate change will affect the planet, and how natural marine biological activity affects climate, are key issues for everyone. Marine plankton have a major influence on the global budgets of atmospheric gases that are climatically active (such as carbon dioxide and nitrous oxide), while changes in weather patterns, increasing sea-surface temperature and increasing acidity of seawater affect the diversity, abundance and activity of marine plankton. As well as ecological implications, any adverse impacts of climate on the ocean biota could have widespread economic implications, as marine organisms have huge socio-economic value, through food production, recreation, nutrient recycling and gas regulation (estimated at £10 trillion yr^{-1} globally; see Further Reading). Evaluating changes in the structure and function of marine plankton communities, and the complex interactions between plankton and the global climate system, crucially depends on ocean time-series studies undertaken over many decades. The Atlantic Meridional Transect programme (AMT) is an ocean time-series study which aims to quantify the temporal and spatial variability in the composition and activity of the plankton of the Atlantic Ocean, the environmental factors that influence this variability, and the consequences of the variability for natural processes that affect climate. To achieve its aim, since 1995 the programme has sampled up to 65 stations along a latitudinal transect between the UK and the Southern Ocean, at 6–24 month intervals (see Further Reading).

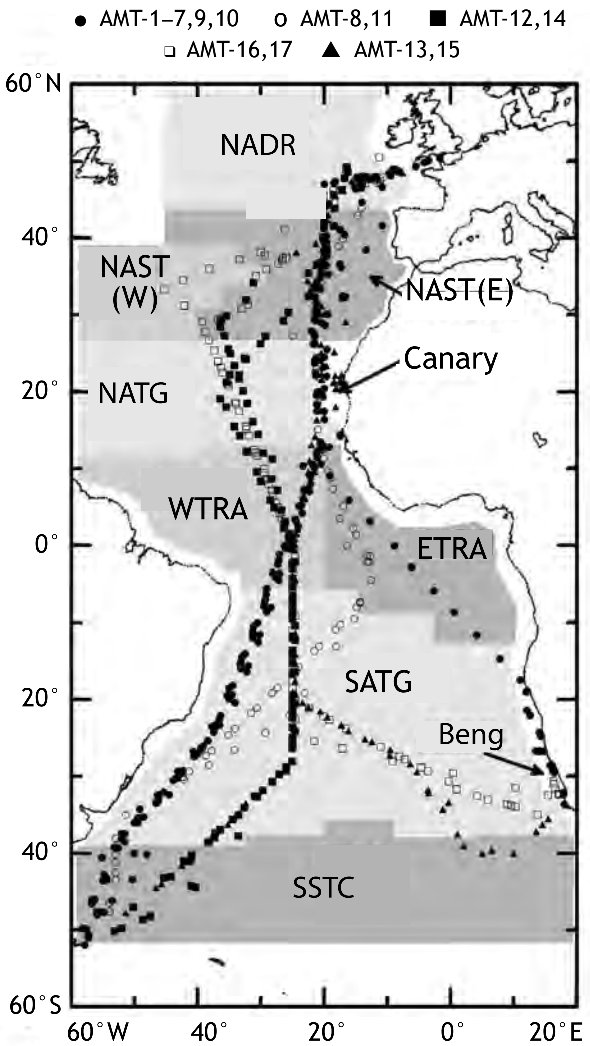
The AMT has followed a range of cruise tracks through the Atlantic Ocean, some determined by scientific objectives, others constrained by ship's logistics (Figure 1). The earlier cruises followed an almost straight-line passage between the UK and the Falkland Islands, and were restricted in the amount of time that the ship was able to stop in order to deploy instruments that could sample below the sea-surface. Priority was therefore given to measurements that could be made either with towed instruments or by pumping surface seawater onboard, and there was a single daily station of about 45 minutes during which there was simultaneous deployment of zooplankton nets and instrumentation for hydrographic and optical measurements. However, between 2003 and 2005, improved funding meant that AMT cruises were able to sample not only the central parts of the North and South Atlantic Ocean where plankton productivity reaches its lowest values, but also the north-west African coast where nutrient-rich waters supersaturated in gases produced by bacteria 'upwell' into surface layers promoting high levels of planktonic production.

The scope of AMT research

The cruises are highly collaborative, and have so far involved researchers and data analysts from more than 10 countries (Figure 2). On each cruise, 28 scientists and technicians measure between 50 and 70 parameters ranging from hydrography (temperature, salinity, concentration of dissolved oxygen, chlorophyll fluorescence), the chemistry of surface waters and the overlying atmosphere along with the composition of the plankton community, through to optical properties of the seawater, aerosols in the atmosphere and up to 16 different measures of plankton activity (Figure 3). This unique dataset is collated, archived and made available to the scientific community through the British Oceanographic Data Centre (BODC),* and has so far contributed

*See p.24 for details of the BODC website, and other relevant sites.

Figure 1 *The cruise tracks of AMT-1 to AMT-17 overlain on the biogeochemical provinces of the Atlantic Ocean defined by Longhurst (1998) (see Further Reading). These provinces are: North Atlantic Drift (NADR); North Atlantic Subtropical Gyral (West) (NAST(W)); North Atlantic Subtropical Gyral (East) (NAST(E)); North Atlantic Tropical Gyral (NATG); Canary Coastal (Canary); Western Tropical Atlantic (WTRA); Eastern Tropical Atlantic (ETRA); South Atlantic Gyral (SATG); Benguela Coastal Current (Beng); and South Subtropical Convergence (SSTC).*



AMT cruises have sampled a range of marine environments, from low-nutrient centres of ocean gyres to nutrient-enriched coastal upwelling areas

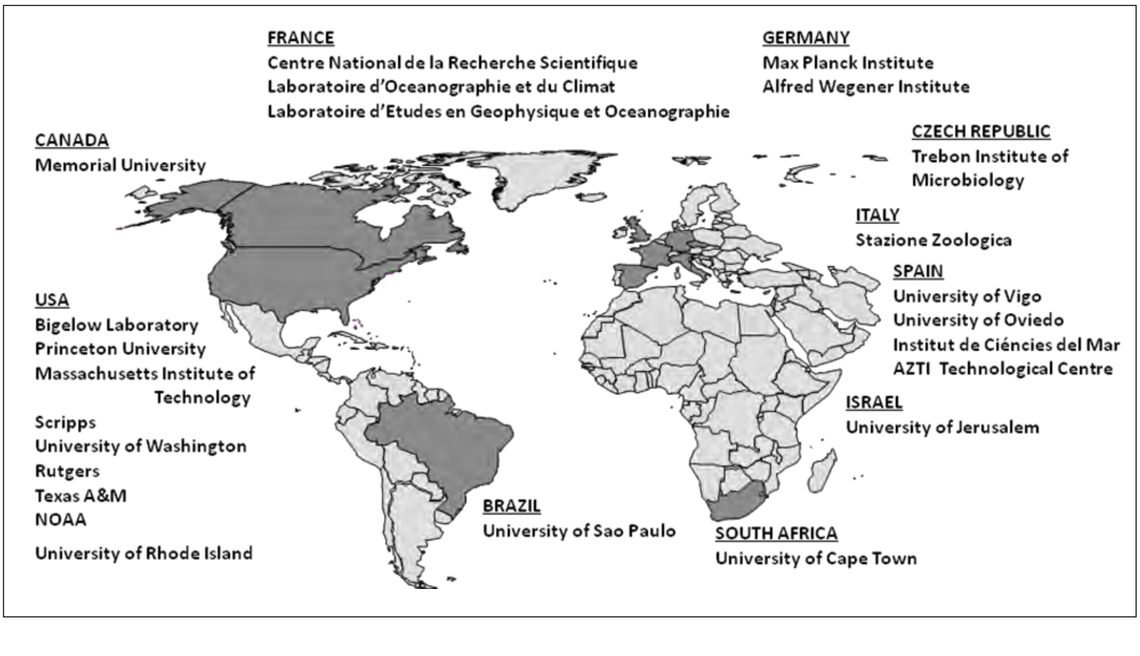
to more than 60 Ph.D theses and 160 peer-reviewed publications in the scientific literature (for a detailed list see www.amt-uk.org).

The research questions addressed by AMT overlap with those of several international programmes sponsored by the Scientific Committee on Oceanic Research (SCOR) and the International Geosphere–Biosphere Programme (IGBP). The Integrated Marine Biogeochemistry and Ecosystem Research programme (IMBER) aims to investigate the sensitivity of marine biogeochemical cycles and ecosystems to global change, on time-scales ranging from years to decades. AMT is contributing to IMBER by creating a decadal dataset of the composition of the microbial community and rates of microbial processes which affect global cycling of carbon, nitrogen, oxygen and sulphur.

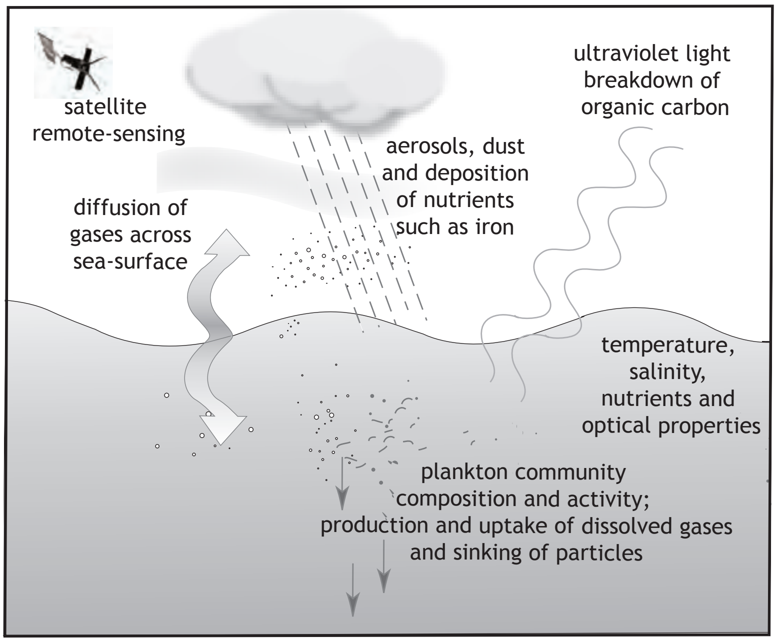
Three other programmes that benefit from data collected by the AMT are GLOBEC, GEOTRACES and SOLAS. GLOBEC – Global Ocean Ecosystem Dynamics – aims to understand how global change will affect the abundance, diversity and productivity of marine populations; GEOTRACES studies the global marine biogeochemical cycles of trace elements and their isotopes; and SOLAS (Surface Ocean – Lower Atmosphere Study) investigates key biogeochemical–physical interactions and feedbacks between the ocean and atmosphere, and how this coupled system affects and is affected by climate and environmental change.

Projects within AMT that contribute to GLOBEC, GEOTRACES and SOLAS include an investigation of the effect of nutrient and trace-metal supply on the growth of the plankton community. *In situ* measurements allow us to determine the decadal variability

Figure 2 *Countries and research establishments contributing to or using AMT data between 2002 and 2006.*



AMT results are processed and/or used by at least 24 research establishments worldwide



AMT research encompasses a wide range of processes affecting and affected by the oceanic plankton community

Figure 3 *Schematic diagram to show the wide range of ecological and biogeochemical processes and parameters investigated during AMT cruises. Aspects of the plankton community that are being quantified include production, respiration, calcification, silicification, nitrate and ammonia uptake, ammonia regeneration, nitrification and nitrogen fixation; also being investigated are grazing of bacteria and phytoplankton by microzooplankton, and loss of dissolved and particulate carbon from the atmosphere–upper ocean system.*

in plankton abundance and production alongside changes in nutrient concentrations, while short-term incubation experiments enable a 'bioassay' of the increase in plankton growth caused by adding various combinations of nutrients to sea-water containing plankton communities collected from different ecosystems within the Atlantic Ocean (Figure 1). Also important in this context are the study of the influence of the structure of the plankton community on the production of methane, nitrous oxide and dimethyl sulphide (DMS), in order to improve ocean-basin-scale estimates of fluxes of these climatically important gases between the ocean and the atmosphere.

The influence of environmental parameters on plankton distribution and activity

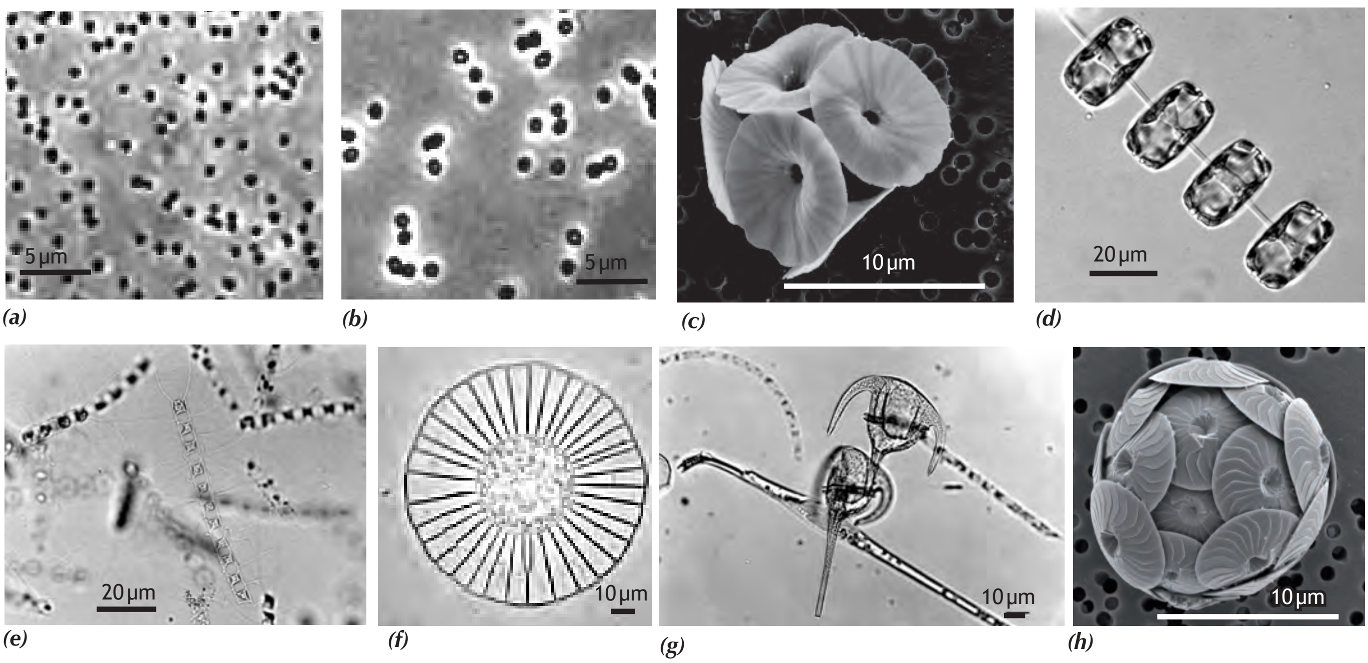
A major outcome of the AMT programme has been the determination of how factors such as temperature, light and nutrient availability influence latitudinal, vertical, seasonal and interannual variability in the structure of the plankton community in the surface 200 m of the Atlantic Ocean, and how this variability relates to the growth of plankton that produce or consume gases that influence climate (cf. Figure 3).

The plankton community contains a complex mix of organisms, which range in size from <1 µm in the case of viruses and bacteria, through phytoplankton such as coccolithophores and diatoms in the 10–50 µm size range, to zooplankton such as protozoans, copepods and krill (0.1 mm–10 cm). The dominance or otherwise of a particular plankton group in a particular

Certain planktonic organisms are characteristically dominant in marine regions with particular nutrient and light conditions

Figure 4 *Areas with very low nutrient levels, such as are found in the mid-ocean gyres, are dominated by **(a)** the picophytoplankton* Prochlorococcus*, while open ocean waters with higher nutrient levels, such as equatorial upwelling regions and the edges of the subtropical gyres, are dominated by **(b)*** Synechococcus. ***(c)*** *The coccolithophore* Umbilicosphaera irregularis *is also found in low-nutrient subtropical waters. Chain-forming diatoms such as **(d)*** Thalassiosira *and **(e)*** Chaetoceros *occur in mid/high-nutrient temperate waters such as the English Channel, as well as subpolar and subtropical waters; while other diatoms such as **(f)*** Planktonella sol *occur in tropical high-nutrient regions. **(g)** Various different species of the dinoflagellate* Ceratium are found throughout the oceans, *and (behind) the rod-like dinoflagellate* Amphisolenia *and **(h)** the coccolithophore* Calcidiscus leptoporus *occur in the mid/high-nutrient waters of tropical coastal upwellings.*

Images by courtesy of Rosmarie Rippka (Institut Pasteur, Unité des Cyanobactéries, France), Alex Poulton (National Oceanography Centre, Southampton) and Claire Widdicombe (Plymouth Marine Laboratory)



location at a particular time is dependent on the physical, chemical and biological environment. One such influence on community structure is the availability of nutrients such as nitrate and phosphate. At the broad scale, larger phytoplankton such as diatoms occur in areas of high nutrients, whereas in regions with very low nutrient concentrations the smallest 'pico'-sized phytoplankton out-compete the larger cells. Research within AMT showed that competition for nutrients also occurs between similar sized phytoplankton.

Analysis of the smallest photosynthetic plankton using laser technology showed that in regions of the ocean with particularly low nutrient concentrations, the genus *Prochlorococcus* (Figure 4(a)) is most abundant, whereas in areas with slightly higher nutrient concentrations, the closely related genus *Synechococcus* (Figure 4(b)) occurs in largest numbers.

Molecular techniques revealed that plankton belonging to the genus *Prochlorococcus* were particularly diverse in terms of their genetic make-up and physiology. Certain subgroups or 'ecotypes' within the genus grow best at high light intensities and so occur most frequently in surface waters, while other distinct subgroups dominate in deeper waters with lower light intensities. The data clearly showed that regions of the ocean with similar nutrient and light conditions allowed the growth of similar populations of unicellular plankton across large spatial scales. When the same molecular and laser techniques were used on a cruise in the following year, the data showed that these large-scale distribution patterns for *Prochlorococcus* ecotypes were remarkably consistent. This indicates that knowing the environmental conditions which favour a particular photosynthetic organism can help to predict what may happen if these environmental conditions change.

First measurements of respiration and nitrification in the South Atlantic Gyre

The cruise track of the most recent AMT cruises has allowed the measurement of some plankton processes in areas where they had never been measured before. One such area is the centre of the South Atlantic Ocean, and the plankton processes measured here for the first time include respiration (which consumes oxygen and produces carbon dioxide) and nitrification (the conversion by bacteria of ammonium to nitrite, and of nitrite to nitrate).

Respiration and photosynthesis

Knowing the magnitude and variability of plankton respiration is crucial to our understanding of the biogeochemistry of the oceans as the balance between respiration (which produces carbon dioxide) and photosynthesis (which consumes carbon dioxide) indicates the proportion of the carbon incorporated during photosynthesis which returns to the atmosphere as carbon dioxide, and that which is available for export to the deep ocean. Carbon that reaches the sea-bed may be buried within sea-floor sediments and so removed from the upper ocean–atmosphere system, resulting in less carbon dioxide being available to re-enter the atmosphere on short time-scales. Respiration data from the centre of the North and South Atlantic Ocean are particularly important as these regions are representative of the vast ocean 'gyres' which cover more than 60% of the global ocean and export up to 50% of global carbon from surface waters to the deep sea.

AMT results have proved to be useful in evaluating the results of numerical models of interactions between ocean, atmosphere and plankton in various climate change scenarios. Such models suggest that increasing sea-surface temperatures will lead to a reduction in photosynthesis in these gyres due to a shortage of the nutrient nitrate (nitrate-limitation) resulting from decreased mixing between warmer surface nutrient-depleted waters and cooler deep nutrient-rich waters. Measurements of the magnitudes of photosynthesis and respiration were made during six AMT cruises between 2003 and 2005 in the North and South Atlantic Gyres, alongside measurements of nitrate concentrations. These data showed that the balance between photosynthesis and respiration is influenced by nitrate-limitation, suggesting that in a warming ocean with increasing nitrate-limitation, phytoplankton photosynthesis will decrease more than plankton respiration, potentially resulting in less planktonic uptake of carbon dioxide from the atmosphere than occurs today.

Nitrification

Until recently, the bacterial process of nitrification was thought to be restricted to deep waters with low light intensities, high concentrations of ammonia and low levels of dissolved oxygen. However, recent AMT studies have measured nitrification in the oxygen-saturated sunlit surface regions of the world's ocean (Figure 5), causing marine scientists to reassess their understanding of the cycling of nitrogen in the marine environment.

Figure 5 *In the laboratory onboard RRS* James Clark Ross*, Darren Clark (Plymouth Marine Laboratory) undertakes the first measurements of nitrification in the South Atlantic Gyre, during cruise AMT-13.*

A sensitive new isotope dilution technique has revealed surprisingly high rates of nitrite and nitrate production

Determination of nitrification using a newly developed, highly sensitive, isotope dilution technique, revealed surprisingly high rates of nitrite and nitrate production, even in the mid-ocean gyres once perceived as oceanic 'deserts'. In the majority of near-surface samples, nitrification could double the background concentration of nitrate in 8 hours. This suggests that the major portion of the nitrate pool in the mid-Atlantic Ocean available for phytoplankton growth is 'regenerated' or derived from bacterial activity within the sunlit surface layer, and not supplied 'new' from below the sunlit surface layer. This is an important distinction, as many estimates of the downward flux of carbon to the deep ocean are derived from the assumption that all nitrate taken up by phytoplankton in the surface sunlit layer is 'new'. These recent AMT data therefore suggest that estimates of carbon export calculated without taking nitrification rates into account, are significant overestimates.

Predicting production of climatically relevant gases using simple measurements

For many microbial processes relevant to climate, measurement is technically difficult and relatively time-consuming, which can lead to a global dataset which contains few, not necessarily representative, data. Since the AMT traverses so many marine ecosystems – from moderate productivity in the temperate regions, through high productivity in coastal upwelling regions, to very low productivity in the mid-ocean gyres (Figure 1) – and collects such a large amount of supporting ecological and biogeochemical data, the potential exists to derive and test predictive relationships between processes that are slow and/or difficult to measure and parameters that are rapid/simpler to measure.

Figure 6 *Measurements of DMS can only be made on board research ships – samples cannot be stored for later analysis. Tom Bell (University of East Anglia) used DMS data he collected during AMT-13 to show that DMS concentrations can be predicted from a knowledge of the depth of the surface mixed layer.*

Measuring DMS concentrations in the surface ocean provides vital information for understanding global climate

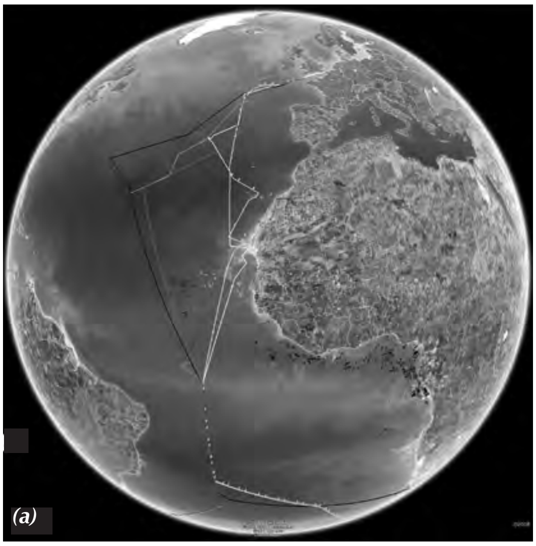
This approach was used with AMT data to estimate both DMS concentrations and the balance between phytoplankton photosynthesis and respiration.

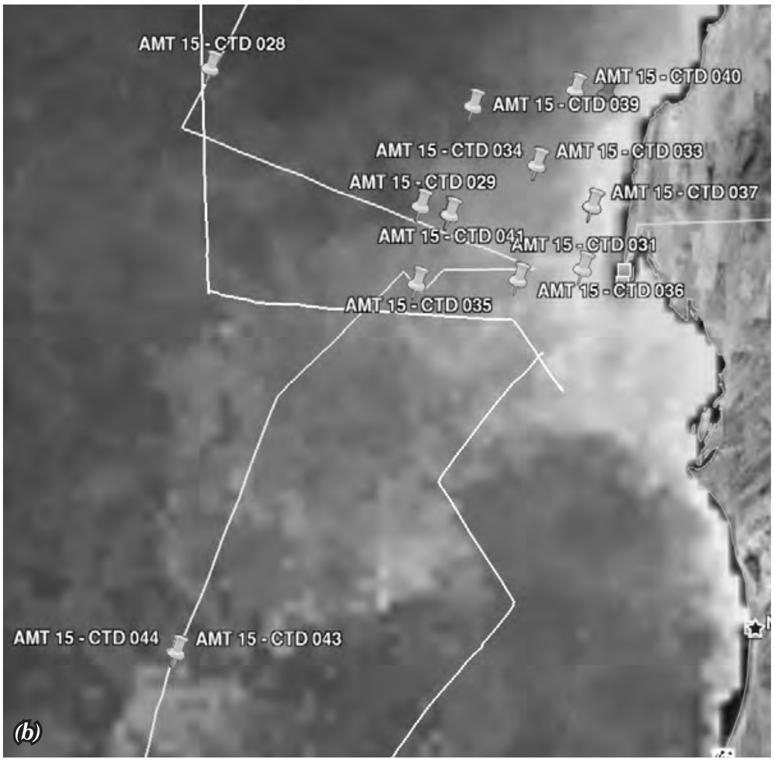
Estimating DMS concentrations

Production of the trace gas dimethyl sulphide in the surface ocean, and emission into the atmosphere, is the dominant biological source of global atmospheric sulphur. Once in the lower atmosphere, DMS oxidizes to sulphate and contributes to aerosols which increase cloud formation, thereby acting to cool global climate. Therefore, DMS concentrations in the surface ocean are an important input parameter for global climate models; however, measurement is time-consuming and relatively few data exist for the mid-Atlantic Ocean. To circumvent these problems, several equations have been proposed to predict DMS concentration from parameters such as phytoplankton biomass (derived from photosynthetic pigments), available light and nutrients, and the depth of the surface mixed layer. A comparative test of these equations was only possible once extra data were collected, in addition to those used in the derivation of the original equations. Measurements of phytoplankton pigments, nutrient concentrations and the depth of the surface mixed layer were therefore collected during five AMT cruises, alongside measurements of surface DMS concentration (Figure 6). These hydrological, chemical and ecological data were then used with the published equations to predict the surface DMS concentrations, and these predictions were compared with the DMS measurements. The predicted DMS data that were closest to the measured DMS data were those derived from an equation which assumed that the product of the DMS concentration and the depth of the surface mixed layer is constant.

Predicting future uptake of CO_2 by plankton

Rates at which the metabolic processes of photosynthesis and respiration occur can be calculated from equations that incorporate information on plankton abundance, the size of the individual organisms present, ambient temperature, and the amount of light available for photosynthesis. Rates of photosynthesis and respiration estimated from these equations and data collected during the AMT-6 cruise, were not significantly different from rates of photosynthesis and respiration derived from measurements of the change in dissolved oxygen during growth incubations of the plankton community on the same cruise. Since optical techniques to measure the abundance and size-distribution of the plankton community are continually being improved, these equations should enable photosynthesis and respiration to be determined at much higher frequency than is currently possible with dissolved oxygen growth incubations. The equations can also be used to predict changes in photosynthesis and respiration in a warming sea. Respiration (or carbon dioxide production) is predicted to increase more than photosynthesis (or carbon dioxide consumption), which would mean that by 2100 the net uptake of carbon dioxide by the plankton in the oceans would be reduced by 21%.





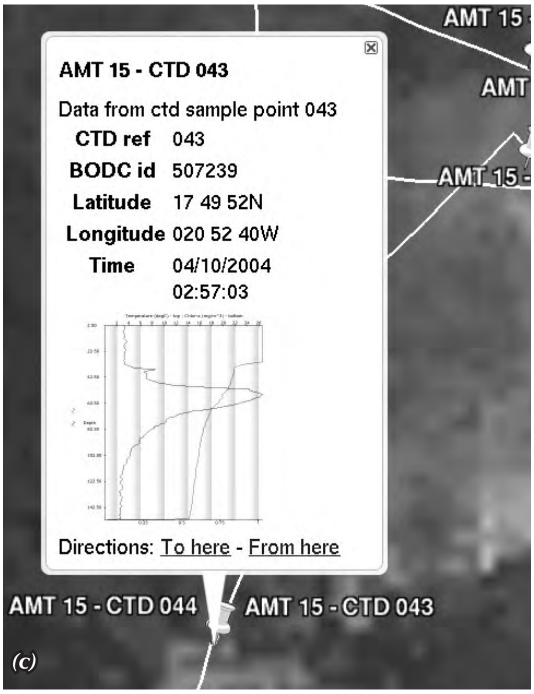


Image processing and Google Earth presentation by courtesy of Mike Grant of the NERC Earth Observation Data Acquisition and Analysis Service

Original satellite data by courtesy of NASA

Figure 7 *Web-based access to AMT results along with sea-surface chlorophyll-a derived from satellite ocean colour (discussed overleaf).*

(a) *Sea-surface chlorophyll with AMT cruise tracks. Lightest areas: high productivity regions associated with equatorial upwelling and upwelling along the African coast; darker areas: low productivity of the ocean gyres (cf. Figure 1). Dark speckles along the African coast are regions where cloud and dust have interfered with the satellite measurements.*

(b) *AMT-15 cruise track crossing the nurient-rich waters off north-west Africa, with sampling stations marked by 'map pins'.*

(c) *Hydrographic data from CTD station 043. In this case, the data shown are in the form of profiles (of temperature and chlorophyll), but they are also available in spreadsheet format.*

Remote sensing and modelling

A major step forward in our understanding of the seasonal and interannual variability of the activity of plankton in different regions of the Atlantic Ocean has come about through deriving relationships between parameters that can be measured on the research ship and those that can be observed via satellites. In this way we can extrapolate in space and interpolate in time from data collected twice a year along a single line through the Atlantic Ocean, to weekly ocean-wide images. Data collected during the first phase of AMT played a significant role in calibrating and validating equations to determine phytoplankton chlorophyll concentrations from ocean colour detected by the *SeaWiFs* satellite. Current research aims to develop an equation relating light scattering detected by the *MODIS* satellite and the concentration of calcium carbonate particles (indicative of calcifying plankton such as coccolithophores) and biogenic silicate (indicative of silicifying plankton such as diatoms) in surface waters of the Atlantic Ocean. The Centre for Observation of Air–Sea Interactions and Fluxes (CASIX) is licensed to use AMT data in order to calibrate and validate equations to quantify the global air–sea flux of carbon dioxide on the basis of remotely sensed parameters.

AMT data are also used to calibrate and validate ecological and biogeochemical numerical models of the cycling of carbon, nitrogen, oxygen and sulphur around the atmosphere–ocean system. Measurements of temperature, salinity, nutrients, dissolved inorganic carbon, DMS and phytoplankton chlorophyll collected during AMT cruises have all been used to initialize models, or compare with model output, during collaborative research at the UK Meteorological Office, the National Oceanography Centre, Southampton, the Max Planck Institute of Meteorology (Hamburg, Germany), the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC, Paris, France) and the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS, Toulouse, France) (cf. Figure 2).

Future AMT

The current or third phase of AMT (2007–2012) is funded by the NERC Marine Centres' strategic research programme 'Oceans 2025' through awards made to Plymouth Marine Laboratory and the National Oceanography Centre, Southampton. The aim is to continue AMT as an open ocean *in situ* observing system, the results of which will (1) give warning of any fundamental change in Atlantic ecosystem functioning, (2) improve forecasts of the ocean's future state and associated socio-economic impacts, and (3) provide the logistical and scientific infrastructure for independently funded national and international scientists who join the AMT cruises. AMT will also continue to support the participation and training of UK postgraduate students and, in collaboration with SCOR and the Partnership for Observation of the Global Oceans (POGO), will encourage cruise participation and scientific collaboration for young researchers from developing countries.

The Oceans 2025 funding will support the science and infrastructure for one 40-day research cruise per year, including core measurements of temperature, salinity, inorganic nutrients, plankton abundance and diversity, phytoplankton pigments, primary production, gross production and respiration, and optical properties of seawater. On each cruise, up to 14 further scientific berths are available to national and international collaborators through open competition. For further details and an application pack, contact Andy Rees at Plymouth Marine Laboratory (apre@pml.ac.uk).

A further aim of the third phase of AMT is to improve the outreach and visualization of the data via the World Wide Web. AMT will assimilate remotely sensed data (e.g. chlorophyll, sea-surface temperature), model fields (e.g. winds, currents) and *in situ* hydrographic data (e.g. temperature, salinity, concentration of dissolved oxygen) in a development of Google Earth (Figure 7). This will enable near real-time presentation of satellite images and *in situ* data alongside access to, and visualization of, previous *in situ* data.

Oceans 2025 also provides the opportunity to link and co-ordinate several well established UK marine time-series studies which measure, monitor and model the hydrography, ecology and biogeochemistry of the Atlantic Ocean and connecting shelf seas (http://www.oceans2025.org/PDFs/Oceans 2025 Theme 10.pdf). For example, AMT will provide spatial context and a broader spectrum of measurements to two time-series stations which lie on its track, the Western Channel Observatory which is situated in the Western English Channel off Plymouth, and the Porcupine Abyssal Plain Observatory, located at 49° N, 16.5° W about 500 km south-west of Ireland.

AMT also contributes to the international effort to determine ocean biogeochemical processes over time-frames that are sufficiently long to allow examination of links between plankton activity and climate forcing. The Hawaii Ocean Time-series (HOT) and Bermuda Atlantic Time-series Study (BATS) were initiated in the mid-1980s as a major component of the Joint Global Ocean Flux Study, and have produced literally hundreds of publications, greatly improving our understanding of the temporal variability in plankton processes that affect cycles of biologically important elements such as carbon, nitrogen, oxygen and sulphur. However, despite repeated acknowledgement by the international community that time-series studies are critical, maintaining funding support for a co-ordinated suite of biogeochemical measurements within each programme has been difficult. In 1999, an international group of physical oceanographers formed the OceanSITES programme to develop a co-ordinated, interdisciplinary, international network of time-series stations, research programmes and scientists to sustain and enhance the use of time-series observations.

In November 2008 the International Ocean Carbon Co-ordination Project (IOCCP) is holding a workshop to mobilize the biogeochemical community to participate in the international network set up through OceanSITES, and to highlight critical research that can only be carried out using time-series studies. The workshop will also assess the technological future of time-series observations, including the use of autonomous instrumentation, ocean-basin-scale arrays of moored sensors and instrumented ships of opportunity. A future network of scientists utilizing data from single geographical point time-series stations (such as HOT and BATS) together with time-series studies along latitudinal transects (such as AMT) can only enhance our understanding of how marine plankton impact upon and react to climate.

Further Reading

Aiken, J., N. Rees, S. Hooker, P. Holligan, A. Bale, D. Robins, G. Moore, R. Harris and D. Pilgrim (2000) The Atlantic Meridional Transect: overview and synthesis of data. *Progress in Oceanography* **45**, 257–312.

Hays, G.C., A.J. Richardson and C. Robinson (2005) Climate change and marine plankton. *Trends in Ecology and Ev*olution **20** (6), 337–44.

Longhurst, A. (1998) *Ecological Geography of the Sea,* Academic Press.

Robinson, C., A.J. Poulton, P.M. Holligan, A.R. Baker, G. Forster, N. Gist, T.D. Jickells, G. Malin, R. Upstill-Goddard, R.G. Williams, E.M.S. Woodward and M.V. Zubkov (2006) The Atlantic Meridional Transect Programme (AMT): a contextual view 1995–2005. *Deep-Sea Research II,* **53**, 1485–1515.

Oceanography Vol. 20, No.2, 2007: Special Issue on 'A Sea of Microbes'.

Carol Robinson is a Reader in Marine and Atmospheric Biogeochemistry and a member of the scientific steering committees of IMBER and GEOTRACES.

Address until recently: Plymouth Marine Laboratory, Prospect Place, Plymouth PL1 3DH.

Present address: School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ.

Email: Carol.Robinson@uea.ac.uk.

Relevant websites (order as in article)

AMT
www.amt-uk.org

British Oceanographic Data Centre (BODC)
www.bodc.ac.uk

Integrated Marine Biogeochemistry and Ecosystem Research programme (IMBER)
www.imber.info

Global Ocean Ecosystem Dynamics (GLOBEC)
www.globec.org

GEOTRACES
www.ldeo.columbia.edu/res/pi/geotraces/

Surface Ocean Lower Atmosphere Study (SOLAS)
www.uea.ac.uk/env/solas/)

Centre for Observation of Air–Sea Interactions and Fluxes (CASIX)
web.pml.ac.uk/casix/

Oceans 2025
www.ocean2025.org

POGO
www.ocean-partners.org/

OceanSITES programme
www.oceansites.org/

International Ocean Carbon Co-ordination Project (IOCCP)
www.ioccp.org/

The Hawaii Ocean Time-series (HOT)
hahana.soest.hawaii.edu/hot/hot_jgofs.html

Bermuda Atlantic Time-series Study (BATS)
bats.bios.edu/

Western Channel Observatory
www.westernchannelobservatory.org.uk/

Porcupine Abyssal Plain Observatory
www.noc.soton.ac.uk/obe/PROJECTS/pap/

Acknowledgement
Figure 4(a) and (b) were first published in R.Rippka *et al.* (2000) *International Journal of Systematic and Evolutionary Microbiology*, **50**, 1833–47.

Marine Science and Tall Ships – past, present and future

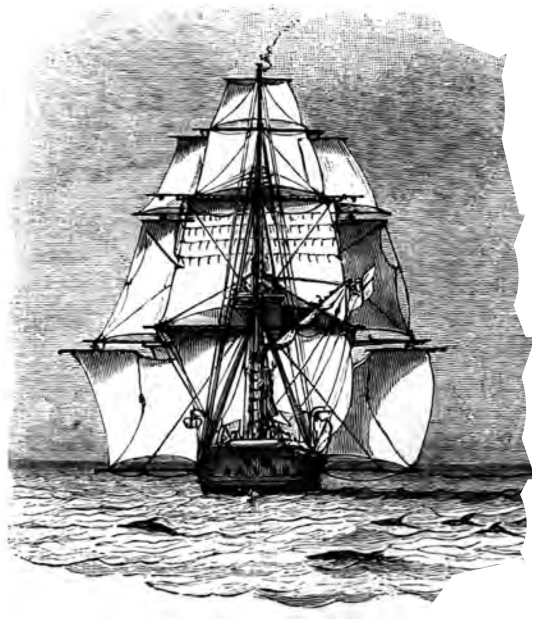
John Patching
Rachael Shreeve
Paul Rodhouse

The sight of a tall ship under full sail can charm even the most hard-headed oceanographer, but to those studying marine science in the deep ocean in the 18th and early 19th centuries, being at the mercy of the winds was yet another problem to be faced alongside the absence of effective instrumentation, the lack of suitable space on board, the death of scientists and crew through disease or accident, and even the loss of the ship itself by storm, shipwreck or piracy. Thus, after marine steam power became available in the first half of the 19th century, its use was enthusiastically embraced by the scientific expeditions that marked the birth of modern oceanography. Sail power, however, has never disappeared completely from the world's research fleets and may be about to make a resurgence.

Marine research under sail in the 19th and 20th centuries

The founding cruises of modern marine science which took place in the first half of the 19th century were carried out without the use of mechanical power. For example, HMS *Beacon,* on which Edward Forbes carried out his Mediterranean studies in 1841–42, and HMS *Beagle,* on which Charles Darwin carried out his pioneering observations in the 1830s (Figure 1), were both pure sailing vessels. But in 1868, when Wyville Thomson asked the admiralty to provide a vessel to carry out deep-sea dredging around Scotland and Ireland, he was given use of HMS *Lightning* which, according to him, was 'perhaps the very oldest paddle-steamer in Her Majesty's navy'.

HMS *Challenger,* though primarily a sailing vessel, was also equipped with steam power for her ground-breaking voyage (1872–76), and from this time onwards, all vessels used for major scientific cruises would be so equipped until (starting from the first decades of the 20th century) steam was superseded by the internal combustion engine. Clearly, the ability to move independently of the wind was a major advantage in passage-making (i.e. travelling to, from and between stations), hauling dredges, and keeping the vessel in one place for sampling etc. – though problems with the last were not fully solved until the advent of dynamic positioning systems in the 1960s. The use of powered winches was particularly welcomed as an alternative to the lengthy and laborious task of deploying and hauling up deep sounding and dredging equipment by hand. Early steam engines



Science before steam: HMS* Beagle *'all sails set'

(From Charles Darwin's A Naturalist's Voyage Round the World *published in 1812)*

Figure 1 *Launched in 1820 as* a *Royal Navy 10-gun* brig,* Beagle *was adapted as a survey vessel and took part in three expeditions, the second of which carried the young Charles Darwin.*

*A *brig has* two square-rigged masts, plus a small fore-and-aft sail on the mainmast (see overleaf).

were, however, inefficient and unreliable and were thus used in combination with sail for propulsion, a practice which continued on all large vessels throughout the 19th century.

For the British Navy, use of sail became an increasing inconvenience with the rapid development of the iron-clad warship. The last battleship to carry masts was HMS *Inflexible* (commissioned 1881) and naval use of sail had ceased before the launch of the dreadnoughts at the turn of the century. However, sail offered commercial users an increased load-carrying capacity because of the absence of heavy and bulky engines and fuel supplies, and an obvious cost-saving, since the wind is free, so its use thus lingered on in parts of the Pacific until the mid-20th century.

The combined use of sail and power for research vessels was still common in the opening decades of the 20th century, largely due to the surge in polar exploration. Screw propulsion was essential for working in or near the pack ice. This made a high demand on fuel, and though bunkering was arranged with whaling stations, the long passages to and from home ports made sail power an attractive proposition. Thus Scott's original *Discovery*, launched in 1901, had coal-fired steam engines, but carried three masts and was rigged as a barque.* As an indicator of the improvements in mechanical propulsion and the move away from sail, her successor RRS *Discovery 2*, launched in 1929, also carried masts but did not make passage under sail, relying instead on oil-fired reciprocating engines with sufficient bunker capacity to steam more than 10 000 miles at 'economic speed'.

*A *barque* is a vessel with three (or more) masts, and square sails on all except the mast nearest the stern; here the sail is aligned parallel to the keel of the ship (and is known as 'fore-and-aft sail'). A *brigantine* is a vessel with a square-rigged foremast and a fore-and-aft rigged mainmast.

Occasional use of sail (combined with power) continued to be found in research vessels throughout the 20th century, especially when the metal bulk and acoustic signature of main engines could interfere with observations. Even in 2001, the Russian research fleet still included two 600 ton three-masted schooners, the last remnants of the *Korall* class, launched in the early 1950s. The *Polyarnyy Odissey* and *Zarya* could each carry a mission crew of ten and were used by the Russian Geophysical Society and the Institute of Earth Magnetism, Ionospheric and Radio Wave Propagation, respectively.

The present

Large traditionally rigged sailing vessels are now very rare within the global scientific research fleet. Using the definition of 'tall ship' proposed by Wilkipedia (fore-and-aft-rigged vessels between 100 to 160 feet in length, and all square-rigged vessels), a web search revealed only three vessels that could be said to fall into this category. The RV *Oceania* is a 370 ton displacement, 49.9 m-long research vessel owned by the Polish Academy of Science. It carries three single square-rigged sails on three 32 m masts. The sails are raised and set by hydraulic winches. The Sea Education Association, Woods Hole, USA, operates two 280–300 ton displacement, 40.8 m-long brigantine-rigged* vessels, the Sailing School Vessels (SSVs) *Corwith Cramer* and *Robert C. Seamans*. Though certified by the US Coast Guard as SSVs, these were both designed for research.

There is, however, a significant use of smaller sailing vessels, sometimes privately owned, and sailing 'ships of convenience', for observational research in areas such as bird and cetacean distribution. An interesting development is the use of such vessels to collect water samples, from which nucleic acids are extracted for meta-

The two vessels operated by the Jubilee Sailing Trust

Figure 2 *The sail training ships* Tenacious *and, in the distance,* Lord Nelson*, both purpose-built for the Jubilee Sailing Trust (see opposite). STS* Lord Nelson *was launched in 1986, and* Tenacious *in 2000. Between them, they have sailed 452 574 miles and taken 28 672 people to sea, including 11 185 physically disabled people.*

genomic studies (i.e. studies of genetic material recovered directly from the environment). The Venter Institute's *Sorcerer 2* expedition is using a modified 95 ft sloop* to sample microbial DNA for subsequent sequencing so as to catalogue the genes of marine microbial communities. It is also intended that similar facilities be incorporated in the replica of the HMS *Beagle* which is to be built to celebrate the 200th anniversary of the birth of Charles Darwin.

There is an increasing interest in the operation of tall ships as multipurpose platfoms. Thus they may be used for recreation and team-building by sail training and also as national or regional 'flagships' with exhibition and reception space. To this can be added their use for teaching and carrying out research in marine science. Such combined use is economically attractive to ship operators.

For marine scientists, sail training tall ships provide a cheap and convenient method of carrying out open-ocean research, offer 'non-scientific' participants a chance to learn something of the marine ecosystem and how it is studied, and allow operators to maximize productive use of their vessels.

Cruise on STS Lord Nelson*, January 2008*

The Jubilee Sailing Trust (JST)† operates two sail training tall ships (Figure 2). Following an initiative between the Future Ship Project for the 21st Century committee (see later) and the JST, the Challenger Society was invited to organize a research cruise on board the JST's Sail Training Ship (STS) *Lord Nelson*. At the Society's AGM in September 2007, it was announced that there would be a one-week scientific cruise on the *Lord Nelson* in January 2008, and those interested in participating were asked to contact the Society with their proposed scientific objectives. Thanks to the efforts of the Challenger Society's Honorary Secretary, Rachael Shreeve, arrangements were made for a team of scientific volunteers (Table 1) to participate in *Lord Nelson* Cruise LN 684 which was scheduled to sail from Las Palmas, Gran Canaria, on 21 January 2008, returning on 28 January.

The original cruise plan was to investigate waters to the north and west of Gran Canaria, but weather forecasts immediately prior to embarkation showed that the wind direction would not favour this, so the area of study was switched to the south of the island (Figure 3). The decision was made jointly by the Chief Scientist and the Master on the basis that there was no need to sample at specific stations and that an important objective for those who had signed up as voyage crew was to spend as much time as possible

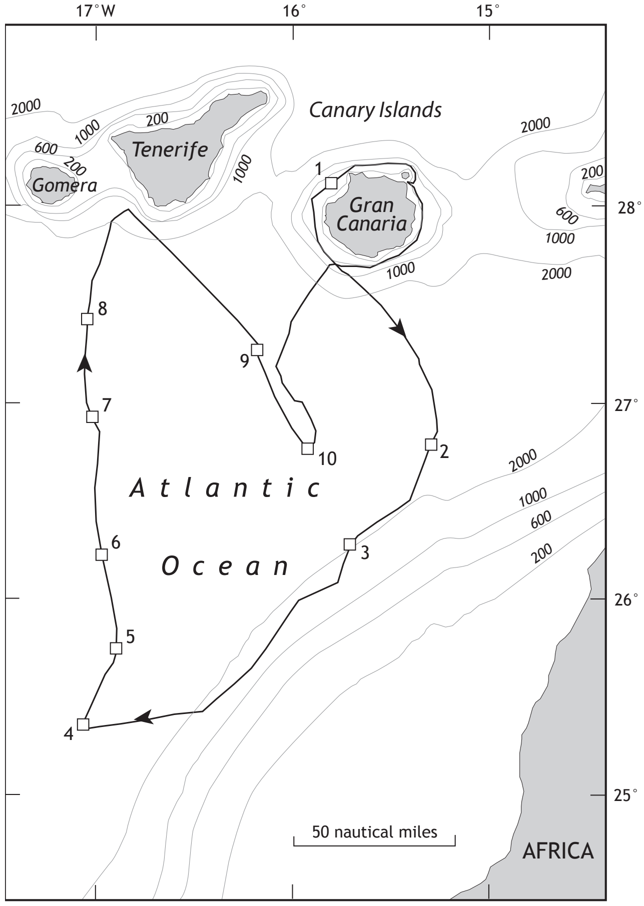


Figure 3 *The track of STS* Lord Nelson *during cruise LN 684, with the positions of sampling stations. Contour depths are in metres. The original intention was to keep to deep water and concentrate on the less studied oceanic phytoplankton. However, adverse winds resulted in more time being spent at the edge of the African continental shelf, which provided the bonus of a series of cetacean sightings.*

Track of STS* Lord Nelson *cruise LN 684 off north-west Africa

Table 1 *Scientists recruited by the Challenger Society for cruise LN 684.*

Name	Affiliation*	Function/research area
John Patching	MRI	Chief Scientist
Colm Moriarty	MRI	Technical assistance
Cilian Roden	GMIT	Phytoplankton: dinoflagellate genus *Histioneis*
Hazel Farrell	MRI	Phytoplankton: dinoflagellates/coccolithophores
Sandra Lyons	MRI	Phytoplankton: dinoflagellates/coccolithophores
Evelyn Keady	NDC	Phytoplankton: dinoflagellates/coccolithophores
Damien Guihen	EOS	Temperature–salinity profiles, GIS
Katherine Crawfurd	PML	On-deck phytoplankton incubations
Gary Caldwell	NU	Zooplankton
Susan Gebbels	DML	Community outreach; bird/cetacean observations
Tamsin Smith	NU	Acoustics
Eleuthera du Breuil	NU	Acoustics/zooplankton
Judy Foster-Smith	EM	Cetacean observations
Arlene Rowan	SAMS	Methanogenesis by pelagic bacteria

*MRI: Martin Ryan Institute, National University of Ireland, Galway; GMIT: Galway Mayo Institute of Technology, Ireland; NDC: National Diagnostics Centre, National University of Ireland, Galway; EOS: Earth and Ocean Sciences, National University of Ireland, Galway; PML: Plymouth Marine Laboratory; DML: Dove Marine Laboratory, Newcastle University, Cullercoats, Tyne and Wear; NU: School of Marine Science and Technology, Newcastle University; EM: Envision Mapping Ltd., Horsley, Northumberland; SAMS: Scottish Association for Marine Science, Dunstaffnage, Scotland.

*A sloop is a single-masted sailing boat, rigged fore-and-aft, with one headsail extending from the foremast to the bowsprit.

†The Jubilee Sailing Trust was established in 1978 with a donation from the Queen's Silver Jubilee Appeal Fund. Its aim is to promote integration between able-bodied and physically disabled adults, by enabling mixed-ability groups (ages 16 to 70+) to crew a tall ship at sea, with able-bodied and physically disabled people participating on as near equal terms as possible.

Sailing vessels exploit a free source of power

Figure 4 *The* Lord Nelson *with a fair wind, photographed from the bowsprit (the spar that extends from the bow). Her top speeds are around 10 knots under sail and 8 knots under power.*

By courtesy of the Jubilee Sailing Trust

under sail. By subsequently making minor adjustments to the cruise plan to allow for changes in the wind etc. it was possible to satisfy the requirements of scientific sampling whilst providing the voyage crew the sailing experience they had paid for.

The main scientific objectives of the cruise were:

- To investigate phytoplankton and zooplankton communities, and stratification of the surface waters of the deep Atlantic, in the area of the Canary Islands.
- To study the response of natural phytoplankton communities to elevated levels of carbon dioxide.
- To carry out observations on cetacean (whale and dolphin) distribution.
- To investigate the biological agents of methanogenesis in surface waters.
- To observe the underwater acoustic characteristics of the ship's hull under different sail regimes.

As well as addressing these objectives, it was intended that the cruise would investigate the logistics of carrying out scientific research under sail in tall ships.

In general, the cruise proved successful from a scientific point of view and also provided valuable insights into the practicalities of working from a tall ship. One obvious disadvantage of a research cruise under sail is the key influence of wind speed and direction on reaching and holding stations. Sailing ships cannot sail directly into the wind but must tack to windward (steer a zig-zag course). It is less convenient to do this with a square-rigged ship like the *Lord Nelson* than with one equipped with fore-and-aft sails (as on a dinghy or yacht) since they are less able to 'point up' (sail obliquely against the wind), and tacking at the end of each leg to windward involves a considerable effort by the crew to brace the yards for the new course.*

As shown in Table 2, more than 90% of the cruise took place under sail, with most of this under sail alone. Table 2 also contains speeds for the cruise under sail and/or power. These are overall averages including time on station and are thus lower than speeds achieved when underway (cf. Figure 4). Cruise plans calling for specific station locations, and with time constraints, could necessitate a greater use of the engines, either alone or in combination with sails, not so much for the increase in speed but for the ability to travel into the wind.

Heaving to for sampling was a new experience for the captain and crew (both permanent and temporary), who are normally concerned with keeping the ship moving as fast as possible rather than stopping it. However, they learnt fast. The captain said that the *Lord Nelson* had been hove to more times during this cruise than in all the rest of her career! Most sampling took place in winds of force 4–6, with a sideways drift of about 1.7 knots (occasionally about 2 knots, and latterly 1 knot or less). Surprisingly, it was heaving to when under engines with only fore-and-aft sails that initially caused the most problems. This involved backing the jib† and running the engines in forward gear, and initially gave a few worrying

*The yards are the horizontal spars which carry the square sails. Bracing the yards involves changing the angle of these sails so that they catch the wind correctly.

†The jib is the triangular sail at the bow; in this context, 'backing' means adjusting a sail so that the wind blows on its front, rather than (as is usual) on its back.

Table 2 *Statistics for activities carried out under different forms of propulsion (derived from the ship's log).*

	Time (hours)	% time	Distance (n.m.)	(km)	(% of total)	Stations worked	Average speed (knots)
Sail	77	62	374	693	59	7	4.9
Motor + sail	39	31	211	391	33	2	5.4
Motor only	8	6	52	96	8	1	6.5
Total	124	100	637	1180	100	10	5.1


(a)


(b)


(c)

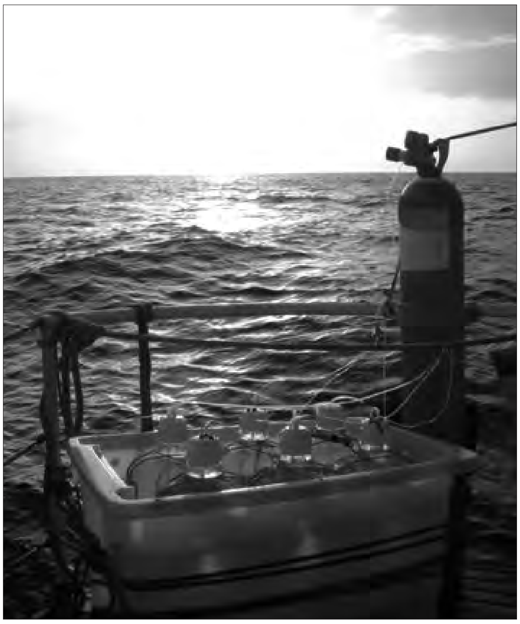

(d)

Figure 5 *On STS* Lord Nelson*, space is at a premium.* ***(a)*** *Plankton nets on the aft deck, ready for deployment.* ***(b)*** *Fixing (preserving) phytoplankton samples on deck – literally!* ***(c)*** *Filtering water samples for chlorophyll analyses.* ***(d)*** *The incubation rig on the aft deck: water samples are being incubated in large plastic carboys through which either air, or an air–carbon dioxide mixture (from the cylinder), is being bubbled.*

Dedicated lab space is a scarce commodity on a tall ship

moments when the ship drifted astern! Under sail only, it was necessary to furl a course (one of the large square sails) and back the foremast sails in order to heave to. This was a fairly physical procedure involving about 18 of the voyage crew, but could be done in about 20 minutes once a routine had been established.

A good team evolved for sampling, centred round Colm Moriarty (the Galway technician), Damien Guihen (physical oceanographer, responsible for the CTD, which determines salinity, temperature and depth) and the Mate, Neil Duncan. The aft deck was an ideal location for sampling, and the Mate had rigged up a davit facing astern with a system of blocks so that the 16 mm rope used for carrying out the vertical plankton hauls could be handled on the side deck. Initially, launch and recovery were by hand – the latter most impressive with a team of 'volunteers' walking the rope forward, peeling off and moving to the back to take up the rope again. Latterly, the mooring capstans were used for hauling. The large-diameter rope was used for its ease of manual handling, but it took up considerable space and also caused drag in the water. This, coupled with the drift of the vessel when on station and the fact that the rope was buoyant, gave rise to angles which were well removed from the ideal vertical alignment when paying out or recovering. A summary comparison of nominal depths (based on the length of rope reeled out) and true sampling depths (Table 3) shows the problems of sampling subsurface water layers with the present system. The use of wire or smaller diameter braided rope and heavier weights on the end of the line could improve matters, but this would rule out veering and hauling by hand and would involve some form of small demountable powered cable drum.

As is typical for tall ships designed for sail training, the *Lord Nelson* has virtually no spare space, either on or below decks, which can be dedicated to on-board scientific activities (cf. Figure 5). One of the on-deck disabled heads was fitted with a table where the NUIG team set up their research

Table 3 *Comparison* of nominal depths (derived from rope paid out) and true sampling depths (measured by means of a Seabird Electronics 37-IM MicroCAT).*

Nominal depth (m)	True depth (m)			
	Max.	Min.	Av.	Median
50	49	29	43.5	45.5
200	186	113	154.6	158.0

*Analysis is of 10 nominal 50 m hauls and 21 nominal 200 m hauls.

Working aloft can provide a welcome break from science!

Figure 6 *Scientist and non-scientists working together to stow the sails before entering harbour.*

microscope and camera system, and a tank for phytoplankton incubations was set up on the aft deck (Figure 5(d)), but, generally, microscopes and other gear were taken out, used wherever (and whenever) space was available, and stowed away afterwards. Thanks to good weather, small raised 'tables' each side of the main mast could be routinely used for sample-handling and low-power microscopy (Figure 5(c)), and the lower mess tables were also available between meals, provided care was taken not to disturb those with bunks in the mess walls.

An important aspect of the cruise was the interaction and collaboration between and within the 13 permanent crew members and the 37 'voyage crew' who had signed up for the cruise. In accordance with the Jubilee Sailing Trust's objectives, the voyage crew contained several disabled participants, though it was decided not to accept wheelchair users for this cruise. Fifteen of the voyage crew had been recruited by the Challenger Society to carry out specific scientific research but the majority (22) had paid to join the cruise as individuals. An informal survey showed that they had done so for two main reasons: first to spend a week at sea with plenty of sailing instead of participating in island-hopping, and secondly, because they were interested in the science that might be taking place. Feedback indicates that they were satisfied on both counts.

Interaction between the crew and the scientists was an important part of the cruise

Figure 7 *At a 'show and tell' session in the bar, non-scientists are introduced to some of the types of phytoplankton that had been recovered. It was found that acceptable 'micrographs' could be taken by holding a basic digital camera against the eye-piece of the microscope.*

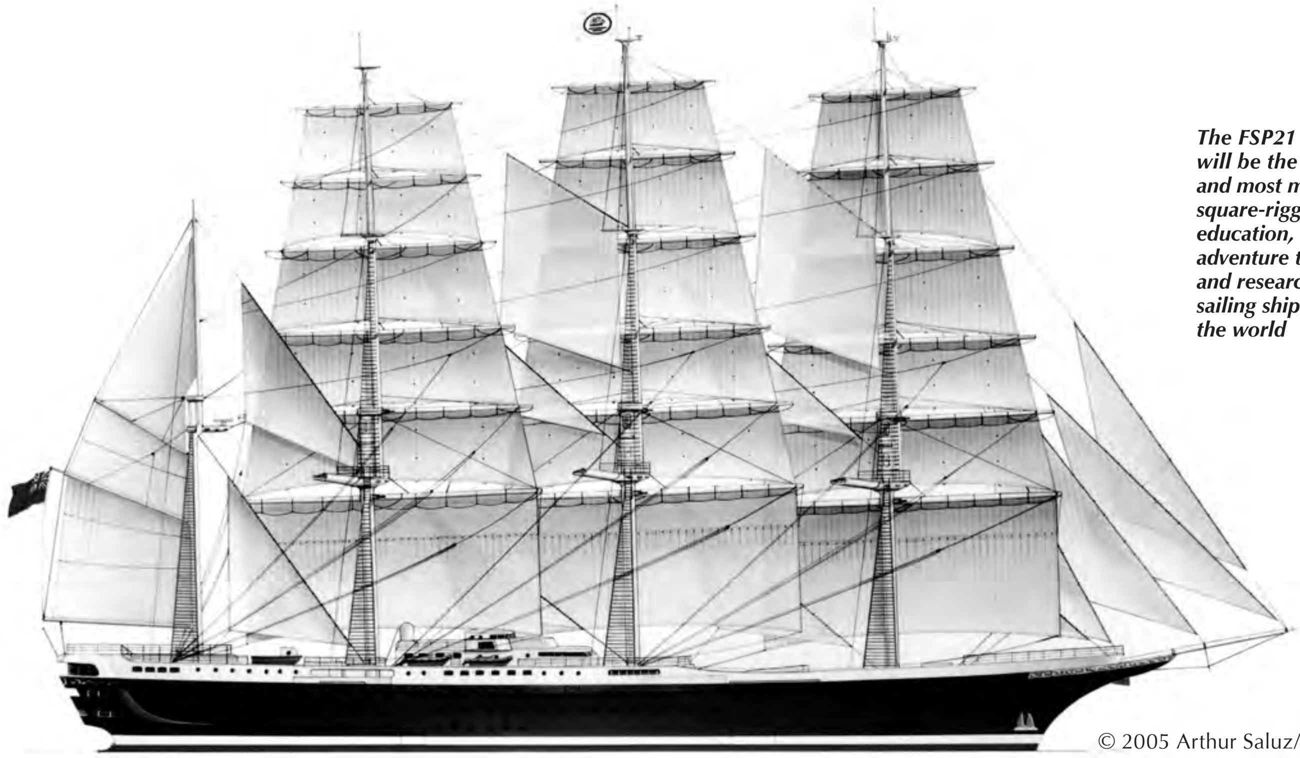
The *Lord Nelson* needs the full participation of both permanent and voyage crews to navigate and sail successfully and keep in good order. All scientists were expected to play their part in standing watches, steering, handling sails, scrubbing and cleaning, and standing mess duty etc. They all did so, appeared to enjoy it, and managed to cope with it and their scientific work without becoming completely exhausted, though if the cruise had been longer it might have been a different story. If future cruises are planned it must be remembered that there is usually no room for 'passengers' on the present generation of sail training ships.

The other kind of interaction not normally found on research vessels concerned the science. Scientists were advised to be outgoing in describing their research to the rest of the crew. In the event, non-scientists were keen to ask questions and participate in what was going on, helping with sample recovery and processing, and with the cetacean survey etc. Short talks on subjects of general interest (sailing etc.) are usually organized for the evenings on *Lord Nelson*, but because of the extra burden of the scientific work on the ship's schedule these were largely abandoned, so, apart from an initial presentation by the Chief Scientist, there was no opportunity to use this method of communication. However, Katherine Crawfurd put up a poster about her work in the bar and two 'show and tell' sessions were organized when all the microscopes were set up and both permanent and voyage crew were invited to 'come and see'. A lot of scientific discussion took place amongst both the temporary and permanent crew during watches, in the bar etc., and arose from genuine interest and excitement about what was being done. Encouraged by the high take-up of berths on this cruise and the positive feedback received from both the temporary and permanent crew, the JST has offered the use of the STS *Tenacious* (Figure 2) for a further cruise in January 2009.

The future

The FSP21 ship and the University of the Oceans

The 2008 *Lord Nelson* research cruise was initiated by the committee of the Future Ship Project for the 21st Century (FSP21) to draw attention to the enormous possibilities that exist for combining science, education and sail training aboard a tall ship – ideas that come together in the concept of the University of Oceans. An essential part of this larger plan is a magnificent new sail training ship for the UK, which has received strong government, industrial and individual support. Initial financial contributions have enabled production of



The FSP21 vessel will be the largest and most modern square-rigged, education, adventure training and research sailing ship in the world

Figure 8 *The tall ship proposed by FSP21 has an environmentally neutral impact. Under sail it should have a speed of 18 knots, under multi-engined biodiesel electric power, a speed of 20 knots, and under battery (or, in the future, hydrogen power), a speed of 10 knots The batteries will be charged (or hydrogen produced) by photovoltaic cells around the hull and in the sails. The 157-m long vessel will provide accommodation for 180 trainees, 20 scientists, 65 crew and 22 passengers.*

a business plan and establishment of a charitable company.

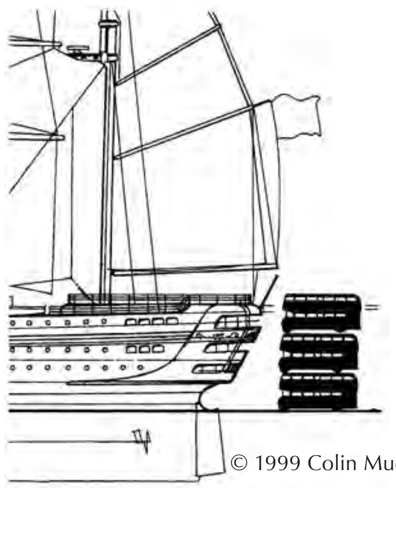
The project has attracted considerable interest from organizations interested in its potential for research into the environmental health of the oceans as well as on the use of renewable energy in the modern maritime world. The vessel will be equipped with facilities for use by research scientists, and by students and trainees as part of an on-board education programme. The facilities will be available for research projects run by organizations and institutions from all over the world.

The mission of the University of the Oceans is to enable young people to experience challenging and life-changing activities in a happy and stimulating environment away from the distractions found on land, to offer academic and vocational opportunities, and to initiate lifelong friendships between young people of all nations through teamwork, tolerance and mutual understanding. The University of the Oceans will undertake research into the environment and the health of the oceans and demonstrate how renewable resources can be used in the marine industry. Through its presence, exhibitions, conferences and corporate events, the University and the FSP21 vessel will display to the world much that is innovative in marine industry, marine science, design, technology and engineering. It will be a flagship for the UK with a distinctive international mission.

Sailing ships of the future

The case for carrying out scientific studies from multi-use tall ships seems well established, but what of the use of sail power by the dedicated research fleet? Along with commercial shipping, this fleet faces a future of increasing scarcity of fossil fuels, and concerns over the impact of using such fuels on global warming. In a way, the present situation is similar to that for research vessels of the 19th and early 20th centuries, faced with the problem of inefficient, fuel-hungry engines. As then, mechanical power is essential for station-keeping, and for deploying and hauling up trawls, dredges and other sampling equipment (although increasing use of free-fall systems could lessen

Figure 9 *Detail of the stern of the proposed FSP21 vessel, with double-decker buses for scale.*



How's this for size!

use of power for sampling). As has been realized by those involved with commercial shipping, the main use of sail will be for passage-making.

Large kites or vertically mounted wind-driven rotors have been proposed for intercontinental freighters. It is possible that such systems could be used for research vessels, though the frequent starting and stopping involved when in a study area requires a system that is relatively easy to deploy and recover. Thus computer-controlled sails of a more or less conventional type might be better than the mega-kites proposed for freighters.

It is possible also that sails could be used, indirectly, to provide the power necessary for station holding and sampling. As well as moving the ship, passage under sail can be used to generate electricity, using the movement of the ship to drive generators via the ship's screw. Sails provide a large area that could be used to harness the power of the Sun, if covered with photovoltaic cells. This approach has been constrained by the need for flexible, cheap cells, but recent major advances in this field look set to make such cells readily available. Both these systems of electricity generation are proposed for the FSP21 vessel (Figure 8). At present, the main constraint on such systems would seem to be the need for cost-effective efficient systems to store the power produced until it is needed.

Sailing vessels offer the advantages of an 'eco-friendly' method of propulsion with a minimal carbon footprint. Further, the quieter, vibration-free environment of a vessel under sail may be useful when attempting observations of marine mammals, or working with optical or acoustic instrumentation etc. Furthermore, tall ships provide an opportunity for instrumentation to measure atmospheric variables above the influence of the ship.

It looks increasingly likely that marine scientists of the future may spend at least part of their career working under sail – though hopefully without the dangers and discomforts faced by their early predecessors!

Further Reading

Rice, A.L. (2007) Marine Science in the Age of Sail *Zoologica Scripta* A short but interesting description of the privations faced by early marine researchers working under sail.

Patching, J.W. (2008) *Lord Nelson* Cruise LN684: Cruise report (30pp. plus appendices). Downloadable from the BODC website: www.bodc.ac.uk/data/information and inventories/cruise inventory (put 'Lord Nelson' in the Free Search box when searching the inventory).

The ES *Orcelle*: The shape of ships to come? *Ocean Challenge,* Vol.14, No.1, 11.

www.jst.org.uk The website of the Jubilee Sailing Trust.

www.universityoftheoceans.com The website of the University of the Oceans and the FSP21.

John Patching is Head of the Marine Micro-organisms Research Unit at the Martin Ryan Institute (Galway, Ireland) and since the 1970s has participated in deep-sea research cruises under sail, steam and the internal combustion engine.

Rachael Shreeve is a marine ecologist who has worked for the British Antarctic Survey for 16 years. She has a passion for working at sea and was a trainee on a tall ship in the 1990s.

Paul Rodhouse is Head of the Biological Sciences Division at the British Antarctic Survey and the scientific member of the FSP21 Executive Committee.

Photographs of life onboard Lord Nelson *are reproduced by courtesy of members of the LN684 voyage crew.*