Mapping and Sampling the Arctic Ridges: A Project Plan

Report from the InterRidge Workshop: Mapping and Sampling the Arctic Ridges
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Table of Contents

Summary of Workshop Recommendations

The following are the main conclusions and recommendations from the workshop:

Where available, the bathymetric information collected from nuclear submarines during the SCICEX program are of sufficiently good quality to support sampling of the Gakkel spreading axis.

The scientific questions that can be uniquely addressed at the Gakkel Ridge are related to mantle processes, melt production and transport and crustal generation at extremely slow spreading rates. Addressing these questions requires a coordinated and systematic program of sampling and geophysical measurements along the Gakkel Ridge. The western (European) end of the Gakkel Ridge, as opposed to the eastern (Laptev Sea) end, should be seismically surveyed and sampled first because it is logistically easier, lies in international waters, has little or no sediment cover in the axis and is relatively well surveyed bathymetrically. The extreme slow spreading rate estimated for the eastern Gakkel makes it an attractive sampling target, in spite of the likely logistical and political difficulties that any cruise might encounter.

All reasonable sampling and seismic survey strategies on the Gakkel Ridge will involve two ships to deal with ice conditions. Both ships should have at least some science capabilities, but the scientific control of the mission must be clearly in the hands of one of the ships.

Planning windows exist in 2001 (*Polarstern*, Germany) and possibly in 2002 (*Healy,* USA) to bring ice-capable research vessels to the Arctic. An international funding effort will be needed to fund a second ship.

Critical scientific objectives in the area of biogeography and hydrothermal processes on the Knipovich Ridge can be addressed concurrently with the geophysical and geochemical studies of the Gakkel Ridge. Such studies can address critical biological and hydrothermal objectives for Arctic Ridge systems in general, while further defining specific objectives for later studies at the Gakkel Ridge.

The eastern termination of the Gakkel Ridge against the Laptev Shelf is a location where an active mid-ocean ridge impinges upon a continent and provides a unique opportunity to study MOR-continent interactions. The structure and active tectonics of the Laptev margin should be investigated during a second phase of field work on the Gakkel Ridge, which might also include sampling of the slowest spreading portion of the ridge.

Although present technology can accomplish many of the geological sampling goals on the Gakkel Ridge, these methods need to be refined, especially by minimization of time in the water, to deal with the special Arctic conditions. A smaller subset of sampling goals, in particular survey work requiring systematic coverage of the seafloor or water column, will likely require autonomous sub-ice vehicles that are at present outside the scope of the immediate funding and technological infrastructure.

Introduction

InterRidge first formally focussed its attention on the Arctic Ridges when it convened the 1994 workshop entitled "Arctic Ridges: Results and Planning" in Kiel. As the title suggests, the aim of this workshop was to collect together as much Arctic ridge data as was available at the time and to initiate dialogue between the many researchers with ridge-related interests north of Iceland. The ensuing workshop report, published in 1997, provided a clear overview of the state of Arctic ridge research at that time and contained several clear recommendations for how Arctic ridge studies should progress. Studying the Gakkel Ridge was identified as the highest priority, as up until that time it had been the subject of several geophysical studies but had been sampled, both for its rocks and sediments, only rarely. The 1994 workshop recommended that both reconnaissance-scale sampling of rocks, sediments and life forms (30-50 km sample spacing) and further geophysical work be carried out urgently.

The aim of the present workshop, with the title "The Arctic Ridges: Mapping and Sampling" was to formulate clear plans for getting these priority targets fulfilled. To achieve this aim workshop participants divided themselves amongst 4 working groups (Mapping, gravity and magnetics; Seismics; Rock and water sampling; and Hydrothermal vent processes) through which all participants could contribute towards the formulation of clear and practicable plans for studying high-priority objectives at Arctic Ridges, and at the Gakkel Ridge in particular. These plans include the identification of research platforms (ships, submarines, aircraft) for carrying out the studies and time windows for their use, estimation of the amount of time necessary for carrying out the planned studies and how many (and what type of) cruises this would involve, knowledge of the different procedures of proposal submission and cruise funding for the various countries concerned, and a clear time-frame in which the goals will be achieved. The results of these debates are presented in this report. It is a clear and concise plan for exploring the last geologically unsampled areas of the global spreading system.

Gakkel Ridge Background and New Results from SCICEX

The new survey results from the recent SCICEX program (see figure on the back cover) using U.S. Navy submarines (in addition to earlier studies (Kristoffersen et al., 1982; Kristoffersen and Husebye, 1985)), provide a basis for rationally planning the detailed sampling and geophysical program developed in this report. During the 1996 and 1998 cruises, large portions of the ridge axis west of 70°E were mapped to a distance of 40 km from the axis. After completion of the work planned for the 1999 cruise almost the entire ridge crest west of 100°E will have been mapped with swath bathymetry, sidescan and gravity data. These new data will reveal the morphology and structure of this extremely slow spreading ridge. The SCICEX underway data complement early Russian (Karasik, 1968) and U.S. (Vogt et al., 1979) aeromagnetic surveys that have been used to constrain the plate tectonic history of the Eurasian Basin determining the unique position of the Gakkel Ridge as the slowest spreading section of the world mid-ocean ridge system.

In the surveyed area west of 70°E, the Gakkel Ridge axis is located within a 20 km-wide deep rift valley. Axial depths between 20°E and 70°E are generally between 4600 m and 4800 m, but locally exceed 5000 m (Coakley and Cochran, 1998). A short portion of the rift axis farther west near 0°E shows axial depths of 4000 - 4350 m (Jokat et al., 1995). Gakkel Ridge axial depths are consistently deeper than observed on the Mid-Atlantic Ridge (MAR) where the maximum depth normally is in the range of 3500 m - 4000 m, only rarely reaching 4500 m depth.

The Gakkel Ridge rift flanks in the three western surveys are at a depth of about 3200 m, also several hundred meters deeper than typically observed at faster-spreading ridges. The ridge flanks are characterized by a lineated fabric of ridge-parallel abyssal hills. The abyssal hills are large and blocky reflecting the importance of tectonic extensional processes. Large scarps with relief of up to 1400 m are common not only at the axial valley, but also on the ridge flanks. Fault bounded troughs with relief of over 1000 m, reaching depths of over 4000 m are observed on the ridge flanks throughout the surveyed area.

The ridge axis to the west of 60°E is segmented at 50-100 km intervals by non-transform discontinuities of less than 20 km offset. The rift valley morphology is very asymmetric within segments. Outside corners are deep with low slopes and do not get much shallower than 3600 m. Inside corner highs are well developed with steep slopes and up to 3 km relief. They are similar to inside corner highs on the MAR, which are large "megamullions" or footwall blocks of low-angle detachment faults (Cann et al., 1997; Tucholke et al., 1998). As a result, exposures of mantle rocks at the seafloor may be widespread along the western Gakkel Ridge.

Large amplitude free-water anomalies are observed over the axis of the Gakkel Ridge, with peak-to-trough amplitudes of 85-150 mGal. These anomalies are 1.5 to 2 times larger than those observed over portions of the MAR with comparable bathymetric relief. Modeling of the crustal thickness and density, constrained by the bathymetry (Coakley and Cochran, 1998) requires crustal thicknesses of less than 4 km to match the free-water gravity anomalies. These conclusions are compatible with the limited seismic refraction data from the Eurasian Basin (Reid and Jackson, 1981)

The Gakkel Ridge rift mountains further east at 95°E are at a depth of >3800 m, 600 m deeper than at the Gakkel Ridge axis west of 60°E and >1000 m deeper than typical for the MAR. The rift valley in the eastern portion of the Gakkel Ridge, near 95°E is largely filled with sediments from the nearby Siberian shelf. In spite of this, the axis is associated with a 70 mGal free-water gravity minimum implying the presence of a large buried rift valley. Simple isostatic calculations imply that the crustal thickness at the eastern Gakkel Ridge axis may be vanishingly thin.

Scientific Objectives

Petrology and Geochemistry

The Gakkel Ridge occupies a unique position among the global spectrum of ridges. It is the slowest spreading mid-ocean ocean ridge, with the full spreading rate declining from 1.3 cm/year at the European end of the ridge near Greenland to 0.6 cm/yr at the eastern end in the Laptev Sea. The fastest spreading rate along the Gakkel Ridge is slower than the slowest spreading rate along the Southwest Indian Ridge (SWIR) — the other very slow spreading ridge that is currently undergoing extensive study. The Gakkel Ridge also has an exceptionally deep rift valley, and the thinnest known crust for a normal ridge. The two stations from which basalts have been recovered suggest that the crust has end member major and trace element characteristics as well (Figs. 5 and 6). Therefore, in many respects, the ridge occupies a unique place as an end-member of the global spectrum. It is virtually unsampled and there is a high quality swath bathymetry and geophysical data set in place for some portions of this ridge. The physical and chemical properties of the Gakkel Ridge should provide fundamental insights into global crustal accretion and mantle processes unattainable from any other source.

Its existence as an end member, however, is only a secondary reason for the petrological study of the ridge. Its primary importance is that the Gakkel Ridge offers a unique combination of the "forcing functions" that control the creation of the ocean crust, and this combination permits tests of competing models for ocean crust creation.

Major forcing functions that have been called upon to be important controls on spreading centers include spreading rate, mantle temperature, mantle source composition, tectonic setting and ridge obliquity. Competing models can usually be classified by which forcing function investigators have chosen to emphasize and model as a fundamental control. Because there are only a small number of ridges on the earth, there are relatively few combinations of these parameters, which makes it difficult to distinguish among these competing models. For example, is the pattern of geochemical variations along the SWIR due to its slow spreading rate, or due to its position above anomalous Indian Ocean mantle, or due to the high obliquity of many of its ridge segments and the fact that the ridge is "transform-dominated"? Is the high standard deviation of all geochemical parameters along the MAR due to its slow spreading rate, or is it simply a characteristic of the North Atlantic Ocean basin and the hot spots that occur there? Is the fact that the East Pacific Rise (EPR) has high geochemical variability at small wavelengths and extreme homogeneity averaged over long wavelengths due to its fast spreading rate, or is it a characteristic of the sub-Pacific mantle?

Study of the Gakkel Ridge provides important input for all of these questions, and many others as well, because of its combination of characteristics. It is very slow spreading, and yet it is not oblique, with no major transform faults. Therefore it allows a separation of variables in terms of obliquity and spreading rate. It is very slow spreading and does not reside in the anomalous Indian Ocean, therefore it can separate spreading rate effects from Indian Ocean effects. It is also relatively homogeneous for long distances in depth along strike, providing a useful comparison to the EPR, which shares this characteristic, and an important contrast to the MAR and SWIR, both of which are influenced by multiple hot spots.

An additional important aspect is that the Gakkel Ridge extends by more than a factor of two the minimum spreading rates available for study along the ocean ridge system. At these slow spreading rates, thermal models of sea floor spreading show that the effect of lithospheric cooling becomes increasingly important, with a reduction in melt generation and in crustal thickness. These two dimensional models do not take into account the possible importance of melt focusing along the ridge, nor are they calibrated with actual values for crustal thickness, lithospheric thickness and extent of melting at super-slow spreading rates. Such calibration is critical for being able to distinguish the relative importance of mantle temperature and spreading rate as controls on the overall thickness and composition of the ocean crust, with implications for the origin of ridges worldwide.

Therefore as an important end member, as the last geologically unsampled ridge, as a unique combination of forcing functions, and as the opportunity for powerful tests of competing models for most aspects of ocean crust creation, the Gakkel Ridge needs to be studied petrologically.

Geophysics

The critical issue that can be addressed using geophysics at Gakkel Ridge better than on any other mid-ocean ridge is how the exceptionally slow spreading rates have influenced melt production in the mantle, melt migration through the lithosphere, crustal genesis and tectonism associated with the seafloor-spreading process. New information is needed to provide more reliable constraints on such problems. Geophysics may shed new insight into these issues by providing information about the physical state of the mantle, the thickness and temperature of the crust, and the morphology and segmentation of the actively spreading axis. Here, active and passive seismic methods are the most important experiments to increase our understanding on the ridge processes.

Crustal thickness, which is a measure of the total melt production rate, is known to be exceptionally thin at the Gakkel Ridge. Gravity studies (Coakley and Cochran, 1998) imply that a crustal thickness of less than 4 km is characteristic of the western Gakkel Ridge. Whether or not crustal thickness varies systematically - and smoothly - with spreading rate needs to be established with additional seismic measurements. Both on and off axis measurements should be made, since spreading rates (as determined by magnetic lineations) have varied with time as well as latitude. Active refraction techniques will also allow for the investigation of structural heterogeneities associated with amagmatic extension, such as uplifted blocks of serpentinite or mega-mullions.

Melt production in the mantle is related to mantle temperature through its effect on the depth range of melting. Anomalously low melt production at ultra-slow spreading rates (resulting in the thin crust mentioned above) has alternatively been ascribed either to an anomalously shallow maximum depth of melting (i.e. anomalously cool upwelling), or to an anomalously deep minimum depth (i.e. a thick lithosphere). Measurements of upper mantle seismic structure provide a method of distinguishing between these models. The recording stations of the passive seismic experiment should be supplemented by hydrophones which can detect micro-seismic activity along and off axis to monitor the current tectonic activity.

The resistivity structure of the oceanic mantle and lithosphere also constrains these models. In the oceans, it is most successful at determining the depth to a conducting layer beneath a more resistive layer (partial melt zone or high temperature region beneath the cooler lithosphere) (Forsyth, 1992). By using the electromagnetic waves over a broad range of frequencies penetrating to different depths in the earth, the resistivity structure as a function of depth can be sampled. These magnetotelluric observation techniques could be conducted on the same locations as the passive seismic stations.

Shipborne magnetic and gravity data should complement the seismic data set. Both data sets will allow to describe the crustal structure in greater detail together with the seismic information. It will also complement the existing data sets concerning smaller wavelengths along and perpendicular to the ridge axis.

The described experiments should be located along axis as well as off axis to describe the present and past evolution of the ridge. Critical areas are around 0-20°E and 60-80°E, where the available data suggest major changes in topography and crustal composition.

A geodynamic understanding of the evolution of the spreading system in the Eurasia Basin can be derived from the sedimentation history of the adjacent basins. Here, parameters such as basement topography or the subsidence rate of the ridge flanks away from the spreading axis give insights into how very slow spreading ridge systems evolve. Seismic imaging techniques can provide this information in great detail. Knowledge of the sedimentary cover over the ridge and the adjacent areas and the subsidence history as determined from mapping reflectors within the seismic section is a critical parameter for interpretation of other geophysical data such as magnetic, gravity and heat flow.

This is especially valid for the Gakkel Ridge close to the Laptev Sea Shelf where it is known from Russian seismic data that the ridge is completely buried by sediments (Sekretov, 1998). Here, the Gakkel Ridge spreading center terminates abruptly against a fracture zone at the base of the Laptev shelf. This transform/continent-ocean boundary separates a well developed mid-ocean ridge from a broad zone of diffuse continental rifting and must have formed early in the history of the Eurasian Basin. It is unknown how crustal and lithospheric structures change from the Eurasian Basin through the rifted Laptev shelf to the unthinned continental crust, and if these changes inhibit further rift propagation, similar to what has been proposed for the northern Red Sea. While it is obvious that this area should be investigated in great detail, the workshop participants judged that it is logistically and thematically impractical to include an investigation of the Laptev margin with the study of melt production and transport and crustal generation at extremely low spreading rates which was deemed the primary objective. An investigation of the easternmost Gakkel Ridge and its interaction with the Laptev Shelf should occur as a second phase of study of the Gakkel Ridge following shortly after the primary field program, and could be integrated with other groups (Nansen Arctic Drilling; MARGINS) who may be interested in these problems.

Hydrothermal Processes

Arctic hydrothermal systems in general have a high probability of supporting novel fauna based on both the relative youth of the basin and ridge system, and their isolation from deep waters of Atlantic and Pacific Basins. While hydrothermal sites on the Knipovich Ridge may go far toward addressing this goal, the Gakkel Ridge is further isolated bathymetrically with at present only a narrow deep-water access route. In addition, because the Gakkel and Knipovich Ridges lie under water which is unstratified during portions of the year, they are singular places along the global mid-ocean ridge system where hydrothermal plumes may penetrate to surface layers, including the euphotic zone and atmosphere above. Thus, there is potential for contributions to surface productivity and the global greenhouse budget. Also, because the ridges spread at an ultra-slow rate, new classes of hydrothermal vents and mineral deposits may be discovered.

Because the likelihood of locating a hydrothermal vent underneath the Arctic sea ice cover is very slim in the time frame of the next five years, hydrothermal investigations should focus on hydrothermal communities in other Arctic environments, such as the well-studied Knipovich Ridge. The hydrothermal processes working group realized that this is somewhat tangential to the thrust of the other working groups, they feel however that at least some of the important goal of arctic hydrothermal research can be achieved in relatively ice-free regions. As the Knipovich Ridge lies well north of Iceland and abuts the Gakkel Ridge it is a likely site for a high degree of endemism in the biological community. The Knipovich Ridge has been well mapped by sonar, and several hydrothermal parameters — including temperature anomalies, metalliferous sediments, and possible relict sulfides — have already been located. It will be important to establish the localization and characterization of both active and inactive hydrothermal systems with an emphasis on biological, chemical, mineralogical features relative to their geological settings. A ridge-scale survey to determine the frequency of venting within the context of the volcanic and morphotectonic setting of the rise axis is highly recommended.

Cruise Plans

A two or three step science plan is envisioned for the Gakkel Ridge. The first phase will follow up on the initial reconnaissance work of the SCICEX project in the western (European) sector of the Gakkel Ridge. This phase will focus on the plumbing-melt distribution and petrological products in this relatively simple plate boundary with a spreading rate of 1.3 cm/yr. Second and subsequent phases should move progressively eastward to focus on the even slower spreading (0.6 cm/yr) eastern (Russian) end of the ridge at its termination against continental crust. The rationale behind this sequence of studies is that first, SCICEX submarine swath bathymetry exists from the western part of the ridge, and is sparse or absent elsewhere. Second, the western Gakkel Ridge is closer to Fram Strait and is therefore logistically easier to reach. Third, much of it lies in international waters, or in EEZs of nations with whom agreements will soon be reached. Parts of the eastern Gakkel Ridge lie in the Russian EEZ. Fourth, there is much less sediment cover along the western part of the ridge, so it will be easier to locate and choose exposed sample sites, in some cases using sediment-thickness data from SCICEX. Under ideal conditions, which are unlikely to be experienced in the Arctic, an initial cruise could sample rocks and some fluids from up to a third to one half of Gakkel Ridge. Sampling on subsequent cruises should proceed to the central and then to the eastern parts of Gakkel Ridge as scientific knowledge and technical experience increase. Despite the additional logistical and operational challenges, the eastern end of Gakkel Ridge is extremely interesting because the spreading rate becomes even slower. This area is, however, structurally complex and will require the input and examination of substantial Russian data prior to cruise planning.

While the workshop participants recognized the importance of proceeding with a focused study of the Gakkel Ridge to meet petrological and geophysical, it is clear that opportunities to study the Knipovich Ridge will provide the earliest means of achieving hydrothermal objectives (biology, geology, chemistry) at Arctic Ridges. Such studies are not the principal focus of the cruise plans given here, but the workshop participants recognized the importance of these objectives and of concurrent cruises to undertake the study of hydrothermal processes at the Knipovich Ridge while preparing for future opportunities to conduct similar studies at the Gakkel Ridge.

The aims of the different interest groups on these cruises are as follows:

Petrology

Sampling of basalts and peridotites should be a major component (at least half) of the first multidisciplinary icebreaker cruise dedicated to the study of Gakkel Ridge, and of subsequent cruises as well. A reconnaissance hydrothermal survey could be efficiently executed in parallel with a rock sampling program by deploying NOAA MAPR devices (Baker and Milburn, 1997) on the wire during every rock sampling attempt. Sampling should include a first-order regional study that would recover rocks approximately every 30 km. This spacing is in accord with global guidelines developed by RIDGE and InterRidge, and is supported by studies of the SWIR and other slow-spreading ridges. Sampling along axis should aim to recover peridotites as well as basalts in a systematic fashion. Samples should be taken as close to the axis as possible, although axial samples may be unattainable in some cases because of ice or bottom sediment conditions. However, even samples that are recovered even *slightly* off-axis would be useful in this regional study. It is unlikely that samples could be effectively recovered at the distances off-axis needed for cross-axis seismic studies. Backscatter and CHIRP seismic data from the 1998 SCICEX cruise show that the rift valley is sediment free to the west of 70°E which will allow a systematic sampling program. Portions of the rift valley on the eastern Gakkel ridge are sediment covered, so sample spacing there may be more variable and dictated by the availability of local outcrops.

In addition to the regional sampling program, somewhat less than half of the sampling effort should be devoted to more detailed studies that focus on specific problems. These could be chosen to complement the work of other disciplines, such as geophysics. They could include a vertical sampling of steep scarps to understand crustal structure; and studies of variation in mantle melting and crustal composition within individual segments. The exact locations of where these studies should be made will become clear as the SCICEX swath bathymetry data begin to be analyzed. Additionally, detailed sampling of hydrothermal fluids, rocks and sediments should be undertaken in areas where the MAPRs indicate hydrothermal plumes. This would fulfill two objectives - the changing strength of the MAPR signal with multiple deployments will help pinpoint the source of hydrothermal venting, and at the same time detailed rock sampling in a hydrothermally active area will be undertaken.

Geophysics

While the new SCICEX side scan and bathymetric data from 1998 and 1999 will give scientists an unprecedented view on the Gakkel Ridge topography, several ice breaker expeditions are needed to collect the full range of geophysical information guided by the then available bathymetry. For the seismic investigations, airguns and streamers of variable size and lengths will be used to acquire high resolution sedimentary and crustal data. Critical for the success of these experiments is the support of a second ice breaker. This ship has to break a more or less ice free channel in which the instruments can be deployed and towed. Therefore, a two ship expedition is essential for the geophysical experiments. The following geophysical methods should be employed during the first interdisciplinary cruises to Gakkel Ridge.

Seismic investigations:

· Active source seismic refraction. Seismic refraction measurements must be made to determine whether or not crustal thickness varies systematically - and smoothly - with spreading rate. Both on and off axis measurements should be made, since spreading rates (as determined by magnetic lineations) have varied with time as well as latitude. At least two long transects (600 km each) perpendicular to the ridge axis deep into the Nansen and Amundsen basins at 60°E and 25°E are required to provide new information on a possible relationship between spreading rate and crustal thickness.

· Passive seismics. Observations of teleseismic, regional, and local earthquakes will greatly improve understanding of the tectonics and deep structure of the Gakkel Ridge. Measurement of upper mantle seismic structure, by either refraction techniques (i.e. Pn velocities) or teleseismics (i.e. P-wave tomography and surface wave dispersion), provides a method of distinguishing between competing models of melt production, since seismic velocity correlates with temperature and melt fraction. This could be accomplished using a 2-D array of instruments centered on the axial valley up to 150 km away. Any passive seismic experiment should also be designed to study micro-earthquakes, which provide critical constrains on the crustal structure and current tectonic activities. The experiment should ideally be located between 0°-10°E. The use of ocean bottom seismometers (OBS) for such an experiment is highly recommended. However, critical for the success of using OBS in an area with heavy pack ice is a safe method to retrieve the instruments and/or data. At present a number of techniques are under considerations, including the use of AUVs and long-term "observatory" style instrument deployments. Long-term (at least 1 year) deployments are crucial to the success of any passive seismic experiment. Until under-ice seismic instrumentation is developed, an interim solution would be to use stations on ice floes. The instruments (with

GPS clock and positioning) should be broadband stations plus at least one hydrophone per station. Instruments can be deployed at the beginning of the cruise and retrieved, or interrogated and downloaded, 30-40 days after the end of the cruise. These experiments would be more feasible if they were supported by a hovercraft or submarine.

· Multichannel seismics. Multichannel seismic investigations perpendicular to the ridge axis across the entire basin will be able to map in detail the sediment distribution. Streamer and airguns should be used for this kind of experiment. Due to problems with ice floes only a short streamer length of 300-1000 m might be suitable. Sonobouys, which could provide wide-angle information up to 30 km, should be deployed to retrieve information on the seismic velocities in the sediments and upper crust.

Other investigations:

· Shipborne magnetic and gravity data to complement the seismic data set and existing data sets.

· Magnetotelluric recording stations should be deployed together with the 2D seismological array to retrieve information on the conductivity of the mantle. In addition, recording instruments should be deployed on ice floes close to the ship for 12 to 24 hours. This can be done in parallel to the sampling activities on the ships.

Hydrothermal Processes

A first-order survey of water column, sediment and heat-flow properties is needed to localize regions of high- and low-temperature hydrothermal potential in regions of bare rock or sediment-covered environments on the Gakkel Ridge. The strategy for accomplishing this may be multi-stepped, initiated by a reconnaissance program during a multidisciplinary cruise that maximizes use of NOAA MAPRs on dredge wires, CTD casts according to a deployment strategy based on topographic or other seafloor features, sediment coring, and heat-flow studies. If compelling indicators of hydrothermal activity are discovered during this reconnaissance program (especially serendipitous collection of sulfides or vent biota in dredge hauls or in ground-truth images from the video grab or other imaging platform), diversion of ship resources to characterize the hydrothermal system should be carefully considered.

Plume prospecting (including microbiology): Traditional vertical CTD/rosette casts will provide reliable data acquisition when equipped with appropriate instrumentation, including nephelometer, Mn and CH4 sniffer, *in-situ* biological sensors, shipboard methane and other water chemistry analyses, and microbial analysis of water samples. Biological sensors that measure biomass and other attributes require technological development. When available, the NOAA MAPR should be used on any wire going over the side to identify hydrothermal plumes.

In cases where OBSs are deployed on the seafloor, current meters and CTDs may also be installed for continuous, long-term sampling of the bottom water.

Heat Flow, Sediment Cores, Grab and/or Dredge Sampling: Because of the paucity of data, heat flow stations should be spaced every 10-25 km when possible. This will help refine the understanding of both the large scale tectonic plate boundary patterns as well as place some controls on the dimensions of segmentation of the present day rise axis. Optimum orientation of the heat flow sampling should be along the ridge axis; off-axis data are also necessary. Sediment cores (up to 20 m in length) should be collected at intervals of 25 km both parallel to the ridge axis as well as off-axis. Cores should be analyzed for metalliferous sediments and pore-water chemistry. In the hydrothermal arena, the cores will provide information about the age, rates and magnitude of past hydrothermal activity. Grab and/or dredge samples should be collected in potential hydrothermal sites.

Macrobiology: In the absence of data on the location of hydrothermal vents, the initial Gakkel Ridge cruise is unlikely to deliver substantial macrofaunal samples. To ensure that cruise participants are prepared for chance encounters with hydrothermal or other interesting faunas, a 'BioBox' equipped with preservatives, sample jars and instructions should be onboard. In addition, a shore-based biologist should be on call for consultation via phone or e-mail should TV-grabs or other sampling/imaging methods discover interesting biology. If vent fauna is encountered, the Chief Scientist should be prepared to pursue a diversion of cruise objectives to ensure that the vent fauna is documented as thoroughly as possible. The InterRidge Office also has copies of the Handbook of Deep-Sea Hydrothermal Vent Fauna which are available on loan to cruises to aid identifying any chance biology recovered during the cruise.

Ship Requirements and Schedules

A proposal to use the *Polarstern* for a science program on the Gakkel Ridge in 2001 has been submitted (Jokat). Subsequent cruises should be scheduled as additional proposals are funded.

Potential ice conditions in the operational area require that *Polarstern* or any of the science-capable icebreakers be accompanied by a second icebreaker. This situation presents an opportunity to develop two-ship science programs that include sampling as well as geophysical studies. The ship(s) that are used for sample recovery must be capable of efficiently and safely deploying the array of tools that are described below. This means that they must have reliable and fast winches with the correct wire or cable characteristics. The trawl winch should be rapidly switchable between conductive cable and 18 mm wire, for example. There must also be space on the deck to store the equipment and process the rocks. In some cases, a crane might be needed to empty dredges. A certain amount of lab space for analytical equipment (or space for a lab van on deck) is also important.

For maximum effectiveness, both ships of a two ship expedition should have science capabilities. However, it is crucial that such an expedition be carefully planned with priorities and contingencies considered and agreed upon by all parties beforehand, and adhered to during the cruise. *Polarstern* has proven herself capable of most of the scientific operations, and should probably be the primary science ship. Under the most favorable ice conditions, the two ships could work nearly independently. Even in this situation, two ships would not be able to accomplish twice the amount of science as one ship, because the ships would need to stay fairly close together. Under the least favorable ice conditions, one ship would become a dedicated icebreaker and accomplish none of the science goals. This latter possibility highlights the need for the second ship (besides the *Polarstern*, for example) to be a highly effective icebreaker. Icebreaking ability should perhaps be the priority in selection of the second ship. If the second ship is provided at a reduced cost, it should *not* be under conditions (such as an additional science program) that would jeopardize any of the science plans for Gakkel Ridge.

Suitable platforms for the second icebreaker include the *Healy* (USA), the *Louis St. Laurant* (Canada), the *Oden* (Sweden), and the *Kapitan Dranitsin Class* (Russia). The new US icebreaker *Healy* (USA) will undertake science as her primary mission so will be fully science capable, and could conceivably serve as either the primary or secondary science icebreaker on some expeditions. She will be ready for science operations in 2001, although her early schedule and her icebreaking capabilities are presently undetermined. Non-scientific icebreakers can rarely perform all of the tasks of a scientific icebreaker, but certain ships could probably be adapted, based on past experiences. The *Oden* (Sweden) is an effective icebreaker and has previously participated in science missions, including an attempt at dredging. She might be the best icebreaker that is also adaptable for scientific work. Russian ice breakers are the most effective at breaking ice and could probably be hired without involving conflicting science plans. However, it is unclear whether they could be adapted at all for scientific work. The *Louis St. Laurent* (Canada) is an effective icebreaker and has successfully sampled Arctic basement rocks. The Canadian Coast Guard is presently developing procedures that would enable an international program to utilize Canadian icebreakers on a cost basis that presumably could be negotiated.

For the seismological program two helicopters are needed, for the deployment and recovery of ice-based seismological and magnetotelluric stations, at times at considerable distances from the ships.

Equipment Needs

Technological developments in sample recovery methods are highly desirable. Rapid vertical sampling techniques, that reliably return sample are urgently needed to work efficiently on the up to 5200 m deep Gakkel Ridge. However the basic goals can be accomplished with existing technology. The suite of sampling tools that are currently available could be adapted to work more effectively and efficiently in the Arctic. Engineering and development work should proceed immediately to ensure that revised and existing sampling methods are tested for Arctic conditions. All of the sampling tools should be available on-board one or both ships of a two ship expedition so that scientists are able to sample under a variety of ice and bottom conditions.

Petrology

Dredges will be useable only under the most favorable ice conditions, since they require extreme maneuverability of the ship. They are capable of recovering samples from steep terrain, and require no further development. Dredging requires a trawl winch and is relatively slow. Several dredges (up to 10) should be on board ships.

The TV grab manufactured by Preussag will be most successful if it can be modified to receive power from the cable and not from batteries. Batteries provide less power and their weight causes the TV grab to be unstable on slopes, which might be common and will provide the best sampling locations. The TV grab is capable of collecting peridotites and basalts. It requires a trawl winch with a fiber optic/conducting cable. Two TV grabs should be on-board.

The wax corer is the fastest sampling method and requires only a hydrographic winch. It works best when collecting fresh glass from medium- and fast-spreading ridges, but has had some success on slow-spreading ridges. It recovers small samples that are insufficient for studies of peridotite and gabbro. The wax corer could be improved, perhaps by making it larger and heavier.

Box corer or piston corers have successfully recovered basement rocks from the Arctic Ocean. This method should be developed further so that larger samples can be recovered more frequently. This may involve making the device heavier or stronger. Two or three of these should be on-board.

Geophysics

Seismic reflection experiments

600 to 1000 m Streamer (2 winches)

Sonobouys for recording wide angle seismics

24 liter Airgun Array

10 liter GI Airgun Array for heavy ice conditions

Seismic refraction experiments

32 liter airgun or 60 liter airgun if ice permits

5-10 REFTEK recording stations

Passive Seismics

around 20 REFTEK recording stations for seismological studies

disposable ocean-bottom seismometers (prototypes?) or a method for safe

instrument retrieval

Others

Shipmounted gravitmeter on Polarstern is available (KSS31)

Magnetic sensors on Polarstern might be available

up to 5 Magnetotelluric recording stations

Hydrothermal Processes

CTD

NOAA MAPR

Heat Flow spear and probes, conductivity apparatus

Remote Sensing - If hydrothermal plumes in the Arctic reach the surface and affect surface characteristics (chemistry, biological productivity, etc.), it may be possible to detect such plumes through the use of airborne or space-based sensors. The current SeaWIFS spacecraft may provide data of sufficient temporal and spatial resolution to observe such plumes, while a variety of airborne sensors may also be used to gain similar data.

APPENDIX: Technological Developments/Solutions for the Future

AUVs: Autonomous underwater vehicles (AUVs) are at present outside the scope of the immediate funding and technological infrastructure. But they have undergone technological improvements in recent years and are fast-becoming capable instrument platforms for benthic and water column exploration. They could potentially contribute to Arctic science operations in the future. The biggest problem with using AUVs in the Arctic is navigation. Magnetic compasses are not usable for most of the Arctic and the performance of inertial/north-seeking systems deteriorates near 90°N. These problems are mostly solvable, but will incur some additional expenses. Long endurance operations (i.e. free of ships) are extremely challenging since the ice cover greatly complicates both navigation, communication and recovery. Currently buoys are being developed which will melt through the ice to solve this problem.

Because AUVs do not require a cable for instrument deployment and data return, they have particularly good characteristics for under-ice exploration of ridge systems in the Arctic. By deploying a vehicle that can accomplish its science objectives and then autonomously rendezvous with a ship, concerns about ice-interference with data collection can be much reduced. A wide range of sensors can be integrated on AUVs. Especially attractive are sensors that could obtain data that cannot be collected easily by SCICEX submarine or surface ships, such as plume parameters and magnetics, as well as high-frequency, near bottom side scan imaging. Additional technological refinements are required to ensure that sufficient range and specific instrumentation capabilities are available to fulfill the growing promise of these vehicles. AUVs have a further advantage in that they are amenable to deployment from platforms of opportunity.

In the future, AUVs might also be used to conduct OBS experiments. While OBSs can be deployed in the Arctic, the problem is their recovery in ice-covered conditions. However disposable OBSs can be built, from which the data could be retrieved with an AUV. The AUV could be used to either download the data from the OBS after hooking in to the OBS on the bottom, or it could retrieve a small pressure case directly from the OBS, or from the underside of the ice after it was released from the OBS. The small pressure case would carry a disk drive with the data.

Of particular interest is the development of small AUVs that could be deployed autonomously through the ice cover to respond to events on the ridge system that might be detected by seismographic stations, etc. Such vehicles are under discussion by NASA in preparation for a mission to Europa, the ice-covered moon of Jupiter that may possess an ocean and hydrothermal systems. While it is unlikely that such a system would be routinely affordable for Arctic ridge studies, a development and test program for the future Europa mission focused on the Gakkel Ridge may be able to return unique data to aid our understanding of Arctic Ridges on Earth.

Other Technology questions to be solved

- What is the best way to carry out a systematic rectilinear mapping survey in ice covered areas? This is specifically needed in the western and eastern ends of the Gakkel that will not covered by the SCICEX surveys.

- Is there a way to collect magnetics data? Aeromagnetic data is excellent but coregistered data sets are needed. Can a 3-component magnetometer be mounted on a ship or AUV?

- Is there any way to do a deep tow type experiment (Argo - near bottom sidescan photographs), possibly using an AUV through a moonpool?

- Is there a way to measure microbial biomass or activity?

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Workshop Participants

Dr. Sergey V. Aplonov
TETHYS Geodynamical Research Center
P.O. Box 788
199155 St. Petersburg
RUSSIA
Tel: +7 812 352 3018
Fax: +7 812 351 8748
aplonov@tethys.spb.su

Prof. Enrico Bonatti
Instituto di Geologia Marina C.N.R.
Universita di Bologna

Via P. Gobetti 101
I-40129 Bologna
ITALY
Tel: +39 51 639 8935 or +1 914 365 8699
Fax: +39 51 639 8939 or +1 914 365 3181
bonatti@ldeo.columbia.edu

Dr. Georgiy A. Cherkashev
Department of Oceanic Minerals
VNIIOkeangeologia
1 Angliysky Prospect
190121 St. Petersburg
RUSSIA
Tel: +7 812 114 5998
Fax: +7 812 114 1470
hydroth@g-ocean.spb.su

Dr. Bernard J. Coakley
Assistant Professor
Department of Geology
Tulane University
New Orleans, Louisiana 70118
USA
Tel: +1 504 862-3168
Fax: +1 504 865-5199
bcoakle@mailhost.tcs.tulane.edu

Dr. James R. Cochran
Lamont-Doherty Earth Observatory
Columbia University
61 Route 9W
P.O. Box 1000
Palisades NY 10964
USA
Tel: +1 914 365 8396
Fax: +1 914 365 8179
jrc@ldeo.columbia.edu

Dr. Kathleen Crane
Department of Geography
Hunter College
695 Park Avenue
New York NY 10021
USA
Tel: +1 202 404-1107
Fax: +1 202 767 0167
kathyc@hp8c.nrl.navy.mil

Dr. Detlef Damaske
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
Postfach 51 01 53
D-30655 Hannover
GERMANY
d.damaske@bgr.de

Dr. Colin W. Devey
Fachbereich 5 Geowissenschaften
Universität Bremen
Postfach 330440
D-28334 Bremen
GERMANY
Tel: +49 421 218 7162
Fax: +49 421 218 7163
cwdevey@uni-bremen.de

Dr. Jane Dionne
Arctic Natural Sciences
National Science Foundation
4301 Wilson Blvd. Room 755
Arlington , VA 22230
USA
Tel: +1 703 306 1033
Fax: +1 703 306 0139
jdionne@nsf.gov

Dr. Margo Edwards
Hawaii Institute of Geophysics
University of Hawaii at Manoa
2525 Correa Road
Honolulu HI 96822
USA
Tel: +1 808 956 5232
Fax: +1 808 956 2538
margo@soest.hawaii.edu

Dieter Franke
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
Postfach 51 01 53
D-30655 Hannover
GERMANY
franke@sdac.hannover.bgr.de

Prof. Dr. Garrik Grikurov
VNIIOkeangeologia
1 Angliysky Prospect
190121 St. Petersburg
RUSSIA
Tel: +7 812 113 8379
Fax: +7 812 114 1470
vniio@g-ocean.spb.su

Dr. Vladimir Glebowsky
VNIIOkeangeologia
1 Angliysky Prospect
190121 St. Petersburg
RUSSIA
Tel: +7 812 114 5892
Fax: +7 812 114 1470
gleb@vniio.nw.ru

Dr. Nancy R. Grindlay
Department of Earth Sciences
University of North Carolina at Wilmington
601 South College Road
Wilmington, NC 28403-3297
USA
Tel: +1 910 256-3721 x223
Fax: +1 910 962-7077
grindlayn@uncwil.edu

Mr. Eric Hellebrand
Abteilung Geochemie
Max-Planck Institut für Chemie
Postfach 3060
D-55020 Mainz
GERMANY
Tel: +49 6131 305 220
Fax: +49 6131 371 051
ehelle@geobar.mpch-mainz.mpg.de

Prof. Karl Hinz
Bundesanstalt für Geowissenschaften und Rohstoffe

Stilleweg 2
D-30655 Hannover
GERMANY
Tel: +49 511 643 3247
Fax: +49 511 643 3247
karl.hinz@bgr.de

Dr. H. Ruth Jackson
Geological Survey of Canada (Atlantic)
Bedford Institute of Oceanography
PO Box 1006
1 Challenger Drive
Dartmouth, NS B2Y 4A2
CANADA
Tel: +1 902 426 3791
Fax: +1 902 426 6152
jacksonr@agc.bio.ns.ca

Dr. Wilfried Jokat
Alfred-Wegener-Institut für Polar- und Meeresforschung
Postfach 120161
Columbusstraße
D-27515 Bremerhaven
GERMANY
Tel: +49 471 4831 211
Fax: +49 471 4831 149
jokat@awi-bremerhaven.de

Frauke Klingelhoefer
Département de Géosciences Marines
Direction des Recherches Océaniques
IFREMER Centre de Brest
B.P. 70
F-29280 Plouzané Cédex
FRANCE
Tel: +33 2 98 22 47 07
Fax: +33 2 98 22 45 49
frauke.klingelhoefer@ifremer.fr

Dr. Yngve Kristoffersen
Institute of Solid Earth Physics
University of Bergen
Allegaten 41
N-5007 Bergen
NORWAY
Tel: +47 55 213 407
Fax: +47 55 320 009
yngve.kristoffersen@ifjf.uib.no

Greg Kurras
Post 842A
University of Hawai'i
Dept. of Marine Geology & Geophysics
1680 East West Rd
Honolulu HI 96822
USA
Tel: +1 808 956 3593
Fax: +1 808 956 6530
kurras@soest.hawaii.edu

Dr. Charles H. Langmuir
Department of Geochemistry
Lamont-Doherty Earth Observatory
Columbia University
P.O. Box 1000
Palisades NY 10964
USA
Tel: +1 914 365 8657
Fax: +1 914 365 8155
langmuir@ldeo.columbia.edu

Dr. Lawrence A. Lawver
Institute for Geophysics
University of Texas at Austin
4412 Spicewood Springs Road, Building 600
Austin, TX 78759-8500
USA
Tel: +1 512 471 0433
Fax: +1 512 475 6338
lawver@utig.ig.utexas.edu

Dr. Paul Mann
Institute for Geophysics
University of Texas at Austin
4412 Spicewood Springs Road
Building 600
Austin, TX 78759-8500
USA
Tel: +1 512 471 0452
Fax: +1 512 471 8844
paulm@utig.ig.utexas.edu

Dr. Sergei P. Maschenkov
VNIIOkeangeologia
1 Angliysky Prospect
190121 St. Petersburg
RUSSIA
Tel: +7 812 114 5892
Fax: +7 812 114 1470
mascha@vniio.nw.ru

Dr. Peter J. Michael
Department of Geosciences
University of Tulsa
600 South College Avenue
Tulsa OK 74104-3189
USA
Tel: +1 918 631 3017
Fax: +1 918 631 2091
pjm@utulsa.edu

Dr. Richard Mühe
Institut für Geowissenschaften
Olshausenstr. 40
D- 24118 Kiel
GERMANY
Tel: +49-431-880-2818
Fax: +49-431-880-4376
rmuehe@gpi.uni-kiel.de

Dr. Sönke Neben
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
D-30655 Hannover
GERMANY
Tel: +49 511 643 3128
Fax: +49 511 643 2304
neben@sdac.hannover.bgr.de

Dr. Nilgun Okay
Istanbul Teknik Universitesi
Maden Fak
Jeoloji Bolumu
Ayazaga, Istanbul 80926
TURKEY
Tel: + 90-2122856143
Fax: + 90-2122856210
okayn@itu.edu.tr

Alexey L. Piskarev
VVNIIOkeangeologia
1 Angliysky Prospect
190121 St. Petersburg
RUSSIA
Tel: +7 812 114 5502
Fax: +7 812 114 1470
piskarev@g-ocean.spb.su

Dr. Christian Reichert
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
Postfach 51 01 53
D-30655 Hannover
GERMANY
Tel: +49 511 643 3244
Fax: +49 511 643 3244
reichert@bgr.de

Dr. Roland Rihm
Institute of Geophysics
Universität Hamburg
Bundesstrasse 55
D-20146 Hamburg
GERMANY
Tel: +49.40.3039.9576 or +49.40.4123-2973
Fax: +49.40.3039.9578 or +49.40.4123-5441
geopro@geopro.de

Dr. Hans Albert Roeser
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
Postfach 51 01 53
D-30655 Hannover
GERMANY
Tel: +49 511 643 2799
Fax: +49 511 643 3663
hans.roeser@bgr.de

Dr. Walter R. Roest
Continental Geoscience Division
Geological Survey of Canada
615 Booth Street
Ottawa, ON K1A 0E9
CANADA
Tel: +1 613 992 1546
Fax: +1 613 952 8987
roest@gsc.nrcan.gc.ca

Dr. John D. Rummel
Marine Resources Center
Marine Biological Laboratory
7 MBL Street
Woods Hole, MA 02543
USA
Tel: +1 (508) 289-7218
Fax: +1 (508) 289-7900
jrummel@mbl.edu

Dr. Yang Shen
University of Rhode Island
Graduate School of Oceanography
Narragansett, RI 02882
USA
Tel: +1 401-874-6709
Fax: +1 401-874-6811
yshen@whoi.edu

Dr. Jonathan E. Snow
Abteilung Geochemie
Max-Planck Institut für Chemie
Postfach 3060
D-55020 Mainz
GERMANY
Tel: +49 6131 305 202
Fax: +49 6131 371 051
jesnow@geobar.mpch-mainz.mpg.de

John W. Steritz
EXXON Exploration Company
16945 Northchase
P.O.Box 4778
Houston, Texas 77210-4778
USA

Dr. Kensaku Tamaki
Ocean Research Institute
University of Tokyo
1-15-1 Minamidai
Nakano-ku, Tokyo 164,
JAPAN
Tel: +81 3 5351 6443
Fax: +81 3 5351 6445
tamaki@ori.u-tokyo.ac.jp

Dr. Franz Tessensohn
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2
Postfach 51 01 53
D-30655 Hannover
GERMANY
franz.tessensohn@bgr.de

Anahita Tikku
Scripps Institution of Oceanography
Univ. of California San Diego
MC-0208
La Jolla, CA 92093-0208
USA
Tel: +1 619-534-0961
Fax: +1 619-534-0784
atikku@ucsd.edu

Dr. Cindy Lee Van Dover
The College of William & Mary
Biology Department
PO Box 8795
328 Millington Hall
Williamsburg, VA 23187
USA
Tel: +1 757 221-2229
Fax: +1 757 221-6483
clvand@facstaff.wm.edu

Iris van der Zander
Institut für Geowissenschaften
Becherweg 21
Universität Mainz,
D-55099 Mainz,
GERMANY
Tel:
Fax: +49 6131 39 4769
iris@geobar.mpch-mainz.mpg.de

Prof. Dr. Viereck-Götte
Institut für Geowissenschaften
Fachgruppe Geochemie
Frierich-Schiller-Universität Jena
Burgweg 11
D-07749
GERMANY
Tel: +49 3641 94 8720
Fax: +49 3641 94 8602
viereck@geo.uni-jena.de

Dr. Estella Weigelt
Alfred-Wegener-Institutes für Polar- und Meeresforschung
Columbusstraße
27568 Bremerhaven
GERMANY
eweigelt@awi-bremerhaven.de

Dr. Cara Wilson
InterRidge Office
Laboratoire de Pétrologie
Université Pierre et Marie Curie (Paris 6)
4 place Jussieu
F-75252 Paris Cédex 05
FRANCE
Tel: +33 1 44 27 75 78
Fax: +33 1 44 27 39 11
intridge@ext.jussieu.fr

Dr. Andrew Zayonchek
VNIIOkeangeologia
1 Angliysky Prospect
190121 St. Petersburg
RUSSIA
Tel: +7 812 210-9454
Fax: +7 812 114 2088
andrew@vniio.nw.ru

Workshop Working Groups

Mapping Working Group: James Cochran (convener), Bernard Coakley, Margo Edwards, Nancy Grindlay, Greg Kurras, Paul Mann, Sergei P. Maschenkov, Hans Albert Roeser, Walter Roest, Kensaku Tamaki, Anahita Tikku, and Andrew Zayonchek.

Seismic Working Group: Wilfried Jokat (convener), Vladimir Glebovsky, Garrik Grikurov, Karl Hinz, Ruth Jackson, Frauke Klingelhoefer, Yngve Kristoffersen, Soenke Neben, Christian Reichert, Roland Rihm, and Yang Shen.

Sampling Working Group: Peter Michael (convener), Enrico Bonatti, Colin Devey, Jane Dionne, Eric Hellebrand, Yngve Kristoffersen, Charlie Langmuir, Larry Lawver, Richard Mühe, Jonathan E. Snow, Cara Wilson and Iris van der Zander.

Hydrothermal Working Group: Cindy Lee Van Dover (convener), Georgiy Cherkashev, Kathy Crane, and John Rummel.