

The Dynamic Continental Margin Between the Mid-Atlantic-Ridge System (Mohns Ridge, Knipovich Ridge) and the Bear Island Region

1. Relevance

The proposed project is part of the IPY consortium 'Plate Tectonics and Polar Gateways in Earth History (PLATES & GATES)'. PLATES & GATES is a network of individually managed projects and project groups that will operate as a coordinated effort among the participating national and/or institutional programs. PLATES & GATES will focus on data acquisition and analyses in both polar regions, which are critical for understanding large time-scale paleo-climatic processes. A list of planned projects (status 06.10.2006) with the PLATES & GATES consortium is added as file PG_list_200610.pdf. The new data on the lithospheric and crustal structures, their ages and evolution, sedimentary formations, petrological fabrics and chemistries, as well as high-resolution bathymetry, will be integrated to provide a substantial basis for paleo-topographic and paleo-geographical grids. Existing data sets will be compiled and integrated with these new data.

Within this consortium, the proposed project will aim at improving our understanding of the structural architecture, the stress conditions and sources, and the dynamics of the continental margin near Bear Island. This will be accomplished by:

- Improved determination of earthquake hypocenters along the mid-Atlantic ridge system (Mohns Ridge, Knipovich Ridge), within the oceanic basin between the ridge systems, and along the continental margin to identify active tectonic structures.
- Investigation of possible migration of seismicity along Mohns Ridge towards the continental shelf, and to investigate the reactivation potential of the Senja Fracture Zone.
- Mapping of crustal deformation of the continental margin in a region of steep slopes with a high potential for geohazards such as submarine slides.
- Detailed recovery of the lithospheric structure from active experiment data, surface wave analysis, receiver-function methods, and S-wave anisotropy assessment.
- Calculation of focal mechanisms (standard methods and full moment tensor inversions) to investigate details of the faulting processes and to understand better the complex regional stress field in this region.
- Contribute to more detailed knowledge of seismic velocities to advance our understanding of the crustal composition and to improve the accuracy of existing and future earthquake locations in the region.

2. Aspects relating to the research project

2.1. Background and status of knowledge

The continental margin along the northern Atlantic Ocean (Fig. 1) has been extensively studied in the past by active and passive seismic experiments (see e.g., Husebye et al., 1975; Mitchell et al., 1990; Bungum et al., 1991; Sellevoll et al., 1991; Eiken, 1994; Høgden, 1999; Bykjeland et al., 2000; Faleide, 2000; Faleide et al., 2000; Mjelde et al., 2002). This has led to important knowledge on the lithospheric structure, the hydrocarbon reservoirs, and parts of the sedimental dynamics. These studies have also shown that a complete understanding of continental margins is only possible when also the deeper crustal and mantle architecture beneath the margins is recovered.

The western Barents Sea – Svalbard continental margin developed mainly as a sheared margin in response to the Cenozoic gradual northward opening of the Norwegian-Greenland

Sea (Faleide et al., 1991, 1993, 1996, Breivik et al., 1999). A rifted margin segment associated with volcanism southwest of Bear Island links sheared margin segments to the south and north. Repeated tectonic and volcanic events at this margin segment reflect a complex plate tectonic evolution of the adjacent oceanic basin involving jump(s) in the spreading axis. The continent-ocean transition occurs over a narrow zone and is covered by a thick sedimentary wedge comprising major depots (submarine fans) along the margin.

The Senja Fracture Zone (SFZ) extends from the Norwegian mainland to the area west of Bear Island, and is generally interpreted as a sheared margin segment resulting from the Early Eocene opening of the North Atlantic (Fig. 2). The present-day active oceanic spreading ridge, the Knipovich Ridge (KR), gradually approaches the West Spitsbergen sheared margin obliquely northwards, and we consider the study area as a key region for revealing the continental breakup processes. Furthermore, the area is essential for understanding the interplay between accretion of oceanic crust and passive (sheared) margin formation further north, where the eastern part of the ridge crest is covered by a thick sedimentary wedge.

On the western side of the KR the Greenland Fracture Zone (GFZ) can be addressed as a similar structure.

However, this fracture looks simpler than the SFZ because it does not define in addition the border between continental and oceanic crust.

Mohns Ridge (MR) (Fig. 2), which is nearly perpendicular to the KR and the SFZ, has a strike pointing directly to the continental margin. Therefore, it has been proposed that the MR is migrating further to the east and possibly into a relatively weak continental lithosphere. Recently achieved surface-wave-tomography results show relatively low S-wave velocities in this region (Levshin et al., 2005; 2007). A detailed knowledge of the lithospheric margin dynamics, from its top to its bottom, is needed there, and our experiment will focus on this.

The very slow spreading KR shows an active but diffuse seismicity pattern and no clear alignment of earthquakes along active segments or transform faults (Fig. 2). In addition, the deep sea between the mid-Atlantic ridge system and the continental margin of the Barents Sea show an unusually high but diffuse seismicity. It is unclear if this is an artefact due to location uncertainties of the events or an expression of the interaction of the ridge with the nearby continental margin. The observed seismicity appears to correlate with the distribution of young (< 2.3 mill. years) sediments in the major fans along the NE Atlantic margins (Byrkjeland et al. 2000).

Several high quality seismic three-component stations (HSP, JMI, KEV, and KBS) and arrays (ARCES, Apatity, SPITS, NORSEAR, NORES, Hagfors, and FINES) are operating in the European Arctic and Northern Europe. Data from these stations will be used during this

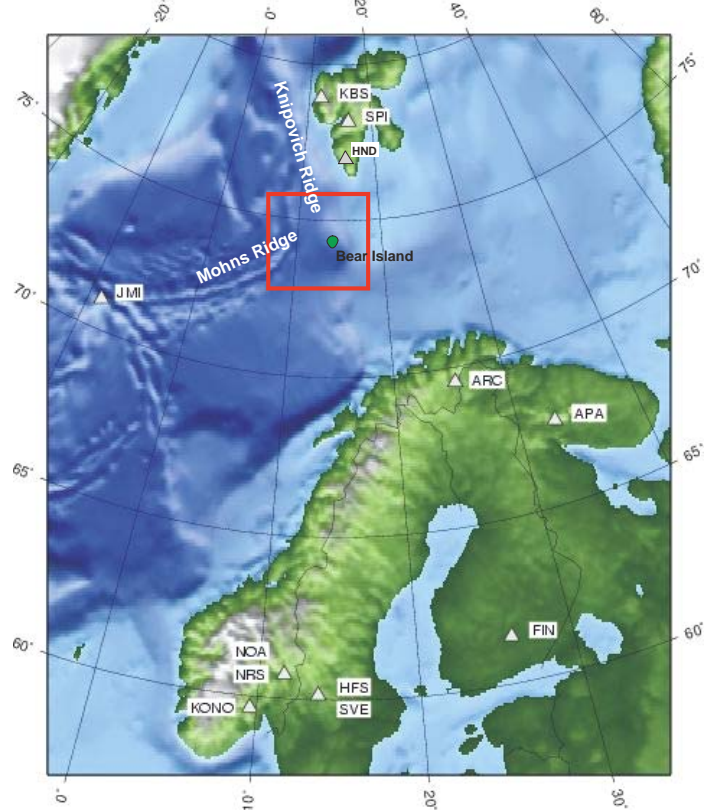
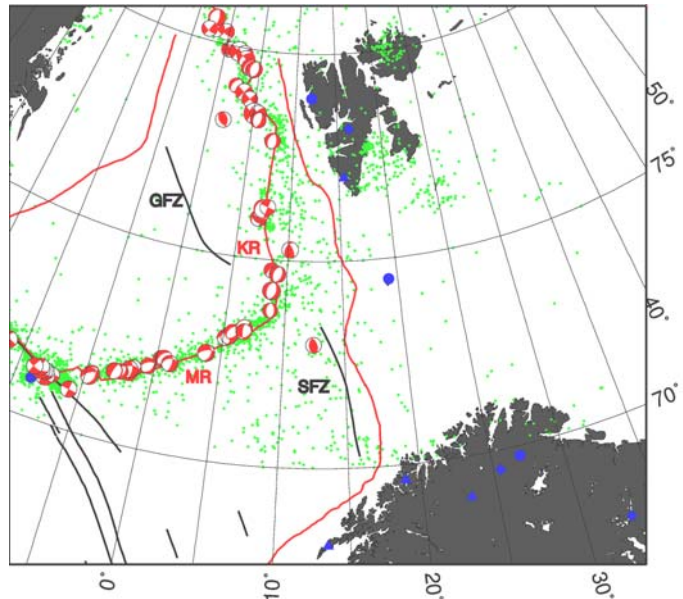


Fig. 1. Area of planned research (red rectangle) on the background of main tectonic elements. Gray triangles show locations of seismic arrays and stations important for the project.

project. In addition, we will have access to the data from the 3C stations of the Norwegian National Seismic Network. In Northern Norway these are the stations Bjørnøya, Kautokeino, Lofoten, and Tromsø.

However, because of the large distances between this seismically active area and the stations (see Figs. 1 and 2) and the relatively high noise level at many of the stations due to the ocean generated microseisms, the epicenter locations of the events in the region around Bear Island are currently associated with relatively large errors. Moreover, we have little control on the event depths. Therefore, new well-located events will dramatically improve our capabilities to understand the seismicity and seismotectonics of this region.

Fig. 2: Seismotectonic map of the region of interest. The red lines show the continental slope (margin) and the mid-Atlantic ridge with Mohns Ridge (MR) and the Knipovich Ridge (KR), the black lines show main tectonic fracture zones, namely the Senja Fracture zone (SFZ) and the Greenland Fracture Zone (GFZ). The fault-plane solutions are copied from the Harvard CMT Catalogue (1976–09.2001) for events with a magnitude $M > 4.7$. The blue points, triangles and diamonds show locations of permanent seismic stations (broad-band stations, short period stations, and seismic arrays, respectively) in the region. The small green dots show all locations of seismic events north of latitude 70° , as far as they are published in the ISC catalogue for the period from 1900 until the end of 1999.



In addition to large location uncertainties, the regional seismicity as observed from land stations has a relatively high cut-off magnitude at about $M = 4$. With the planned passive seismological experiment (see Fig. 3), a threshold magnitude of $M = 2$ can be expected. When extrapolating the magnitude-frequency distribution as observed in global catalogues, we estimate about 500 magnitude 2 events over a period of 6 months. This will be sufficient for first quantitative results with respect to seismicity patterns and as input for a neotectonic interpretation.

Only a few earthquake source mechanisms have so far been estimated for this region. They all come from larger events for which moment-tensor solutions could be estimated from globally distributed stations. The catalogue of the Harvard Group for the years 1976 until 2006 contains only 16 such solutions in this area up to 78° North (Fig. 2). However, this catalogue does contain source mechanisms for two earthquakes of special interest. The first event (mb 5.4, ISC) occurred on 02 July 1991 close to the northern end of the SFZ, below the sedimentary wedge, and the second event (mb 5.5, ISC) occurred on 03 February 2000, clearly east of the mid-Atlantic ridge system. The depths of both events were estimated to about 14 km by using the surface reflection pP, which is a relatively large source depth for events in the oceanic crust. Both events have oblique thrust mechanisms, in contrast to the strike-slip or normal fault mechanisms as typical for the mid-Atlantic ridge system. Note that Byrkjeland et al. (2000) also reports on two strike-slip mechanisms under the Bear Island fan and an oblique-thrust mechanism on the southern flank of the fan. This indicates another, not yet understood tectonic regime for the zone between the ridge systems and the continental margin.

More and better focal mechanism solutions, either estimated with standard methods or full moment tensor inversions, are necessary to characterize the active structures near the ridge, in the oceanic crust between the ridge and the shelf region and in the shelf region itself. Of particular interest is here the northern “tip region” of the SFZ. It is not known whether the SFZ intersects with the narrow margin near Bear Island and whether it may be somehow connected with the Knipovich-Mohns-Ridge system. If so, a seismogenic stress release on this fracture zone could bear a major potential for the triggering of submarine slides. In fact, major slides have been identified along the southern part of the Barents slope and the Lofoten-Vesterålen slope (Dehls et al., 2000). Focal solutions are also important to understand the crustal stress field in the region. To a first order, stress is extensional along the ridge system and compressional on Svalbard (Mitchell et al., 1990). The state of stress on Bear Island is however not known, and we moreover do not know whether the transition from extensional to compressional stress may be occurring in the region of our experiment. Mitchell et al. (1990) have proposed that ridge push forces are controlling this stress transition.

2.2. Objectives

The objectives are described in detail in the ‘Principal objective and sub-goals’ of the *grant application form*.

2.3. Approaches, hypotheses and choice of method

The key to improving our knowledge of the complex crust and lithosphere in the study area around Bear Island towards the mid-Atlantic ridge system, is a field experiment that is specifically designed to reveal the structural elements and the active seismicity. Solid earth field experiments in ocean regions are logistically much more difficult and expensive than on land, and often require participation from several institutions with complementary skills. The opportunities within the IPY 2007-2008 have enabled us to establish an international group of experts from Norway (NORSAR, the University of Bergen, the University of Oslo), Germany (the Alfred Wegener Institute, the University of Potsdam) and Poland (the University of Warsaw, Institute of Geophysics-Polish Academy of Sciences), with a long record of geophysical projects in the Arctic. The logistic resources of the participants include ocean bottom seismometers, broadband seismic instruments, ships, streamers, seismic sources and technicians to carry out the experiments.

Following the properly designed field experiments, the data will be subjected to advanced analysis for deriving the structural elements and geophysical parameters of the region. Again, the participating partners cover a wide range of expertise from interpretation of refraction, reflection and wide-angle seismic data, structural interpretation, analysis of data from arrays and three-component stations, earthquake location, seismotectonics and surface wave analysis.

With these new data at hand, using the modern analysis methods of the different project partners, we expect to expand significantly our geophysical knowledge of the area which is currently associated with numerous questions.

2.4. The project plan

This project of multinational cooperation is divided into two main parts. The first phase will be the active / passive experiment and the second phase will be devoted to the data processing and interpretation. The combination of active and passive experiments and the data from the distributed seismological arrays and stations will provide a unique opportunity to study the region of interest.

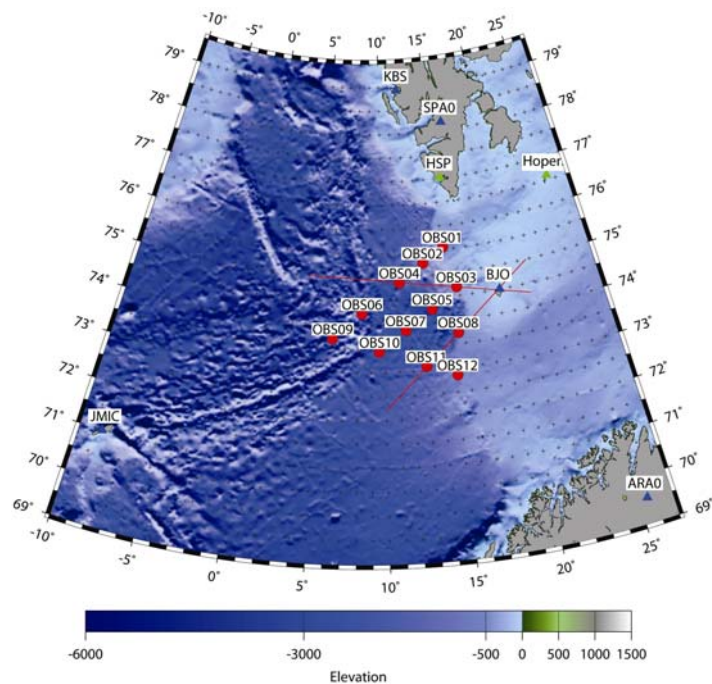
The passive experiment will monitor the seismic activity and thereby the actual tectonic stress field of the region by mapping regions of active seismicity and estimating the needed fault plane solutions.

The active profiling experiment will provide detailed information about the velocity structure and the distribution of major geological and tectonic elements down to the upper mantle. This information will then be utilized in (re)locating all seismic events in the region on the basis of a new, improved velocity model for the region.

First Phase: The Field Activities (2007 – 2008)

- Installation of 12 broadband ocean bottom seismometers (OBSs) provided by the German pool for amphibian seismology (DEPAS, <http://www.awi-bremerhaven.de/php/GPH/linkweb.php?page=obs>). The 12 OBSs will be installed in the deep sea from the mid-Atlantic ridge system (MR, KR) to Bear Island, and along the continental margin to the north to form a profile of stations together with the planned broadband station at Hornsund and the existing stations on Svalbard (see green symbols in Fig. 2). The deployment is planned for the end of September 2007, under the responsibility of the University of Bergen. The disassembly of these 12 stations is planned for the autumn of 2008 after the planned active experiment.

Fig. 3: Planned position of the different instrumental installations during the field experiment: Red points OBSs, green triangles broadband stations on Hopen and at Hornsund, near the blue triangle the Bear Island array, and red lines the reflection/refraction profiles.



- Installation of two broadband seismometers (see the green symbols in Fig. 3) at the Polish observatory at Hornsund on Spitsbergen (HSP) and on Hopen. These stations will be operated in parallel to the 12 OBSs between autumn 2007 and autumn 2008. The broadband seismometer at Hornsund is planned as an additional sensor temporally installed at the Polish polar station. The broadband seismometer on Hopen will be installed during the yearly maintenance visit in 2007 as an upgrade of the existing short period seismometer by the University of Bergen (Prof. J. Havskov), which is responsible for the Norwegian National Seismological Network (NNSN). The broadband station at Hornsund will be installed under the responsibility of NORSAR with support by our Polish colleagues.
- Installation of a small seismic array (13 three-component seismometers) on Bear Island (close to the blue triangle on Bear Island in Fig. 3) for the summer season 2008 (University

of Potsdam). It is planned to install the array in late May, 2008. However, because of the snow and ice conditions on Bear Island, the installation of this array may be delayed until late June, 2008. We plan to operate the array until October, 2008, depending on access possibilities of the island either by ships of the Norwegian Coast Guard and the Norwegian Meteorological Service. These two organizations are the responsible authorities for Bear Island and will be contacted for all logistic issues.

- An active seismic refraction/reflection experiment along two profiles crossing the margin and Bear Island (see the red lines in Fig. 3). The plan is to observe the airgun shots and small yield explosion sources fired along these two lines with about 50 short period seismometers located on Bear Island (University of Warsaw and Polish Academy of Sciences), a 3 km long digital multichannel streamer, and 10 – 15 OBSs (both provided by the University of Bergen). The active experiment is planned for autumn 2008. Both profiles of about 450 to 500 km length will start about 20 to 30 km east of Bear Island and continue in a westward direction from the island. In addition, gravity and magnetic data will be acquired.

The first profile is planned to the northwest, crossing the continental margin and the KR at about 75° North. The second profile will go to the southwest in direction of the sedimentary wedge covering the (unknown) continuation of the SFZ. In addition all active sources will also be observed with the temporary small aperture array on Bear Island, the ocean bottom network, the ca. 50 polish stations on Bear Island, and depending on the source yield with the seismometers on Hopen, Spitsbergen and in Northern Fennoscandia.

Second Phase: The Data Processing and Analysis (2008 – 2010)

The groups in Bergen and Warsaw have a long tradition and expertise in collecting and interpreting refraction and wide-angle reflection seismic data. They have also solid experience with experiments in the Arctic. Standard analysis tools for modelling and travel-time tomography will be used to analyse the data. Gravity and magnetic data will further constrain the density model and help to identify structural anomalies.

In addition, the observation of the active sources with seismic stations will give us valuable data to calibrate the installed seismic network, but also the permanent stations, which observe these sources (Taylor, 1999; Schweitzer, 2000). It is known (e.g., Schweitzer, 2001) that backazimuth and slowness observations of seismic phases as recorded by small aperture arrays, have to be calibrated. The calibration of the Bear Island array will be a special part of the data analysis at NORSAR.

One main goal of our analysis is to obtain a 3D structural and geological picture of this continental margin. Therefore, the data from the passive experiment will be analysed using seismological techniques like receiver function analysis for P and S waves, S-wave splitting, and surface wave dispersion analysis, to map in more detail the crustal thickness in the area, to investigate the stress distribution in the lithosphere, and to retrieve mean S-velocity models outside the profiles of the active experiment, in particular along the continental margin.

We will compile available data from international data bases and include them in our analysis. All new data will be integrated with the existing geophysical and geological data that the University of Oslo has compiled and interpreted during more than 25 years of margin studies in the region. The goal is to build a 3D geological model for the study area. High-resolution bathymetry data and high-resolution shallow seismics are important tools to study the neotectonic structures on the seafloor.

NORSAR, AWI and the University Potsdam have long and solid experience in collecting and analysing seismological data. This experience will be used to retrieve all necessary parameters for precise location of all observed events in the region. As a new methodological approach, we will test whether the three-component array on Bear Island can be used for

high-resolution conversion phase studies, and investigate how this supplements the conventional reflection and refraction seismics.

Efforts will also be made to identify and study potentially unstable sediment masses along the continental slope, as expressed by shallow micro-earthquakes indicating neotectonic faults. In the geological past giant debris avalanches have occurred in the area of investigation. Such events may potentially re-occur today, leading to flood catastrophes (tsunamis) and other geohazards. In this context the two reverse-faulting earthquakes, as reported in the Harvard catalogue, are of special interest. They may have occurred at shallower depths than estimated by the seismological data centers, thereby indicating larger movements in the sedimentary cover of the oceanic crust.

2.5. Budget

A detailed budget is attached as file *cost-plan_rev.pdf* to the *grant application form*.

2.6. Project management, organisation and cooperation

The project will be managed and coordinated by NORSAR, while the participating institutions will have responsibility for their respective sub-projects. After the data acquisition part of the project, the data will be analyzed and interpreted at the participating institutions. An important part of the coordination will be to organize workshops for planning the project details, for discussion of the scientific results and for organizing common publications.

The partners in this project, as listed in the *grant application form*, are described as follows:

NORSAR - An independent foundation, which conducts research, development and consulting within various fields of seismology and applied geophysics, including seismological verification of the nuclear-test-ban treaty. NORSAR is today one of the world's largest seismological observatories, with more than 30 years of experience with advanced seismological processing and data analysis techniques. The overall project management will be carried out by Dr. Johannes Schweitzer, who has a wide experience with internationally cooperative projects. Examples of such projects are instrument deployments in Norway and associated data analysis (MASI99 - Schweitzer, 1999), and the EU funded projects MEREDIAN and SRESAT, aimed at real-time data distribution and scientific training. NORSAR's contribution to the new large international EU funded projects NERIES and SAFER will also be co-headed by Dr. Schweitzer.

The Department of Geosciences, University of Oslo – This group, headed by Prof. Jan Inge Faleide, has a very long record of research activities aimed at investigation of the Norwegian continental shelf/margin and adjacent areas. Emphasis has been on seismic interpretation and structural mapping in order to understand the margin formation and evolution.

The Institute of Geophysics – Polish Academy of Sciences

The Institute of Geophysics – University of Warsaw

These two Polish groups, headed by Prof. Alexander Guterch and Prof. Marek Grad, respectively, has since 1970 acquired more than 20.000 km of refraction and wide angle reflection profiles in continental Europe, about 5000 km near vertical reflection and refraction and wide angle reflection profiles in Western Antarctica and about 2000 km refraction and wide angle reflection profiles in the region of the Svalbard Archipelago. The results have been published in about 150 papers (mainly international).

The Department of Geosciences, University of Bergen – This group, lead by Prof. Rolf Mjelde, has since 1992 acquired more than 10.000 km of 2D OBS profiles on the mid-Norwegian margin. The results have been published in ca. 30 papers in international journals. The same group has since 1999 acquired ca. 2000 km multichannel streamer data along the northern part of the Knipovich Ridge.

The Institute of Geophysics, University of Potsdam – This group, lead by Dr. Frank Krüger, has for several years worked on different seismological subjects like teleseismic structural studies, determination of source mechanisms and general array seismology studies. This institute was NORSAR’s cooperative partner in the MASI99 field experiment in northern Norway.

The Alfred Wegener Institute (AWI) is a large research center mainly operating in polar and marine regions. Within geophysical research the institute has a well-accepted expertise in conducting standard marine geophysical experiments including the deployment of ocean bottom seismometers and the interpretation of seismological data sets. Dr. Mechita Schmidt-Aursch will lead the contribution from AWI.

The main contributions from the different participants are listed in the following table:

NORSAR	Project management and coordination. Collection of seismic data from regional arrays and stations, and distribution of these data to the other project partners. Application of array processing software to the data from the Bear Island array and the OBS array. Earthquake location. Contributions to surface wave analysis.
The Department of Geosciences, University of Oslo	Structure-geological and tectonic interpretation of the results and development of a 3D geological model of the area.
The Institute of Geophysics, Polish Academy of Sciences and The Institute of Geophysics, University of Warsaw	Acquisition and analysis of reflection and wide-angle seismic data from the region around Bear Island. Logistic support for deployments of OBSs and stations on Bear Island.
The Department of Geosciences, University of Bergen	Logistic support for deployments of OBSs and stations on Bear Island. Acquisition, analysis and interpretation of reflection and wide-angle seismic data.
The Institute of Geophysics, University of Potsdam	Acquisition of seismic array data on Bear Island. Analysis of data from events at regional and teleseismic distances. Inversion for focal mechanisms.
The Alfred Wegener Institute, Bremerhaven	Acquisition and analysis of broadband ocean bottom data.

3. Perspectives and compliance with strategic documents

3.1. Compliance with strategic documents

The focus on the Arctic region is well established in NORSAR’s strategic documents for the time period 2006-2010 (*Virksomhetsplan for NORSAR for perioden 2006 – 2010*, in Norwegian). Specifically, the participation in projects under the umbrella International Polar Year 2007 – 2008 is explicitly stated as a primary goal in this document.

For the other partners, the long history of projects targeting the Arctic region shows that the proposed project is very central within the scope of their activities.

3.2. Relevance to society

The proposed project addresses geophysical problems of general interest like mapping of the lithospheric structure of the region and the development of the continental shelf. However, the results from this study may add to our knowledge about potential hydrocarbon resources

in the region and potential for geohazards in terms of slope stability and associated avalanches.

The University in Bergen will give undergraduate or graduate students the opportunity to participate in the active experiments as part of their education.

The data interpretation will be accomplished by young scientist (postdoc level) and will be part of Master and Ph.D. theses at all participating institutions.

3.3. Environmental perspectives

The project itself will have no permanent environmental impact. All installed seismic stations will be removed from the sea bottom (OBSs) and Bear Island in autumn 2008. The installation of the broadband station at Hornsund may become permanent but without environmental impact. The installation of a broadband sensor on Hopen is just an exchange of existing equipment without any environmental impact. However, the access to the environmentally vulnerable areas of Bear Island will be done in accordance with the guidelines given by the responsible authorities (Norwegian Meteorological Institute and the Governor of Svalbard).

3.4. Ethical aspects

This project does not contain any ethically relevant aspects

3.5. Gender equality and gender perspectives

This project does not contain any gender relevant aspects.

3.6. Data

The project will follow the general IPY data policy.

4. Communication with users and exploitation of results

4.1 Communication with users

Users of the project results will be mainly the scientific community also working in the European Arctic. The project is part of the IPY Consortium PLATES & GATES and all its results will be reported to the Consortium and disseminated by common publications in scientific and popular scientific journals, and on the web-page of the Consortium (platesgates.geo.su.se), which is open for the public.

4.2. Dissemination plan

A detailed description of the dissemination plans of the scientific results are provided under the 'Project Publication Plan'.

All broadband data (OBSs, mini-array, 3C stations) will be archived at NORSAR and at ORFEUS, the European broadband data centre. Both institutions follow an open data policy and give web-access to their data archives. The broadband OBS data will also be archived at the Alfred Wegener Institute.

Data from the active experiment will be archived both at the University of Bergen and at the University of Warszawa.

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