BY PHILIP P.E. WEAVER, ANTJE BOETIUS, ROBERTO DANOVARO, ANDRÉ FREIWALD, VIKKI GUNN, SERGE HEUSSNER, TELMO MORATO, INGO SCHEWE, AND SYBILLE VAN DEN HOVE

The Future of Integrated Deep-Sea Research in Europe

The HERMIONE Project

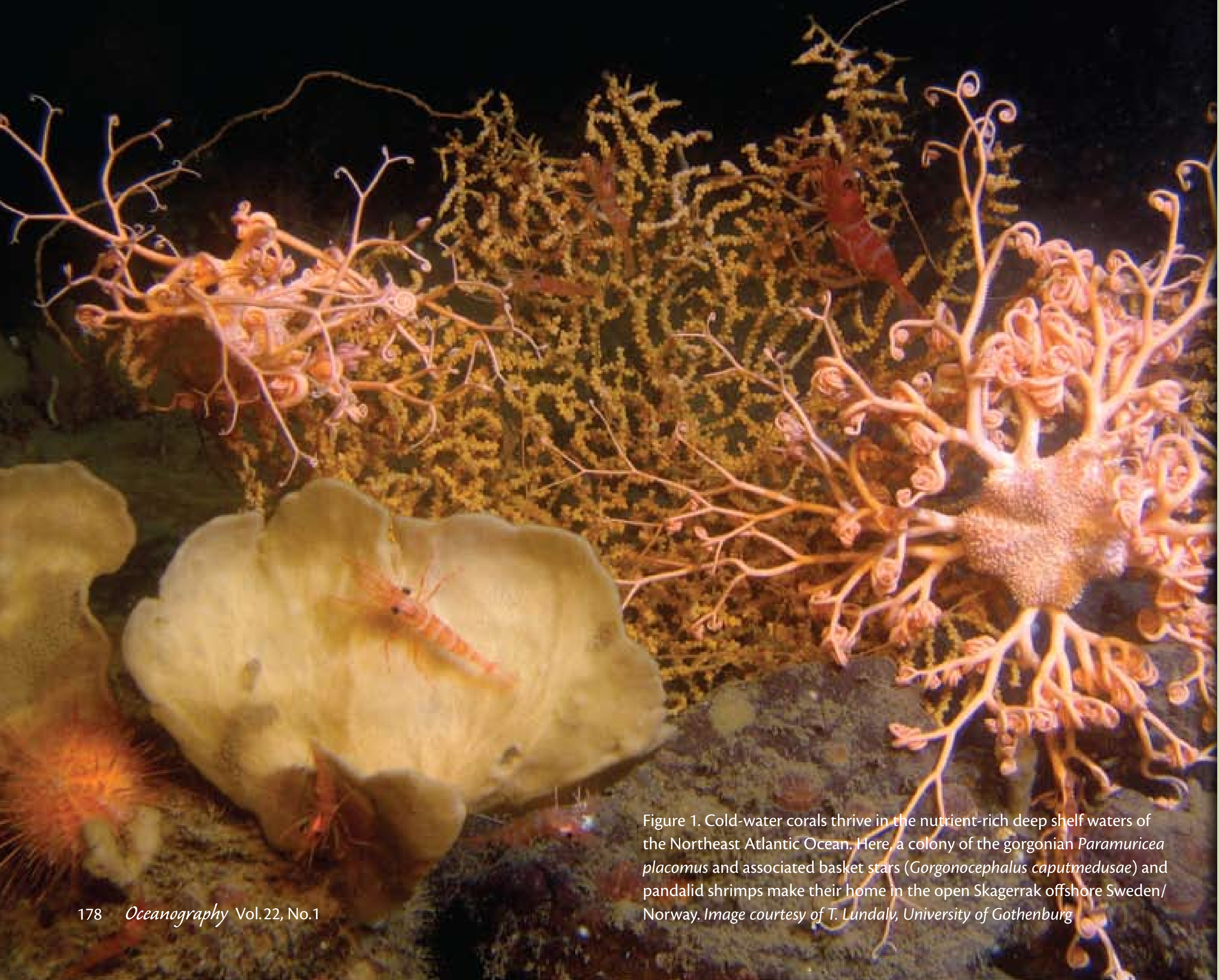

Figure 1. Cold-water corals thrive in the nutrient-rich deep shelf waters of the Northeast Atlantic Ocean. Here, a colony of the gorgonian *Paramuricea placomus* and associated basket stars (*Gorgonocephalus caputmedusae*) and pandalid shrimps make their home in the open Skagerrak offshore Sweden/Norway. *Image courtesy of T. Lundälv, University of Gothenburg*

ABSTRACT. This issue of *Oceanography* mainly describes results from the HERMES project, which comes to a close in spring 2009. Building on the success of HERMES, the European Commission has funded a new project that will begin as HERMES ends. This project, entitled HERMIONE (Hotspot Ecosystem Research and Man's Impact on European Seas), will have a greater focus on human impacts in the deep-sea environment and will place more emphasis on the translation of information into policy. It will have a wider public outreach program and will include new areas of research, such as seamounts and hydrothermal vents. The HERMIONE project will address issues raised in the EC foresight document, *The Deep-Sea Frontier: Science Challenges for a Sustainable Future* (Cochonat et al., 2007), and will focus on four key objectives. These follow a logical progression, from investigating the physical dimensions of ecosystems, to understanding how they function and interconnect, to studying how they are impacted by human activity, to ensuring that this project can contribute to their sustainable management and protection. The HERMIONE consortium comprises 38 partners, including four small businesses, from 13 countries across Europe.

INTRODUCTION

The HERMIONE project plans to investigate ecosystems at critical sites on Europe's deep-ocean margin, including the Mediterranean, Northeast Atlantic, and part of the Arctic Ocean. Even these remote areas are being affected by humankind, either through the indirect effects of climate change or directly through exploitation of deep-sea resources. Urgent questions need to be addressed, such as what will be the impact of climate change on deep-sea ecosystems? What changes are expected in deep-sea ecosystem functioning? How do species interconnect between isolated communities? What are the direct effects of humankind's impact and how can we adapt or mitigate them so as to use the ocean in a sustainable manner? Answering these questions requires complex experiments combined with long-term monitoring of sensitive environments. It also requires an interdisciplinary approach that includes benthic biology, biogeochemistry, microbiology, sedimentary processes, physical oceanography, and socio-economics.

HERMIONE will address issues raised in the EC foresight document, *The Deep-Sea Frontier: Science Challenges for a Sustainable Future* (Cochonat et al., 2007). It will build on the success of previous projects such as HERMES but will tackle new areas, for example, providing essential information on ecosystem dynamics at potential long-term deep-sea observatory sites and in Arctic areas where climate change will be more pronounced. Other topics of interest include cold water cascading in the Mediterranean (Canals et al., 2006, this issue) that are driven by cold winter winds that may weaken as climate warms, leading to reduced ventilation of deep Mediterranean waters (Canals et al., 2006). In addition, we plan to investigate seamounts as potential areas of high biodiversity that are under threat from bottom trawling (Clark et al., 2006) and to compare and/or relate the chemosynthetic communities found at cold seeps to those living at hot vent sites on the Mid-Atlantic Ridge.

Four key scientific objectives have been identified for HERMIONE (Box 1). These follow a logical progression, from investigating the physical dimensions of ecosystems, to understanding how they function and interconnect, to studying how they are impacted by human activity, to ensuring that this project can contribute to their sustainable management and protection.

The scientific side of the work program will be complemented by an extensive public outreach program, notably through the inclusion of four aquaria in Italy, the UK, and Greece. These aquaria will disseminate project information and results, the concepts behind the research, and the need to care for our deep-sea environment to a broad cross section of the public across Europe. A wider audience will be targeted through the use of global Web-based tools, such as Google Earth and other e-resources.

DATA COLLECTION

Exploring and investigating the deep sea is expensive and difficult to achieve because it requires large infrastructure in the form of ocean-going ships and expensive equipment such as remotely operated vehicles (ROVs) to reach the seafloor. Although the larger nations of Europe maintain a high level of ocean research, considerable added value is gained by working together; facilitating equipment sharing, knowledge, and personnel exchange; and standardizing sampling practices and accessibility of data and knowledge. The result is increased productivity, more efficient use of ship time, and, ultimately, higher-impact research.

We anticipate that HERMIONE will benefit from over 1000 days of ship time. The cruises will collect data using expensive, large-scale facilities such as side-scan sonar, swath bathymetry, ROVs, benthic landers, geochemical samplers, and instrumented moorings. The use of ROVs will be critical to this project, which depends on precise sampling of biological specimens and vent fluids and locating seabed experiments in optimal positions. Large arrays of instrumented moorings, shared by different partner institutions, will be deployed in common experimental areas, thus allowing us to develop experimental strategies beyond any national capacity.

KEY ECOSYSTEMS TO BE STUDIED

Open Slopes and Basins

Slopes and deep basins comprise > 90% of the ocean environment and 65% of Earth's surface. Their profound involvement in global biogeochemical and ecological processes makes these ecosystems essential for the sustainable functioning of our biosphere and for human wellbeing. Many of the goods (biomass, bioactive molecules, oil, gas) and services (climate regulation, nutrient regeneration, food) provided by deep-sea ecosystems are produced and stored in slopes and deep basins.

In the deep-sea, diversity varies on local, regional, and global scales (Stuart et al., 2003). Understanding the mechanisms that produce these geographic patterns and boundaries among deep-sea ecosystems is one of the most challenging aspects of marine ecology. One documented trend is the parabolic relationship between depth and species diversity (Rex et al., 2005), but this pattern is apparently not consistent in all systems, nor for all taxonomic groups. A variety of biological explanations have been proposed for why species diversity changes with depth, including

Box 1. HERMIONE Objectives

1. To investigate the dimensions, distribution, and interconnection of deep-sea ecosystems
2. To understand changes in deep-sea ecosystems related to key factors, including climate change, human impacts, and the impact of large-scale episodic events
3. To understand the biological capacities and specific adaptations of deep-sea organisms, and investigate the importance of biodiversity in the functioning of deep-water ecosystems
4. To provide stakeholders and policy-makers with scientific knowledge to support deep-sea governance aimed at the sustainable management of resources and the conservation of ecosystems

Figure 2. The HERMIONE study areas. Many study areas intentionally overlap with those of the HERMES project, enabling HERMIONE to build on and extend previous research, and allow much-needed time-series data collection to continue.

competition, predation, patch dynamics, environmental heterogeneity, productivity, and various combinations of these. During HERMES, a significant body of information on local diversity was acquired at large spatial scales, along bathymetric patterns, in various hotspot ecosystems, and at different latitudes. These data are of paramount importance in understanding the factors controlling the distribution of biodiversity on continental slopes at spatial scales of several hundreds to thousands of kilometers. But these data also reveal that the deep sea is composed of mosaics of habitats in which the proximity of other hotspot ecosystems can influence the biodiversity, biological capacity, and ecological processes of the deep-sea slopes and basins. Further studies are needed to understand these relationships and the interconnection among shallow, bathyal, and abyssal ecosystems.

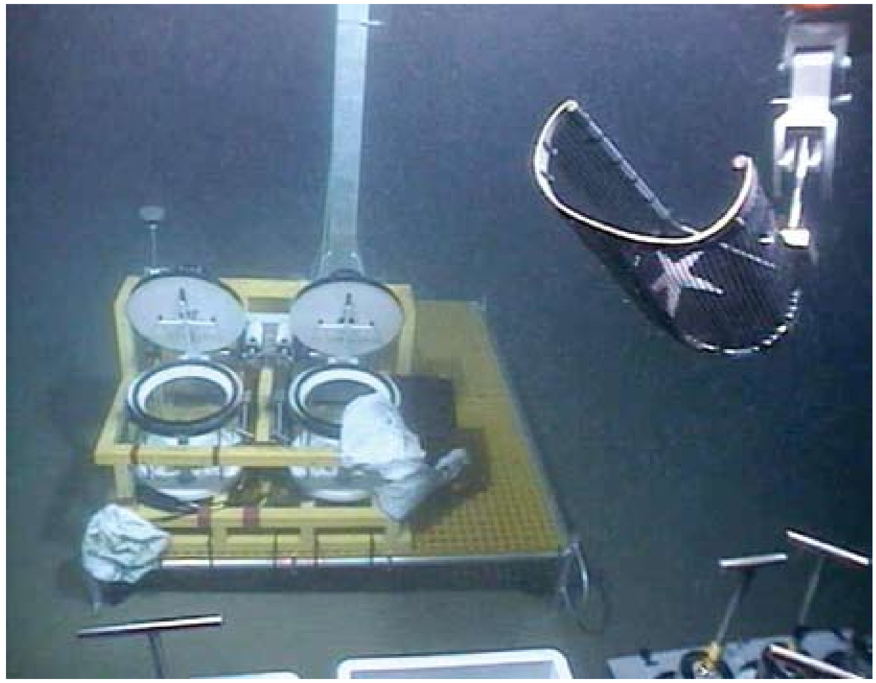

Figure 3. Humankind's impact on the deep sea. Litter, particularly plastic bags, is a common sight on the video camera footage from remotely operated vehicles deployed to investigate the deep sea. Here, plastic bags have accumulated on an incubation experiment deployed at 1400-m water depth in the Setubal Canyon offshore Portugal. *Image from ROV* Isis *video, cruise JC10/2007, courtesy of National Oceanography Centre, Southampton*

Recent modeling shows that ~ 85% of the methane reservoir along continental margins could be destabilized as a result of the warming of bottom waters by 3°C. Seafloor warming will significantly affect one of the largest and richest ecosystems on Earth with unknown consequences for the structure, dynamics, and metabolism of the benthos. The role of climatic variation in regulating marine populations and communities is poorly understood, and there are few data on the impact of climate change on the deep ocean (Danovaro et al., 2004). In the Porcupine Abyssal Plain, large-scale changes in a wide range of benthic fauna have occurred in the last two decades related to the flux of organic matter to the seafloor (Billett et al., 2001), and similar changes in the micro- to megafaunal components have been suggested for the deep Mediterranean basin (Danovaro et al., 2001). Unraveling the impact of recent climate change from natural variation is extremely difficult, especially in the deep sea where long-term records are rare. HERMIONE will add to long-term measurements in the western Mediterranean where a continuous 15-year time series can be examined, and in the eastern Mediterranean where long-term observations of deep bottom waters have been ongoing for more than 20 years. These long time series are important because deep-sea systems can

Philip P.E. Weaver *(p.weaver@noc.soton.ac.uk) is HERMES Coordinator, National Oceanography Centre, University of Southampton, Southampton, UK.* **Antje Boetius** *is Head, Habitat Group, and Professor, Max Planck Institute for Marine Microbiology, Bremen, Germany.* **Roberto Danovaro** *is Director, Department of Marine Sciences, Università Politecnica delle Marche, Ancona, Italy.* **André Freiwald** *is Professor, GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Erlangen, Germany.* **Vikki Gunn** *is HERMES Project Manager, National Oceanography Centre, University of Southampton, Southampton, UK.* **Serge Heussner** *is Director of Research, Centre de formation et de recherche sur l'environnement marin (CEFREM), CNRS-Université de Perpignan Via Domitia, Perpignan, France.* **Telmo Morato** *is a fisheries biologist in the Departamento de Oceanografia e Pescas, Universidade dos Açores, Portugal.* **Ingo Schewe** *is a deep-sea ecologist at the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.* **Sybille van den Hove** *is Director and Partner, MEDIAN, Barcelona, Spain.*

vary radically with time (Billett et al., 2001), in relation not only to changes in quality and quantity of organic matter input (Wigham et al., 2003) but also to changes in the formation of deep waters (Canals et al., 2006). HERMIONE scientists will document potential changes in other areas, such as the recent changes in biomass at the Hausgarten deep-sea observatory in the Arctic, and they will study the decadal variability of flushing events on the Portuguese canyons via analysis and modeling of historical, meteorological, and hydrodynamic data.

Landslides disturb the deep benthic ecosystem by both remolding the seafloor and modifying its topography, thus exposing new surfaces for colonization. These events can promote high levels of deep-sea biodiversity through the creation of a mosaic of different topographic conditions and by offering new opportunities for colonization and speciation. Effort is required to identify the impacts of landslides of different sizes, depths, and ages. These studies will require high three-dimensional resolution, direct observations, remote sampling, and interdisciplinary investigations involving sedimentological, biogeochemical, and biological aspects (e.g., genomics, molecular biology, microbiology, and biodiversity analyses) at all trophic levels. It is hypothesized that unstable slopes can create a dynamic mosaic of environmental conditions that sustain high biodiversity levels and promote the turnover of deep-sea biodiversity. This hypothesis will be tested using an integrated and interdisciplinary approach based on the data and information acquired during the HERMES project and by means of new sampling activities developed for stable and unstable slopes using high spatial (bathymetric) resolution and hierarchical sampling strategy.

Dense water cascading is one of the main mechanisms of matter and energy transfer from the surface to the deep ocean. The frequency and intensity of such events profoundly impacts slope and basin ecosystems through transport of fresh, highly nutritive organic matter and sediment on short time scales. These events have a potentially important role in global carbon budgets (Canals et al., 2006, this issue). Episodic cascading events could induce significant modifications of slope and basin biodiversity on global scales, but little is known about how biodiversity has been affected by recent changes in the deep sea. For instance, there is evidence that deep-sea biodiversity can be strongly affected by the modified physico-chemical conditions that occurred between 1992 and 1994 in the Cretan Sea (eastern Mediterranean), causing a significant shift in faunal abundance and diversity (Danovaro et al., 2004). There is also evidence that this process can alter the population dynamics of commercial deep-sea species over large areas, but the overall ecological consequences of this phenomenon are almost completely unknown (Company et al., 2008). HERMIONE will investigate the consequences of dense shelf water cascading (DSWC) on benthic diversity, functional traits, biological capacity, and biogeochemical cycles in slope and basin ecosystems. Known DSWC areas targeted by HERMIONE are the western Mediterranean (with data available from 1989–2007), the Adriatic Sea, the eastern Mediterranean, and the Arctic Ocean off the Svalbard Islands. The results will provide new input toward a better understanding of the potential large-scale consequences of these episodic events.

Investigation of terrestrial ecosystems suggests that biodiversity loss may impair the sustainability of ecosystem functioning and production of goods and services. Although slope and basin ecosystems represent the largest reservoir of biomass on Earth and host a large proportion of undiscovered biodiversity, the data needed to evaluate the consequences of biodiversity loss on the functioning of these ecosystems are largely insufficient to define specific policy actions. A recent global-scale study relating benthic biodiversity to several independent indicators of ecosystem functioning demonstrated that deep-sea ecosystem functioning and efficiency are exponentially related to biodiversity (Danovaro et al., 2008b). These results suggest that higher biodiversity supports higher rates of ecosystem processes and increased efficiency within these processes. The exponential relationships imply that positive functional interactions (ecological facilitation) are common in Earth's largest biome. However, these data need further validation. Do recent findings apply differently to slopes and basin ecosystems? To date, deep-sea studies have been based on analyses of one or few taxa. Thus, there is an urgent need to move toward a multilevel diversity approach that can assess the biodiversity patterns of prokaryotes, protozoa (forams), meiofauna, macrofauna, and megafauna, linking these data with the variables describing ecosystem functioning (Danovaro et al., 2008a) and the production of essential goods and services. HERMIONE will investigate multilevel biodiversity with several independent indicators of ecosystem functioning and efficiency. These results, together with additional molecular and phylogenetic analyses, will clarify how biodiversity loss in deep-sea ecosystems can cause the reduction of their functions. The final aim is (1) to provide quantitative estimates of the potential consequence of biodiversity loss on deep-sea ecosystem functions and on the ability of deep-sea biodiversity to adapt to current changes, and (2) to mitigate the direct/indirect anthropogenic impact on slope and deep basin ecosystems. These data will be used in conceptual models integrating, for the first time, deep-sea biodiversity and quantitative analyses of ecosystem functioning and processes.

Figure 4. Canyons are home to a huge variety of fauna, including this filter-feeding community discovered on a rocky overhang in the Lisbon Canyon offshore Portugal. *Image courtesy of National Oceanography Centre, Southampton/Cruise JC10*

Canyon Ecosystems

Submarine canyons are deep incisions of the continental shelf and slope that dissect much of the European margin. Some canyons are closely connected to major river outflow systems, while others funnel large quantities of sediment from the continental shelf into deep water. The hydrography, sedimentology, and biogeochemistry of canyons are complex, with faunal communities living on hard substrata as well as in mobile sediments.

Over the last two decades, scientific interest in canyons has focused on understanding the role of continental margins and canyons as sources or sinks for carbon, and their relation with the functioning and integrated management of the coastal zone. A number of initiatives, such as the EU-funded EUROMARGE, OMEX, and EUROSTRATAFORM projects, have demonstrated that canyons are major pathways for transport and burial of organic carbon in the ocean, with high variability within and among canyons (e.g., Heussner et al., 1999, 2006), and fast-track pathways for material transported from the land to the deep sea (Khripounoff et al., 2003; Canals et al., 2006). Determining physical processes controlling particle transfer, such as internal waves and storm events, is critical to understanding the production of nepheloid layers (particle-rich layers above the ocean floor) by resuspension (Quaresma et al., 2007) and the enhancement of primary productivity at canyon heads. Cross-contour flows, local upwelling, wave reflections, and cascading of dense, turbid shelf waters all occur above or inside canyons (Huthnance, 1995). Where three-dimensional, high-resolution models have been applied, they show enhancements of energy along the canyon floor and walls (Ulses et al., 2007). There is great temporal variation (from days to years) in the creation of nepheloid layers, and fluxes can vary over several orders of magnitude (milligrams to tens of grams m^{-2} d^{-1}). Variability is greater at short scales of days to weeks, suggesting that particle transfer is largely event-driven. Where fluxes within canyons have been compared to those on the open slope, they have been found to be two to four times greater within canyons, emphasizing their channeling effect (Heussner et al., 2006). The terrigenous character of canyon sediments indicates that terrigenous sources of detritus dominate over the flux of pelagic components. The high sedimentation rates and elevated levels of organic carbon indicate that canyons are preferential accumulation sites for organic carbon (Etcheber et al., 1999). However, only a few canyons across the Northwest Mediterranean and Northeast Atlantic margins have been investigated in detail; thus, transport processes and mass fluxes of particles, including organic matter, anthropogenic substances, and urban waste to the deep-sea and their sites of final deposition remain largely unknown (van Weering and Weaver, 2007). HERMIONE will investigate the processes governing sediment transport and deposition in selected canyons and their temporal variability over a range of time scales in five different biogeochemical provinces: (1) Svalbard, in the Barents Sea, (2) Ireland, (3) Portugal, (4) the western Mediterranean, and (5) the eastern Mediterranean. HERMIONE will also establish the importance of canyons in maintaining high biodiversity levels, as hotspots of biological activity, and as specific habitats for endemic species.

The capacity of canyons to focus and concentrate organic matter leads to (1) high standing stocks of animals, and (2) a great variety of faunal groups, from microbes to cetaceans. The species and abundances differ within and among canyons and are related to downward particle fluxes, topography, and hydrographic features of individual canyons (Vetter and Dayton, 1998). Many endemic species inhabit canyons (Gili et al., 2000), but this observation may reflect our lack of knowledge of the inter-canyon variability among species. We do not yet know if canyons play a role as sources of larvae and juveniles for populations on the wider continental slope (Tyler and Ramirez-Llodra, 2002). Previous research indicates the importance of various zooplankton groups acting as links to fish and mammal populations, and the important role that vertical migration of zooplankton and micronekton plays in carbon and nitrogen transfer. Cetacean abundance is generally higher in and around canyons owing to the concentration of food resources. The benthos varies depending on depth, current regime, and organic matter input. Canyons are important in the channeling of macrophyte debris, affecting the relative abundance of some species. Results on the relationship of species composition, abundance, and biomass to organic input remain contradictory (Garcia et al., 2007) and highlight the importance of gaining a clearer understanding of faunal distribution in canyon systems.

Our view of biological processes in canyons has changed considerably in the last few years due to increased use of submersibles and ROVs and other video-guided technologies. It has become obvious that there is great diversity in canyon fauna as there is great diversity in canyon environments. However, many aspects of their ecological role and contribution to the functioning of the whole deep-sea ecosystem remain unexplored. The diversity of canyon systems makes it difficult to reach generalizations that will be useful in creating policies for holistic ecosystem management without: (1) a comparison of canyons from different biogeochemical provinces and topographic settings, (2) coordinated, interdisciplinary projects relating the fauna to environmental variables regulating their distributions, and (3) surveys taking into account natural or anthropogenic factors that disturb life in canyons. HERMIONE will examine canyon ecosystems in light of the complex interactions among habitat (topography, water masses, currents, nature of substratum), mass and energy transfer, and intrinsic biological properties. Current questions about the functioning of canyon ecosystems concern not only their interrelationship/dependence on physical and geological processes (e.g., rates and composition of fluid flow, frequency of landslides, rates of canyon flushing) but also their sensitivity to the direct human impacts (e.g., fishing activities), transfer of contaminants, environmental change, and the biological capacities of marine organisms.

Seamounts

Seamounts are defined as "undersea mountains whose summits rise more than 1000 meters above the surrounding seafloor and exhibit a conical shape with a circular, elliptical or more elongate base" (Wessel, 2007). The best estimates suggest that there may be between 1000 and 2800 large seamounts of more than 1000-m height in the Atlantic Ocean and about 60 in the Mediterranean (Kitchingman et al., 2007). Seamounts are hotspots of marine life (Pitcher et al., 2007). They enhance water flow through localized tides, eddies, and upwelling, and these physical processes may enhance primary production (PP) over and around seamounts (White et al., 2007). On the seamount floor there are often rich communities dominated by suspension feeders such as gorgonians and other corals (Rogers et al., 2007). Many form colonies or even reefs, as in the case of *Lophelia pertusa*, which provide extra complexity and structure to seamounts. Though the diversity and localized distribution of species living in these communities are recognized, their biology and life histories remain poorly studied, although we do know that some of these species may be extremely long-lived (e.g., > 100 years).

The species richness and diversity of fish fauna on seamounts is well documented. Although the number of investigated seamounts is small, it is increasingly evident that the associated fish assemblages display specific adaptations to these habitats and represent a relatively large and unique portion of fish biodiversity (Morato and Clark, 2007). Among the fish living on (or visiting) seamounts, several species have raised much attention because of their high abundance and commercial value, including orange roughy, (*Hoplostethus atlanticus*) and alfosinos (*Beryx splendens* and *B. decadactylus*) (Morato and Clark, 2007). These fish aggregate on seamounts and have been intensively exploited since the late 1970s. "Seamount" fishes, particularly "seamount-aggregating" fishes, have higher intrinsic vulnerability than other groups of fishes due to their longer lifespan, later sexual maturity, slower growth, and lower natural mortality (Morato et al., 2006). A number of seamount populations have already been depleted and some species will become extinct if fishing on seamounts continues at current or even reduced levels. Deep-sea trawling also causes extensive damage to benthic habitats (Gianni, 2004). There is growing evidence of extensive collateral damage of, for example, cold-water coral reefs and sponge aggregations by fishing trawls (Hall Spencer et al., 2002). Deep-sea corals and deep-sea sponges are long-lived (~ 1000 years), colonial reef-building organisms. Recovery from damage may take thousands of years, if they recover at all. Resilience may be low in highly structured deep-sea ecosystems based on reef-building, long-lived species, at least in comparison to shallow habitats.

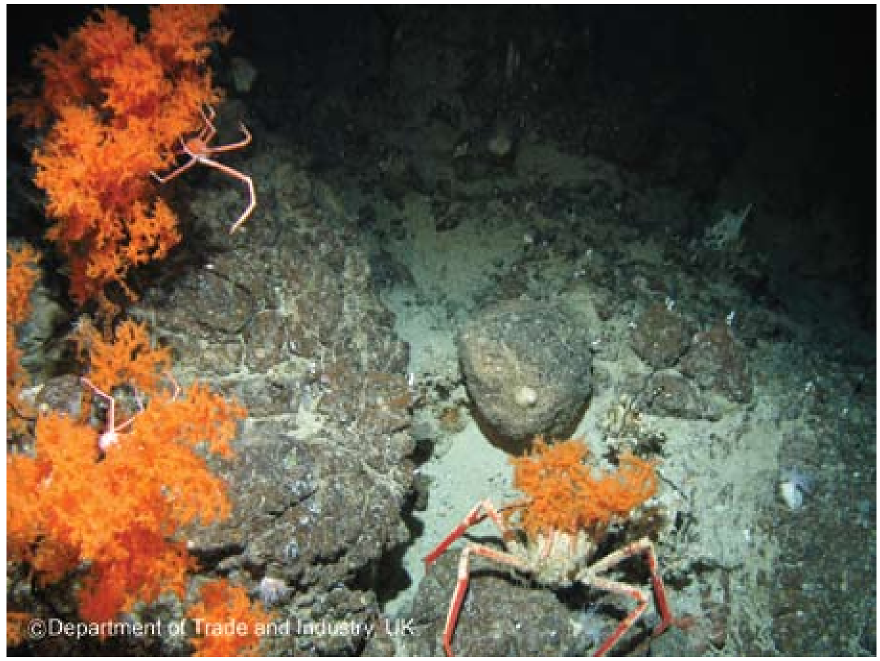

Figure 5. Large spider crab, live antipatharian corals, and associated crustaceans photographed on a seamount in the Northeast Atlantic. The photograph was collected under the Strategic Environmental Assessment of Area 7. *Courtesy of the Department for Business Enterprise and Regulatory Reform (BERR), UK (formerly the Department of Trade and Industry, or DTI)*

Seamounts support high levels of biodiversity together with high levels of endemism. However, practically no information is available on the spatial distribution of benthic biodiversity in close proximity to seamounts and on coupling between biodiversity and ecosystem functioning along spatial gradients and ecotones (i.e., transition areas) between seamount ecosystems and adjacent ecosystems. Such data are essential to improve our knowledge on the role seamounts play in biodiversity and ecosystem functioning in the interconnection with the adjacent deep basins. HERMIONE will help to characterize and describe seamounts in European Atlantic and Mediterranean ocean margins. We will determine whether selected seamounts influence the standing stock, species diversity, or community structure of macrofauna in surrounding deep-sea sediments. Additionally, experimental studies will examine interconnectivity between seamounts with adjacent ecosystems (e.g., on open slopes and basins).

Scientific knowledge on seamounts is still limited, and many fundamental questions about the functioning of their ecosystems remain a challenge to deep-sea science. For example, it has been hypothesized that seamounts play important roles in ocean biodiversity, such as acting as centers of speciation, refugia for relict populations, or stepping stones for transoceanic dispersal. But at present, these hypotheses still need to be tested in the field. In the HERMIONE project, we will help to clarify specific adaptations of deep-sea organisms inhabiting seamounts and the adjacent deep-sea basins in relation to their ecology and will provide new insights into the importance of the different structural and functional attributes of biodiversity in the functioning of seamount ecosystems.

Cold-Water Coral Ecosystems

Deep-sea coral ecosystems are most extensive along the Northeast Atlantic margin and deep shelves, and represent important biodiversity hotspots. These corals construct deep-water reefs and carbonate mounds in some margin areas, while in other areas corals are in decline for unknown reasons. Reefs and mounds document environmental change caused by both natural and anthropogenic forces on historic to geologic time scales—a prerequisite for forecasting reef migration and future biodiversity changes (Roberts et al., 2006).

The true distribution of deep-water coral ecosystems along the wide European deep-sea frontier is becoming better known (Wheeler et al., 2007). Several coral hotspots can be identified, for example, the Scandinavian margin, the Rockall-Porcupine margin, and the central Mediterranean margin. How are these coral hotspots connected and how did they arise? HERMIONE will address these questions by genotyping the reef-building corals and associated key species such as sponges to develop a phylogeographic picture of the spread or isolation of coral populations. Intense mapping done during the HERMES project shows that flourishing reef ecosystems are surrounded by areas of dead coral frameworks and rubble plates. These coral "graveyards" play an important role in attracting a rich micro- to mega-fauna, and evidence suggests that these grounds are prime candidates for coral ecosystem replenishment. HERMIONE will tackle the unsolved questions of how live and dead ecosystems are temporally and spatially interconnected in a margin-wide context and if there is a cause-and-effect process that switches coral ecosystems on and off. Revisiting and monitoring known pristine and damaged coral reef sites will enable us, for the first time, to provide time-series data using a new generation of benthic landers.

The Mediterranean coral ecosystem was believed to be in decline as a consequence of natural global change related to warming of deep-sea oceanic circulation, but a new hotspot area of living coral in the central Mediterranean Sea has been discovered (see Freiwald et al., this issue). How are these populations connected to the prospering Atlantic populations? Will further warming in the Mediterranean cause environmental stress to the Mediterranean corals, and will the corals expand further north into the Arctic? A specific target will be the cascading effect of dense shelf waters that are funneled through canyons into the deep sea. In the Atlantic Ocean and Mediterranean Sea, known cascading areas are rich in prospering coral ecosystems. HERMIONE will provide input to the development of forecasting models to better understand the migration of these valuable deep-sea ecosystems and their responses to environmental change.

Though cold-water coral ecosystems support high biodiversity, provide important paleoclimatic archives, and are widespread on both sides of the North Atlantic Ocean, they have not been studied at a basin scale. This limitation means our understanding of genetic links between coral ecosystems and their significance as potential centers of endemism and speciation have not yet been realized. Without this type of information, conservation strategies (including networks of marine protected areas) cannot be developed for cold-water coral ecosystems.

High-resolution mapping, video-

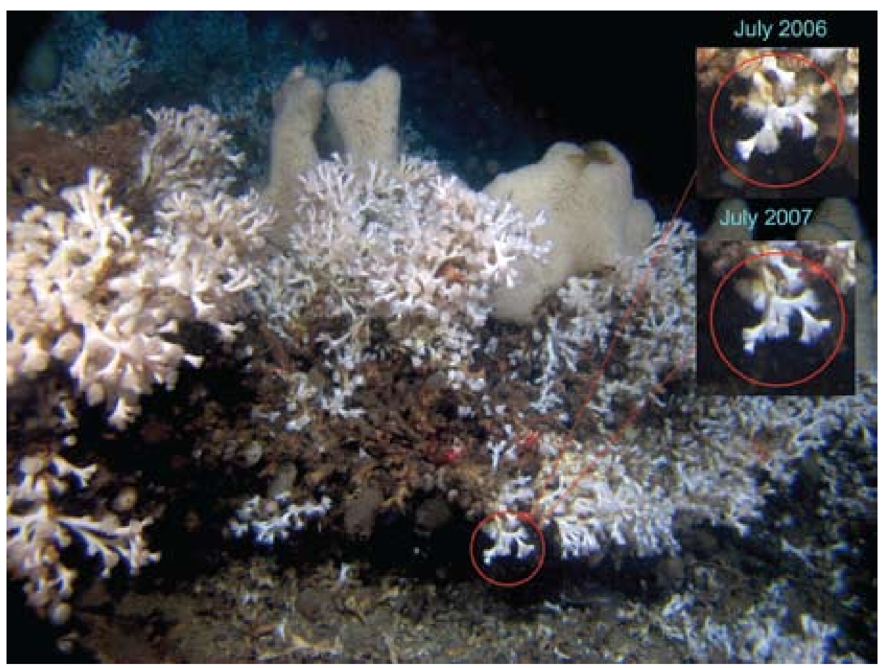

Figure 6. Evidence of regeneration? Previous studies indicate that regrowth of coral reefs after destruction by fishing trawlers may be possible, albeit very slowly (see Lavaleye et al., this issue). This image shows part of a coral colony (*Lophelia pertusa*) at the Tisler reef (offshore Sweden), within a transect that has been regularly monitored since 2004, when the reef became protected, for studies of recovery from trawl damage. Inset: Close-ups of a coral branch photographed at a one-year interval, showing growth of approximately 6 mm in a year. *Images courtesy of T. Lundalv, University of Gothenburg*

graphic seafloor observation, and carefully planned sampling provided an insight into cold-water coral ecosystems in European seas during HERMES. A variety of geological and oceanographic factors were identified that appear to structure ecosystem distribution and spatial dimensions. Yet very little is known about biological drivers of ecosystem distribution, such as dispersal mechanisms, larval settlement, reproduction and life-cycle timing, competition and cooperation among species and communities, and physiological thresholds with regard to population distribution. To understand ecosystem resilience, it is critical to know the interconnection among ecosystems and their communities. In a multilevel interdisciplinary approach, HERMIONE will assess the biodiversity patterns of prokaryotes, protozoans, meiofauna, macrofauna, and megafauna using a molecular/phylogenetic approach and genomic investigation of key species; this work will link the data with the environmental variables that describe ecosystem functioning. The HERMES data set lists more than 2000 species occurring in cold-water reef habitats worldwide, with some key species showing a mutual relationship with coral habitats in terms of biomass and abundance. HERMIONE will explore the ecophysiology (respiration, growth, calcification, reproduction) of corals and related key species in aquaria experiments and analyze the environmental conditions that enable corals to form habitats in canyons and on seamounts.

Figure 7. Chemosynthetic fauna at a hydrothermal vent site on the Mid-Atlantic Ridge. *Image taken with ROV* Quest 4000*, courtesy of MARUM, University of Bremen*

Chemosynthetic Ecosystems

Chemosynthetic ecosystems, including hot vents, cold seeps, mud volcanoes, and sulfidic brine pools, are highly fractured and diverse deep-water habitats shaped by dynamic, small- and large-scale geological processes that vary substantially in time and space. The discovery of hydrothermal vents, cold seeps, and gas hydrates in subsurface sediments and rocks showed that significant ecosystems on Earth could be fueled by reduced chemical substances (H_2S, H_2, Fe, CH_4) and other hydrocarbons (Jørgensen and Boetius, 2007). These ecosystems show the highest biomass and productivity of all deep-water ecosystems. The huge diversity of genomic capabilities in chemosynthetic ecosystems has not been comprehensively explored, and knowledge continually expands as new organisms are discovered. Research at seeps and vents has profoundly altered our perspective on the physiological limits of organisms and their versatility with respect to energy sources. The dominant species in these ecosystems form remarkable and very efficient symbiotic associations with bacterial primary producers, a process that has major consequences for evolutionary biology. Only a tiny fraction of the microbiota at vents and seeps has been identified, and a huge diversity remains to be discovered. Larger animals inhabiting chemosynthetic ecosystems display intriguing life cycles and reproduction and dispersal strategies. Recently, public awareness of biodiversity has increased substantially, not only due to its vulnerability to human impacts (including climate change) but also with regard to its potential relevance to bioprospecting and biotechnology.

Microorganisms involved in methane cycling and carbonate formation have important functions that control greenhouse gases (Boetius et al., 2000; Parkes et al., 2007). Vast amounts of methane are formed from thermogenic catalysis or microbial diagenesis of organic matter in the seabed. Upon reaching

Box 2. The HERMIONE Consortium

The 38 HERMIONE Consortium partners represent a total of 13 European countries, and includes four small business partners.

- National Oceanography Centre, Southampton, UK (Coordinator)
- Institut français de recherche pour l'exploitation de la mer, France
- Royal NIOZ, The Netherlands
- University of Barcelona, Spain
- Hellenic Centre for Marine Research, Greece
- IFM-GEOMAR, Germany
- Consiglio Nazionale della Richerche, Italy
- Alfred Wegener Institute, Germany
- University of Tromsø, Norway
- National University of Ireland, Galway, Ireland
- Friedrich-Alexander University Erlangen-Nuremberg, Germany
- Universiteit Gent, Belgium
- Consejo Superior de Investigaciones Scientificas, Spain
- Consorzio Nazionale Interuniversitario per le Scienze del Mare, Italy
- Max Planck Institute for Marine Microbiology, Germany
- Université de Perpignan Centre de Formation et de Recherche sur l'Environnment Marin (CNRS-CEFREM), France
- Instituto Hidrografico, Portugal
- Jacobs University Bremen, Germany
- University of Bremen, Germany
- Cardiff University, UK
- Institute of Marine Research, Norway
- University of Gothenburg, Sweden
- University of Southampton, UK
- Netherlands Institute of Ecology, The Netherlands
- University of Aberdeen, UK
- University of Liverpool, UK
- Scottish Association for Marine Science, UK
- University of Aveiro, Portugal
- Université de Pierre et Marie Curie, France
- P.P. Shirshov Institute, Russia
- United Nations Environment Programme
- University of the Azores, Portugal
- MEDIAN, Spain
- ArchimediX, Germany
- University of Thessaly, Greece
- University College Cork, Ireland
- National Marine Aquarium, UK
- Acquario di Genova, Italy

the stability zone for the formation of clathrate, oversaturated methane can be trapped and stored in the seabed as gas hydrate. Where sulfate occurs from downward diffusion of seawater or from advection of sulfate-rich fluids, such hydrates may be controlled by microbial methane consumption. When associated with high fluid flow and strong temperature gradients, the gas can escape the biological filter (Niemann et al., 2006), unlike diffusionally controlled marine sediments (Parkes et al., 2007). Our understanding of how much gas hydrate lies hidden below the seafloor, and our ability to identify the feedback mechanisms among global warming, geodynamics, and biological control, remains limited. Furthermore, the connection among seafloor structure and dynamics, episodic or even catastrophic geological events, and the formation, distribution, and longevity of chemosynthetic ecosystems is yet to be explored.

Lack of information on the life histories of animals and microbes restricted to chemosynthetic ecosystems and their dispersal remains a key limitation in understanding the interconnectivity and resilience of these dynamic ecosystems (Pradillon et al., 2007). Interconnectivity can be studied at different geographical scales, as well as among vents, seeps, and other habitats. This research requires a combination of biological, oceanographic, and biogeographical studies, including population biology using genomic markers to assess gene flow. HERMIONE provides the unique opportunity to investigate the distribution, structure, and similarity of chemosynthetic ecosystems across cold seeps, hydrothermal vents, and large food falls via an experimental approach. Most work will focus on known active cold seep systems such as those of the eastern Mediterranean (Olu-Le Roy et al., 2004; Dupré et al., 2007), the Nordic margin (Niemann et al., 2006), and the hot vents of the Mid-Atlantic Ridge (Desbruyères et al., 2001). We will also explore new systems in the Hatton Basin associated with faulting, and off Norway related to subsurface gas accumulations. Methods include modern molecular approaches, quantitative biodiversity assessment and comparative community analysis, identifying environmental factors defining habitats, and using a Web-based Geographic Information System (GIS) for innovative mapping. In addition, paleogenetics will be applied to a study of past chemosynthetic ecosystems.

Global warming and subsequent temperature increases in bottom water will lead to instabilities in the hydrate capacitor, and will boost chemosynthetic activity in seawater and on the seafloor. These ocean bottom processes may contribute positive feedback to climate change. Hydrate-bearing seeps and mud volcanoes are natural laboratories for these processes. The distribution and structure of cold seep communities can serve as an indicator for changes in methane fluxes related to hydrate formation or dissociation (Niemann et al., 2006). More than 100 seabed "pockmarks" (200–600 m in diameter) were observed on the slope of the western Svalbard margin within previously mapped gas hydrate provinces (Vanneste et al., 2005). These sites lie within one of the most important impact areas for hydrate instabilities due to their vicinity to the warm West Svalbard current. By combining multibeam echosounder data and three-dimensional seismic data with in situ seep and water column studies, it will be possible to assess how the present-day fluid flow system drives the chemosynthetic communities, and where and how a potential change in the gas hydrate province will increase not only fluid flow but also chemosynthetic zones.

The great variety of microbial metabolism in reduced environments is an ultimate challenge to understanding biological capacities driving ecosystem function and distribution. The key groups to be assessed, along with their genomic functioning, in this project are the methanogens, methanotrophs, thiotrophs, and hydrogenotrophs, as well as all organisms and physiological capacities related to CO_2 fixation, including carbonate precipitation. Methanogens play an important role in the degradation of organic matter by converting low molecular weight compounds into CH_4. Molecular and isotopic data suggest that most of the methane produced and stored in marine sediments at continental margins is of biogenic origin (Reeburgh, 2007). Chemoautotrophic primary production via CO_2 fixation is the reason for the ten- to ten-thousandfold higher biomasses at vents and seeps compared to surrounding environments (Sibuet and Olu-Le Roy, 2002). Carbonate precipitation in association with vents and seeps is also highly relevant to ecosystem structure as it shapes the seafloor for the settlement of hardground fauna (Dupré et al., 2007).

An important remaining question concerns the relationship between biodiversity (species richness and relative abundance) and distinct functions of ecosystems. In terms of methane as a potential greenhouse gas, biological communities act as important filters, generally controlling 30–100% of emissions as dissolved or free gas (Niemann et al., 2006). Field observations have identified widespread occurrence of fluid seepage at ~ 200-m depth in the Sicily Channel associated with huge emissions of methane (10^3–10^6 t y^{-1}). In the Bratten area on the Nordic margin, several shallow seeps have been detected that are associated with cold-water corals. HERMIONE will study the difference in community structure and functioning at cold seeps of varying activity at different water depths. In addition to traditional tools, we will use DNA barcoding for the rapid assessment of biodiversity and for the identification of cryptic taxa (Moura et al., 2008).

SOCIO-ECONOMICS, OCEAN GOVERNANCE, AND SCIENCE-POLICY INTERFACES

The fourth HERMIONE objective is "to provide stakeholders and policymakers with scientific knowledge to support deep-sea governance aimed at the sustainable management of resources and the conservation of ecosystems." To achieve this goal, there is a need for genuine interdisciplinary natural-social science research that will permit integration of knowledge emerging from the natural sciences into the socio-economic and governance work of the project and feed results of the latter back into the natural science work.

The Deep-sea Frontier Initiative (Cochonat et al., 2007) and a recent UNEP/HERMES study (UNEP, 2007) showed the urgency and the magnitude of the task of developing socio-economic and governance research for the deep sea in support of ocean governance. HERMIONE will contribute to this effort by carrying out socio-economic research on anthropogenic impacts, mapping anthropogenic activities that impact the deep sea, reviewing ecosystem goods and services, assessing potential for quantifying and valuing these services (including a specific case-study valuation of Norwegian cold-water corals), and reviewing governance regimes, principles, policy instruments, and management tools (including case studies on policy instruments and management tools in the Bratten and Kosterfjord areas in Norway and the Azores Marine Park).

HERMIONE will also continue to develop and implement appropriate science-policy interfaces to ensure policy relevance of the research and to facilitate rapid translation of research into policy advice at national, European, and international levels (see Grehan et al., this issue).

EXPECTED IMPACTS

In light of increasing realization that humans have had an extensive impact on the ocean and seas, over the last 10–15 years the international community has adopted ambitious goals and targets to safeguard the marine environment and its resources. During the 2002 World Summit on Sustainable Development held in Johannesburg, among other things, world leaders agreed on: achieving a significant reduction in the current rate of loss of biological diversity by 2010, the introduction of an ecosystems approach to marine resource assessment and management by 2010, and the designation of a network of marine protected areas by 2012 (UN, 2002, Chapter IV). At the European level, many of these goals and targets have been incorporated into national action plans and various

European policies adopted under the EU and the OSPAR and Barcelona Conventions, to which the EU is a Party. The European Parliament and Council adopted the Marine Strategy Directive on June 17, 2008. It constitutes the environmental pillar of future maritime policy (EC, 2007). The Directive stresses that, "Account should also be taken of biodiversity and the potential for marine research associated with deep-water environments" (EU, 2008). Under OSPAR[1], work has begun on preparing a Quality Status Report of the Northeast Atlantic, and on reviewing implementation of the commitments made at the 2003 OSPAR ministerial meeting in time for the follow-up meeting in 2010.

A crucial requirement for implementing all of these goals, targets, policies, and processes is the availability of sound, high-quality scientific data and information from the marine environment to assess the progress achieved and to set the directions for further work. It is here that HERMIONE will have its greatest impact. The interdisciplinary research planned under HERMIONE is designed to fill the knowledge gap about threatened deep-sea marine ecosystems and their environments. It will reveal the impact of man on these ecosystems, both directly (via bottom trawling, for example) and indirectly, via climate change. The results will provide national, regional (EU), and global policy- and decision-makers with the information needed to establish policies to ensure sustainable use of the deep ocean.

For further information about the progress of this project see the Web site at: http://www.eu-hermione.net.

IMPORTANT NOTE: Please note that the HERMIONE project is currently undergoing contract negotiations with the European Commission. The project is due to start on April 1, 2009, subject to the successful conclusion of these negotiations.

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