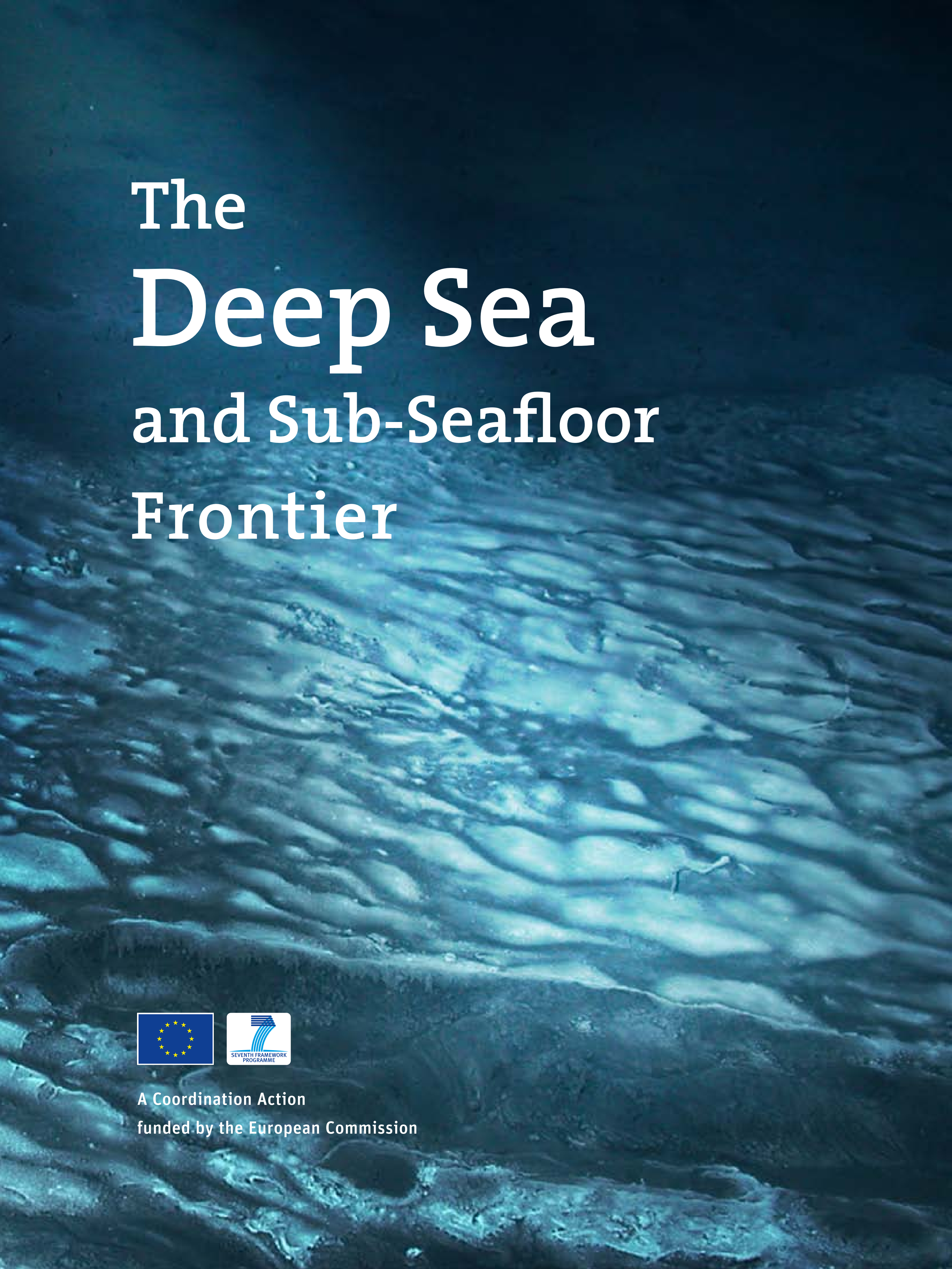

The Deep Sea and Sub-Seafloor Frontier

A Coordination Action
funded by the European Commission

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Content

Deep sea matters

The deep sea, which makes up the major part of the world ocean, is a remote, cryptic habitat whose functioning within the Earth system is imperative for human existence as we know it. About 90% of all known species live in the oceans and seas, and within this environment the seabed contains the highest biodiversity on the planet, with about 98% of all marine species. Many of these are highly specialised, some are very long-lived, and we understand almost none of the ecosystems in any detail.

The marine environment is particularly important to the European Union because 50% of its territory lies offshore, 25 member states have coastlines, nearly 50% of its citizens live within 50 km of the coast and 4.8 million EU inhabitants are directly employed in maritime activities[1]. The deep sea is increasingly under pressure owing to human activities such as bottom trawling, hydrocarbon extraction, deep sea mining and bio-prospecting. In the future, this pressure could lead to effects detrimental to the well-being of Europe's population. The discovery of potentially unique genetic resources has increased the commercial interest in deep sea research but at the same time has raised questions about ownership of these resources. The legal framework for sustainable exploitation of seabed resources is currently under discussion and is being addressed through initiatives such as the EU's Green Paper on the Future European Maritime Policy and mechanisms outside national jurisdictions, such as the United Nations Convention on the Law of the Sea and the International Seabed Authority. These examples show that modern ocean science must take into account and interact with societal, legal and policy aspects.

The remoteness of the deep sea leads to a heavy reliance on technology to carry out forefront research, and as equipment has improved over the years we have begun to see the deep sea environment with increasing clarity. A move towards the responsible utilisation of the deep seafloor requires the expansion, modernisation and integration of marine research across Europe. Basic European research and science-driven technological development both play major roles, and continuous improvement of research and infrastructure integration in concert with industry and policymaking is needed.

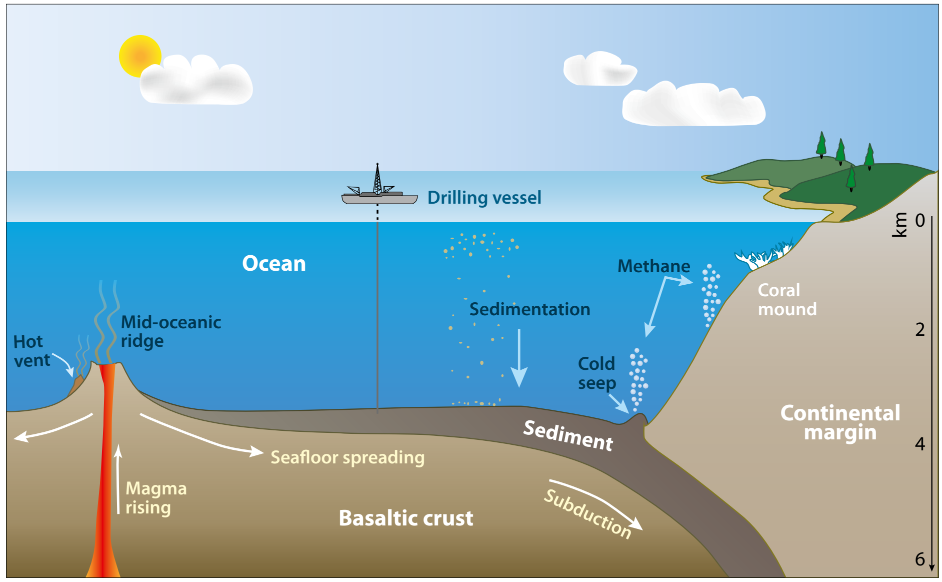
In this position paper we present the emerging scientific questions and approaches in the deep sea together with the related societal challenges and demands in a complex and dynamic Earth system. Results from several thematic workshops covering all fields of deep sea research are juxtaposed with the most recent EU policies, and the Common Strategic Framework of research and innovation in Europe. The deep sea, and the seafloor and subseafloor records in particular, represent a unique key to the past. Understanding the evolution of our planet and deep ecosystems, episodicity in earthquake records or variability in climate is mandatory to anticipating upcoming challenges and developing mitigation strategies.

Forging a European maritime strategy

When the European Commission published its strategic objectives at the onset of the Deep Sea & Sub-Seafloor Frontier (DS^3F), the "need for an all-embracing maritime policy aimed at developing a thriving maritime economy, in an environmentally sustainable manner" was recognised. Such a policy needs to be supported by excellence in marine scientific research, technology and innovation, as sketched in *Europe 2020*[2] and other key initiatives. As its flagship programme, Innovation Union[2] was adopted in October 2010 and is seen as a major step towards European economic recovery and renewed competitiveness. To attain these objectives, the Common Strategic Framework for Research and Innovation *Horizon 2020*[3], starting in 2014, is set to be the largest programme for research and innovation in Europe, as is currently the Seventh Framework Programme for Research and Technological Development.

As land-based natural resources become exhausted, our focus turns increasingly towards the sea. Indeed, the oppor-

Understanding the ocean at depth
Schematic overview of some of the main physical processes and structures along a cross-sectional profile through the deep sea, many of which are incompletely understood.



tunities and potential benefits for people and industry presented by the sea are enormous. However, the seas and oceans are changing rapidly through a combination of human and natural pressures. These changes have major societal implications; for our health, our well-being, for food and energy supply, and for the very natural support systems that make the Earth's climate and environment habitable. As stated in the Ostend Declaration 2010[4], these often called „grand challenges" encompass the seas and oceans as the largest ecosystem, covering 71% of the globe. Scientists, in concert with policymakers and stakeholders, have the responsibility to prepare for changes inflicted upon the marine realm and to work towards their mitigation and global solutions for societal welfare.

It is often human activities that exert environmental pressures threatening the safety of coastal settlements, ecosystems and biodiversity and preventing sustainable maritime activities. Science and technology provide one of the keys for reconciling sustainable economic growth in maritime activities with environmental conservation, but the large number of ongoing research activities needs coordination and cross-sectoral integration. Only thus can system complexity and interactions be properly addressed and new forms of governance in research through consensus and continuous dialogue be introduced. The way forward is described in the communication on the "European Strategy for Marine and Maritime Research", released in September 2008. DS³F is contributing the deep sea aspects emerging at present such as marine resources and biodiversity, and – equally important – past records, for example of climate change, ecosystem evolution and resource formation at and beneath the seafloor. The major aim of DS³F is to promote the dialogue between marine science and maritime policy.

DS³F gathered scientists from Europe's major ocean research centres and universities to identify the primary issues that need to be addressed in sub-seafloor drilling with relevance to deep sea ecosystem research in the next 10-15 years, i.e. for *Horizon 2020* and beyond. This group has evolved from the Deep Sea Frontier (DSF) international symposium (June 2006) and subsequent collaborations. With the DS³F submission, we proposed a coordinated action within Europe that is related to the use of seafloor imaging, drilling and sub-seafloor sampling in deep sea ecosystem research, including a better predictive capacity of the response of deep sea ecosystems to environmental change. Such an approach is becoming important as human influence on these remote environments is escalating through activities such as fishing, hydrocarbon exploration and exploitation, mineral extraction and marine biotechnology, and all this overprinted by climate change and pollution.

The EU Green Paper "Towards a future maritime policy for the Union: a European vision of the oceans and seas" will eventually lead to an EU Maritime Policy. The two mainstays of this policy are the Lisbon Strategy (related to economic growth) and the improvement of the status of the ocean (related to maintaining a healthy marine environment). Most recently, a number of initiatives have followed up on these strategies, namely the 'Integrated Maritime Policy' green paper[5] (June 2006), the Aberdeen (June 2007) and Venice Platform (November 2008) declarations, the ECORD ERA-Net[6] (2009), or most recently the MARCOM+ initiative. Therefore, the DS³F research plan is strongly linked to the development of the environmental pillar of the EU maritime policy, which provides the legal impetus concerning the protection

Visits to the deep sea
The manned research submersible NAUTILE, operated by IFREMER France, represents part of the seagoing technology required to understand ocean processes.

and conservation of the marine environment[7].

The main focus of deep sea research is the interface between the geosphere and the hydrosphere, comprised of the seafloor and the upper kilometres beneath the seafloor. This part is easily drillable, where – depending on the geodynamic setting – processes as variable as ocean crust formation including ore deposition, sediment dewatering during compaction, gas hydrate processes, catastrophic landsliding, mud volcanism, earthquake slip, or growth of cold-water coral reefs may occur. It is also the depth window where processes fuelling ecosystems on the seafloor, but also in the sub-seafloor (deep biosphere), are most active. Recently, exploration drilling for gas hydrates, extraction of mineral resources and hydrocarbons and CO_2 sequestration has entered water depths of 2000 m and beyond, but its impact on the marine ecosystems has not been examined or understood sufficiently.

There is presently an emerging need in Europe for cutting edge research and innovation, which is essential to ensure competitiveness, growth and jobs at a variety of levels and in many different fields, including the ocean. DS³F involved scientists, stakeholders and socio-economists who explored research needs and built a bridge towards policymakers, in particular regarding strategies for future European activities in sub-seafloor sampling in environmentally sensitive areas. The proposed activities and research goals will enhance the understanding of the functioning of deep sea ecosystems and improve strategies for a prediction of their future evolution. They will contribute to the development of new techniques and methods to study the deep sea geo-biosphere system and its interaction with climate and other forcing factors (geohazards, human impact) in the past, present and future. Products of this initiative developed from specific workshops as well as from multidisciplinary conferences bringing together Europe's experts in seafloor observations, deep sea ecosystem development and subseafloor drilling with environmental agencies, policy makers and industry.

Individual projects addressing various aspects of deep sea and sub-seafloor developments had already been underway and one of the important objectives of the DS³F initiative was to connect to those[8] and also provide links to EU policies in order to formulate integrated and socially relevant research activities for the future. In essence, illuminating the Earth through deep sea research and sub-seafloor sampling, observation and experimentation is the ultimate strategy for a sustainable use of the ocean and for a reliable mitigation of ocean processes affecting society in the future. The international execution of the DS³F White Paper will foster unique intellectual capacity building in terms of the advancement of science and technology in Europe, and in global sharing of data and scientific expertise. The objectives outlined include a strong commitment to public engagement and outreach, with the goal of making the science accessible and relevant on our changing planet.

An introduction to the thematic chapters

All parts of the Earth system—the solid Earth, hydrosphere, atmosphere, cryosphere, and biosphere—are intricately linked and their interplay determines the habitability of our planet. This interplay between biological and geological processes governing the complex environments has been broken into thematic packages concerning the deep ocean. The initial work package structure of DS³F had three themes closer to life sciences and another three concerned with geoscientific themes that govern life in the (deep) ocean. Those themes have been bracketed by overarching expert groups on marine infrastructures and on sub-seafloor sampling and measurements. The latter aspect of sampling records from the past as a key to the future is central to the entire DS³F approach.

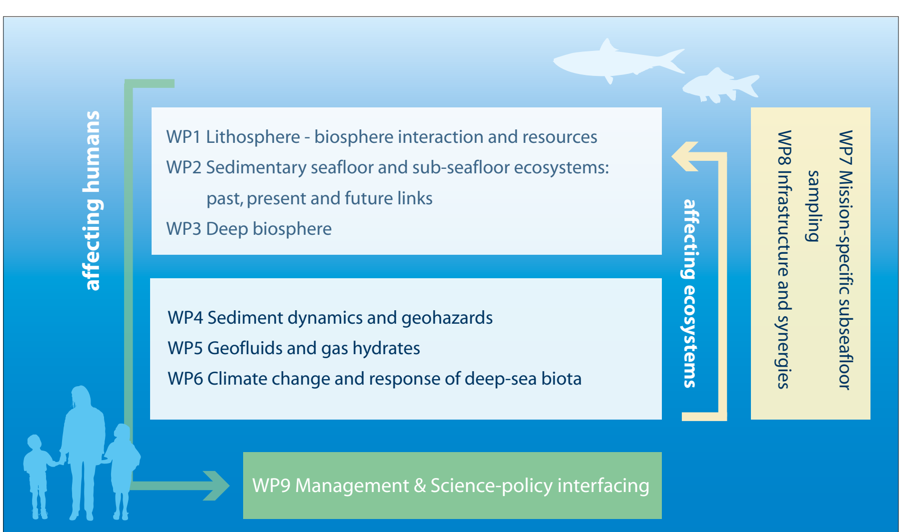
From the initial six themes in the field of bio-geosciences, four major topics have been identified as most crucial: Climate, Ecosystems, Geohazards and Resources. These topics are the backbone of the DS³F White paper and will illuminate Earth in its deepest portion, above as well as below the surface, and show prominent parallels to the ESF Marine Board position papers[9], or the new IODP Science Plan[10].

Gaining an improved understanding of the deep sea has direct societal relevance because this system provides a vital part of human welfare through its regulating effect on climate and the environment for marine ecosystems. Determining Earth system sensitivity in a changing world is crucial to preparing for and mitigating the impacts of climate change, geohazards, and decreasing biodiversity. Also, the ocean represents the largest aquifer (in the sub-seafloor) and reservoir (the basins), and the largest carbon pool. Furthermore, it hosts tremendous resources such as deep sea minerals, gas hydrates, seafood and – last but not least – water. As a consequence, assessing the impact of ocean acidification, warming and sea level change at mid- to long-term is vital to understanding short-term variability in rapid, episodic processes such as earthquakes, slides and tsunamis. For many, if not all of these processes, keys for the future can be found in the past, i.e. in the sub-seafloor. These buried records, millions of years long, reveal the Earth's climatic, biological, chemical, and geological history. In addition, observatories on or beneath the seafloor may enable real-time monitoring of fluid-related processes that are central to the workings of earthquakes and resource formation. Many of the governing processes are cyclic or episodic, and only long-term observations will unravel their nature and significance.

Scientific drilling and sampling in the sub-seafloor, followed by time series measurements in key locations, is the only means to decipher signals of regional and global change or hazardous events in the past. Neither the deep biosphere, likely the largest biomass pool in the global carbon cycle, nor other extremophiles at hydrothermal vents (>400°C), beneath salt bodies or in areas of low energy supply would have been discovered without drilling. Tapping into the deep Earth beneath the ocean further allows to couple instruments to the rock, this way recording signals from depths otherwise inaccessible to direct study. This way, key questions such as the following can be addressed: What are the limits of life on our planet? How does environmental change influence the evolution of marine ecosystems? How do deep Earth processes affect the Earth's exterior environment? What are the underlying mechanisms of geological hazards?

Thus, DS³F unfolds a strategy for future research which encompasses the deep sea as an entity of the water body, the sedimentary interface as well as the underground down to depth where large Carbon reservoirs and significant biomass, long climatic records from the past as well as frequent geohazard heritage are found. Here, hundreds of metres below the seafloor, processes of societal importance can be studied with industry collaboration, in particular in fields where scientific exploration and commercial exploitation meet. The section "Implementation" lays out what technology and infrastructure is required, highlights Europe's particular strengths, and discusses how systems may be implemented to address the emerging scientific and societal challenges in *Europe 2020*[2].

In essence, DS³F tries to tie scientific challenges to economic and societal needs and to incorporate training and education on a broad level in order to truly link science and policymaking. This aspect will be revisited in "Grand Challenges" once the main themes and emerging fields in deep sea research have been introduced.



The Deep Sea & Sub-Seafloor Frontier
DS³F was divided into nine expert groups, which held individual workshops and interacted at overarching conferences. All relevant aspects of Life and Earth Sciences in the deep ocean and sub-seafloor (Work Packages 1-6) were bracketed by technological requirements (Work Packages 7-8) and their link to society and policymaking (Work Package 9).

Revealing the history of Climate

Ocean floor sediment cores allow reconstruction of past environmental conditions, and this knowledge is needed to understand Earth system processes on a wide range of scales in space and time. The oceans are a major influence on the Earth's climate and provide the unique temporally continuous sedimentary archive that records Earth processes. The information this contains is critical to our understanding of how the planet works.

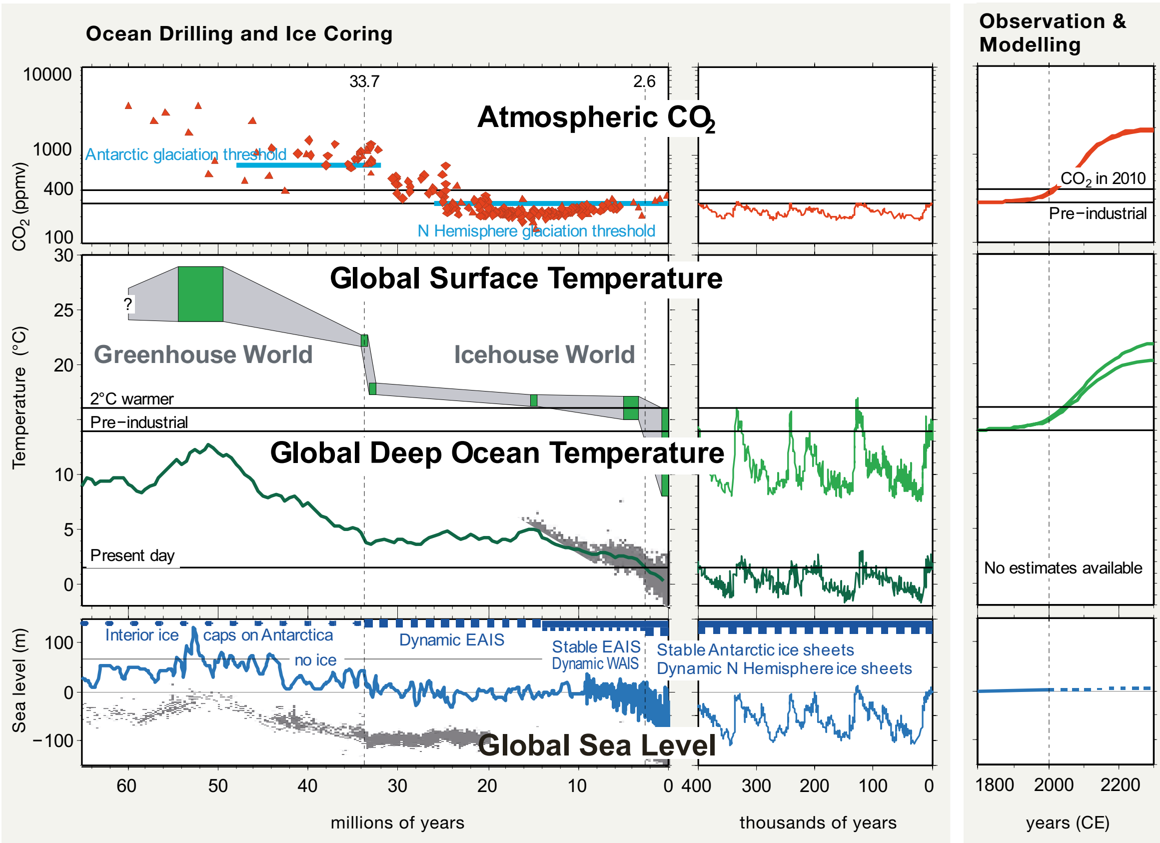
Obtaining sub-seafloor samples by sediment coring, and the pioneering palaeoclimate research it has spawned, have been central to our present understanding of fundamental Earth Science. In addition, this work has provided discoveries relevant for society such as the role of atmospheric CO_2 in moderating global climate, past changes in ocean acidification, and the variability in polar processes and rapid climatic and ocean change. Sub-seafloor samples contain key information on global and regional temperatures, ocean currents and overturning circulation, seawater pH and alkalinity, the hydrological cycle, sea level, ice volume, and the feedback mechanisms between elements of the climatic system. Palaeoclimatic research has illuminated the nature of climate variability and confirmed the global nature of high amplitude yet short-lived oscillations such as Dansgaard-Oeschger cycles, Heinrich events, monsoons, the El Niño Southern Oscillation, and millennial scale variability.

Records from climate archives are the only way to extend historical and instrumental records of climate and to obtain environmental reconstructions from time periods with larger amplitude perturbations under different boundary conditions. Marine sediment cores allow the spatial correlation of records with ice cores, lake records and terrestrial archives on time scales ranging from annual through geological. Sediment cores and samples are the only means by which we are able to extend the Earth's environmental history to times and resolutions not accessible through other methods that more closely resemble conditions predicted for the next few centuries and beyond, and to those that allow us to test and improve climate and Earth system models.

The understanding obtained from ocean drilling is essential if society is to succeed in meeting the challenges of recent and projected changes in the Earth's surface environment. These arise from human activity and complex natural feedbacks, and as a consequence of the fact that atmospheric greenhouse gas levels will soon exceed any experienced during at least the past 20 million years. Key responses that are accessible through coring include climate sensitivity and polar amplification in response to large scale perturbations or extreme events, latitudinal heat transport, ice sheet stability and sea level change, ocean acidification and its ecological impacts, and changes in ocean circulation and biogeochemistry in the context of climate variability on different time scales. DS^3F has identified a number of high priority themes for future research.

Climate sensitivity and carbon cycles

Increasing atmospheric CO_2 is the main driving force for future projected climatic change. The rate of this increase is dependent on the addition of carbon to the atmosphere, but also on a range of feedbacks within the carbon cycle. Such feedbacks play a significant role in regional climate change through their influence on ecosystems, albedo and water budgets, and they operate on different time scales. Understanding these biogeochemical feedbacks in the carbon cycle is thus fundamental to the prediction of future climate change. Important aspects of this cycle operate on time scales that make palaeoclimatology a powerful tool for better quantification. The major hypothesis to be addressed by sub-seafloor sampling is: "Sediment records can provide otherwise inaccessible high-resolution palaeoclimate records on



Climate reconstruction and modelling

Global sea surface and deep sea temperature, and sea level change over the past 65 million years (left), the more recent Earth history (centre), and from historical time towards the future (right). Note some model-derived CO_2- glaciation thresholds for Antarctica and the Northern Hemisphere are shown for comparison with the geological record. Interestingly, future IPCC projections of rising CO_2 over the next century fall within the range inferred for the earlier Cenozoic, illustrating the value of deep sea research for climate change mitigation.

a multitude of time scales that provide information on the coupling between global temperatures and greenhouse gas concentrations, and provide insights into the feedback processes that will allow a reduction in uncertainty of climate sensitivity and climate feedbacks for future climate predictions". Future research must answer how Earth system sensitivity has changed in the past, and how atmospheric CO_2 levels and temperatures varied through time[11].

Ocean acidification

The ocean is the largest sink for anthropogenic CO_2 and has absorbed nearly one third of the carbon released to the atmosphere by fossil fuel combustion. Since the beginning of the Industrial Revolution, ocean acidity has increased by 30%, at a rate 100 times faster than any change in acidity experienced by marine organisms for at least the last 20 million years[12].

Model simulations of the ocean/atmosphere response to the eventual complete utilisation of fossil fuels indicate that atmospheric CO_2 will rise to levels that Earth likely has not experienced for at least 20 million years. The surface ocean may undergo acidification which will make large parts of the water column undersaturated for $CaCO_3$ and reduce or even inhibit shell formation of many organisms, including mollusks, foraminifers, phytoplankton and corals (including the deep sea dwelling cold-water corals). The absorption of fossil fuel CO_2 by the ocean is not instantaneous, and we do not know how much CO_2 can be absorbed by the oceans, where and how it spreads, how fast it is neutralised, or how acidification will affect organic carbon production and oceanic biota[13].

Future research needs to establish the sensitivity of biological calcification to the saturation state of seawater, the natural variability of seawater carbonate saturation, the long-term trend, and the recent detectable response by marine biota. We need to establish the feedbacks between marine biota and the ocean carbon cycle and the impacts of sequestration within the ocean or under the seafloor.

Sea level change

One of the most societally-relevant objectives is to understand the history and impact of global (eustatic) sea level fluctuations at different time scales.

In the last few decades most sea level rise has been from the thermal expansion of the oceans but ice sheets provide the greatest potential risk for future sea level rise because of their volume, which is equivalent to a rise in sea level of 64 m.

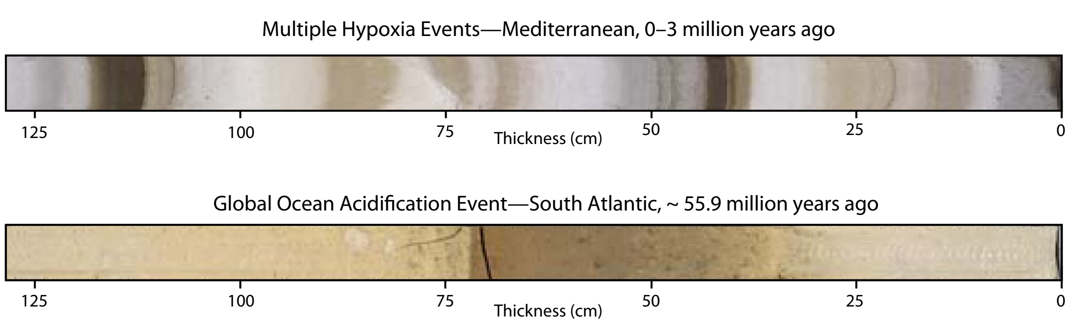
Satellite-based mass balance estimates show that ice sheets have recently begun to loose ice, with projections to 2100 suggesting an increase in the order of 20 times the 1993-2003 average. Uncertainties in sea level projections are large because ice sheet dynamics as climate warms are still poorly understood. Because the instrumental record of sea level extends back only to about 150 years, the refinement of the predictions of sea level rise and of its impact on shoreline stability and habitability for the coming decades and centuries requires the acquisition of sea level records on a wide range of time scales. Over the past 100 million years, changes in sea level reflect the evolution of global climate from a time characterised by small to medium sized and ephemeral Antarctic ice sheets (100 to 33 million years ago), through a time when large ice sheets existed only in Antarctica (34 to 2.5 million years ago), to a world with a large Antarctic ice sheet and variable Northern Hemisphere ice sheets (2.5 million years to the present), when the Earth has been colder than at any time in the last 65 million years.

Over the past approximately 800 thousand years, the cyclic growth and decay of ice sheets induced rapid sea-level change approximately every 100 thousand years, with maximum amplitudes of 120–140 m. However, the timing, rates, and contributions of various ice sheets to these changes remain poorly known, making possible future scenarios difficult to predict. The reconstruction of evolving global ice sheet volumes will primarily rely on the timing and magnitude of sea level change during interglacial and glacial periods, typified by relative sea level maxima and minima. Variations in sea level can be estimated from shoreline markers, oxygen isotopes ($\partial^{18}O$), and the flooding history of continental margins and cratons.

Future research needs to resolve how fast sea level has changed in the past[14], how sea level change is related to the relative stabilities of the northern hemisphere, and the west and east Antarctic ice sheets, and how sea level has varied spatially in response to the non-isostatic adjustment of sea level in response to the gravitational attraction exerted by large ice sheets.

Ecosystems and climate variability

Marine sediment-forming plankton is important because it constitutes the base of the food chain in the oceans, and it influences and responds to global climate. Therefore, its fossil remains are the backbone of reconstructions of past conditions in the oceans and the history of global climate. The co-evolution of our planet and life is of fundamental interest. Yet, we currently have little knowledge about how our environment, and the species we depend upon, will respond to future global change. Gaining an improved understanding of marine ecosystems has direct societal relevance because these systems provide a vital part of human welfare, such as food availability. An improved understand-



Coring the past as a key to the future
Gravity and piston coring on standard research vessels still provide some of the most valuable sub-seafloor archives covering some thousands to hundreds of thousands of years before present. Climate reconstruction is feasible when using reliable proxies from such cores. Deep sea cores record dramatic global and regional ocean acidification and hypoxia. Hypoxia, or a pronounced decrease in water column oxygenation, preserves organic matter and creates sapropels (see top right: core from the Mediterranean Sea, ODP Site 964). The dramatic dissolution of seafloor carbonate that created the red, clay-rich horizon shown in South Atlantic ODP core 1262 (bottom right) was a global acidification event that occurred at the Palaeocene-Eocene boundary ~56 million years ago, most likely as a result of methane release to the atmosphere after gas hydrate dissociation following an ocean warming event.

Isotopes reflect ocean warming
Stable isotope analysis (right) is carried out on dissolved calcareous micro-organisms from sediment cores (left), which is used as a proxy for climate reconstruction in the past. Given that microrganisms precipitate their shells from sea-water constituents, their minerals "record" the palaeo-temperature for present study.

ing of these systems is also key to the understanding of the dynamics of the global biosphere. Ocean sediments are central to understanding the role of the biosphere in Earth evolution because they contain the continuous temporal records of how marine communities both respond to and force climate change. Productivity of marine plankton and the long term storage of its fossil remains in deep sea sediments is a major component in the carbon cycle. Establishing the detailed workings between productivity, the carbon cycle and global climate is crucial for construction of global biogeochemical models. This information is needed in order to reduce uncertainties in models of global climate change. A key goal is to determine the link between productivity variations and climate through time (the past 100 million years). Exploiting the richness of the marine fossil record can address key issues in the evolution of life and the rate of evolutionary change. Knowledge about the dynamics of speciation and extinction is relevant not only to modern evolutionary theory, but also to evaluating the sensitivity of life to global change. Such information is of great value to stratigraphers worldwide. A second key goal is to further develop and refine the history of evolutionary change among marine plankton communities, and hence the biostratigraphic information contained in this evolution. The fact that marine microfossils contain within them diverse chemical clues to their life environment makes a powerful combination for reconstruction of ocean palaeoecology and palaeoclimate. A third key goal is to obtain highly resolved temporal records of palaeoecology and palaeoclimate from various geographical and environmental settings in order to reconstruct rates and amplitudes of climate change through time.

Modern climate oscillates in a few preferred patterns or modes (e.g. the North Atlantic/Arctic Oscillation, the El Niño Southern Oscillation [ENSO]', the Pacific Decadal Oscillation, and the Southern Annular Mode). One way to narrow uncertainty in future projections is to understand how these climate modes have varied in response to a range of external forcings and past climate states. Palaeo-environments offer critical case studies, spanning the full range of potential future climate states, for evaluating climate modes under increased anthropogenic greenhouse forcing. Only recently have proxy techniques and deep sea archives allowed modes of climate variability to be examined beyond the instrumental period. Together with modelling, these reconstructions provide the basis for substantial improvements in regional climate predictability in the future. For example, there has been significant progress in theoretical understanding of ENSO, which exhibits the largest interannual variability in the global climate system. The wide impacts of ENSO on regional climate, ecosystems and societies make it a key focus for both adaptation of society to short-term variability and as a dynamical component of longer-term change. Despite progress in the prediction of short-term seasonal variations in ENSO, there is no consensus on how tropical Pacific mean-climate and ENSO variability might change as a function of increasing greenhouse gases. We need to establish whether the observational period captures the full extent of variability in leading climate modes and the dependency of climate modes on climate boundary conditions (will there be change as the Earth warms?). We need to decipher the imprints of climate mode shifts recorded in ocean archives and establish what these tell us about how ecosystem and biota changes affect, and are affected by, changes in climate modes.

Marine planktonic algae, including diatoms, coccolithophores and dinoflagellates, provide about 45% of the global annual net primary productivity. Future research will need to explore how perturbations to plankton succession impact food chain and biogeochemical cycling of carbon, nitrogen, phosphate, and other elements. We need to establish how shifts in deep-ocean circulation modes affect deep sea ecosystems and biogeochemical cycles, whether we can we quantify the feedback mechanisms between deep-ocean biosphere, biogeochemistry and climate, and the relationship with primary productivity and ocean ventilation, particularly in the context of large scale oxygen minimum zones.

Ice coverage in the Arctic
An Arctic cod under the Arctic sea ice that is trying to hide behind a ctenophore (comb jellyfish *Bolynopsis*). Temporal variations in ice coverage represent a challenge for both ecosystems and mankind.

Ocean ventilation

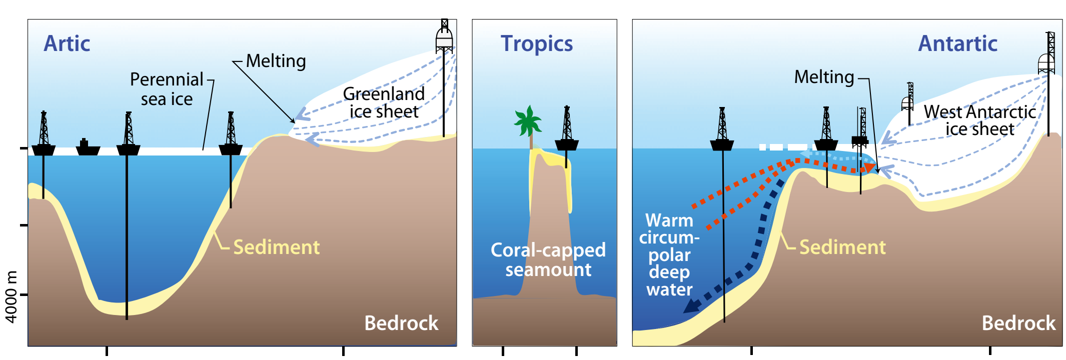
Ocean ventilation and circulation play significant roles in regional and global environments via their influence on the physical, chemical, and biological processes determining carbon storage, ocean oxygenation, and regional temperatures.

Particularly relevant is the role of Atlantic meridional overturning circulation (AMOC) in transporting heat into the North Atlantic region and anthropogenic CO_2 into the deep ocean. Deep sea sediment archives demonstrate that the AMOC has varied considerably during the last 2 million years (the Pleistocene) to cause global climate changes of magnitude and rapidity far beyond that recorded over the last hundred years of direct instrumental observations[15]. To fully understand how AMOC variability on ‘human time scales’ can impact on European climate and ocean ecosystems, new ‘high resolution’ records that extend the modern observational database further are crucial.

We need to establish which processes exert direct control on natural deep ocean variability in terms of temperature, water mass structure, chemical properties and nutrient inventories on time scales ranging from sub-decadal to multi-millennial, how these ocean changes impact and control the biodiversity and functioning of deep ocean ecosystems and whether we can identify early warning signs from the sedimentary record that herald changes in the deep sea environment associated with tipping points and periods of accelerated climate change.

Evolution of the hydrological cycle

Rapid or long-term changes in the hydrological cycle can cause single or multiple extreme flood and drought events, on the one hand, and preset more arid or humid climate conditions at a regional scale, on the other. The latter determines the balance in the amount of precipitation, prospering vegetation and river runoff compared to the extent of desertification and



Climate change between the poles
Proposed IODP drilling strategy from pole to pole to collect records linking climate, ice sheet, and sea level histories on geologic time scales. The climate history derived from these records is used to test numerical ice-atmosphere ocean and their ability to project future sea level rise. Red arrows represent warm water flow accelerating ice loss from West Antarctica.

eolian transport as well as between physical and chemical weathering. Thus, the hydrological cycle controls the eolian and fluvial supply of a huge detrital sediment load into the ocean and, more important for the marine biota, the supply of inorganic dissolved and particulate biochemically relevant elements.

The responses of marine biota to changes in the rates of nutrient and freshwater supply are not well known (diatoms vs. coccoliths, foraminifera vs. radiolaria), nor is the adaptation to the evolution of sedimentary systems, slope failures and hydrocarbon seeping in the deep sea fan systems beyond the shelves. Pressing questions that can only be answered by studying geological archives of past climate change are focused on three large-scale climatic features that influence continental patterns of precipitation. These relate to variations of the intertropical convergence zone, monsoons and mid-latitude storm tracks.

Cryosphere, Arctic and Antarctic research

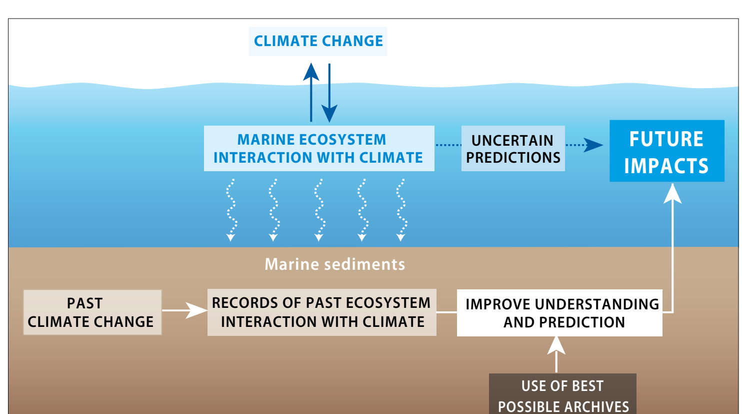
The high-latitude regions of the Arctic Ocean and Antarctica are undergoing some of the fastest temperature and ice volume changes on the planet. To understand high latitude climate and ice cover change, it is necessary to sample the history stored in the sediments of the Arctic Ocean, and to decipher the climate history and sensitivity of Antarctica. Arctic Ocean sediments, except for the piston-cored superficial record, have been sampled only on the Lomonosov Ridge during the Arctic Coring Expedition (ACEX) in 2004 and in 1993 in the ice-free waters in the Fram Strait/Yermak Plateau area (ODP Leg 151) [16]. Antarctica has been drilled most recently around Wilkes Land in 2010, but a large number of proposals are targeting ice sheet stability, history, and behaviour during extreme warmth, which is crucial to provide boundary conditions for past, present and future changes of sea level, and climate feedback systems. We need to establish the contribution of continental ice to the rate and magnitude of sea level changes both in the past and projected into the future

and whether sectors of marine-based ice sheets experience "runaway collapse" as climate warms. Can ocean drilling provide constraints on past rates of this process? It is unclear how palaeo-ice sheets responded when Earth's atmosphere had 400 or 600-1000 ppm CO_2, what a "Greenhouse Earth" looked like in the polar regions, and whether Antarctica can sustain any ice sheets when the atmospheric CO_2 concentration is above 1000 ppm.

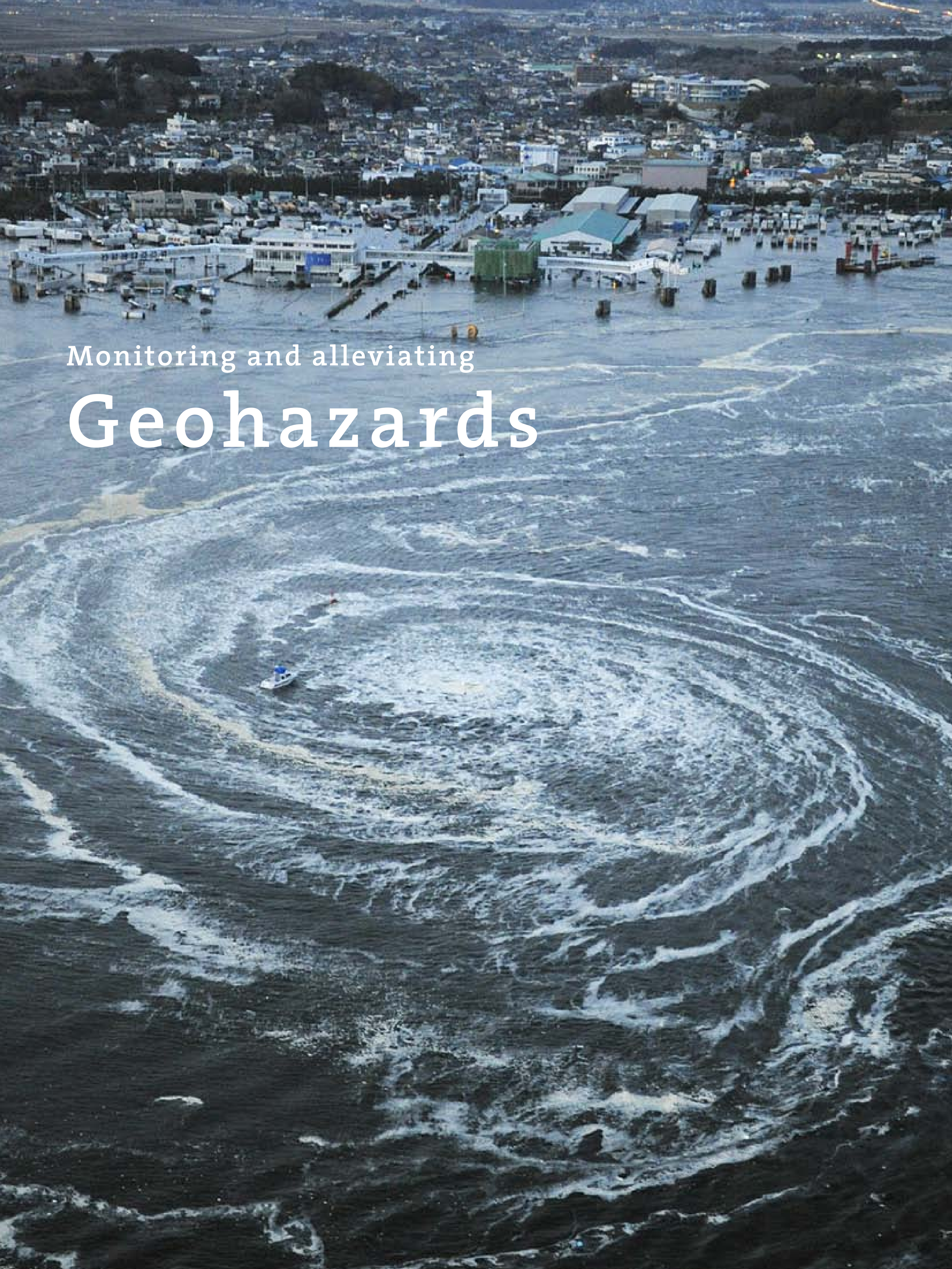
Breaking the ice (left)
The converted ice-breaker Vidar Viking, the Oden and the nuclear powered Sovetskiy Soyuz, met for ACEX (Arctic Coring Expedition) IODP Leg 302 at the Lomonossow Ridge, Central Arctic Ocean. The campaign recovered the first long climate records from this area and provided crucial data for climate mitigation.

How sediments help us understand the climate system in the past, the present and the future

* Reconstructing how Earth system sensitivity has changed in the past, and how atmospheric CO_2 levels and temperatures have varied through time reveals how global temperatures and greenhouse gas concentrations are coupled and reduces uncertainty about climate sensitivity and climate feedbacks for future climate predictions.
* Assessing the biotic impact of ocean acidification is important to adapting to the effects of future acidification changes on food sources and biotic diversity and the sensitivity of biological calcification.
* Reconstructing evolving global ice sheet volumes to estimate variations in sea level and determining how sea level change is related to the relative stabilities of ice sheets is of prime importance to adapting to and mitigating sea level rise.
* Identifying early warning signs from the sedimentary record that herald thresholds and periods of accelerated climate change will help in understanding Earth system and climate sensitivity. This is crucial to preparing for and mitigating the impacts of climate change.
* Understanding the evolution of the hydrological cycle and ocean ventilation has important implications of the future evolution of flood events, freshwater supply, and greenhouse gas concentrations.
* Exploring how perturbations to plankton succession impact food chains and biogeochemical cycling of carbon, nitrogen, and phosphate will improve global biogeochemical models. This will reduce uncertainties in models of global climate change and help determine the link between productivity variations and climate through time.
* Extracting information about the dynamics of speciation and extinction and reconstructing the evolution of ocean palaeoecology and palaeoclimate gives insight into evolution and into the sensitivity of life to global change.
* Deciphering the imprints of climate mode shifts recorded in ocean archives will help establish what these tell us about how ecosystem and biota changes affect, and are affected by, changes in climate modes.



The key to climate mitigation
Schematic how sediment archives storing information from ecosystems and climates can be utilised via numerical climate, ocean, ice sheet, and Earth system modeling to improve the assessment of future impacts. Ultimately, advancing models beyond basic climate scenario projections and toward prediction of our future climate change requires sufficient knowledge of Earth's prior responses to natural fluctuations in greenhouse gases and other climate forcings.



Monitoring and alleviating

Geohazards

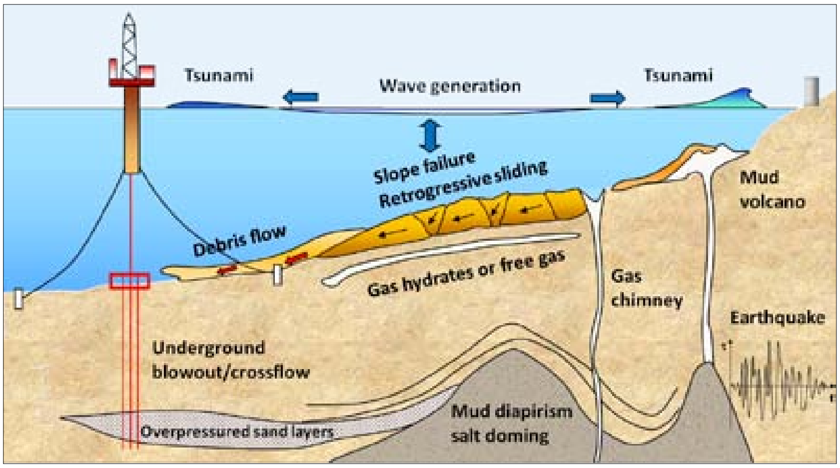
The apparent recent increase in the number of geohazards, and in large magnitude earthquakes and associated landslides and tsunamis in particular, is of major global concern. Disaster prevention and resilience are essential for human well-being. Research on submarine geohazards, accompanied by technological advancement in collaboration with industry, has to focus on monitoring, early detection and warning. At times of global change, gas hydrate dissociation in the Arctic may become another emerging threat.

Geohazards belong to the family of "natural hazards", which include "all atmospheric, hydrologic, geologic and wildfire phenomena that, because of their location, severity, and frequency, have the potential to affect humans, their structures, or their activities adversely" [17]. They are caused by geological conditions or processes – such as an earthquake, landslide, tsunami or a volcanic eruption – which represent serious threats to human lives, property and the natural and built environment, regardless of a continental or marine origin. Offshore geohazards are widespread phenomena that may involve both long-term and short-term geological processes. Geohazards can attain huge dimensions (e.g. the area impacted by a large tsunami or a submarine landslide) and seriously affect society and economic systems, from local to regional scales, as demonstrated, for instance, by the Great East Japan (Tohoku) earthquake and tsunami of March 2011 and the Sumatra-Andaman earthquake and tsunami of December 2004 in the Indian Ocean. Geohazards can also be provoked by human activity, as in the case of the mud eruption in East Java on 29 May 2006, triggered by drilling for hydrocarbons through over-pressured geological formations, or the oil spill in the Gulf of Mexico in April 2010.

The geographical spread of offshore geohazards is often several orders of magnitude larger than that of geohazards on land. Prevention and resilience are crucial to preventing hazards from developing into disasters or to reducing their consequences, so that mitigation, preparedness, response and recovery often hardly reconcile with the different levels of vulnerability, social, economic and cultural characteristics of the affected areas. Predictive capabilities are therefore extremely important and require improved understanding of the mechanisms involved in offshore geohazards, starting from pre-conditioning factors, causes and triggers.

Offshore geohazards can also have catastrophic effects on enormous areas of the natural submarine environment and its ecosystems, which may need decades to recover, as illustrated by the Tohoku and Sumatra tsunamis and other recent events such as storm-triggered abrasion of benthic communities on continental shelves or volcanic eruptions acidifying the surrounding waters and seafloor, as for the La Restinga submarine eruption in El Hierro, Canary Islands, which was active for almost six months in 2011.

A clear trend has been observed in the last 100 years of increasing number of natural hazard events per year[18], including earthquakes, floods and cyclones. Caution should be used in interpreting such observations as due to an increased climatic forcing on natural hazards as space occupation by urban areas, industries and infrastructures has raised dramatically the vulnerability of large sectors of our society. The risk is given by the product of probability of occurrence of a geohazard and probability that that hazard produces damage (vulnerability). Research must concentrate on hazard assessment whether or not climatic forcing is suspected to be involved, as the increased vulnerability is undoubtedly increasing the risk for society and environment. This is particularly vital for the deep sea marine environment. Offshore geohazards are often not accounted for in global statistics, although clear evidence of the impact of submarine geohazards on society is attested throughout the history of mankind (most importantly in the Mediterranean region[19], Japan and China).



Causes and effects of geohazards
Offshore natural hazards: Earthquakes, submarine slides and tsunamis and some of their potential trigger mechanisms shown schematically. Although often a consequence of the natural evolution of continental margins and rarely man-made, all of these processes represent a severe hazard to society and infrastructure.

Submarine landslides

Submarine slope failure and subsequent sediment mass-transport affect continental margins from the shelf to the abyssal plain. Sediment remobilisation may also affect coastal zones, either by local rock falls or landsliding or by submarine retrogressive failure moving landward. However, landslides occur mainly along ocean margins because here slope gradients are steepest, sediment accumulation rates are highest, and several other geological processes concur to determine submarine slope instability. Submarine landslides pose societal and environmental risks to offshore infrastructures (platforms, pipelines, cables, sub-sea installations) and coastal areas, and may dramatically change the marine environment. The occurrence of submarine landslides, their magnitude and recurrence depend on the interaction among several pre-conditioning mechanisms that include sedimentary history, diagenesis, fluid flow regime, hydrology of the adjacent coastal zone, gas hydrate dissociation, the seismic cycle, and evolution of volcanic island margins. Research on submarine landslides may hence aid in understanding palaeo-seismicity (i.e. through the determination of recurrence rates of deposits triggered by earthquakes), impacts of climate change, and building of sedimentary sequences in ocean margins and basins that are relevant to hydrocarbon reservoir exploration and characterisation.

Research on submarine slope stability is now approaching a new era. Recognition of the magnitude and distribution of events in European waters has been achieved in the last decade, mostly through research projects funded within EC Framework Programmes. An outstanding and unique milestone for the understanding of submarine landslides was the Ormen Lange project funded by a consortium of oil companies offshore mid-Norway. Industry-academia cooperation was motivated there by the fact that one of Europe's largest gas reservoirs lies just below the headwall scar of the largest submarine landslide in Europe, the Storegga Slide. The Ormen Lange study acquired one of the most comprehensive multidisciplinary data sets on submarine slope failure and illuminated processes along the glaciated North Atlantic continental margin.

In Europe, slope failures of different magnitude have been documented everywhere along its continental margins, and several compilations have been made in order to obtain background information to systematically address current knowledge and future challenges[20]. It has further been shown that many large slope failures in the Atlantic and Mediterranean may not have been caused by gas hydrate dissociation (see next paragraph), but rather by the complex climatic control exerted by the Quaternary climatic cycles involving glaciation and deglaciation in parallel with sea level fall and rise[21]. It must also be stressed that landslides are not restricted to the continental slopes as such, but may affect the shelf or coast. Recent systematic geophysical mapping reveals a wealth of smaller-scale landslides occurring in the immediate vicinity of human settlements so that neither onshore-offshore relationships nor human interference can be ignored. This is particularly important in near-coastal, formerly glaciated areas where many historical landslides were at least partly induced by human interference facilitated by the presence of quick clays.

Gas hydrates

Gas hydrates are ice-like crystalline solids formed from a mixture of water and natural (often methane) gas, which form cements, nodes or layers within the sediment. In addition to their potential role as a future energy resource, gas hydrates are an important component in slope stability, as they modify the geotechnical properties of sediments and rocks by cementing them. Both global warming and erosion might lead to seafloor destabilisation events in continental margins and induce a positive feedback mechanism of methane release in the atmosphere, known as the controversially debated "clathrate gun hypothesis"[22]. Mining gas hydrates usually relies on dissolving the ice-like crystals and recovering the released methane. Managing the large volumes of freshwater being set free by hydrate mining in a controlled fashion is a tremendous technological challenge.

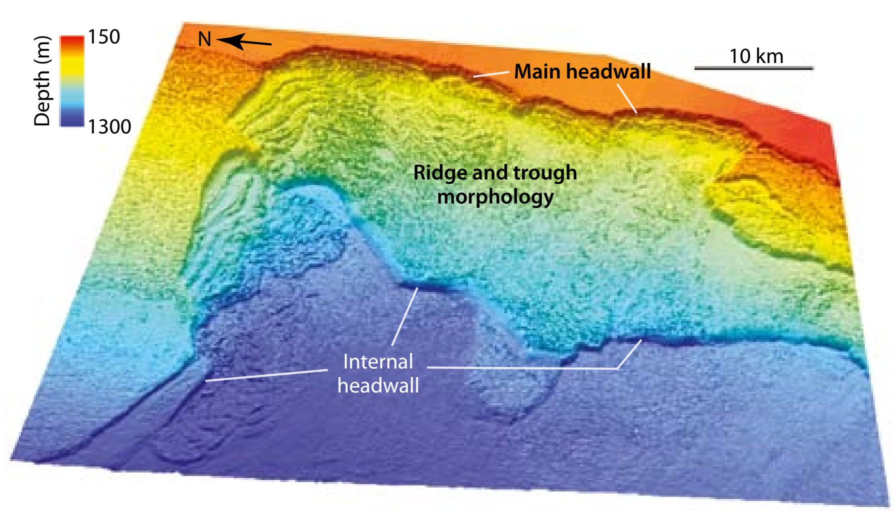
Interstitial fluid overpressure, including that caused by natural gases, is often identified as a relevant factor for the reduction of the effective stress of continental slope sediments. The consequent reduction of the shear strength of the sediments creates a situation where any even small perturbation may lead the slope to fail. Gas charging of shallow continental slope sediments may occur either by *in situ* production of biogenic methane in areas of high organic matter accumulation, or by upward migration of deep thermogenic gas along faults and permeable strata. Gas-induced interstitial overpressure in ocean margins can also result from gas hydrate dissociation or dissolution induced primarily by changes of *in situ* temperature and pressure conditions. On the other hand, the cause-effect relationship between gas emissions and submarine landslides may be reversed. The instantaneous removal of the overburden in the headwall domain of the slide causes a decrease of the total stress on the interstitial fluids of the exhumed sediments when they are in compaction disequilibrium condition. Gas exsolution and/or gas hydrate dissociation could therefore produce gas emissions in the water column overlying landslides which might reach the atmosphere.

Earthquakes

Earthquakes occur as a function of sudden stress release from plate tectonic movement. Approximately 90% of all stress accumulated along plate boundaries and major active faults drops in subduction settings. During large magnitude earthquakes the seafloor may show surface ruptures followed by subsequent submarine landslides and/or tsunamis. The most recent example of such a cascading effect in European waters is the catastrophic May 2003 Boumerdes-Zemmouri earthquake in northern Algeria. The tremor triggered extensive landsliding along 300 km of the continental slope, leading to 29 communication cable breaks during the four hours following the main shock, and a tsunami that propagated over the Western Mediterranean Basin and sank about 200 boats in the Balearic Archipelago. Seismic activity in Europe mainly concentrates in the Mediterranean region, with the seismic hazard being higher in the Eastern Basin. Seismic activity is moderate in the Western Mediterranean Basin and Southwestern Iberian margin, although great earthquakes may also occur with a recurrence interval of around 1800 years. As an example, one of the largest earthquakes and tsunamis in Europe took place in the year 1755 southwest of Portugal, resulting in the destruction of Lisbon, at that time one of the main capitals of the world. Some degree of seismicity also occurs in Scandinavia due to postglacial isostatic rebound, though hypocentres are mostly situated inland.

Tsunamis

Tsunamis are the most serious offshore geohazard because of their potential geographic spread and devastating potential. Tsunamis are generated either by earthquakes, slope failures (coastal and submarine), volcanic eruptions or – less commonly – impacts of large extraterrestrial bodies. The first three sources have been recorded since historical times in numerous locations worldwide, whereas the fourth is known from the geological record (e.g. the Eltanin Impact in the southwest Pacific Ocean[23]). Highly catastrophic volcanogenic tsunamis, such as Santorini in the Mediterranean Sea or Krakatoa in the Indian Ocean, have been experienced in the last few millennia and centuries. Destructive seismogenic tsunamis have occurred as recently as the last decade as a result of series of subduction megathrust earthquakes, such as the 2004 Mw 9.2 Sumatra-Andaman, the 2010 Mw 8.8 Chile, and the 2011 Mw 9.0 Great East Japan earthquakes. The destruction they caused is also related to increased vulnerability due to dense human settling along the shoreline (Sumatra tsunami) and placement of critical infrastructures, such as nuclear power plants, on the coast (Great East Japan tsunami). Catastrophic tsunamis have been also reported in Europe during historical times, the most damaging being the Lisbon earthquake and tsunami in 1755, which was felt in Scandinavia and caused lake level fluctuations in Switzerland, the tsunami hitting Portugal and Spain, the Azores, North Africa and the Cape Verde islands. Geological evidence has also been provided on catastrophic tsunamis in prehistoric times (for example the Storegga Slide or the



Submarine mass wasting
Shaded relief bathymetry image of the central part of the upper Storegga Slide, a huge landslide that unleashed a major tsunami offshore Norway some 8000 to 6000 yrs ago. Potential triggers include gas hydrate dissociation and weak contouritic clays.

Canary Islands tsunamis). The area most prone to tsunamis is the Mediterranean Sea, especially its central and eastern regions, where active plate subduction takes place. Although the Eastern Mediterranean is the seismically most active region in Europe, the latest large earthquake and tsunami dates back to 365 AD, when Crete was uplifted substantially and a tsunami destroyed the Pharos lighthouse, one of the Seven World Wonders[19]. One emerging question in geohazard research is the length of the seismic cycle and when another rupture and associated tsunami may occur.

Given the mature collisional setting in southern Europe and the long recurrence interval, a rupture of the Hellenic Trench seems overdue. Similarly, experts speculate that a future mega-tsunami may result from a new massive flank collapse in the Canary Islands, resembling those whose evidence is found repeatedly in the geological record. Scientists and policymakers in Europe have to anticipate such events by providing the appropriate infrastructure for their study as well as early warning capability to alert society.

Prevention and mitigation of geohazards

The economic and social implications of offshore geohazards are manifold. Compared to geohazards on land, offshore events have longer recurrence cycles and are capable of affecting larger areas, often among the most vulnerable in the planet (rural and urban coastal communities). Offshore geohazards therefore involve elevated risk as they hold a terrific potential for infrastructure destruction, ecosystem alteration and loss of human lives. With the purpose of mitigating the damage, the EU and other governmental bodies have reacted to recent disasters by calling for collaborative approaches integrating scientists, policymakers, administrators, and experts in public perception of geohazards. Priority action, in order to be prepared for major devastating events such as the Crete 365 AD earthquake and tsunami, includes the implementation of an early warning system, which in the Mediterranean could be built on the cabled deep sea observatories already in operation (see "Implementation") plus autonomous buoys.

Furthermore, the forecasted dramatic increase of industrial activity in the deep sea (deep conventional energy resources, non-hydrocarbon energy resources, mineral resources, communication cable networks, pipeline networks, offshore CO_2 storage) implies that careful attention must be given both to naturally triggered geohazards and to risks induced by human activities leading to seafloor destabilisation or uncontrolled escape of overpressured fluids in the marine environment. In particular, the mining of shallow methane hydrate deposits in the near future would require *in situ* hydrate phase change, which may hamper their sediment-hardening capability, eventually leading to failure.

Because of the potentially dramatic losses and associated socio-economic implications, novel approaches for geohazard prevention and mitigation are probably among the most challenging and urgent endeavors in offshore research. Currently, the best (i.e. most reliable) warning is anticipated tsunami travel time so that detection of precursory phenomena *prior* to an event may add valuable time to disaster response.

Innovative options to detect precursory phenomena owing to stress changes in the deeper Earth include long-term monitoring of pore pressure, temperature, or gas chemistry[24]. Such seafloor and sub-seafloor technology is particularly powerful when installed in hydrologically active areas (faults, mud volcanoes, seeps) linked to real-time data transfer. More common systems such as tsunami warning systems are equally efficient means, as has been recently seen when alerts were sent after large earthquakes off Sumatra by the system installed after the 2004 rupture. State-of-the-art research and development as well as its implementation involve political decisionmaking and monetary investment, with the added difficulty of the essentially unpredictable nature of offshore geohazards.

Other crucial fields of hazard research include the study of sediment mass transport and sediment-laden bottom water flows on continental slopes and within submarine canyons. Canyon dynamics build areas of hampered slope stability. The physical state of submarine continental slopes must be monitored in areas of incipient failure, introducing integrated approaches of slope stability analysis, enhanced borehole investigations and repeated high-resolution seafloor mapping in the deep sea realm. In European continental margins, the increasing number and intensity of extra-tropical storms are expected to increase sediment-laden flows within canyons and the return period

Earthquake slip causing beach uplift
Photographs showing Ululaju Beach, Busung-Simeulue, Indonesia before (left) and after (right) the large 2004 Sumatra EQ and tsunami in the Indian Ocean. Note uplifted beach rocks owing to EQ slip.

Early tsunami detection
Surface buoy (left) and signs along a beach (right) as part of a Tsunami Early Warning System in Indonesia.

of high-energy hydrodynamic events[25], which may lead to enhanced erosion, destabilisation and destruction of benthic communities in addition to likely significant implications for pollutants and litter dispersal, fisheries and safety of seabed infrastructures.

The technological challenge in the understanding of offshore geohazards is to improve the capability of *in situ* sampling and measurement (in boreholes and at the seafloor) and high-quality sampling for geotechnical laboratory testing. These were not part of typical research schemes in the past, and are now recognised by the international community as milestones for future investigations. However, state-of-the art platforms and tools that have been developed for seafloor and sub-surface monitoring, mainly with the purpose of supporting industrial activity, are expensive, especially because their use must be planned and supported in the long term (multi-year and decades). If a European Maritime Strategy as part of policies such as *Europe 2020*[2] or *A resource-efficient Europe*[26] envisages deep sea mining for minerals, hydrocarbons or gas hydrates, it would be mandatory for policymakers to fund the required infrastructure for sustainable monitoring of areas at risk of natural (or man-made) hazards.

It seems obvious that an integrated, multi-disciplinary approach is essential in the offshore geohazards field, also involving stakeholders and the offshore industry wherever possible. Clearly, some of the future studies will have to go hand in hand with the industry since their focus on the deep-water areas is rapidly growing; this is the only way to reach the competitiveness and growth envisioned in *Europe 2020*[2].

Understanding submarine geohazards: research needs and societal challenges

* Offshore geohazards are capable of affecting large areas, often among the most vulnerable in the planet and hold a terrific potential for infrastructure destruction, ecosystem alteration and loss of human lives.
* Research that unravels the historical records of geohazards in the ocean is pivotal for future risk assessment. Such mitigation efforts are best supported by long term, real-time monitoring of precursor phenomena and manifestations of sudden changes (e.g. along seismic areas or continental slopes showing signs of recent and incipient failure).
* The forecasted dramatic increase of industrial activity in the deep sea means that careful attention must be given both to naturally triggered geohazards and to risks induced by human activities.
* The increasing number and intensity of extra-tropical storms may lead to enhanced erosion, destabilisation and destruction of benthic communities in addition to implications for pollutants and litter dispersal, fisheries and safety of seabed infrastructures.
* Research on submarine landslides to understand palaeo-seismicity, the influence of climate change, and building of sedimentary sequences in ocean margins and basins is highly relevant to hydrocarbon reservoir exploration and characterisation.
* Because of the potentially dramatic threat to human lives, property and the natural and built environment, novel approaches for geohazard prevention and mitigation are probably among the most challenging and urgent endeavours in offshore and coastal research. This encompasses improved detection of precursors such as increasing pore pressure, and temperature and changes in gas chemistry in hydrologically active areas.
* Scientists and policymakers in Europe have to anticipate future catastrophic events by providing the appropriate infrastructure for their study as well as early warning capability to alert society.

Exploring marine

Ecosystems

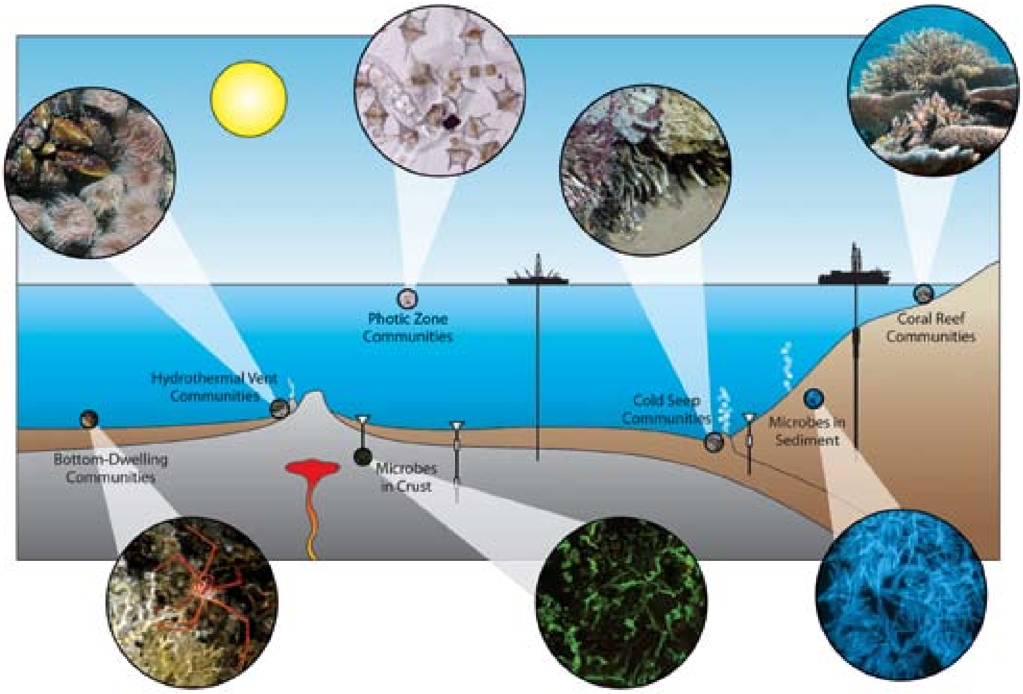
The past two decades of marine research have seen a veritable explosion in the exploration and discovery of deep sea marine ecosystems. Recent developments in seafloor imaging, geophysics and understanding of deep sub-seafloor hydrology have altered our perception of the underlying physical and chemical nature of ecosystem habitats.

We now have an enhanced ability to image and directly sample deep sea ecosystems using remotely operated vehicles and a new generation of drilling equipment and other sampling devices. This has also accelerated the effort to sample more difficult targets such as ecosystems located at hydrothermal vents near seamounts and outcrops; on cold-water coral-bearing ledges; near gas seeps and at mud volcanoes, and in deep sub-surface sediments – which host one of the largest biomass reservoirs on Earth. This has all occurred with significant European participation and leadership.

Recent discoveries of deep seascape ecosystems

New discoveries, such as the stunning serpentine-hosted ecosystems along the Mid-Atlantic Ridge, continue unabated. The serendipitous discovery of the Lost City hydrothermal field, characterised by metal-poor, <100°C, high pH fluids (9-11) with high concentrations of hydrogen, methane, C2+ alkanes, and formate, has particularly stimulated interest in the geophysical, geochemical and biological consequences of serpentinisation (transformation of rocks from the Earth's mantle) for the global marine system. This discovery is paired with the reported presence of microbial niches in seafloor serpentinites[27]. Thus, it is important to identify critical factors that control abiotic formation and uptake of alkanes, not only to understand ecosystems where energy is extremely limited, but also to gain insight into physico-chemical conditions for the origin of life in primordial mid-ocean hydrothermal systems at times long before organisms could generate hydrocarbons for microbial metabolism by alternative biosynthetic pathways[28].

Another exciting revelation within the last two decades is the high diversity of microbial life at the deep sea seafloor and sub-seafloor. Micro-organisms are ubiquitous in the marine deep biosphere, pervading the deepest sediments drilled so far as well as the oceanic crust, with complex prokaryotic communities consisting of thousands of different species. The number of species is currently only defined from the genetic diversity detected in extracted DNA. Most of these species, in particular those among the archaea, are only distantly related to known cultivated micro-organisms. These discoveries have resulted in new important research questions regarding the extent and origin of diversity, how diversity is linked to space and time, and which organisms carry out key ecosystem functions in the deep biosphere that harbours half of all bacteria and archaea on Earth. These micro-organisms subsist in million-year old sediments by the slow degradation of deeply buried organic matter and have metabolic rates that are orders of magnitude below rates measured in laboratory cultures. Yet, they are responsible for a nearly complete mineralisation of organic carbon in the seabed and are thereby gatekeepers for the oxygen balance in the atmosphere over geological



Abundant life at depth
The presence and size of the deep biosphere may affect the Earth system in ways we have yet to appreciate. Chemosynthetic microbes play a major role in the global carbon cycle and produce huge amounts of biomass in extreme environments such as hydrothermal vents, mud volcanoes, and deep-sea hydrocarbon seeps.

time-scales. The slow pace of subsurface microbial life remains a great challenge to our understanding of the limits to life on our planet. This hidden, vast biological diversity of bacteria and archaea needs to be investigated in much more detail, in order to describe which species are present, how they vary spatially and temporally, how they will respond to the changing environmental conditions, and to explore their enormous potential for bio-prospecting (biotechnological, pharmaceutical and industrial applications).

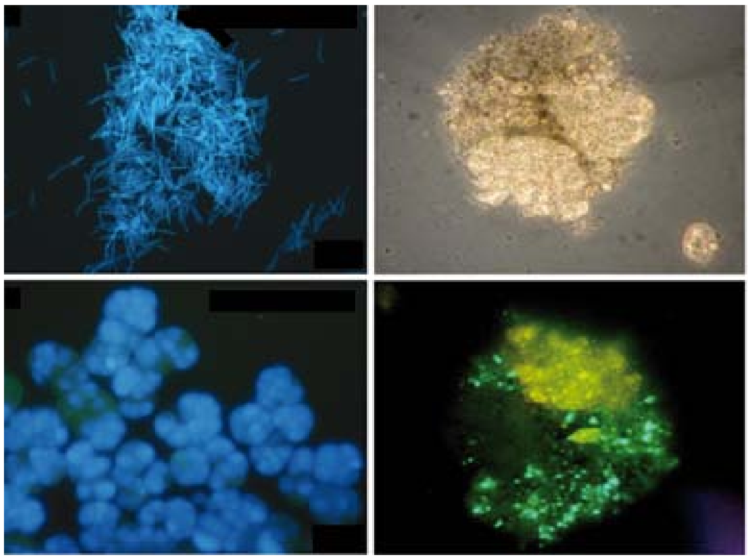
Further recent discoveries include dramatic sedimentary seafloor features such as deep water coral mounds and mud volcanoes closely associated with distinct faunal and microbial communities. Deep water coral ecosystems produce coral build-ups or "deep-water coral mounds" that reach up to 350 meters. Their initiation and growth, followed by death and erosion, are closely linked to glacial and interglacial changes in ocean circulation and chemistry and eventual food supply[29]. In contrast, mud volcano ecosystems are fed with fluids and mud rich in methane from below. The oxidation of this methane leads to the formation of distinct methane and hydrogen sulfide based ecosystems, as well as authigenic carbonate structures on the seafloor and in the sub-seafloor. Other seafloor sedimentary features that have only begun to be explored include the three dimensional structure of continental margin canyon walls, and the "hadal ocean" or ultra-deep regions of the world's oceans.

The deep sea seascape is much more diverse and heterogeneous than previously recognised, both at small and large scales. The results from numerous oceanographic investigations and the scientific ocean drilling programs (e.g. IODP[8]) over the past three decades have changed the long-held view that the entire oceanic lithosphere is uniform in architecture and thickness, and have led to the recognition of fundamental differences in crustal accretion and alteration processes related to spreading rates. Nevertheless, deep sea seafloor and sub-seafloor ecosystems are still mostly unexplored and highly undersampled; we have very limited understanding of the diversity of habitats in the seafloor seascape. These unexplored habitats include but are not restricted to: trenches, areas around seamounts, mid-ocean ridges (including sediment cover), vertically structured ecosystems on escarpments and canyon walls, and emerging deep sea ecosystems under retreating ice in the Arctic. Moreover, and perhaps most importantly, the 'natural' variability of the sub-seafloor in time is poorly understood. Fluxes of energy and matter across the seafloor-seawater interface are 'ecosystem services', so if we are to understand how humankind is perturbing the benthic ecosystem, we need to know how these vary on short (human) time scales.

The greatly confused response to the recent Deep Water Horizon disaster in the Gulf of Mexico has made it frighteningly clear how little we know about how seafloor ecosystems are structured and how they function. Humans will continue to venture into the deep sea and use the deep sea seafloor as a resource. Accidents will happen. The economically viable precautions that we undertake, and our response to unforeseen problems that arise, can only be mitigated by a thorough understanding as to how the seafloor functions.

Life under extreme energy limitations

Extreme energy limitation is the major feature of many deep sea seafloor and sub-seafloor environments[30]. This limitation has been shown by quantification of the microbial cells living deep within marine sediments. By experimental measurement or by reaction-transport modelling of the rate of organic carbon mineralisation it is then possible to calculate the mean cell-specific rate of carbon metabolism. Recently, a novel approach has been de-



Wealth of microbes in the sub-seafloor
Clockwise from lower right: UV microscope image showing blue-green, autoflourescent, methanogens on iron sulphide precipitate; corresponding light microscope image; *Methanobacterium sp.*; and *Methanosarcina sp.*, the latter two from sediments offshore Japan. Innovative cultivation techniques will open a window to understanding of genetic, metabolic, and evolutionary characteristics of subseafloor life.

veloped by which the turnover of microbial biomass can be calculated from the slow inter-conversion (racemisation) between D- and L-forms of specific amino acids in bacteria. Compared to surface sediments the rates of microbial metabolic activity in the deep biosphere are orders of magnitude lower, impeding the detection of microbial activity in the deep biosphere. Thus, microbial processes in the deep biosphere are operating on a significantly lower level and on different time scales that require the development of more sensitive analytical methods.

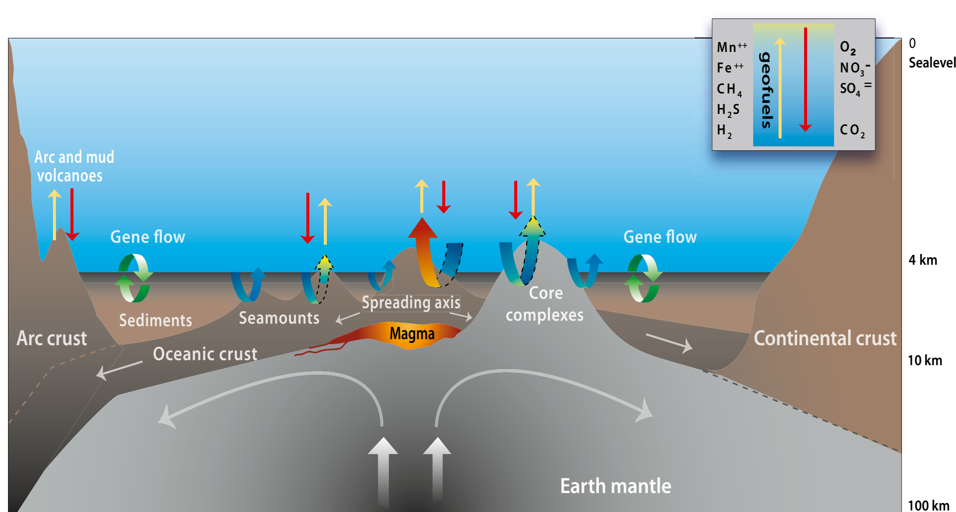
Food web operation in a food-limited world and the population dynamics of deep sea fauna are still poorly understood. For instance, the deep sea may be more prone to boom-bust cycles. There is interest in how changing nutrient and oxygen concentrations over time may have effects on benthic faunal activity. Furthermore, elucidating faunal activity over geological time, e.g. after the Cambrian explosion, has implications for our understanding of changing seawater chemistry.

Recent studies have highlighted the important role of viruses in surface deep sea sediment ecosystems. Benthic viruses are major players in the global biogeochemical cycles, in deep sea metabolism and the functioning of the largest ecosystem of the biosphere. Viral infections release extracellular DNA that might represent a source of nutrients for prokaryotic metabolism, due to its high lability and content of organic nitrogen and phosphorus. This large sedimentary DNA pool can provide almost half of the prokaryotic demand for organic phosphorus. However, the genetic diversity of benthic viruses, as well the biogeochemical role of the extracellular DNA in the overall deep sea functioning, are still largely unexplored.

Strong interactions between organisms and rocks

Studies of diverse hydrothermal systems and natural rock samples have brought to light key processes that sustain seafloor and sub-seafloor chemosynthetic communities at mid-ocean ridge environments.

Geofuels in dynamic deep-sea settings
Schematic representation of the major dark oceanic environments, ranging from mid-ocean ridges to continental margins, and the fluxes that are observed. The wealth of processes represents a substantial part of global element cycles.



Corals make home for wolffish
Two wolffish *(Anarhichas lupus)* found a home in the coral framework of one of the coral reefs in the Kosterfjord, Sweden destroyed by trawling.

Examples are chemolithoautotrophy and dark CO_2 fixation and primary production as well as symbiosis. However, the knowledge of driving processes underlying these interactions as well as their temporal and spatial variability is still very limited. The local fixation of carbon through biologically-driven or abiotic chemosynthesis and sequestration of carbon through alteration processes may be much greater than previously recognised.

The plumbing of the deep sub-surface ocean

Fluid, gas and solid transport are essential for life. For ecosystems to fully function, energy rich compounds must come in contact with oxidizing capacity. In addition to photosynthesis, another fascinating source of sustenance for deep life is primary degassing of magmas injected into the oceanic crust or ejected at the seafloor along the mid-ocean ridges. Magma degassing releases carbon along with other volatile species, such as the nutrients nitrogen and phosphorus that are delivered to the hydrothermal systems. The primary budget strongly varies as a function of the deep mantle source composition, the degree of melting experienced and the fractionation of the products in the crustal intrusions.

Defining the regional primary budget and its temporal variation will allow to recognise the primary control on hydrothermal cycles (from the onset to death of a hydrothermal system) and thus on pioneer life colonisation of the deep crustal rocks and its evolution from chemolithoautotrophy to heterotrophy.

Along the mid-ocean ridges, deep ecosystems are nested in primary magmatic rocks contributing to mineral degradation and forcing crystallisation of new phases[27]. Deep colonisation deeply affects the primary mass transfer from the geosphere to the hydrosphere, regulating not only carbon and nutrients but also other species involved in mineral dissolution and reprecipitation such as magnesium, calcium and iron. At the global scale, the effect of deep ecosystems may have a heavy impact on the whole element load to the hydrosphere.

We note that the entire volume of the ocean circulates through the seafloor-seawater interface every million years just through the action of animals ventilating their surface seafloor sediment habitats. Because the seafloor is host to up to two-thirds of the Earth's microbial population, understanding the controls on fluxes of energy and matter, and the processes that regulate them, is crucial for answering some of the big scientific questions, including the evolution and distribution of life and the operation of the carbon cycle.

If we are to understand the role of sub-seafloor ecosystems in biogeochemical cycles, we need to know about the connectivity of the deep-surface reservoirs to surface sediments and the ocean. What

Creatures hidden in the dark
Pink swimming sea cucumber, *Enypniastes*, seen at appx. 2500 m water depth in the Celebes Sea. The majority of all marine organisms live in the deep ocean, and a stunning variety has recently been catalogued in the Census of Marine Life project.

Ecosystem goods and services
Table illustrating how the different ecosystem habitats provide valuable goods and services for mankind. The spread of such benefits ranges from scientific, cultural and spiritual to a wide spectrum for society, e.g. food, fossil fuels or biotechnological products. So far, good knowledge does not exist in any of the settings.

HABITATS ECOSYSTEMS	Organic matter input/ chemosynthetic primary production	Nutrient cycling	Resilience	Habitat	Food, minerals, oil, gas	Micro-organisms	Climate regulation	Bio-remediation	Educational, scientific, spiritual
Continental shelves	some	little	little	some	some	no	no	little	little
Continental slopes	some	little	no	little	some	no	no	little	little
Abyssal plains	some	little	no	little	little	no	no	little	little
Submarine canyons	little	little	no	little	little	no	no	little	little
Deep-sea trenches	little	no	no	little	little	no	no	little	no
Seamounts	some	little	no	some	some	no	no	no	little
Carbonate mounds	little	little	no	little	no	no	no	no	no
Hydrothermal vents	some	no	no	some	some	some	no	no	some
Cold seeps	little	little	little	little	some	some	little	little	little
Mud volcanoes	little	little	no	little	little	some	little	no	little
Cold-water corals	some	no	little	some	some	no	no	no	some
Deep-sea sponge fields	little	no	no	little	no	no	no	no	little
Whale falls	some	little	little	little	little	little	no	no	no

good knowledge
some knowledge
little knowledge
no knowledge

controls fluid flow, fluid migration pathways and residence times of fluids in the sub-surface? How does fluid flow affect microbial activity and food web function?

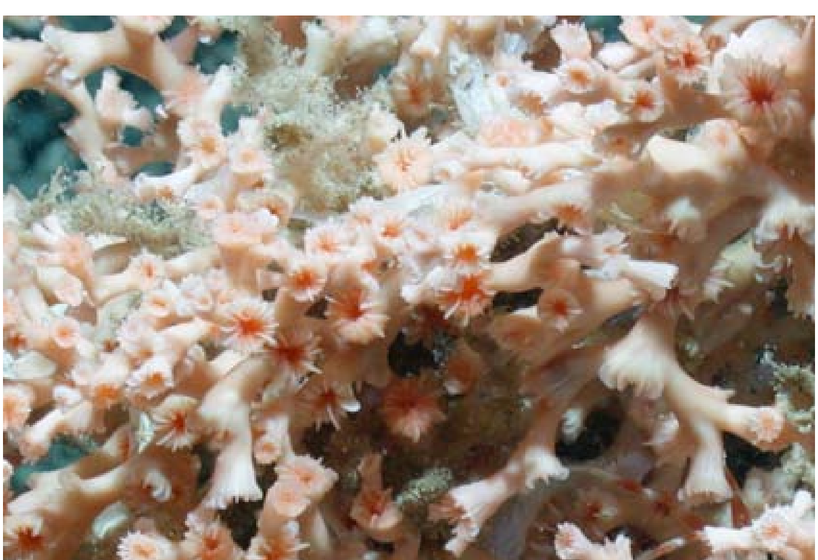
The ocean floor in a changing world: An archive of past oceans and climates

Changes in nutrient cycling and carbon fluxes have impacted and will continue to impact the deep seafloor and sub-seafloor ecosystem. Moreover, as eutrophication of our coastal and shelf seas becomes more widespread, we look to the sedimentary record and also to modern sub-oxic and anoxic environments to inform us about how the level of seawater oxygenation affects seafloor and sub-seafloor biota (and vice-versa), and how areas recover when oxygenated conditions return.

The seafloor acts as an active diagenetic filter for the deep archive of proxies used to deconvolute past ocean chemistry and climate states. That is, organisms at the surface sediment injest, modify and produce minerals and compounds that reach the seafloor. These compounds and minerals, or "proxies", are diagnostic not only for ecosystems, but for the water column itself. The determination, evaluation and calibration of "proxies" belongs to a large and rapidly evolving field that depends on the thorough understanding of seafloor ecosystems. The role of these proxies for reconstructions of past conditions in the oceans and the history of global climate has been elaborated in the "Climate" section.

Feedback between climate and the seafloor

The seafloor is not only a record of inputs and fluxes, but provides the contact to the vast and enormous reservoirs of reduced carbon and carbonate buffer capacity of the sub-seafloor. A clear and measurable feedback with implications for climate is



Corals at depth
Sclerectinian cold water coral, *Lophelia pertusa*, observed at Porcupine Seabight, off Ireland, in water depth of ~700 m. Unlike shallow-water coral in tropical areas, cold water species live in the dark and feed by filtering seawater for suspended nutrients.

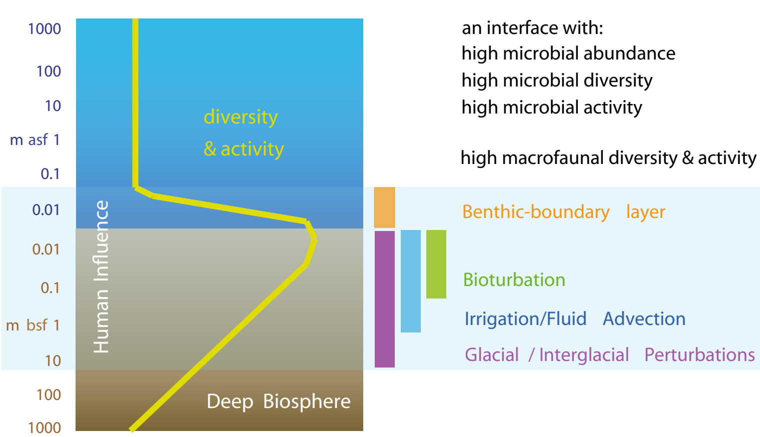
gas hydrate and methane reserve destabilisation. Another important issue is the role of sedimentary carbonates as a buffer against ocean acidification. Sedimentary $CaCO_3$ dissolution is key for global models addressing ocean acidification, but the effects of respiratory activity (microbial and faunal) on carbonate dissolution are very poorly parameterised. Alterations in the rates and extent of interaction between seafloor and potential climate-altering geochemical reservoirs such as sedimentary carbonates or methane hydrates are modulated by the surface and sub-seafloor faunal and microbial communities.

Understanding of the basic nutrient cycles in the water column and in surface sediments is rapidly evolving. Human alteration of the nutrient cycles in the ocean will continue to increase over the coming generations. Understanding how these changes translate into enhanced fluxes of food (i.e. energy) for ecosystems at the seafloor and will require long-term ecosystem observation.

Ecosystems as a resource

We close this discussion with the recognition that marine ecosystems have value and may provide certain "ecosystem services" for humans[32]. These values may be economic, societal, or even spiritually based. Ecosystem services range from supporting services for habitat and nutrient cycling to provisioning services (food, freshwater, fuel, wood, etc.), regulating services (climate, diseases, food, water quality, etc.) and cultural services (i.e. aesthetic, educational, recreational). Deep sea ecosystems are an important resource in that they provide a number of "ecosystem services", all providing several kinds of benefits to humankind.

Estimates of the value of ecosystem goods and services depend on a number



Biodiversity in the deep sea
Ecosystem diversity and activity as a function of depth above and below seafloor (asf, bsf). The maximum number of organisms is found along the sediment-water interface. Although the sub-seafloor abundance is decreasing exponentially with depth, the biomass associated with the deep biosphere has a strong impact on global C cycling.

Ecosystem diversity (left)
Subarctic sunflower stars, *Pycnopodia helianthoides*, at the seafloor in shallow waters off Knight Island in Prince William Sound, Alaska.

Predator and prey
The squat lobster *Munida rugosa* tries its' luck, getting this close to the small cephalopode *Rossia sp.*, which has small crustaceans as preferred food items.

of issues, any of them more or less subjective. Nevertheless, our valuation of an ecosystem's goods and services rests on a solid quantitative scientific understanding of that particular ecosystem and how it functions in the ocean as a whole. However, with the exception of a few well-documented deep sea ecosystems, the scientific understanding of known deep sea ecosystems is paltry at best (see above Table[32]).

Further remarks on the potential of marine life as a resource and the possible impacts of exploitation are made in the next sections.

Deep sea ecosystems: research frontiers and societal benefits

* Marine ecosystems have value and provide economic, societal, or even spiritually based "ecosystem services" for humans. The vast biological diversity of micro-organisms in the deep sea harbours enormous potential for biotechnological, pharmaceutical and industrial applications.
* Fluxes of energy and matter across the seafloor-seawater interface are 'ecosystem services', affecting, for example, how the deep sea environment reacts to human intervention. Here, long term seafloor observatories for prolonged time series measurements are needed.
* Identifying natural seafloor laboratories will allow rock sampling of million-years time series along seafloor spreading flow lines to recognise the evolution of the primary engine for long term control over climate evolution. There, sub-seafloor efforts such as coring, sub-sampling, and scientific drilling help to elucidate processes and rates affecting sub-seafloor ecosystems.
* Micro to nano-scale analyses of carbon speciation and *in situ* biological molecule characterisation and distribution in rock-hosted micro-ecosystems are needed. This should include the development of tools for imaging and analysing surface interaction and biofilms along microbial and mineral interfaces.
* The sedimentary record gives us insight about how seawater oxygenation affects seafloor and sub-seafloor biota and how areas – for example coastal regions degraded by eutrophication – recover when oxygenated conditions return.
* Better knowledge about the role of sub-seafloor ecosystems in biogeochemical cycles – and thus in the global carbon cycle – could lead to improvement of climate change prediction models.

Biotechnology as future resource
Many marine and deep sea organisms may provide crucial products for biotechnology and other emerging fields, and their study *in situ* will shed important insights concerning their sustainable exploitation and cultivation *in vitro*. Example shows a photobioreactor with *Physcomitrella patens.*

Responsible use of deep sea

Resources

Smart, sustainable and inclusive growth is an overarching issue that occupies decision makers around the world. Increasing consumption rates, human population growth and the rapid industrialisation of highly populated countries, such as, China, India and Brazil, most recently joined by South Africa, combined with an overall higher standard of living are resulting in the depletion of available resources at increasing rates. The deep sea and its sub-seafloor offer raw materials, fuels and biological resources, but a thorough system understanding is mandatory for their sustainable use.

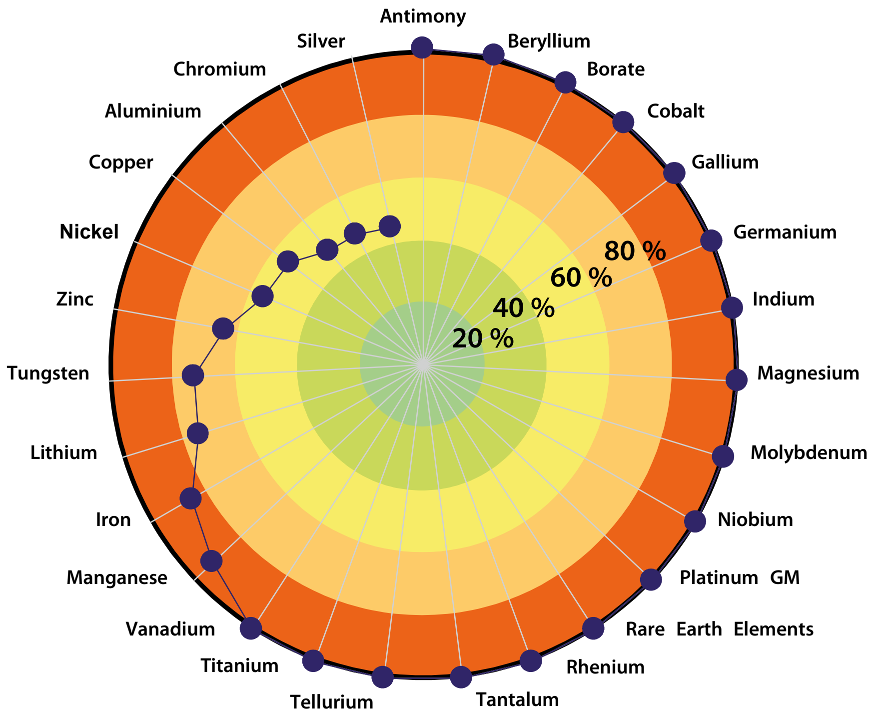
The expansion of the world population from 6 to 9 billion will intensify global competition for natural resources and put pressure on the environment. As known reserves of minerals are being exhausted, worries about access to raw materials, including base and strategic minerals, increase. The rise in the price of several important metals, for example copper, has prompted Germany and France, amongst others, to initiate concerted activities to ensure access to strategic minerals, and Europe has launched several initiatives over the last years related to raw materials. In fact, Europe depends on imports for many of these materials that it needs for construction and for its heavy and high-tech industries. Recycling, resource efficiency and the search for alternative materials are essential, but most specialists agree that this will not suffice and that there is a need to find new primary deposits. *Horizon 2020*[3] clearly lays out these stakes for Europe and stresses the need to seek global solutions. Without question, the ocean must be considered part of any worldwide solution and requires understanding the processes that create resources and the identification of the boundary conditions necessary to predict, limit and mitigate potentially negative consequences of their exploitation.

The deep sea and its sub-seafloor contain a vast reservoir of renewable and non-renewable physical and biological resources that are rapidly gaining in scientific as well as economic interest. Amongst these resources, we count mineral resources of three types: hydrothermal sulfides, polymetallic nodules and manganese crusts, but also gas hydrates that form under certain conditions along continental margins, and biological resources of the deep seafloor with biotechnological and pharmaceutical applications, amongst others. In some hydrothermal environments along mid-ocean ridges, there is a potential for the formation of natural hydrogen, which can be used as an energy vector. Finally, the use of the sub-seafloor for CO_2 storage is an issue that is debated and needs to be contemplated in the context of the use of the deep ocean and pressing climate change issues.

Mineral resources

In this section we explore in more detail the different resources of the deep ocean and the potential consequences of their exploitation. We have opted to exclude conventional hydrocarbons from our analysis because we consider that the industry is mature, despite the fact that it is evolving towards deeper and deeper exploitation of this energy resource. In as far as environmental issues relate to deep offshore oil and gas, we believe that these can be addressed within a more general framework of resource exploitation, including the use of biological resources and minerals.

Marine mining will become a reality in this century, if not this decade. The exploitation of copper and gold-rich hydrothermal sulfides in the waters of Papua New Guinea, the Solwara 1 project, will likely start soon at 1600 m water depth. A key



Precious deep-sea minerals
Import dependence of Europe in 2006, for selected critical raw materials, as published in a Report by the European Commission. Note that the value for Gallium is not reliable, due to significant changes for different years.

issue is the development of legislation to regulate prospecting, exploration and exploitation activities and their environmental impacts. Within the Exclusive Economic Zones (EEZ) of coastal states, more or less well-developed national mining codes exist, but they are often devoid of constraining environmental considerations. For what is referred to as the Area, the international part of the seabed, the International Seabed Authority (ISA) developed the regulation for exploration of polymetallic nodules in the late nineties. Subsequently, in 2010, ISA adopted the mining code for the prospecting and exploration of hydrothermal sulfides. Not surprisingly, two states immediately deposited applications for exploration contracts with the Authority: China and Russia for areas located along the southwest Indian Ridge and the central Mid-Atlantic Ridge, respectively. These applications were approved by the ISA Council following positive recommendations made by the Legal and Technical Commission (LTC) during the 17th session in July 2011. Other states, such as France, Germany, Brazil and Korea are in the starting blocks to explore in the Area.

While the ISA has been proactive in developing rules, regulations, and procedures that incorporate standards for the protection and preservation of the marine environment during exploration for and extraction of mineral resources, it is not specifically charged with conservation or management processes. Under the present regulatory regime of the Area, environmental protection decisions are more driven by mining interests than by global community interests in conservation. At a time when the international community is raising awareness on the issues of deep sea mining and its impact on the environment, Europe has to take the lead on some of the large outstanding scientific questions.

Other resources

In addition to minerals, hydrogen production is an important aspect of hydrothermal systems hosted in ultramafic rocks. To date it is not known whether there is enough to be exploited as an alterative energy source nor how exploitation would influence fluid flow paths and microbial activity. In addition, there is much to be learned about the importance of serpentinisation processes for natural CO_2 sequestration from seawater and the effect of CO_2 injection in stimulating microbial growth. Much can be learned from natural hydrothermal systems about how certain elements are cycled biologically. In the future, there will be a need to combine CO_2 sequestration experiments[34] with geomicrobiological experiments (see “Challenges” below).

Gas hydrates are storing significant amounts of methane in marine sediments along the continental margins of Europe. Composed of methane trapped in a cage of water molecules, these hydrates are only stable under certain high pressure and low temperature conditions. Climate change may induce significant modifications to the regions where hydrate deposits may start to melt, with potentially significant consequences. Approaches such as government-funded project SUGAR (Submarine Gas Hydrate Reservoirs) in Germany aim to address these issues and contemplate a potential for CO_2 storage (e.g. as CO_2-hydrate) in these specific formations while recovering the methane. One main criterion is environmental safety and sustainability (see “Geohazards”).

With respect to biological resources, there is a vast potential of marine genetic resources, however, a lack of clear guidelines as to the use and abuse of these materials exists. What we need is a better understanding of the links between the diversity of deep sea communities and the availability of chemical substrates and energy underlying the functioning of these ecosystems and their response to disturbance and stresses. Better constraints are required on the diversity of carbon fixation pathways, metabolic pathways, and feedbacks of the biological communities on the export of material to the water column. Experimental strategies and tools to address these questions on the seafloor are also needed. These questions are not farfetched, as practical applications of marine biological resources are envisaged in many different fields relevant to society.

Over the last decades, scientific exploration has led to the discovery of many types of ecosystems, of which many present a significant potential for future resources, both physical and biological. However, modern mapping exists over only a very small portion of the seafloor, and the sampling of the seafloor and subsurface is very sparse, despite the enormous efforts undertaken within the framework of international scientific drilling programs. Hence, much about the composition and global distribution of these resources on the seafloor and within the subsurface, their quantitative importance for global chemical cycles and biological activity, and the potential impacts of exploitation on ocean chemistry and ecosystems is incompletely understood, to say the least.

Renewable and non-renewable resources

Europe, with a combined EEZ of member states larger than 24 million km², has an important role to play in defining strategies for future resource utilisation, starting with fundamental and applied scientific research to answer the many questions that surround the use of both renewable and non-renewable resources:

- What is the global distribution of deep sea resources, and their potential for exploitation?
- How do we assess the potential impacts of exploitation of deep sea resources for the economy, for the environment and for society?
- How can Europe contribute to responsible use of non-renewable deep sea resources, in particular mineral resources, and to responsible mining in the international area?
- How can biological resources of the deep sea and sub-seafloor be exploited in a sustainable fashion, while protecting the biodiversity of the extremophilic communities?

Beyond locating and assessing the potential of the various resources, the most important issue in terms of marine research related to resources and priorities in this time of rapid change, is the understanding of the impact of seafloor exploitation on the immediate environment and the subsequent consequences on the larger ocean system. In fact, the response of the ecosystem to disturbances, whether they be natural or anthropogenic, has been observed at only very few sites. The dynamics of vent communities and their eco-geochemical drivers still need to be determined for most habitats. We need to better understand the distribution, composition and connectivity of the deep seafloor communities living under extreme conditions, in order to comprehend their capacity to recover after disturbances. The impact, for example, of element remobilisation (e.g. suphur, heavy metals) is completely unknown. Controls on chemosynthetic carbon fixation and growth rates are mostly unidentified. It is hence important to get a better understanding of the interactions that take place at the seafloor and in the sub-seafloor, between seawater, the lithosphere and the biosphere.

A variety of mineral resources
Three types of mineral resources of the deep sea. From left to right: A polymetallic nodule, an example of manganese crust and a chimney with hydrothermal sulfides.

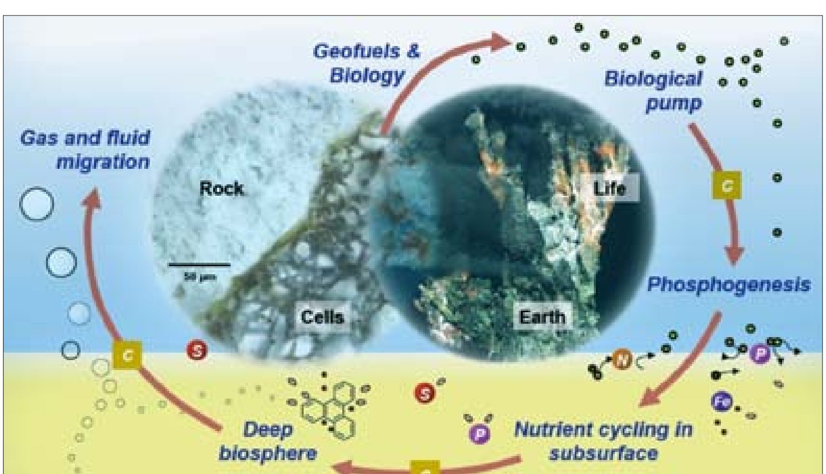
The chemical and isotopic composition of seawater reflects a dynamic balance between the supply and removal of elements. These fluxes are dominated by fluvial inputs, hydrothermal exchange, biological exchange, and sedimentary removal. Their magnitudes depend on global geologic processes, such as seafloor spreading and mountain building, climate conditions, and biological activity. Since the discovery of hydrothermal vents on the seafloor, it has been recognised that seawater-derived fluids circulate through the oceanic crust and, thus, fluids sampled at mid-ocean ridges and along the ridge flanks provide records of past seawater-rock exchanges. Along continental margins cold-water fluid vent systems have been discovered with associated unique animal and bacterial communities[31]. Seamounts and arc volcanoes are other environments of interest.

Geotectonic settings along the ridges are highly diverse and have extremely variable substrates, with basalt dominating at fast and intermediate-spreading ridge environments and ultramafic and gabbroic rocks dominating at slow-spreading ridges. To these, we can add andesitic and felsic rocks and magmas rich in volatiles characteristic of subduction zones. Continual discoveries of hydrothermal systems hosted in diverse substrates have highlighted the importance of hydrothermal energy and chemical element transfer from the lithosphere to the biosphere. Initially, heat and mass transfer were considered to primarily occur at discrete, isolated, hydrothermally active hotspots around the global ridge system and to have a minor impact on the global ocean carbon cycles. However, recent results suggest that both the local fixation of carbon through chemosynthesis and sequestration of carbon through alteration processes may be much greater than previously recognised. Fluid flow occurs – and has taken place for tens of millions of years – not only at mid-ocean ridges where flow rates and temperatures are high, but also through the aging ridge flanks and in other settings far from the ridge system[31].

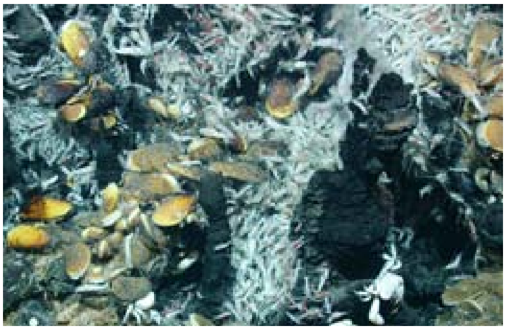
The fluids at ridge flanks transport massive amounts of heat from the cooling oceanic lithosphere and facilitate the exchange of chemicals between the ocean and the basaltic basement. These exchanges affect the composition of seawater, the oceanic lithosphere itself and, through subduction, the mantle and arc magmas. Material that eventually is recycled back into the deeper mantle carries with it the imprints of Earth's exterior environment. Thus, long-lived convection and fluid-rock interactions in ridge flank environments and in off-axis, serpentinite-hosted hydrothermal systems have the potential to sustain a diverse deep biosphere and sequester carbon from seawater over extensive areas of the oceanic lithosphere and over long geological time scales.

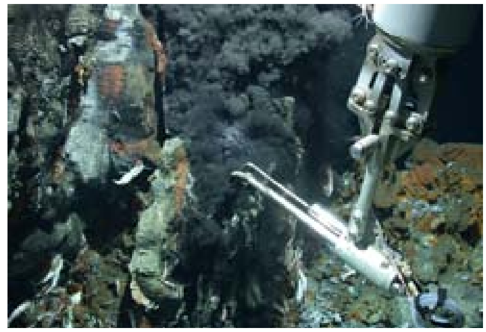
Fluid cycling

Hydrothermal input of iron affects phytoplankton growth in the ocean and influences the global carbon pump. Investigations of iron speciation in hydrothermal plumes have revealed that a fraction of dissolved iron was stabilised by surface complexation with organic particles. Hydrothermal iron and copper have recently been shown to be also complicated by dissolved organic matter, resulting in long residence times and greater dispersal distances in the oceans than previously thought possible. Likewise, nanoparticles of iron sulfide may be dispersed over long distances in the oceans. Another new insight is that atmospheric forcing may affect deep sea



Geosphere-biosphere interaction
Schematic representation of the interactions between seawater, rocks and life in the deep sea and sub-seafloor. Many of the processes shown represent important elements in chemical nutrient cycles and bear potential for societal use.





Extreme lifeforms at hot springs
Hydrothermal sulfide precipitates along the Mid-Atlantic Ridge (5°S) show abundant and diverse ecosystems (left) despite temperature measurements exceeding 400°C (right). Apart from very local studies, not much is known about the resources and ecosystems along active vs. inactive ridge segments at spreading centres.

currents and provide a mechanism for spreading these metals in the deep sea[36]. Although their implications on a global scale remain poorly understood, these recent discoveries highlight the importance of hydrothermal exchange between the lithosphere and the oceans in global geochemical and biogeochemical cycles.

Deep sea mining is both a technological challenge and an environmental concern. However, as far as technological development is concerned, deep offshore petroleum exploitation has already taken up the challenge and demonstrated its feasibility. Only a few years ago, the threshold of 2000 m water depth seemed difficult to overcome, but today technological advances allow routine wells at 3000 m water depth, or more. However, dealing with environmental consequences of an accident at such depths is very problematic, as demonstrated by the recent Deep Water Horizon blowout in the Gulf of Mexico. Europe can play a significant role in the comprehension of the processes, the assessment of risks, and the development of appropriate regulations. Another example concerns the diamond mining offshore Namibia, where technological advances allow for deeper and deeper exploitation and at significant distances from the coast. It seems likely that many of the technologies currently under development will be adapted and/or modified to allow for deep sea mineral exploitation. If Europe is not present, for example in the Area, others will be there instead.

Towards a European research strategy for responsible use

Strategies to address the open questions identified above involve monitoring and sampling both on and below the seafloor. Characterisation of fluids venting on the seabed and the associated biological communities provides insights into the processes occurring deep below the seafloor. Direct drilling projects in different geodynamic settings will be required and will need to be based on a thorough initial investigation of the systems using more conventional approaches and multidisciplinary oceanographic investigations. Interdisciplinary integrated studies, modelling and experimental approaches are still challenges that will need to be met in the coming decade of mid-ocean ridge research.

An important aspect of future research should concentrate on alteration processes and their effects on microbial activity on the seafloor and in the subsurface, including long-term monitoring and sampling in different geodynamic settings. Future ocean drilling and sampling of the oceanic lithosphere of a variety of ages and with different architectures are essential. This is needed to better quantify the depth distribution and extent of alteration of the lithosphere with time and to help characterise the heat and mass exchange from spreading centers where fluid flow is vigorous, extending to older oceanic lithosphere where fluid flow and mass transfer become slow.

Future advances in our knowledge of lithosphere-biosphere processes can only be made by sub-seafloor sampling, by quantifying the nature and rates of *in situ* microbiological activity, and by determining permeability structure and chemical transport properties. It will be necessary to have opportunities for fluid sampling and active monitoring, including single and multiple borehole experiments. Current long-term observations of sub-seafloor hydro-geologic systems, as part of both monitoring and active experimentation, are transforming our view of fluid-sediment-rock-microbial interactions. Continued development of drilling, sampling, and sensor technology will help with collection of data and materials from increasingly challenging environments, including those with high temperatures, extreme pH, and high strain rates.

Impact assessment

Long-term *in situ* observation laboratories at the seafloor, coupled with quantitative sampling strategies carried out by Remotely Operated Vehicles (ROV) will help to start understanding lithosphere-biosphere interactions and how fluid flow influences the faunal communities. Knowing the temporal and spatial dynamics of hydrothermal fluids is crucial to understanding the distribution and also the diversity of fauna, since the fauna is directly exposed to stress at hydrothermal vents due to the physical and chemical properties of fluids but is also dependent on the

Studying the „Early Earth"
Lost City segment oft he Mid-Atlantic spreading ridge, an area where white, massive carbonate precipitates form in conjunction with basaltic crust. Lost City is believed to represent an equivalent to early Earth processes at a spreading centre.

chemical energy that is fuelling microbial life, the basis of the food chain at deep sea hydrothermal vents.

The length scale of lithospheric variability at slow spreading ridges, the implications for fluid flow paths and fluxes, and the life these systems sustain are poorly constrained. Previous expeditions and drilling in the Atlantic and Indian Oceans[37] have concentrated on a few, relatively deep holes, thereby providing minimal information about the extent or scale of lateral heterogeneity. These studies have nevertheless highlighted the complex vertical heterogeneity in oceanic lithosphere composition, deformation, and hydrothermal alteration. European efforts have made major contributions to understanding these variations at slow- and ultra-slow spreading ridges, and this wide knowledge base will provide an invaluable basis for future studies of the Mid-Atlantic Ridge and the Arctic Ridge system.

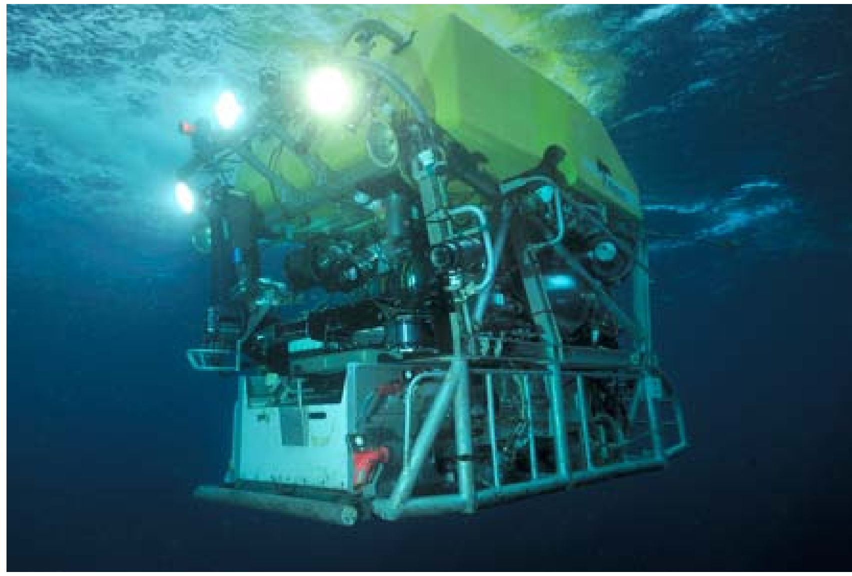
Better knowledge is needed to understand microbe-metal interactions and how they influence or enhance metal uptake. In particular, we do not yet understand the role of microbes on metal uptake or concentration, nor do we know how the ecology or microbial communities are influenced by perturbations – whether natural or through exploitation of deep sea resources. Studies of hydrothermal processes and microbial activity in the deep subsurface of ridge environments also have potential for advances in biotechnical applications.

In order to assess the impacts of deep sea resource exploitation, it is crucial to study the sites before perturbations have occurred. It is entirely unknown whether the response of fauna may be different depending on the geographic area and geological constraints. It is also not known what impact resource exploration and exploitation will have on biodiversity or the local geochemical properties of the systems. Unique life has developed in one of the most extreme environments on Earth. Animals and microbes have to cope with stressors such as high temperatures, low pH, and toxic chemical compounds, and their genes and proteins have to function under these circumstances. Unraveling these processes can have crucial impact on biotechnological or medical applications in the future and the destruction of entire species before they were even discovered can be a great loss for society.

Europe's responsibility

In conclusion, Europe should be able to use the pressure that constitutes access to natural resources of the deep sea as an

Methane hydrate as hydrocarbon resource?
Massive gas hydrate chips filling fractures and voids in clay mineral-rich mud. Such methane hydrates cement the muds and hence stabilise continental slopes. If dissociated, water and methane gas is released and the slope sediment may fail. Given their abundance, gas hydrates may be viewed as major hydrocarbon resource.



Exploring and working at depth
Deep water ROV (Remotely Operated Vehicle) VICTOR, operated by IFREMER France, and similar vehicles represent excellent tools to study deep sea resources and the impact of deep-sea mining.

advantage for the creation of knowledge about the functioning of deep sea ecosystems and extremophile communities. Benefits that can be expected from enhanced coordination of field and laboratory studies within Europe include facilitating access to ships and submersibles for exploration, observation (monitoring) and sampling, including drilling, encouraging synergies in the development of new mission-specific technologies and coordinating efforts for their design and implementation, developing experimental platforms to elucidate driving and active processes and rates, and promoting the development of (bio)geochemical models. Deep sea research would also benefit greatly by expanding the EuroFleets concept and providing a mechanism to share ship time to minimise transit time. New developments will also require new sources of funding, such as taking part in the Deep Carbon Observatory[38].

An aspect of European collaboration with respect to the responsible exploitation of deep sea resources is that we will need to advance quickly to better understand the impact of exploitation on the surrounding deep sea environment and the effect that these direct impacts can potentially have on more global cycles.

Resources of the deep sea and sub-seafloor: consequences for research, policymaking and society

* Coordination of member state research in relation to deep sea resources and assessment of environmental impacts of their potential exploitation is to be realised at a European level.
* The development of a European deep sea exploration strategy for physical and biological resources in national and international waters is vital in order to diversify Europe's access to raw materials and remain at the forefront of biological prospecting.
* Mid-ocean ridge systems are only now in the process of being studied in some detail, and given their diversity in activity, life forms and processes, it is vital to foster research and optimise protection.
* Infrastructure (e.g. ships) and technology for exploration and evaluation of deep sea and sub-seafloor resources (biological, chemical, geological, geophysical, drilling, logging) is mandatory and can benefit from an overarching European approach (e.g. ESFRI[39]).
* Active long-term experiments as well as observatories provide the only means to reliably characterise the geological processes and ecosystem functioning and how mining affects them[40].
* Europe is a world leader in seabed drilling tools (down to ~200 m sub-seafloor), and enhancement of this market and associated seagoing technologies will ensure independent access to sub-seafloor research and resources as well as creating jobs and economic growth.

Implementation

of deep sea research technology

Although substantial progress has been made during the last decades, in particular due to industry's growing interest in deep offshore activities, investigating the deep sea and sub-seafloor remains a technological challenge. Implementation of the DS^{3}F White Paper will therefore require not only a coordinated access to existing infrastructure at the European level, but also the development of innovative technologies and new approaches.

Implementing state-of-the-art deep sea research requires complex instrumentation and will always remain expensive. However, science and industry both benefit from technological collaboration. Concentrating such efforts in a few geographical areas of particular interest to Europe will enhance efficiency. Furthermore, there is a need for technological advancement and innovation in a number of areas.

Research vessels and associated facilities

Access to research vessels is absolutely crucial for investigating the deep sea and sub-seafloor. Nearly all European countries own and operate research vessels capable of working in the deep sea environment. They are equipped with a wide range of tools and facilities varying from standard sampling and seafloor imaging tools, such as swath bathymetry, side scan sonar, 2D seismics, magnetics, gravity, for example, to sophisticated equipment, such as long coring and drilling systems, external vehicles, 3D seismics equipment, and deployable seabed observatories. The use of facilities is mostly inter-exchangeable among the largest and most modern European research vessels, which meet technical standards in terms of Dynamic Positioning, A-frame size, strength and power, or deck space.

The European effort to facilitate access to research vessels of the European fleet focuses on two initiatives. The Offshore Facility Exchange Group[41] fosters and supervises exchange of ship time to optimise the use of the vessels and associated facilities among the participating countries (France, Germany, Netherlands, Norway, Spain and UK). The EC-funded programme EUROFLEETS[42] provides ship-time and associated tools to European researchers, in particular to those with restricted access to national research vessels. This scheme has proven to be efficient but limited in terms of number of days offered to scientists with respect to demand. EUROFLEETS 2 has been proposed to follow up with improvements to facilitate collaborative research in the deep sea. This could encompass the promotion and organisation of a coordinated approach to offer access to ice-breaker facilities, if Europe wants to remain at the forefront of scientifically, politically and economically important Arctic research.

The success of any research project involving sub-seafloor sampling at decametric to kilometric scale, let alone the deployment of seafloor and sub-seafloor observatories, depends largely on the quality of the seafloor and sub-seafloor imaging. Facilities for acquisition and processing of industry-standard deep penetration digital 2D long offset seismics or high-resolution single-channel 3D seismics are relatively simple and affordable, however, they are scarce in academia and should be made available at a European level. Multi-channel 3D seismics is currently not available to European academic institutions, however, its use is essential to understanding the sub-seafloor structure with unprecedented detail. Using seismic cubes previously collected by exploration companies would be one solution out of the dilemma, and co-operation with industry and coordination of funding at the international level will be mandatory to achieve this objective.

The variety and efficiency of deep sea vehicles operated from research vessels have expanded during the last twenty years, following in particular the industry progress. Manned submersibles offer the largest variety of scientific observation in the deep sea. France, the USA, Japan, and now also China operate manned submersibles in deep waters (beyond 2000 m). However, ROVs are now widely used for near bottom surveys, manipulation, i.e. rock and fluid sampling, as well as installation of complex instrumentation on the deep seafloor. France, the UK, Germany, Belgium, Norway and, more recently, Italy operate deep sea ROVs that have proved particularly efficient for studying hydrothermal fields or cold seeps. A fleet of Autonomous Underwater Vehicles (AUVs) is now operated from research vessels. Cheaper and easier to operate, they have now become absolutely essential for high-resolution seabed surveys but seem otherwise restricted in payload.

A large variety of sampling devices are commonly deployed from research vessels. Europe has been at the forefront in the development of two important devices. The "Calypso Corer" developed and operated by the French Polar Institute (IPEV) and capable of collecting long cores (up to 70 m) in sediment formations, is the key tool to address recent environmental changes. Remotely operated seabed drills, deployed on the seafloor from conventional research vessels have been used recently as a relatively cheap alternative to the employment of drilling vessels when drilling targets are shallow (within 100 m at present). The British Geological Survey RockDrill and the MARUM MeBo[43] have pioneered in the development of seabed drills for scientific purposes, whose use is rapidly expanding in research projects worldwide. The technological development needs to aim at the extension of water depth range, penetration, and payload.

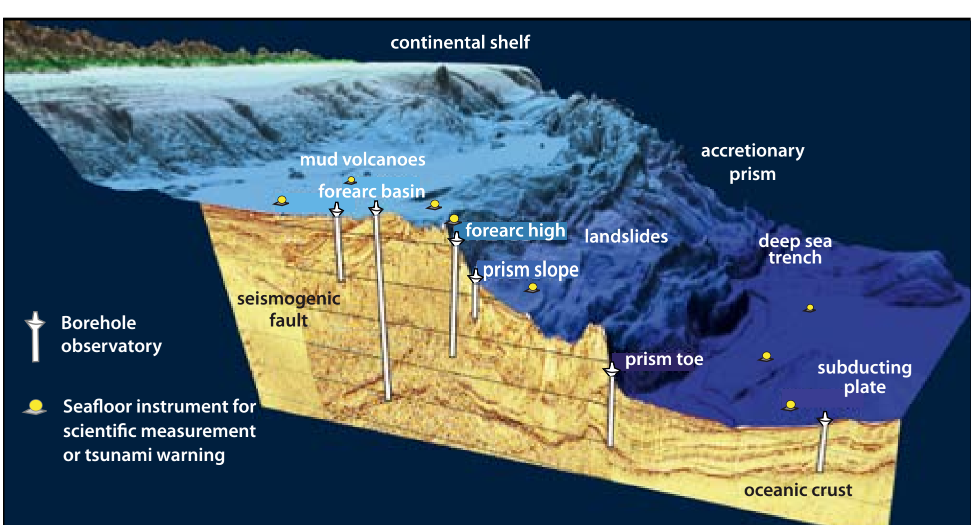
Innovation as well as growth of such emerging technological fields is vital, and science collaborating with industry on improved deep sea drills, vehicles and associated sensors should be promoted and facilitated (as sketched in *Horizon 2020*[3]).

Seafloor observatories

The processes that occur in the oceans over time have a direct impact on human societies, so that it is crucial to improve our understanding of their breadth. Sustained and integrated observations are required that appreciate the interconnectedness of atmospheric, surface ocean, biological pump, deep sea, and solid-Earth dynamics and that address:

- Natural and anthropogenic change,
- Interactions between ecosystem services, biodiversity, biogeochemistry, physics, and climate,
- Impacts of exploration and extraction of energy, minerals, and living resources,
- Geohazard early warning capability for earthquakes, tsunamis, gas-hydrate release, and slope instability and failure.

In situ observations, ideally over time, are essential to the creation and the revision of experimental and model frameworks. Marine time-series data constitute a minor



Monitoring subduction zone earthquakes
3D view of the Nankai Trough sub-subduction zone including a large accretionary complex with instrumented boreholes and seafloor observatory infrastructure. This comprehensive, multidisciplinerary project is an example how complex phenomena such as earthquake nucleation and hazard mitigation can be tackled by deep sea science.

Linking the seafloor to satellites
IFREMER surface buoy prior to deployment in the Ligurian Sea, western Mediterranean. The buoy is moored at the seafloor and communicates with seafloor instruments via acoustic modems.

fraction of existing data sets available for studying the climatic influences with very little data available from the deep sea[44]. Measurements by research ships provide valuable information, but are limited to favourable weather conditions and are too infrequent to characterise most processes, often missing important extreme and/or less frequent environmental or ecological variation.

The need for long-term time series of key measurements on or below the seafloor to monitor active processes has led the international community to promote the installation of long-term multidisciplinary seafloor observatories providing continuous data sets from a variety of fields necessary to build a comprehensive picture of the earth-ocean system (including geosciences, physical oceanography, biogeochemistry, and marine ecology).

Depending on the application, seafloor observatories can either be attached to a cable, which provides power and enables data transfer, or they can operate as independent benthic and moored instruments. Data, however, can also be transmitted through acoustic networks that are connected to a satellite-linked buoy. Mobile systems, such as benthic rovers and autonomous underwater vehicles (AUVs) can also be used to expand the spatial extent of a node. Cabled infrastructures provide important benefits, including real-time data transfer and interaction with observatory activity as well as a rapid geohazard early warning system[44].

Real-time deep sea access

Initiatives have been launched at the international level, with the cabled observatory Neptune (NorthEast Pacific Time-Series Undersea Networked Experiments) in Canada on the Juan de Fuca plate, OOI (Ocean Observatories Initiative) in the US, DONET (Dense Oceanfloor Network System for Earthquake and Tsunamis) in Japan, IMOS (Integrated Marine Observing System) in Australia, MACHO (Marine Cabled Hosted Observatory) in Taiwan, and, very recently, ECSSOS (Seafloor Observation System in the East China Sea) in China.

In Europe, this identified need led to the setup of a European Multidisciplinary Seafloor Observatory (EMSO)[45]. EMSO is a geographically distributed research infrastructure of ESFRI, constituted by a network of fixed-point deep sea observatories (nodes) around the European continental margin from the Arctic to the Mediterranean through the Atlantic. EMSO nodes are addressed to Marine Ecosystems, Climate Change and Geohazards long-term monitoring and to interdisciplinary studies. It will ensure the technological and scientific framework for the investigation of the environmental processes related to the interaction between the geosphere, biosphere, and hydrosphere, either via a cabled backbone providing internet connection to the shore or acoustic stand-alone stations transmitting data to relay buoys which are able to provide a satellite link to the shore.

EMSO builds on ESONET (European Seafloor Observatory Network), which was funded as Coordination Action and later as Network of Excellence by the European Commission. The Preparatory Phase of EMSO, funded under the umbrella of the Framework Programme 7-Capacities, is aiming at creating a European Research Infrastructure Consortium (ERIC) as the legal organisation with full members from Italy, France, Germany, Greece, Romania, Spain, Norway and UK. EMSO infrastructure will be essential reference and support for any type of research and activity in the deep sea and clearly attests that progress in marine technology (sensor development, data acquisition and transmission) requires a wide collaboration with the industry involved.

Examples of emerging needs for observatories include: (i) continuous high-standard quality monitoring as a fundamental tool of reference and control for scientific, industrial and commercial activities of exploration and extraction of resources, (ii) reliable monitoring of earthquake precursors, tsunamis, or gas emissions in gas hydrate areas to provide efficient early warning for society, and (iii) the development of specific tools for marine observatories based on niches European technology companies have occupied (both shallow-water test beds and deep sea sites). Such an approach is in line with EU Research & Innovation policies for a pan-European observation system for geosciences[45]

Ocean drilling

Ocean drilling remains the only way of directly accessing the sub-seafloor to substantial depths (greater than 100m). Besides the study of sediment and rock samples, downhole logging of boreholes provides information on *in situ* conditions. In addition, boreholes can be used to deploy long-term observatories for monitoring seismicity, fluid flow, thermal state, stress state, and strain. Since the late sixties, scientific ocean drilling has been traditionally accomplished within the frame of international programmes. In the current phase of IODP (2003-2013), in order to play a more significant role within the program, European partners have decided to form the consortium ECORD, an initiative supported by the European Commission with the ERA-Net ECORDnet[6]. By pooling the funds from its member countries, ECORD has been able to become an operator within IODP and implement expeditions in pack ice-covered areas (ACEX expedition in the Arctic[16]) or in extremely shallow water (drowned coral reefs of Tahiti and the Great Barrier Reef, shallow

Samples from kilometres the seafloor
The derrick of DV Chikyu, which measures more than 100 m above sealevel and hosts several kilometers of drill pipe for research in IODP.
The „doghouse“ of DV Chikyu from which ocean engineers control drilling operations on the rigfloor.

Core curation
Some of the ~146 km of core material stored at the Bremen Core Repository, one of the three centres for sustainable curation of IODP materials worldwide.

Archiving data for future genarations
An informatics expert during maintenance work of the PANGAEA website, an open access portal for marine scientific data as part of WDC (World Data Centre) MARE.

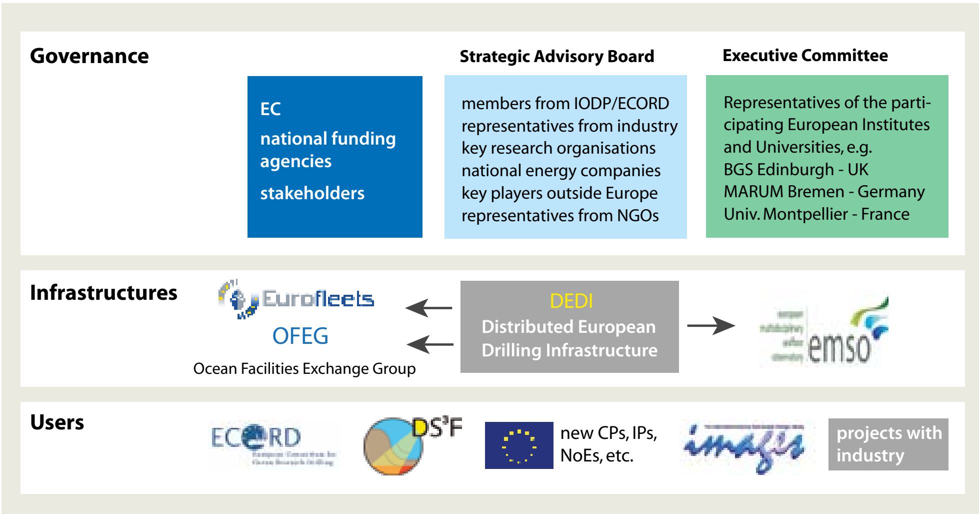
shelves in the Atlantic and Baltic Seas). This was made possible by developing the concept of "mission specific platforms", platforms of opportunity contracted from the commercial sector. MSPs complement the two other vessels operated within IODP. The JOIDES Resolution, a standard drilling vessel funded by the US, operates in all oceans and is particularly fitted for palaeoclimate and deep biosphere research. With its riser system, a technology commonly used in the oil industry, the Chikyu, funded by Japan, opens access to drilling deeper (down to 6-7 km) and in unstable formations.

Like *Horizon 2020*[3], the new phase of ocean drilling will start in 2014, and in the new (anticipated) framework ECORD will be more independent in planning and more flexible in scheduling. To implement more expeditions, ECORD will also seek additional funding on a project basis from an assortment of funding sources, including governments, foundations and industry. An ECORD expert panel will be a key actor in developing a dialogue on projects of mutual interest with industry and other entities, for example in the Arctic. It is also envisioned that the European Commission will co-fund drilling operations for specific projects within *Horizon 2020*. ECORD has also decided to expand the concept of mission-specific platforms (MSP) beyond drilling from a traditional drilling platform. Seabed drills and the Calypso Corer are now being considered as cheaper alternatives for projects that require samples from relatively shallow depths, which would make those devices – all European engineering developments – better recognised globally.

To encompass most oceanic environments and address DS^{3}F scientific challenges, a continued access to JOIDES Resolution and Chikyu remains essential. Moreover, the intellectual benefits of scientists participating in an international programme of this scope and of interacting with colleagues from all around the world is invaluable.

Data management and analysis

Massive amounts of high quality data exist, but are often difficult to access. The successive drilling programmes have developed a remarkable policy for cores and data archiving. All cores from 50+ years of drilling are stored in three core repositories, with one located in Europe at MARUM (Bremen, Germany), and are accessible upon request. All data acquired are in online open-access. This unique example of sustainability was made possible through a dedicated systematic funding scheme and preserves valuable core material with records of climate variability, ecosystem change and geohazard events. It should be considered as model. Although most international and national funding agencies require databank deposition, the incentives to do so are poor and not very rewarding (i.e. data upload is time-consuming and data reports are usually not citable in a citation index). At the same time, deep sea data collection is expensive and every effort has to be made to extract the most



The need for a research infrastructure
Pert diagram of the envisaged „Distributed European Drilling Infrastructure", which is already partly realised and presents a versatile element in European deep sea research.

information out of the existing data. To make data bases such as WDC MARE[46] even more powerful, incentives for upload and quality control should be developed, and programmes for meta-analysis are needed. This will also enable better representation of seafloor and sub-seafloor ecosystem processes in Earth System Models of Intermediate Complexity (EMICS).

The concept of "Distributed European Drilling Infrastructure" for research

Sub-seafloor sampling and instrumentation will be crucial to addressing a wide range of the scientific targets of the deep sea frontier. Although access to drilling should be maintained with a continued membership in IODP (realised via comingled funds from national funding agencies in Europe), the community has identified a number of technological improvements and developments necessary to address the scientific goals, such as:

- Improvement of coring techniques to increase recovery rate and core quality in difficult formations and to collect clean, uncontaminated samples for deep biosphere studies,
- Lighter and safer techniques to maintain *in situ* (pressure) conditions from the sub-seafloor to the laboratory, essential for gas hydrates and deep biosphere studies,
- Ability to drill in high temperature conditions (>300°C) to mine geothermal energy,
- Enhancement of seabed drill performance (extend drilling depth, implement *in situ* measurements and logging and fluid sampling, install observatories).

DS³F emphasises that Europe has a strong leadership in some of these necessary technologies both in the private enterprise and academic sectors. However, expertise is disseminated in various universities and institutes as well as small and medium enterprises. To make significant progress, strong transnational collaboration between research and operational groups across Europe will be beneficial. This is underway, given that ECORD science operations are successfully managed by the British Geological Survey (BGS) for platform contracting and operation as well as by MARUM Bremen (Germany) to oversee the shore-based core analyses as well as curation and storage of 146 km of sub-seafloor records. EPC (European Petrophysics Consortium), a consortium composed of the University of Leicester (UK), Geoscience Montpellier (France) and the University of Aachen (Germany), is responsible for downhole and petrophysics measurements and has developed logging tools. BGS and MARUM Bremen are also leaders for scientific seabed drills. With its experience in drilling for geothermal energy, ISOR (Iceland) has a strong expertise in drilling at high temperatures. GFZ Potsdam (Germany) hosts the ICDP (International Continental Scientific Drilling Program) and has therefore strong experience in continental and lake drilling.

To take advantage of the existing expertise all over Europe, it is recommended to set up a "Distributed European Drilling Infrastructure" to better serve the technological needs of the science community. This recommendation is also supported by ECORD[6] and first contacts among the major possible actors have already started to ensure that this initiative will be recognised by ESFRI[39] and supported by the European Commission[46]. Indeed, such an infrastructure will facilitate:

- Stronger collaboration between research and operational groups across Europe,
- Sharing of knowledge and experience in order to facilitate the necessary improvement of existing technologies,
- Development of joint projects and joint approaches to attract funding,
- Provision of capabilities for sustainable use of samples and data, following the excellent model of the successive ocean drilling programs that is based on open access,

- Training for younger generations (see also "Challenges"),
- Access to European facilities and assistance in pre-site survey data acquisition and processing, and
- Cooperation with other programmes as well as with international partners.

This distributed infrastructure will be open to all scientists in Europe, either via organised programmes (such as ECORD/IODP and IMAGES[8]) or as a support to projects developed by individual principal investigators. Sharing expertise with the ICDP is crucial, because ocean and continental drilling operate common tools and have the same data management and core curation issues.

The distributed infrastructure approach will make the interaction with other existing infrastructures easier. This will be key for the relationship with EMSO[45], which is currently lacking direct access to the subseafloor.

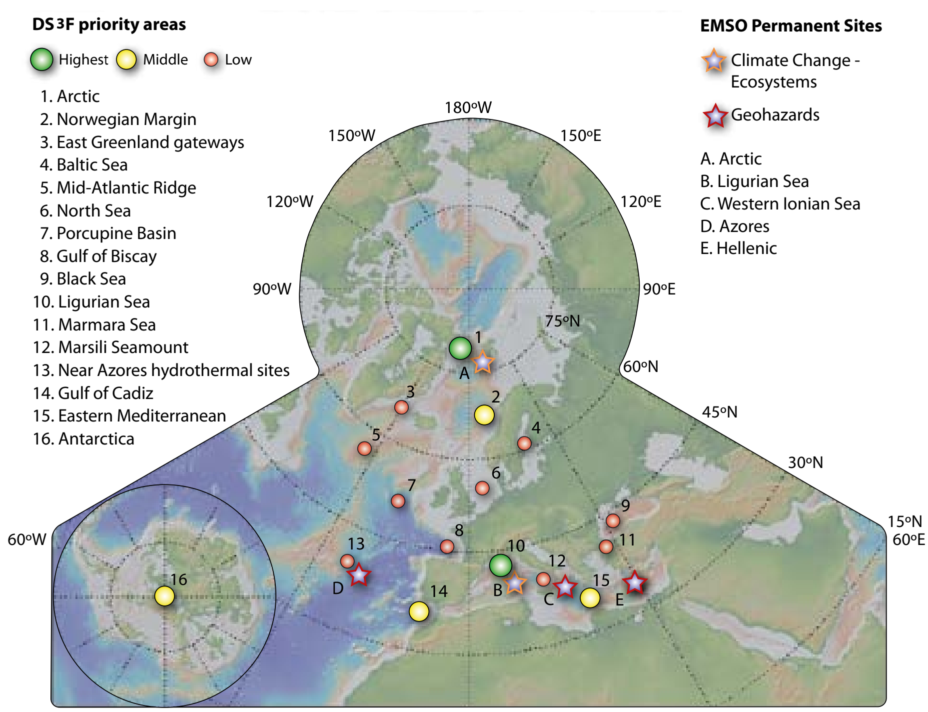
Regional challenges

Certain regions of the deep sea are exceptionally relevant for their global connection, or because their complexity allows their study as a laboratory for testing hypotheses of global implications. The regionally-driven approach to the study of the deep sea therefore must be introduced for long-term, complex research initiatives that require the shared use of research infrastructure, a robust logistical support, and a planning and management structure that guarantees continuity of resources.

Three regions have been identified as highest priority by the DS^{3}F consortium: the Arctic and Norwegian margin, the Mediterranean Sea and the Mid-Atlantic Ridge. The Arctic Ocean is a region with high sensitivity to climate change. It is known that the natural environment here is responding faster to anthropogenic forcing than low-latitude regions, for example with respect to ocean acidification. Furthermore, the anthropogenic impact in the area is expected to increase rapidly as a consequence of decreasing sea-ice coverage and the increase in industrial activity related to exploitation of natural resources and maritime trade.

Changes in the Arctic Ocean environment are induced primarily by the varying thermal state of the deep and intermediate oceanic water masses flowing from the temperate Atlantic Ocean to the north as an extension of the Gulf Stream. The sediments underlying the path of such currents are therefore the best candidate as high resolution archive of palaeoceanographic changes that have led to the present oceanographic conditions. The Norwegian continental margin and the Fram strait (between Svalbard and Greenland) can be viewed as oceanic gateways to the Arctic. The Fram Strait is an ideal location for the monitoring of the environmental changes in the deep sea, both in terms of influx of warmer water masses to the Arctic Ocean and outflow of cold waters towards the western North Atlantic. In order to understand the climatic history of the High Arctic Ocean, one of the least known regions of the planet, it is mandatory to be able to access top-class ice breaking research infrastructures and sample the marine sediments filling the basin and draping its ridges.

Methane gas emissions have been ob-



Quo vadis, DS3F?
Regional foci of the DS3F community, as established during 8 ad-hoc workshops and two overarching conferences in 2010-2012. Note good agreement with sites of cabled observatories to ensure time series measurements in addition to one-time campaigns.

Sharing research vessels in Europe
Research vessels represent valuable mobile infrastructure for marine researchers, and the European Commission and national agencies support the EUROFLEETS programme and OFEG to efficiently share the platforms between countries.

served in this region, and they are considered to be the result of gas hydrate phase changes induced by global warming. However, the knowledge of both the source of methane in the sub-seafloor and the details of the ocean warming trend is not yet sufficient to extrapolate the observations to near-future predictions. The potential deep sea contribution of methane to the water column and eventually to the atmosphere is therefore an open issue of highest scientific and societal importance.

Some of the most catastrophic failures of continental margins, which have also generated important tsunami waves, are known from the Norwegian margin and the Arctic Ocean. A debated hypothesis is that such events are climatically modulated and occurred preferentially during periods of natural global warming. Understanding past catastrophic events is therefore essential for assessing hazards and mitigating the impact of future anthropogenic warming, in view of the predicted increase of human impact and the long-distance impact of induced tsunamis (see also "Geohazards").

Despite its relatively small size and its land-locked nature, the Mediterranean Basin includes deep sea regions in a complex tectonic and sedimentary setting. It has been defined as a 'natural laboratory' for understanding oceanographic processes from the physical, chemical, biological and geological perspectives. The Mediterranean region is extremely vulnerable to submarine geohazards as a consequence of its dense coastal population (approximately 160 mio.), with extreme peaks during holiday seasons (an extra 140 mio.), and a dense network of seabed structures (cables, pipelines).

There is an outstanding historical record of climate change and natural hazards with extraordinary implications for human evolution. The oceanic circulation in the Mediterranean Sea is driven by the interaction of several climatic regimes which include the Atlantic as well as desert and continental climates. Marine sediments are therefore a precious archive for the study of atmosphere-oceanic interactions which have influenced the entire Northern Atlantic Ocean and even the entire globe in the recent geological past. Mediterranean Sea deep sea ecosystems are severely impacted by those natural variations and more recently also by anthropogenic activity such as exploitation of fish stocks and other natural resources.

It was with the discovery of the huge provinces of mud volcanoes and cold seeps in the Mediterranean Sea that some of the most innovative findings were made concerning extreme deep sea habitats and microbial activity at the seafloor. These regions provide unique opportunities for the long-term study and monitoring of cold seeps as well as hot vents and will help unravel deep-seated process at depths inaccessible to direct sampling. The understanding of the impact of the deep basin salt deposition during the Late Miocene (Messinian Salinity Crisis) on the generation of deep-seated fluids as well as their migration and extrusion at the seafloor is an open field with potential impact on the assessment of submarine geohazards with respect to society and environment and also in the area of deep biosphere in extreme environments.

The Mediterranean Sea is also a promising region with respect to the exploitation of geothermal energy resources and non-hydrocarbon mineral resources related to the extensive active volcanic provinces of the Tyrrhenian Sea (e.g. Marsili seamount), Sicily channel, and Aegean Sea. It also hosts all three deep sea cabled observatories in Europe: NESTOR (Greece), NEMO (Sicily) and ANTARES (France).

The Mid-Atlantic spreading ridge from the equator to the Arctic region is identified as a laboratory for future investigations regarding the basic processes of lithosphere-biosphere interactions, the understanding of diversity of extremophilic communities at hydrothermal vents, and especially for assessing global distributions and potential environmental impact of seafloor exploitation of deep sea mineral resources. The region has been studied using different approaches, including several deep holes with ODP and IODP drilling expeditions (most recently North Pond[48]), HERMES/HERMIONE ecosystem studies[49], and monitoring during ESONET and EMSO[45].

For several hydrothermal fields the necessary background information exists to plan high-resolution seafloor mapping and observational activity, intensive sampling with densely spaced shallow boreholes employing the seabed drilling techniques with the implementation of high-temperature tools, and installation of seafloor and sub-seafloor monitoring tools. Key sites include the Azores vicinity, the Atlantis Massif and the Lost City hydrothermal fields as well as Jan Mayan and Loki's Castle along the Mohns-Knipovich Ridge system close to Svalbard. The study of these fields will provide information of global relevance for slow and ultra-slow spreading centre systems, active and inactive ridge segments, and pioneer studies on the potential sites for exploitation of deep sea mineral resources closest to the main European territory.

Despite the regional focus, the DS^{3}F science community underlines that besides the above areas there are many regions in European and global seas and oceans which also bear strong scientific targets. They were just not identified by the majority but fewer of the work packages. Future funding by the European Commission and other funding agencies has hence to mediate between emerging research areas of overarching significance versus others of specific interest (see DS^{3}F map).

Implementing DS^{3}F: Benefits for Europe

* A better understanding of geohazards and appropriate warning systems will make the Mediterranean coast, the most vulnerable ocean margin in Europe, "a better place".
* New smart and affordable technologies for sub-seafloor sampling are required, and Europe has already occupied the niche of seafloor drills and associated technologies – with a potential for growth and jobs.
* Places such as the French Riviera have maximum amounts of insured capital, maximum risk from geohazards (earthquakes, landslides, tsunamis, flashfloods, storms), but minimum mitigation/prevention measures.
* A Distributed European Drilling research infrastructure would logically follow up other ESFRI initiatives such as EMSO or EUROFLEETS and will add considerable value to deep sea research at moderate cost given most of it has been established in the ECORD/ECORD-Net framework.

Listening to Mt. Etna's activity
A marine engineer working on the maintenance of the GEOSTAR seafloor observatory node before its deployment to the sea bottom offshore Sicily. Here, a seafloor cable has been laid for real-time monitoring of deep sea processes in the Mediterranean Sea.

Grand Challenges

for science and society

Deep sea research is a central element in addressing a number of the emerging fundamental issues in a rapidly growing world, so-called "Grand Challenges". These include climate change, environmental quality, food and energy security, as well as health and well-being. The challenges can represent not only problems, but also economic and societal opportunities.

What has already been set out in the Lisbon agenda concerning the European Union's strategy for competitiveness and growth has more recently been formulated in documents such as *Europe 2020*[2] and some of its central elements such as Innovation Union, with *Horizon 2020*[3] as a common strategic framework for EU Research and Innovation funding. Within the next decade, Europe aims at a 20% increase in energy efficiency, 20% energy from renewables and 20% reduction in greenhouse gases, coupled with an increased research and development budget (target: 3% of the EU's GDP). This "smart growth" further encompasses higher employment rates owing to better educational attainment, as outlined in *ET 2020* or *Youth on the move*[51]. Given the role of the ocean in the Earth system and the vast opportunities the ocean, and the deep sea in particular, links between the Deep Sea & Sub-Seafloor Frontier initiative and European society must be established.

As a crucial link between research and development and economic interest, the European Commission has established *Horizon 2020* as a Common Strategic Framework with three main pillars: Excellent Science, Industrial Leadership, and Societal Challenges. These priorities are intertwined.

Priorities and Challenges of Horizon 2020 within Europe 2020

DS³F has the potential to achieve scientific excellence, assuming that state of the art research infrastructure is available to investigate the deep sea and its sub-seafloor. Such infrastructure usually cannot be run by individual research groups or even countries because of the high cost involved, the number of researchers required, and the huge amount of data generated. As a result, the research is highly collaborative in nature and an ideal environment to form networks between researchers of different nationalities, expertise and experience. Young students are trained by more experienced researchers. Education and outreach are natural components of the seagoing experience.

Traditionally, scientific excellence crucially relies on engineering advancements with the potential for providing new and improved ways to achieve scientific objectives. Therefore, research and innovation within the field of seagoing technology is needed to achieve scientific objectives and improve cost and time efficiencies. DS³F has identified fields in which Europe has the potential for producing world-class technology leading to industrial leadership, for example in exploration drills and monitoring technology in the field of renewable energies such as geothermal, offshore wind and seafloor resources.

Companies, and small and medium sized enterprises (SME), in particular from areas such as petroleum or mining industries, are desirable collaborators in research endeavors in the marine realm.

Many DS3F research themes are of interest for industry and there is plenty of mutual interest and complementary expertise. Examples include science accompanying commercial projects to carry out impact assessments for ecosystems during and after exploitation, scientists providing the bridge to policymaking by defining the framework how protective measures could be realised, and how responsible use of the oceans and seas leads to an Integrated Maritime Policy for Europe.

Many of the roles deep sea researchers can take are intimately linked to societal challenges and the various demands for public well-being. The highly relevant and even critical role of DS3F research for challenges within the third pillar of *HORIZON2020*[2] is briefly discussed in the following.

Demographic change and well-being

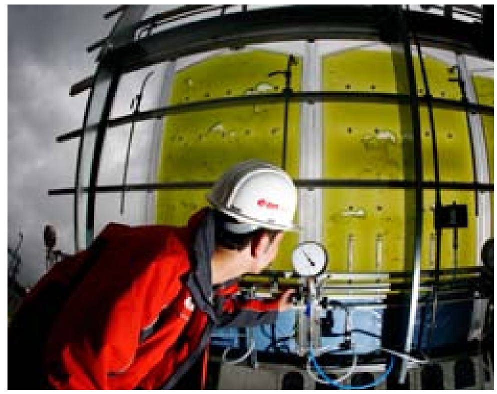
Submarine geohazards have important consequences for society in terms of lives lost, environmental damage, and economic impact on society. Improved understanding and constraint on the controlling factors, governing processes and recurrence intervals of earthquakes, landslides and tsunamis can greatly benefit society and the health and well-being of individuals.

Replacing luck:
The need for early warning
Photographs of damage associated with the large tsunami triggered by the 2011 Tohoku EQ, Japan. The tsunami destroyed an area of appx. 560 km² (Geospatial Information Authority Japan) and had an estimated economic cost of 235 billion US Dollars (World Bank).

Secure, clean and efficient energy

The deep sea and sub-seafloor hold huge potential for clean renewable energy, ranging from hydrothermal energy production from mid-ocean ridges to wind and wave energy. DS3F science is indirectly related to secure, clean and efficient energy, for example through scientific investigations of hydrothermal systems and site investigations for safe seafloor installations in terms of risks for offshore geohazards. Episodic geohazards often imply destruction of infrastructure, both in the offshore and near-shore environment.

Despite current initiatives to develop alternative, cost-effective, reliable energy sources, hydrocarbons will continue to be a major component of the energy mix in Europe for much of the 21st century. Hence, the impact of such exploration and exploitation, which is progressing towards deeper and deeper water, is to be reliably assessed. Both the petroleum and tectonic communities are interested in the mechanisms of continental break-up, ocean basin formation (when hydrocarbon reservoirs develop), and slope stability and seismicity related threat to modern hydrocarbon technology (rigs, pipelines, etc.). An even more significant issue in this time of change may be the understanding of the impact of seafloor exploitation on the immediate environment and the subsequent consequences on the ocean as a whole. The response of the ecosystem to disturbances has been observed at a limited number of



Marine resources for clean energy
Conventional coal power plant (left) vs. biochemical reactor (right), the latter being free of emissions and using photosynthesis or microbial reactions to produce energy.

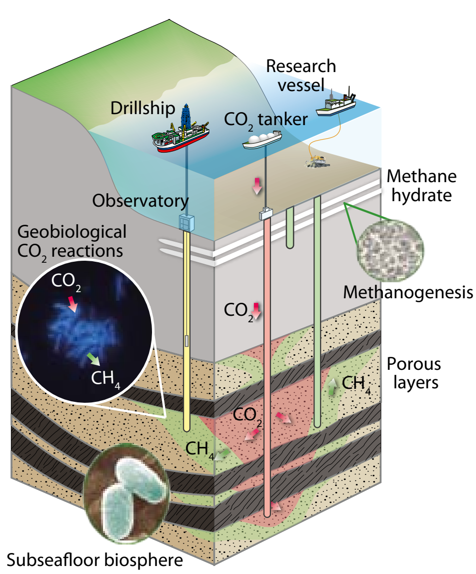
sites, and the exact nature of the eco-geochemical drivers as well as growth rates and other processes still need to be determined for most habitats. We need to better understand the distribution, composition and connectivity of the deep seafloor communities in order to comprehend their capacity to recover, which is naturally hampered in such specialised communities.

Gas hydrates are one of the largest hydrocarbon reservoirs but their potential as an energy resource or geohazard requires improved understanding of their formation mechanisms, extent, and stability (currently underway at a national level, for example in Japan, but preferably carried out in a European or international framework).

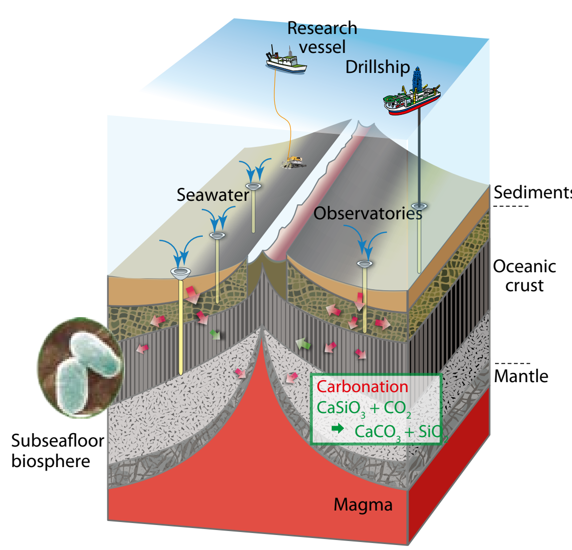
Similarly, sub-seafloor environments of shale-hosted gas or coal-bed methane provide opportunities to understand the nature and role of microbial communities in generating and biodegrading hydrocarbons, as well as potentially providing environments for CO_2 storage. Ongoing and ancient reactions between the ocean and sub-seafloor basalt and peridotite may lead to alternative approaches for storing CO_2. *In situ* monitoring and perturbation experiments enabled by scientific ocean drilling offer an opportunity for fundamental research on geological capture and storage of CO_2 in both sedimentary formations and the igneous crust. Borehole ex-

CO_2 sequestration and future reservoirs
In situ monitoring and perturbation experiments enabled by scientific ocean drilling offer an opportunity for fundamental research on geological capture and storage of CO_2 in both sedimentary formations (left) and the igneous crust (right). Continuous access for sampling and monitoring will assess the extent, distribution, and rates of microbial processes and fluid-rock interactions that may contribute to successful carbon sequestration through a natural CO_2/organics-bioreactor system.

Active CO_2 Sequestration and Experimentation



Natural CO_2 Sequestration



periments are needed to measure key subseafloor physical properties that control fluid migration, particularly permeability, porosity, fracture density and orientation, and storage properties. Continuous access for sampling and monitoring will assess the extent, distribution, and rates of microbial processes and fluid-rock interactions that may contribute to successful carbon sequestration through a natural CO_2/organics-bioreactor system. Ocean drilling provides a means to evaluate carbon capture and sequestration schemes based on carbonate-producing fluid-basalt or peridotite reactions, to monitor plume migration and fluid geochemical evolution through time, and to investigate the potential for enhancing natural carbonation processes. Once scientific evaluation gives way to full-scale CO_2 sequestration, monitoring will assist in managing Earth's environment and sustaining natural resources (e.g. by having sequestration actively support methane reservoir formation for future generations).

Last, but not least, ocean ridges have huge, albeit challenging to harness, geothermal reserves. Seawater reacts with mantle rocks, leading to the formation of H_2, and these abiotic hydrocarbons are potential avenues for alternative energy research. Simple geothermal mining, in particular in regions of moderate water depths or proximity to islands (Azores, Iceland, but also the Arctic) represents opportunities of an *a priori* affordable clean energy source.

Climate action, resource efficiency and raw materials

Obtaining estimates for Earth system and climate sensitivity is crucial to preparing for and mitigating the impacts of global change. An understanding of future rates of sea level change based on past observations is of prime importance to adapting to and militating sea level rise. Understanding the evolution of the hydrological cycle and ocean ventilation has important implications regarding the future evolution of flood events, freshwater supply, and greenhouse gas concentrations.

The deep sea and its sub-seafloor contain a vast reservoir of renewable and nonrenewable physical and biological resources that are rapidly gaining in scientific and economic interest. There are mineral re-

Food as ecosystem service for society
Overfishing and resilience of ecosystems to deep sea fisheries are of crucial concern for society given the growing demand for food globally. Deep-water trawling is particularly problematic as it leaves a large environmental footprint, especially where fishing occurs in areas of vulnerable habitat such as cold-water coral reefs.

Innovative scientific and economical niches
Marine biotechnology is an emerging discipline based on the use of marine natural resources. The oceans encompass over 99% of the biosphere, representing the greatest extremes of temperature, light, and pressure encountered by life. Adaptation to these environments has led to a rich marine bio- and genetic-diversity with potential biotechnological applications related to drug discovery, environmental remediation, increasing sea food supply and safety, and developing new resources and industrial processes.

sources (hydrothermal sulfides, polymetallic nodules and manganese crusts), huge quantities of gas-hydrates buried along continental margins, and biological resources of the deep seafloor with biotechnological and pharmaceutical application. Marine mining is becoming a reality this century. Related to hydrothermal systems, there is a potential for natural hydrogen from serpentinisation reactions, which may be used as an energy vector.

When assessing resources for the 21st century, scientific exploration has led to the discovery of various types of deposits, but modern mapping exists over only a very small portion of the seafloor, and the sampling of the subsurface is very sparse, despite the enormous efforts undertaken within the framework of the EU, the scientific ocean drilling program, or national efforts. Hence, much about the composition and global distribution of these resources on and within the subsurface, their quantitative importance for global chemical cycles and biological activity, and the potential impacts of exploitation on ocean chemistry and ecosystems is incompletely understood. At the same time, population growth and the ever-rising standard of living in our global society have led to exponential increase in the need for food, water, energy, metals, novel biochemical compounds, and waste storage (e.g. CO_2, nuclear waste), among other resources. The secured supply of hydrocarbons and strategic minerals are major concerns of governments and industry worldwide. With over 70% of our planet covered by ocean and more than 90% of it in the deep sea realm, the seafloor is potentially a significant source of new frontier and nontraditional resources. DS^{3}F has thus identified both the emerging scientific questions and appropriate technological means to explore and eventually responsibly exploit the seafloor and underground for deep sea minerals. In this, scientific ocean drilling will continue to play a valuable role in order to establish a reliable 3D-assessment of resource opportunities. Seawater-rock interactions can lead to the formation of major base (Cu, Zn, Pb) and precious metal (Au, Ag) and metalloid deposits. The extreme environment (for example high temperatures, extreme pH, high salinity) in these and other seafloor regions such as deep sedimentary basins or mud volcanoes has led to the evolution of highly adapted microbial communities with the potential to reveal through bio-prospecting novel chemical compounds of medical and industrial value. At the same time, these vents are a window to life and stages of „early Earth“ evolution, and utmost care has to be applied when exploring or even exploiting them[40].

Much of the above is in accordance with *A resource-efficient Europe*[26], a strategy of the EU which addresses energy, climate, food, innovation/industry and environmental policy. DS^{3}F has made its initial contribution to such strategies in this foresight paper (see also boxes concluding the individual chapters). In a next step, science and policy have to work jointly on detailing the strategy in the various policy areas.

Education and training

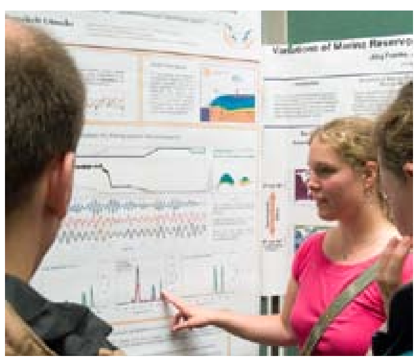
Training the next generation of marine scientists has to be one of the foremost objectives in DS³F, in particular since the fields covered, for example, in this foresight paper all encompass future societal demands and challenges. Education and training are particularly critical in Europe since many Europeans leave education or training without qualification and hence fail to match labour market demands. Less than a third aged 25-34 hold a university degree, compared to approximately 40% in the USA and 50% in Japan, and only two European universities rank among the Top 20[50].

DS³F acknowledges the importance of ocean sciences and the challenges this complex system bears for future generations. Many recent ocean research initiatives already address the future long-term societal demands by involving teachers as well as young students and fascinating them with the unknowns in the deep sea. This has successfully been done for over a decade by UNESCO-IOC (Intergovernmental Oceanographic Commission) in the field of deep sea research, when 12 annual international "Training-Through-Research" (TTR) cruises were carried out in the Atlantic Ocean, Mediterranean and Black Seas on board Russian research vessels. Eleven international conferences were held within the programme. At the TTR conferences, students (as well as scientists) presented their research results. Many of these students now hold high-level positions at European oceanographic centres, universities, or in industry, and similar programmes are vital to reach the objectives of *Europe 2020*[2] and Youth on the move[51].

Also, large efforts are being undertaken with respect to legacy, and, in particular, material cored in the deep sea has to be maintained and curated for future analysis using new techniques. – One example: nobody thought about deep sea mass spectrometers or AUVs several decades ago. Cataloging of results and large data archives for both scientific and public domain use is mandatory, but handling the tremendous amounts of long-term data or ensuring compatibility of formats and standards for instrument use are a true challenge (see "Implementation", observatories).

Publishing data has an overall positive impact on the quality and availability of scientific data and provides the necessary incentives for data producers as well as data users. Existing procedures are varying and cannot be seen as final. It is crucial that data sets are consistently structured and that they are citable and fully documented so the quality can be assessed and usage of data is reliable and efficient. Data publication services need to be integrated into the traditional science publication process (e.g. via Digital Object Identifiers – DOI) and require a coherent system consisting of libraries, science publishers and certified data repositories, for example as supplied by the new ICSU World Data System (WDS).

Scientific higher education institutions need well-prepared and motivated students approaching university. Education and training should therefore focus on future students, that is high-school pupils and their teachers. Following European Geosciences Union (EGU) policy on education, long-lasting initiatives must be started to spread "first-hand scientific information to science teachers of primary and secondary schools, significantly shortening the time between discovery and textbook, and to provide the teachers with material that can be directly transported to the classroom". Activities should range from focused "Workshops", "Teachers at Sea" programmes, permanent "School-Researchers Interaction" via the internet, "School Participation" in deep sea research programs to "Internet-Based Educational Programmes". Given the relevance of the deep sea for future energy, resources, safety, and climate change, educational activity focusing on the Deep Sea should be inspired by the principles of "Education for Sustainable Development"[52]. Similarly to the outer space, the deep sea and the ocean in general can be seen by pupils and teachers as an appealing environment, the Earth's inner space, in which most of the future scientific discoveries will concentrate at the frontier of knowledge. The deep sea will be seen as an opportunity for stimulating curiosity towards scientific research and development of professional careers.



Invest in Europe's brilliant minds
Left: Poster presentations during workshops of PhD students from Europe provide an excellent opportunity for exchange of knowledge and learning soft skills for scientific publication of research results.
Right: European high-school teachers gathered at the EGU General Assembly for the annual Geoscience Information for Teachers (GIFT) workshops organised by the EGU Committee on Education.

Public Outreach

Informing and inspiring the public about the fascinating deep sea realm is at the heart of DS³F recommendations. Here, a lot is to be learned from the ECORD-Net, and EU ERA-Net project[6] that turned into an international research effort in its own right, now part of IODP[8] where all data and publications are available to everybody for over 50 years. The international scientific drilling community has a well-developed e-infrastructure with open access to high quality data and core samples after the initial data moratorium period. The data is excellent for education and outreach activities, and no restrictions exist concerning accessibility of data and publications for more than 50 years.

In addition to a predominantly scientific use of results, the key findings of deep sea research together with their societal implications have to reach a wider, non-expert audience. Such dissemination of information is important since life-long learning has to be a mandatory priority in a rapidly changing world. Presentation of scientific findings in an exciting way may stimulate learning, enhance creativity and innovation, and will result in employment, economic success, and full participation in European society.

In practice, small-scale initiatives have started, but there is room for expansion. Apart from the obvious things such as "open ship" during port calls, there are opportunities for teachers to sail on research cruises and report to shore to their pupils. Both in IODP and national cruises, there are also efforts by industry to enhance collaboration between academia and industry. For graduate students and early career scientists, there are opportunities such as summer schools (both within ECORD and IODP[8], but also organised by university federations). Many initiatives also have fellowship programmes and opportunities for mini-proposals to get travel support, etc. – a mechanism which is to be exploited in the future.

When regarding the opportunities of modern – and in particular social – media, there is an ocean of opportunities ahead of us. Even small research vessels offer internet access nowadays, so that results (and photos and videos) from remote places on Earth may be published in blogs in quasi-real time. At times after the first internet boom, but with longer-term prospects for the global online medium continuing to be bright, science has to seek avenues led by social media, search and video side-by-side with industry. This view is supported by a recently shifted skew towards older age groups within the „online population". Science has now to appreciate what the world's leading marketers have realised a while ago: at the heart of the social media movement lies a method to transform the manner in which brands communicate with their consumers. With the appropriate language and mechanisms, this path may be used to disseminate science results so that they sink in.

Pass on knowledge to the next generation
Exhibition of deep sea science and technology in a German shopping mall. Children are fascinated by ocean discovery and, in this case, drive a miniature ROV through a fish tank

Grand Challenges: opportunities for science and society

* The deep sea and its sub-seafloor contain a vast reservoir of physical, mineral and biological resources that are rapidly coming into the window of exploitation. Assessing the opportunities and the risks involved requires a serious commitment to excellent deep sea research.
* There are numerous areas in this field in which Europe has cutting-edge technological potential. These include drilling and monitoring technology in the field of renewable energies such as geothermal, offshore wind and seafloor resources. Scientific ocean drilling will continue to play a valuable role, for example in the exploration of resource opportunities, in obtaining estimates for ecosystem and Earth climate sensitivity, or in improving our understanding about the controlling factors, governing processes and recurrence intervals of submarine geohazards.
* In Europe, there is also the scientific expertise needed to define a framework for policymakers for environmental protection measures and to carry out ecological impact assessments before, during and after commercial exploitation. Taking up these societal challenges will strengthen European scientific and educational networks and promote the development of world-class technology and industrial leadership.

Notes

1 http://www.european-network-of-maritime-clusters.eu/downloads/4_56.pdf
European maritime sectors are clustered in about 10 countries: NW Europe for traditional sectors and SW Europe for coastal tourism as well as fisheries; 186 bill € of added value

2 http://ec.europa.eu/eu2020
http://ec.europa.eu/research/innovation-union/index_en.cfm

3 http://ec.europa.eu/research/horizon2020/

4 The Ostend Declaration, formulated during the Euroceans2010 meeting in October 2010, states: The European marine and maritime research community stands ready to provide knowledge, services and support to the European Union and its Member and Associated States, recognising that “The Seas and Oceans are one of the Grand Challenges for the 21st Century”. For full text, refer to http://eurocean2010.eu/declaration

5 Integrated Maritime Policy; see summary of activities: http://www.europarl.europa.eu/ftu/pdf/en/FTU_4.4.9.pdf

6 ECORD = European Consortium for Ocean Research Drilling, initially started as an EC-funded ERA-Net, then turned into the European branch of the Integrated Ocean Drilling Program (IODP[8]); see also new ECORD business plan for 2013-2023 at http:// www.ecord.org/pub/Future_of_ECORD-2013-2023.pdf
ERA-Net, European Research Area Network: The objective of the ERA-NET scheme is to step up the cooperation and coordination of research activities carried out at national or regional level in the Member States and Associated States through the networking of research activities conducted at national or regional level, and the mutual opening of national and regional research programmes. See http://cordis.europa.eu/coordination/era-net.htm

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9 See Publications and Foresight sections at http://www.marineboard.eu/

10 http://www.iodp.org/science-plan-for-2013-2023; illustrations that originate from work done by editors and contributors to the IODP New Science Plan were provided by Jamus Collier, namely: p.11, p.13 (bottom), p.24, part of p.25 (top), and p.51 (bottom).

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Youth on the Move is a comprehensive package of policy initiatives on education and employment for young people in Europe; see http://europa.eu/youthonthemove/

52 http://www.unesco.org/new/en/education/themes/leading-the-international-agenda/education-for-sustainable-development/

Credits

Cover MARUM Bremen/A. Boetius (White thiotrophic bacterial mats at the Amon mud volcano, Eastern Mediterranean Sea), p.5 Aktuel Naturvidenskab, p.6 Ifremer/O. Dugornay, p.7 MARUM Bremen/A. Kopf, p.8 Alfred-Wegener-Institute/F. Roedel, p.10 Springer/P.J. Barrett, p.11 IODP-MI, p.12 MARUM Bremen/ A. Kopf, V. Diekamp, p.13 top Univ. of Alaska, Fairbanks/K. Iken, p.13 bottom IODP-MI/ C. Schoof, p.14 ECORD, p.15 MARUM Bremen/H. Pälike, p.16 ddpimages/AP/Kyodo News, p.18 Norwegian Geotechnical Institute, p.19 IODP-MI/Springer Science and Business Media, p.20 Leibniz Univ. Hannover/W. Kongko, p.21 GFZ Potsdam (left), iStockphoto/T. McCaig (right), p.22 Nautical Science Faculty Woods Hole/P.A. Sacks, p.24 IODP-MI/C. Devey, M. Montresor, B. Orcutt, S.W. Ross, A. Vanreusel, and Coral Disease Working Group, p.25 top IODP-MI/H. Imachi (left row), Univ. Cardiff/J. Parkes (right row), p.25 bottom Univ. Bremen/W. Bach, p.26 top HERMIONE/Univ. Gothenburg/T. Lundalv, p.26 bottom WHOI/L.P. Madin, p.27 top UNEP/S. van den Hove, V. Moreau, p.27 bottom MARUM Bremen/D. Hebbeln, p.28 top Univ. of Alaska, Fairbanks/ K. Iken (left), HERMIONE/Univ. Gothenburg/T. Lundalv (right), p.28 bottom MPI Bremen/T. Ferdelman, p.29 Univ. Freiburg/F. Reski, p.30 MARUM Bremen/A. Koschinsky, p.32 European Commission/ Ifremer/W. Roest, p.33 Ifremer/ Y. Fouquet, p.34 MARUM Bremen/Y.-S. Lin, K.-U. Hinrichs, p.35 MARUM Bremen/A. Koschinsky, p.36 top School of Oceanography, University of Washington and NOAA Ocean Explorer/D.S. Kelley p.36 bottom MARUM Bremen/A. Kopf, p.37 Ifremer/O. Dugornay, p.38 MARUM Bremen/T. Klein, p.40 IODP-MI/A. Kopf, p.41 MARUM Bremen/A. Kopf, p.42 MARUM Bremen/A. Kopf, p.43 MARUM Bremen/V. Diekamp, p.44 IPGP/C. Mevel, p.45 OGS Trieste/ A. Camerlenghi, p.46 MARUM Bremen/A. Kopf, p.47 INGV/L. Innocenzi, p.48 ddpimages/AP/Color China Photo, p.50 S. Vaughan (www.stephenvaughan.co.uk), p.51 top iStockphoto/T.W. van Urk, ddpimages /dapd/R. Magunia p.51 bottom IODP-MI/F. Inagaki, p.52 Johann Heinrich von Thünen Institut - OSF/C. Zimmermann, p.53 iStockphoto/J. Moraes (left), MARUM Bremen/V. Diekamp (right), p.54 MARUM Bremen/V. Diekamp (left), EGU Committee on Education/L. Mariani (right), p.55 MARUM Bremen/V. Diekamp

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