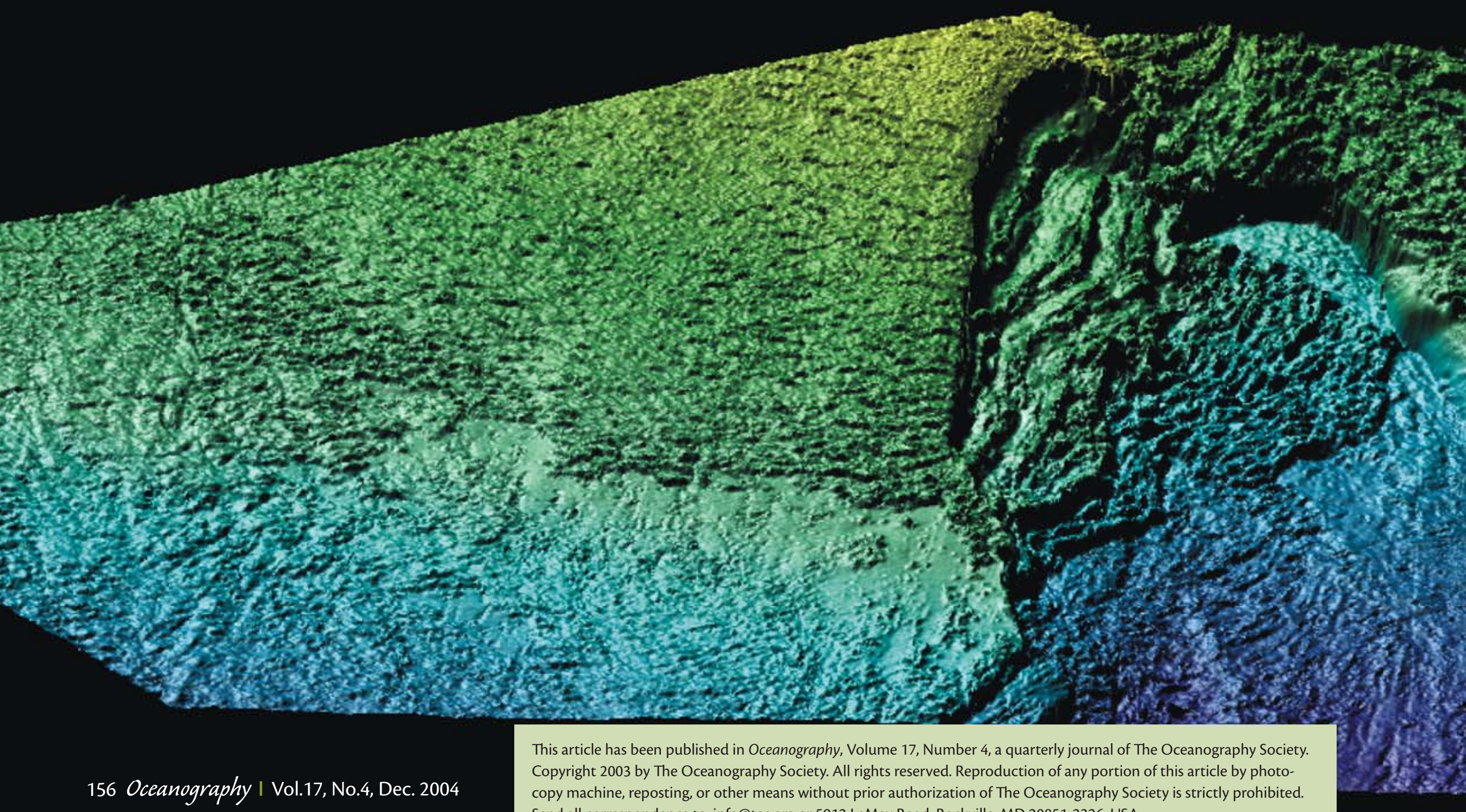
EUROpean Deep Ocean Margins (EURODOM)

A New Training-Through-Research Frontier

BY BEN DE MOL, VEERLE HUVENNE, STEFAN BÜNZ, TIAGO ALVES, MIQUEL CANALS, AND VIKKI GUNN



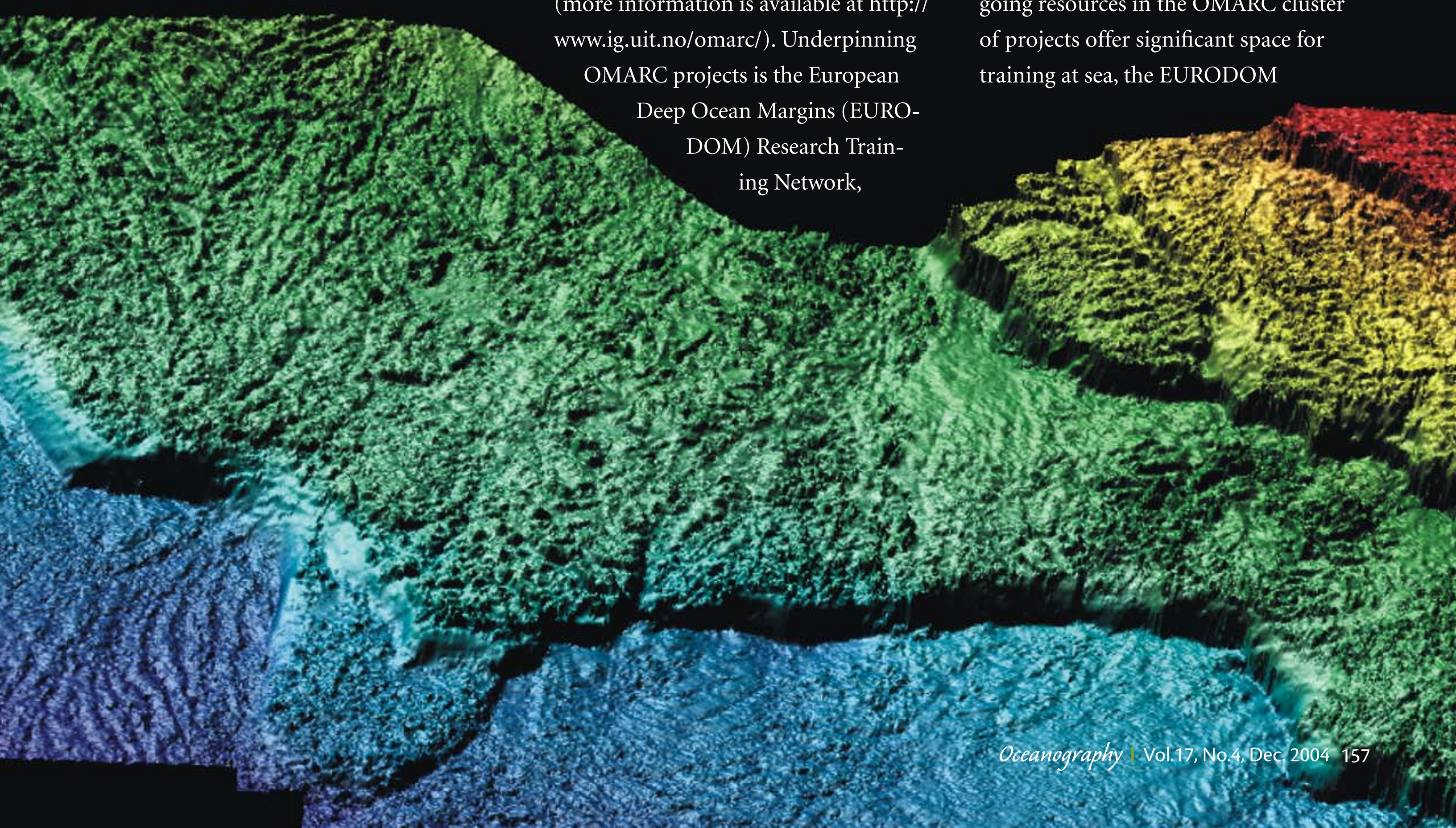
THE HUMAN CAPITAL COMPONENT IN EUROPEAN OCEAN MARGIN RESEARCH PROJECTS

A critical component of ongoing ocean margin research in Europe is the involvement of young researchers, many of whom will eventually build careers in this field. As part of the European Commission's various Framework Programmes, a number of schemes provide opportunities and funding for young researchers to contribute to European ocean margin research. Within the current Framework Five (FP5) Programme (1998-2002, but ongoing until 2006), the Improving Human Research Potential and the Socio-Economic Base Programme (also commonly known as the Human Potential Programme) was initiated to support training and mobility of researchers from virtually all scientific fields throughout Europe. Under this Human Potential Programme, opportunities for young researchers are channelled through two schemes: (1) the Marie Curie Fellowships, which are awarded to outstanding individual pre- and post-doctoral researchers; and (2) Marie Curie Research Training Networks (RTNs), which involve teams of researchers.

RTNs support research teams from a wide range of scientific disciplines with a common research goal. These teams form a network, usually comprising at least five teams from three different countries, to provide pre- and post-doctoral training for researchers up to the age of 35. The primary objective of these networks is to supply "training-through-research" within the frame of high-quality international collaborative research projects.

The Ocean Margins Deep Sea Research Consortium (OMARC) represents a cluster of 15 European margin projects (see Mienert et al., this issue) that aims to develop synergies in areas such as fluid flow, biosphere/geosphere coupling, seismic imaging methods, ocean drilling, and long-term observatories (more information is available at http://www.ig.uit.no/omarc/). Underpinning OMARC projects is the European Deep Ocean Margins (EURODOM) Research Training Network, funded through the EC's Human Potential Programme. EURODOM takes advantage of the training-through-research possibilities within the OMARC cluster, and provides the cluster with a major educational component.

The general goal of EURODOM is to provide advanced training and educational opportunities for pre- and post-doctoral researchers to foster the linkages among marine geosciences, the environment, and the hydrocarbon industry as far as they relate to deep ocean margins around Europe. The scientific focus of the EURODOM program is on (1) submarine slope stability and (2) deep-water coral reefs and carbonate mounds. EURODOM aims to train young researchers in fields at the interface of Earth and life sciences, at the crossroads between academia and industry, and at the frontier of exploration for energy resources. The continental slope and the deep-water coral reef provinces on Europe's margins provide ideal target areas. While the seagoing resources in the OMARC cluster of projects offer significant space for training at sea, the EURODOM



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network partners offer some of the best data processing and analytical facilities in Europe (more information is available at http://geomar.geo.ub.es/eurodom/).

Since its start in fall 2002, for a four-year period, EURODOM has appointed 13 young researchers from eight different countries in western and eastern Europe to carry out deep ocean margin research in the eight partner institutions. A joint first seminar on project management and communication skills, and a scientific workshop, took place in Barcelona in March and April 2004 with the participation of EURODOM scientists, external experts, and all the EURODOM young researchers.

THE CHALLENGE OF DEEP OCEAN MARGINS—THE FOCUS OF EURODOM RESEARCH

Ocean margins mark the transition zones between continents and oceans, where the bulk of sediments are deposited and 50 percent of marine productivity takes place. Coastal zones have always been vital for humankind in terms of exploitation of resources, as well as commerce and communication. However, ocean margins are also of great scientific value: scientists have studied them to investigate global climate, sea-level changes, the biogeochemical cycle, and the flux of fluids from the lithosphere to the ocean and eventually to the atmosphere.

During the last decade, however, scientific and socio-economic interest has spread into deeper waters, beyond the shelf break to the continental slope—a zone we herein refer to as the "Deep Ocean Margin" (DOM). The recognition of the widespread occurrence of submarine landslides and the discovery of deep-water corals and associated communities are just two examples that illustrate the dynamic nature of the DOM. Understanding the mechanisms, architecture, and consequences of submarine landslides is of great importance due to the increasing interest in natural resources in DOM areas, to the geological contribution that landslides make in shaping ocean margins, and to the potential of landslides to trigger large tsunamis that would impact coastal areas (Locat and Mienert, 2003). Deep-water corals are just one example of the variability and diversity of Earth's ecosystems. A sound comprehension of their occurrence is essential in order to understand biological activity and related geological processes, and to permit sustainable resource exploitation and effective preservation of these deep-water habitats. The socio-economic impact of these studies is significant and requires multidisciplinary studies, carried out by specialists, well trained in the fields of biology and geology, able to ensure the future safe and sustainable use and resource exploitation of our DOMs and Exclusive Economic Zones.

CONTINENTAL SLOPE STABILITY

Submarine landslides occur in the sedimentary successions of virtually all passive and active ocean margins. They happen on all scales involving up 20,000 km^3 of sediment and covering an area of up to 113,000 km^2.

Most of today's knowledge of submarine landslides originates from the analysis of two-dimensional seismic data and seafloor acoustic imagery. However, because submarine landslides are clearly three-dimensional structures, an integration of three-dimensional seismic data into their analysis will facilitate a better understanding of their morphology, and driving and triggering mechanisms. The recent availability of such data sets through the hydrocarbon industry allows us to study submarine landslides in three

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dimensions. This will clearly increase our knowledge of characteristics and architectures of different types of landslides. We will also gain insights in sediment dynamics during landslide events.

While submarine landslides can often be readily identified using acoustic seabed mapping techniques (e.g., seismic profiles, side-scan sonar, and swath bathymetry) the mechanisms leading to slope instability and the triggering of landslides are still poorly understood (Locat, 2001). In fact, there are only a few submarine landslides for which the trigger is known with certainty, for example, the Grand Banks Slide, which was set off by an earthquake (Piper et al., 1999).

Submarine landslides may be triggered by changes in the water pressure over potentially unstable sediments during sea-level variations and earthquakes. Important factors include the presence of weak strata in sediments, gas hydrate dissociation, or the build-up of excess pore-pressure due to rapid sedimentation. Climatic changes and related sea-level variations can cause both the destabilization of gas hydrates and the deglaciation of shelf areas (Mienert et al., 1998). In this latter process, associated isostatic rebound may cause earthquakes and changes in depositional processes responsible for submarine landslides.

Landslides can generate tsunamis that are large enough to damage coastal lowlands. Recent investigations have shown that tsunamis are associated with submarine landslides rather than with earthquake activity as previously reported (Heinrich et al., 2000), although an earthquake can be a precursor for a landslide. The growing development of marine resources and offshore constructions in coastal areas and the increasing concern of global climate change demand a better understanding of marine geohazards such as submarine landslides.

EURODOM Activity on Slope Stability

The investigations of EURODOM researchers are focused on the European margins. On these, submarine landslides occur at different scales and in various settings, from the glacial-dominated margins of the polar regions to the river-dominated margins of the Atlantic Ocean and the semi-arid regions of the Mediterranean Sea, each with their specific climatic, tectonic, and sedimentary setting.

The large submarine Storegga Slide on the mid-Norwegian margin is one of the slides the group will work on (Bryn

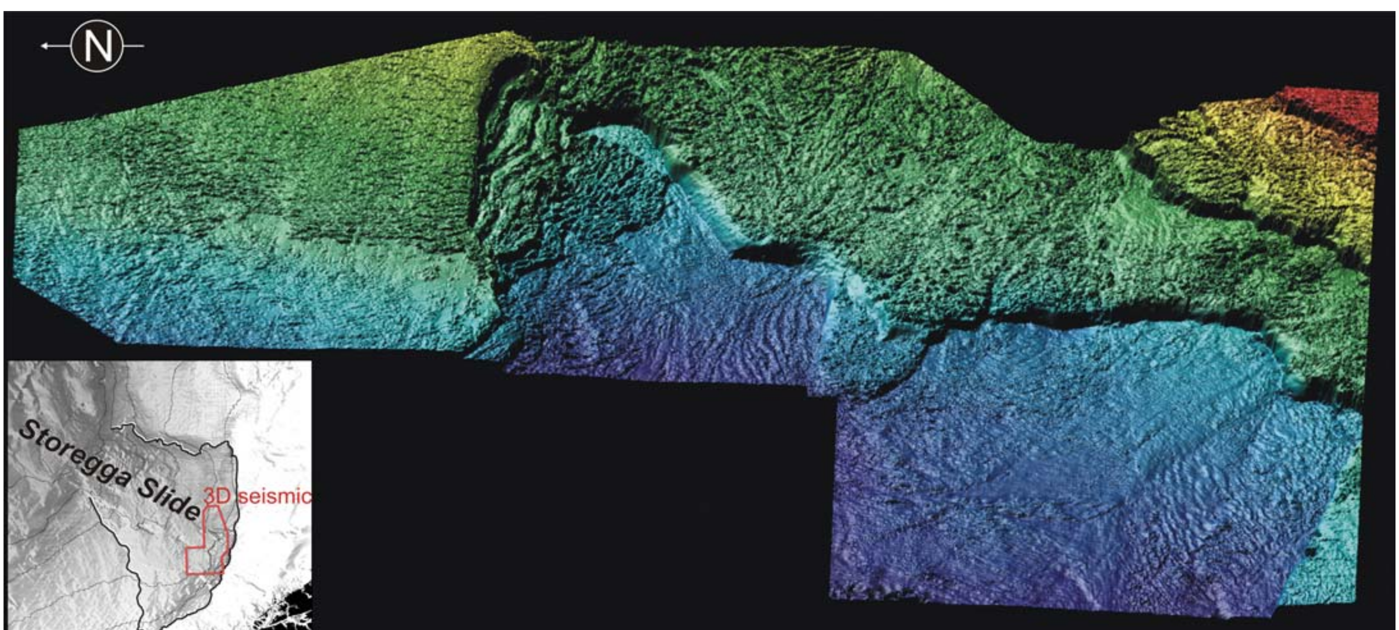

Figure 1. Three-dimensional view of the seabed of the headwall area of the Storegga Slide, offshore Norway, extracted from three-dimensional seismic data (see inset). The seabed is illuminated from the northeast. Three major headwalls are visible, The seafloor is characterized by sediment blocks. This area overlies one of Europe's largest gas reservoirs in the Ormen Lange Dome. Data courtesy of Norsk Hydro AS, Oslo, Norway.

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et al., 2003; Figure 1). This slide cuts deeply into the sediments of the Møre Basin. It has a maximum run-out from the shelf break to the abyssal plain of 800 km. The eastern headwall reaches up to 300 m in height and extends for about 300 km from north to south along the shelf break. The submarine landslide transported approximately 3400 km^3 of sediments, and occurred in several phases, which took place within a very short period of time approximately 8,200 years ago. The multiphase Storegga Slide is the last of a series of slide events linked to Pleistocene climatic fluctuations (Bryn et al., 2003).

Yet, there are still many open questions about the Storegga Slide. For example, did leaking gas from the underlying Ormen Lange gas reservoir influence the stability of the sediments by creating weak, overpressured layers? Did gas hydrates, which are widespread at the northern flank of the Storegga Slide (Bünz et al., 2003), play a role in the sliding as suggested by Vogt and Jung (2002)? The research undertaken within EURODOM will help to further clarify such issues.

Offshore Portugal, historic seismic activity has been responsible for triggering landslides and associated sediment flows (turbidity currents and debris flows), many of which are known to have transported sediment into the Iberia, Tagus, and Horseshoe Abyssal Plains (Figure 2). Recorded seismicity indicates moderate to low seismic activity offshore Portugal, interrupted by larger events (e.g., Lisbon's 1755 earthquake) characterized by their destructive effect on the Portuguese and Northwest African margins. The periodicity of these larger events is of the order of 200 years, posing the problem of obtaining, at present, accurate seismic information for a correct identification of seismic-related landslides offshore Portugal.

Greece, on the other hand, is the European country with the highest seismic activity. Most of the mass-wasting features on the Greek margin are earthquake-triggered. Accompanying the recent geological evolution of the Hellenic Plate, landslides identified on the Greek margin are of fairly recent age, mostly formed after the Middle Pleistocene (<120,000 years ago) (Lykousis et al., 2003). This observation poses an interesting potential for analogue studies between the West European margins and the seismically active Greek margin. Thus, EURODOM is aiming to compare areas offshore Portugal to seismically active regions of the Greek margin.

In essence, such a combined study tries to compare areas along the two latter margins that are geologically similar to some extent. For instance, the northern Aegean Sea comprises a southeast-tilted margin, containing several transtensional basins. The combined processes of extension and (lateral) fault movement in these basins are somewhat similar to those that occurred on the southwestern Portuguese margin during parts of the Cenozoic (i.e., the last 65 million years; Alves et al., 2003). The Gulf of Corinth is an extensional basin that replicates the early stages of evolution of the western Iberian margin, prior to continental break-up, and is an excellent example of a fault-controlled basin of relatively high seismicity. On the south-western Cretan margin, submarine canyons and associated erosional features occur that are, by their close relationship to major tectonic lineaments (such as faults and plate boundaries), to some extent comparable to the fault-controlled submarine canyons from offshore Portugal.

Future work within EURODOM will include the compilation and acquisition of bathymetric, side scan, seismic reflection, and sediment information in key study areas, such as submarine landslides that have little data coverage so far or margin segments that have not yet been surveyed. Following a new trend within continental slope analysis, a statistical analysis of landslide features (e.g., on the Greek and Portuguese margin) will be attempted in order to quantitatively characterize the morphology of submarine canyons, gullies, and landslide scars and their relation to the underlying geology. Furthermore, the failed sediments will be sampled and analyzed in terms of geotechnical properties (both in the lab and in situ). This analysis will help to identify and quantify sediment types prone to failure (e.g., possible "weak layers"). Geotechnical parameters will also be used by a group of modelers within the project to calculate the risk of a new slide occurring, allowing concise risk analyses to be performed for selected areas.

DEEP-WATER CORALS AND REEFS

Deep-water corals are species that live in relatively cold waters (4 to 13°C) in the aphotic zone of the world's ocean margins (Figure 3). They are adapted to a life without algal symbiosis, and are

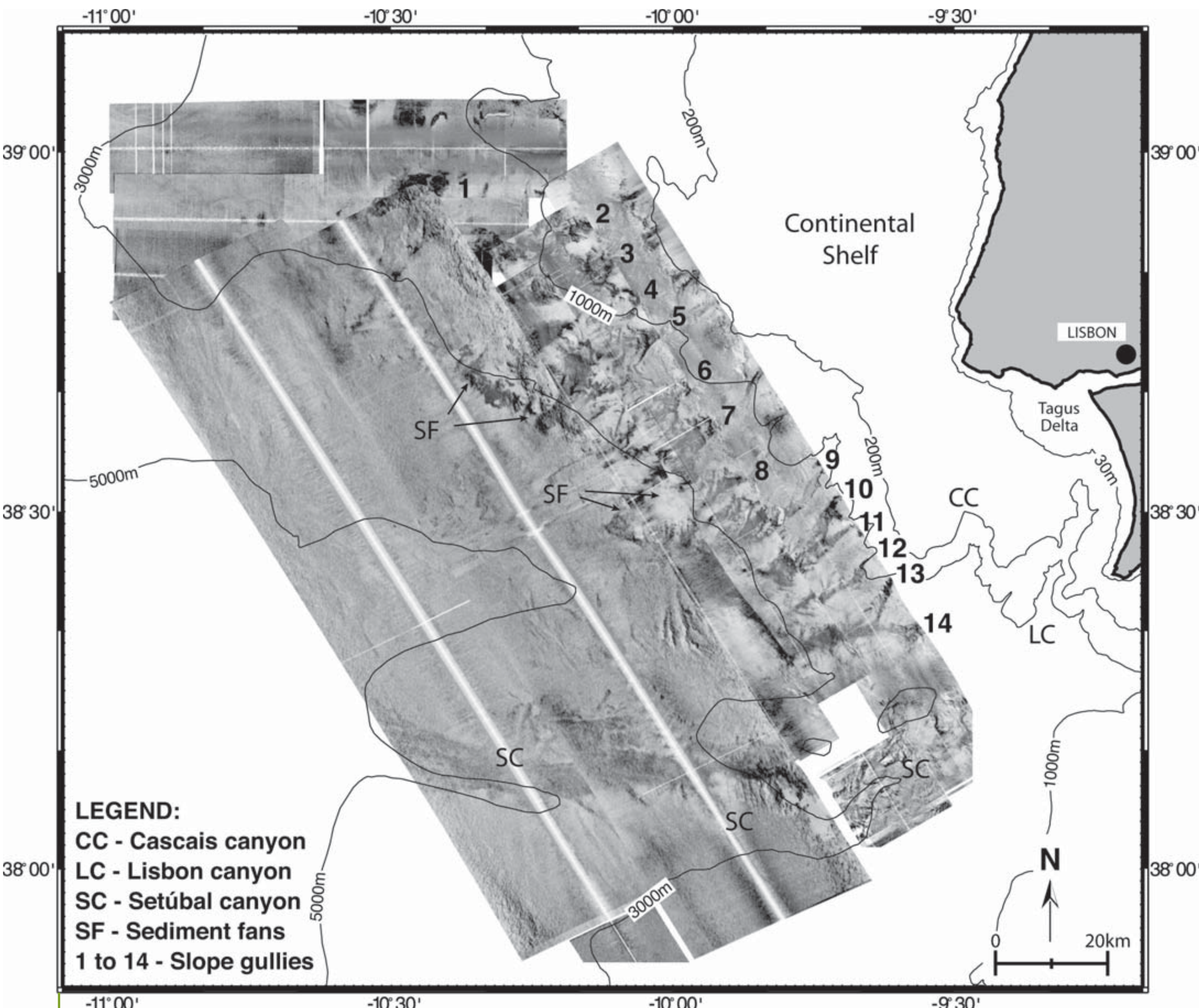

Figure 2. Side-scan sonar surveying (performed with the OKEAN system) is one of the seafloor mapping techniques used to study slope instability features offshore Lisbon, Portugal, at the western Iberian margin. Note the pervasive gullying of the continental slope and the recent deposition of sediment fans on the continental rise. Such seabed features illustrate the recent transport and destabilization of sediment along the margin. Modified from Alves et al. (2003).

Figure 3. Living *Lopehlia pertusa* corals at about 285 m water depth, Sula Reef Complex offshore Norway. Photo courtesy of André Freiwald, Universität Erlangen-Nürnberg.

widespread, especially along the European margins in the Atlantic Ocean and to a smaller extent in the Mediterranean Sea. Deep-water corals are suspension feeders, and therefore they are commonly found along bathymetric highs such as seamounts, ridges, pinnacles, and mounds, where currents tend to be enhanced and thus increase the food availability (Freiwald, 2002). The actual distribution of deep-water corals is controlled by nutrient supply, current activity, slow sedimentation rates, and a hard substratum on which to settle (Rogers, 1999)

Only two specimens of deep-water corals are known as extensive reef builders: *Lophelia pertusa* and *Madrepora occulata*, supported by other species such as *Desmophyllum*, *Dendrophyllia* and *Stenocyathus*. Deep-water coral build-ups have now been described along the European margins offshore Norway, Ireland, Scotland, Spain, and Italy in water depths ranging from 150 to 1300 m (Figure 4). The most spectacular deep-water reefs, up to 200 m high and 5 km across, have been mapped in the Porcupine Seabight and Rockall Trough (offshore Ireland and the United Kingdom; Figure 5).

Biodiversity and Human Impact

Deep-water reef structures clearly provide a large number of habitats for a wide range of invertebrates, and create crucial habitats and reproductive grounds for commercially important fisheries including sea bass, snapper, porgy, rock shrimp, and calico shrimp, and thus draw the commercial fishing industry into these fragile areas (Costello et al., 2003). Human activities constitute the most serious threat to these fragile corals. Destructive bottom trawling, marine construction works, and oil and gas exploration and exploitation have the potential to destroy large areas of coral habitat in relatively short periods of time. Recent measures taken by the British and Irish governments and by the EC now protect some of the reefs in the Porcupine Seabight and Rockall Trough against deep-sea trawling. These reefs have been designated the status of "Special Areas of Conservation," under the EC Habitats Directive.

Origin and Development History

One of the most challenging objectives of the deep coral reef research is to unravel the origin and development history of the build-ups, particularly the environmental conditions of the start-up phase and the controlling factors. Two main hypotheses are proposed to explain the sharply bound provinces of coral reefs. The first school of thought links the development of coral reefs to specific oceanographic conditions required for coral growth, in combination with the seabed morphology that controls the food and sediment supply through its effect on the local bottom currents (De Mol et al., 2002). A second school of thought suggests that development is controlled by local fluid seepage, creating a suitable substratum favoring coral growth. In most cases, it is argued that autogenic carbonate precipitation by oxidation of methane gas at the seabed creates a hard substratum on which the corals can settle (e.g., Hovland and Risk, 2003). Furthermore, fluid seepage controls (either directly or indirectly) the nutrient supply for the framework builders by means of chemosynthetic bacteria. These bacteria increase the biological activity and act as the base of the food web to which the deep-water corals belong. The latter hypothesis implies that coral reef development relies mostly on the fluid seepage for both the start-up and later development phases. A combined hypothesis suggests that coral reef initiation is based on the fluid seepage model and later mound development is steered by currents (Henriet et al., 2002).

EURODOM Research on Deep-Water Corals

One of the targets within EURODOM is to increase the understanding of deep-water coral reef initiation and development, including the possible role of fluid migration and of the specific ecology of deep-water corals. These insights might help the interpretation of fossil mud mounds, which are probably the fossil counterparts of the present deep-water coral reefs. It is well known that mud mounds have good reservoir characteristics and are target sites for the hydrocarbon industry. The seepage hypothesis described above prompted the intriguing thought that migrating hydrocarbons might have the potential to create their own reservoir. Furthermore, an increased understanding of the biology of the deep-water coral ecosystems will help in the assessment of the human impacts on these habitats, and will support the installation of sustainable management schemes and protection measures.

However, the presently available data on deep-water coral reefs is minimal and the study of the initial develop-

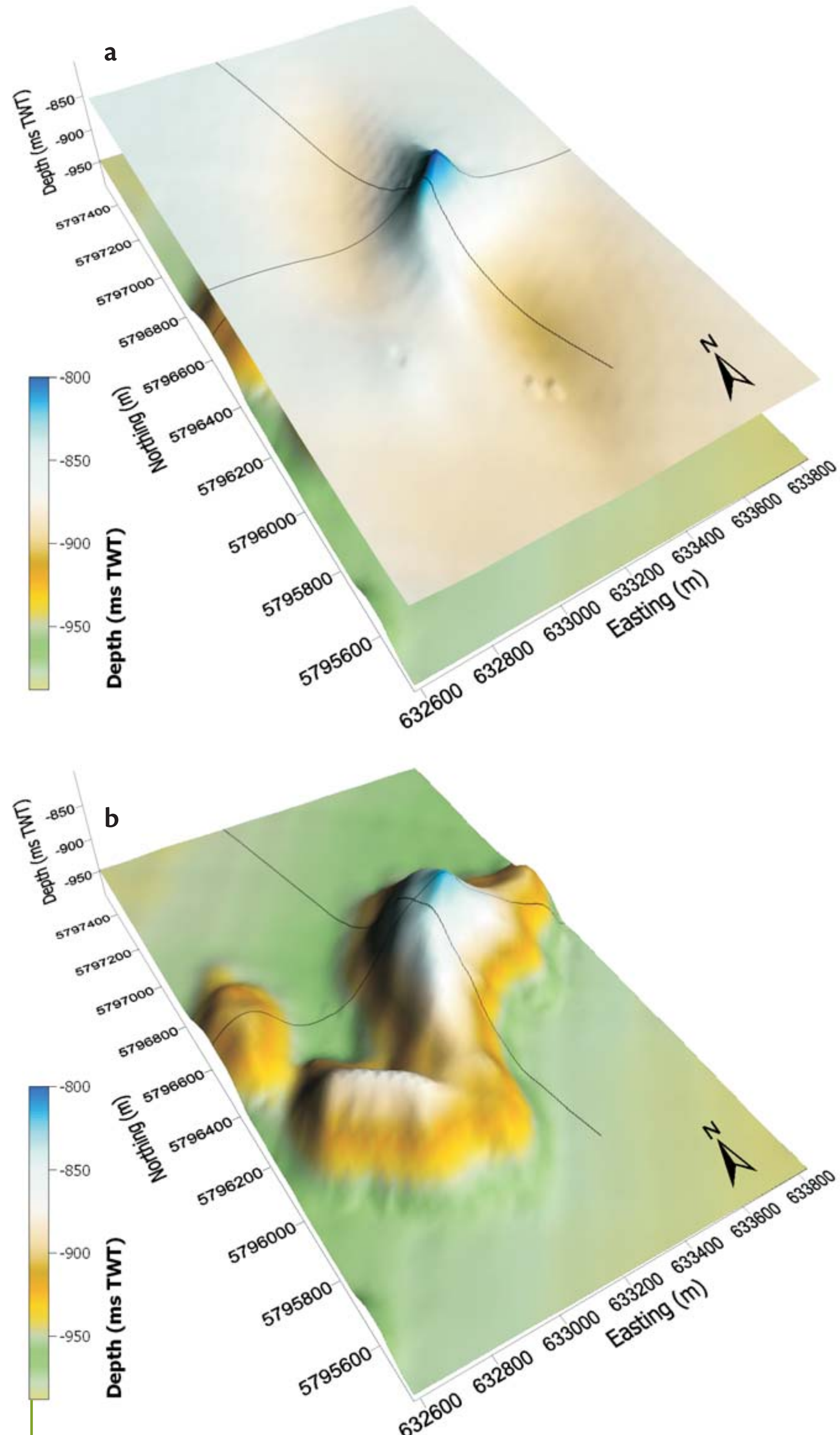

Figure 4. Three-dimensional model of partly buried deep-water coral reef ("Mound Perseverance") in the Magellan mound province, Porcupine Seabight, west of Ireland; this model was derived from three-dimensional seismic data. Panel (a) shows the seafloor expression of the deep-water reef. Panel (b) shows the full reef shape on the reef base reflection. The total height of the mound is ca. 160 m. Although most of this reef is buried nowadays, it clearly was a complex structure, creating a varied habitat for a large fauna. Data courtesy of Statoil Exploration Ltd. (Ireland) and partners Conoco Ltd. (United Kingdom), Enterprise Energy Ireland Ltd., and Dana Petroleum plc (public limited company, United Kingdom), and Chevron UK Ltd.

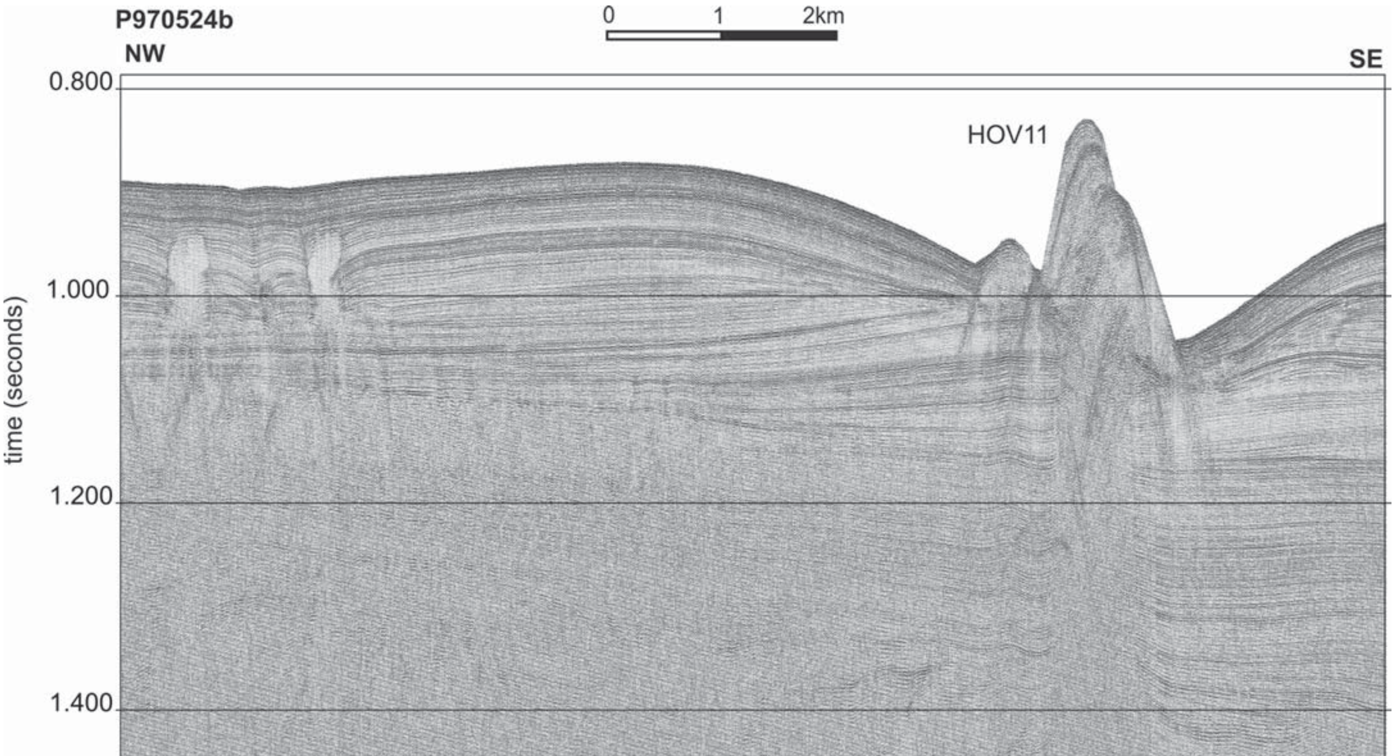

Figure 5. High-resolution seismic profile trough a large deep-water coral reef and a set of buried coral reefs in the Hovland and Magellan mound provinces in the Porcupine Seabight in the Northeast Atlantic. Seismic data reveal the morphology and stratigraphical context of the reefs (for additional examples see De Mol et al., 2002, and Huvenne et al., 2003).

ment phase of deep-water coral reefs is problematic due to lack of scientific data. Therefore, the EURODOM project will contribute to the preparation of scientific deep-drilling experiments (e.g., through the Integrated Ocean Drilling Program, proposal 573-full) through deep-water coral reefs, which should allow the analysis of the internal structure of the coral reefs and the physicochemical environment at the start-up phase.

Second, attention is also focused on small, possibly initial, coral build-ups, as examples of present-day, deep-water, coral reef start-up (e.g., the Darwin mounds in the Rockall Trough and the Moira mounds in the Porcupine Seabight). In particular, the relation between coral growth and the sedimentary environment is being studied in detail. It appears that a delicate balance needs to be maintained between these two factors before an initial (but also a more mature) deep-water coral reef can develop successfully. Understanding these mechanisms is critical to understanding deep-water coral ecology and coral reef formation processes.

A third facet of the coral research is the geobiology and species ecology of the corals and the reef communities. Detailed taxonomical and biological studies will bring more insight to species composition and variability of mound communities, and will result in the formulation of a set of recommendations for sustainable management and preservation of these unique habitats.

Finally, an inventory of the distribution of deep-water corals along the European margin will be set up within a geographical information system (GIS) environment, which will support deep-water coral research as a whole, and also the development of management schemes and protection measures. Special attention will be given to the distribution of deep-water corals in the Mediterranean Sea, where some intriguing new coral discoveries were recently made.

CONCLUSION

To study these different scientific problems, several young researchers (doctoral students and post-docs) are appointed within the RTN, and are supported by a group of senior scientists who are specialists in specific fields. With support from the RTN, these researchers tackle different facets of these problems, in a coordinated manner, by long- and short-term stays at guest institutions, attending specially organized workshops on deep-water corals and slope instabilities, and participating in scientific research cruises. Through the program, young researchers obtain training in scientific practice in a variety of fields, including topics other than their specialty. The outcome of the RTN EURODOM will be an increased knowledge concerning submarine landslides and deep-water corals. Moreover, this program will create new interdisciplinary scientific relationships and form a group of young scientists, skilled in deep-ocean margin processes, especially in high-level multidisciplinary research projects, such as those on slope stability and deep-water corals, who are embedded in the core of marine (margin) research within Europe.

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