InterRidge 1994 Arctic Ridges:
Results and Planning Workshop Report

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1. SUMMARY AND THE MAJOR WORKSHOP RECOMMENDATIONS

All ridges south of the permanently-iced Arctic Ocean have been the subjects of at least first order studies and are accessible with normal research vessels. The Gakkel Ridge in the Arctic Ocean is in contrast virtually unstudied. Therefore the major conclusion of the Arctic Ocean workshop was that **studies of the Gakkel Ridge should have highest priority.** The Gakkel Ridge is perhaps not only the most important arctic target but also the most important world-wide ridge target as it is in many respects unique in the global spreading system and represents an end-member for testing many models of ridge processes, both geological and biological. The following is a list of the first-order scientific aims for the Gakkel Ridge program:
A reconnaissance (30-50 km sample spacing) sampling of volcanics, sediments and biology along the Gakkel Ridge. Presently-available bathymetric information should be sufficient to permit this sampling. The *R.V. Polarstern* is perhaps the most suitable vehicle for this sampling.

Collection of geophysical data pertaining to the crust and mantle structure of the Gakkel Ridge
The detailed ridge-related points and questions which will be addressed by these studies are:
Collecting improved gravimetric and detailed bathymetric information on the ridge. This information may be best collected in some cases by submarine, and will elucidate the segmentation and regions of volcanic activity of the ridge.
Determining the seismic structure of the Arctic crust and mantle. How thick is the crust, how much melting is taking place, are there axial magma chambers?
How is the magma generation process affected by ever lower spreading rates? The Gakkel Ridge has the Earth's slowest spreading rates (and the spreading rate decreases from west to east along the ridge) and so effects of cooling from above, if they do occur, should be most visible here.
Does melting occur at all at the eastern end of the Gakkel Ridge? At such slow spreading rates the asthenospheric mantle may be able to rise to the surface so slowly that it does not melt.
How does the hydrothermal system function on this deep, slow-spreading sediment-starved ridge?
How has life evolved to cope with an environment where the major food input is hydrothermal?
The options of exotic platforms for performing Arctic Ocean ridge studies (nuclear submarines, ice drift stations, hovercraft) are discussed and evaluated in some detail, and may prove useful for investigating this inaccessible ridge region.

1.2 INTRODUCTION

The Arctic system of spreading centers extends from the Kolbeinsey Ridge at the northern margin of Iceland to the termination of the Mid-Atlantic Ridge (MAR) spreading system on the Laptev Shelf in the Arctic Ocean. The Gakkel portion of the ridge in the Arctic Ocean is the least explored part of the global ocean ridge system. Almost every segment of the Arctic ridge system is anomalous in some way. The Kolbeinsey Ridge is anomalously shallow and may represent the extreme in mantle temperature for a normal ocean ridge. A recent French survey of the axial valley of the Mohns Ridge discovered short, en echelon spreading centers that are oblique to the trend of the axis. The Knipovich Ridge, which is tucked-in against the Norwegian-Svalbard Margin, trends at about 75° to the trend of Mohns Ridge or 15° to the general spreading direction in the Norwegian-Greenland Sea. The Gakkel Ridge, which is an extension of the MAR into the Arctic Ocean, is anomalously deep and is the slowest spreading major ridge segment in the world's oceans. The Gakkel spreading axis is almost completely cut off from normal sediment supply by a constant ice covering and large ridge-flank highs. The spreading rate diminishes almost to zero as the Gakkel ridge approaches the pole of rotation and dies out on approaching the Laptev Shelf.

These unique characteristics and settings of the Arctic ridge system pose intriguing scientific questions that are relevant to understanding the global ridge system. The ridges also provide a unique opportunity to study the mantle composition beneath the Earth's pole. Because of the high northern latitudes and the Arctic ice cap, study of the ridge system is associated with special logistical difficulties that require optimal and co-ordinated use of the few suitable research platforms. The Arctic is also bordered by many nations with national and scientific interests in the region. Therefore the Arctic spreading centers pose exciting scientific opportunities to further the understanding of the ridge system and the upper mantle, and study of them requires the coordination of the diverse interests of scientists from many nations.

In order to further investigation of the Arctic spreading centers, an InterRidge meeting was convened in Kiel in November, 1994. The forty seven participants summarized the existing knowledge base for the region, discussed the scientific problems that could be uniquely addressed along the Arctic ridges, and considered the logistical difficulties that needed to be overcome to mount an effective program.

2. GEOPHYSICAL OBJECTIVES AT ARCTIC RIDGES

2.1 Crustal structure

The critical issue at the Arctic ridges is how their 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. Geophysics provides 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.

The phenomenology of ridge segmentation is directly addressed with swath mapping and side-scan imaging techniques. Where good coverage exists (only on the ice-free ridges), an unusual type of en echelon segmentation has been found. Spreading is often oblique to the overall trend of the ridge axis, with the offsets accommodating quite large bends of the ridge that on other ridges might be more typically accommodated by transform faults. Whether this en echelon segmentation extends into the ice-covered, ultra-slow spreading Gakkel Ridge, or whether the ridge has a different morphology there, is unknown, owing to the current poor bathymetric coverage. Defining the morphology and segmentation (if any) of Gakkel Ridge by new swath mapping is a priority objective.

Crustal thickness, which is a measure of the total melt production rate, is known to be exceptionally thin in the Arctic spreading axes, with a minimum of 3 km being reported for the westernmost 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.

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). 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 these models, since seismic velocity correlates with temperature and melt fraction.

Seismic investigations also retrieve information about the crustal structure of the active ridge system. High resolution refraction seismic and tomographic studies, using microearthquakes, provide critical constrains on the crustal structure and current tectonic activities. Determining the relationship between spreading velocity and crustal thickness is relevant to defining variability along the global ridge system. Combining refraction and tomographic methods may detect the existence of, and constrain the size of, magma chambers along the ridge system.

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 topography of the former ridge give insights into how 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 is a critical parameter for interpretion of other geophysical data such as magnetic, gravity, heat flow and microseismicity. This is especially valid for the Gakkel Ridge close to the Laptev Sea Shelf. Here, it is known from Russian seismic data that the ridge is completely buried by sediments (Sorokin, personal communication).

2.1.1 Plan for geophysical exploration and data acquisition

One of the objectives of the Global Studies theme of InterRidge is the acquisition of new data, and the assembling of pre-existing data, in the ice-covered regions of the Arctic Ocean, where existing data are extremely sparse. The Arctic Ocean has an order of magnitude less data density than ice-free oceans. Two aspects of increasing the data coverage are the release of data previously unavailable to the scientific community and the acquisition of new data.

The Arctic region has large sets of unpublished data, collected by aircraft and submarines during the cold war, that were classified "secret" by both the US and the former USSR and are unavailable to civilian scientists. The restructuring of Russia has opened a window of opportunity to exchange datasets. Current political instability in Russia and other republics of the former Soviet Union increases the need for this to be done in an expedient manner. The unpublished datasets will require a variety of analyses such as digitization, editing and merging before they will become useful. For an example of the techniques, processing and high quality product that can be obtained see Verhoef et al. (1995).

2.1.2 Possible methods to gain the required information

(a) Potential field measurements

New regional data are required. The significance of ridge segmentation is as yet obscure, and needs to be related to melt transport through the crust and tectonic stresses associated with rifting. High resolution gravity will be helpful here in providing subsurface density structure. Aircraft are available and equipped to measure aerogravity and aeromagnetics that can easily reach 95% of the deep water regions of the Arctic. These measurements will not only provide regional tectonic constraints but will enable sampling and seismic experiments to be properly planned. These techniques can also be used to advantage along the margin of East Greenland and the Canadian Archipelago.

(b) Swath bathymetry

The bathymetric data along the ridge acquired by spot sounding and conventional echo sounders are inadequate to define the complex 3-D structures of the Arctic ridges. Swath bathymetry has proved to be an invaluable tool on other ridges. It will be especially difficult to map Gakkel Ridge because of the ice cover. Towed instrument systems such as the GLORIA or SeaMARC systems will be difficult to use because of their vulnerability to damage by broken ice in the channel behind the ship. Data acquired by hull-mounted swath mapping systems are degraded by the noise of ice breaking. An expensive solution to this problem is to have an extra icebreaker escort the survey ship into ice-covered regions. Swath mapping systems mounted on a nuclear submarine would be particularly suited for surveying in the central Arctic basins because they can cruise unimpeded below the ice, and in addition provide an exceptionally quiet and stable platform. (See also Access to the Arctic Ocean).

(c) Seismic reflection and refraction

Seismic information is critical for constraining models of ridge structure and tectonic activity and is required for an integrated interpretation of all existing datasets.

Seismic reflection profiles across the Gakkel Ridge are an essential part of the data suite required for understanding the processes at slow spreading ridges, but the difficulty of towing equipment behind an icebreaker has inhibited the collection of seismic reflection profiles. However, recent innovations by Grantz et al. (1993) have shown that collecting seismic data by towing airguns and a streamer is possible. Collecting seismic reflection data in ice-covered areas puts restrictions on the length of the streamer and support of a second icebreaker is highly recommended in order to obtain good quality data.

Seismic refraction experiments have been carried out from ice camps and air-transported teams. In open waters, two ship experiments, such as expanding spread and constant offset profiling, provide powerful tools for defining the crustal structure (Stoffa and Buhl, 1979). Ocean bottom seismometers (OBSs) and seismic arrays on the ice or on the seafloor can be used in an active or passive mode to probe the structure and tectonic activity of the ridge.

Microseismicity studies using arrays deployed on the ice and OBSs can provide stress orientations.

3. PETROLOGICAL OBJECTIVES AT ARCTIC RIDGES

3.1 Introduction

The Kolbeinsey, Mohns and Knipovich Ridges have been sampled at a reconnaissance scale (Figure 1), and many of the geochemical data and interpretations have been published and are discussed below. These ridges provide excellent opportunities for mesoscale studies of MOR magmatism, especially with the recent publication of new maps and images. (see section 9.2, Vogt personal communication). In striking contrast, only 2 very small samples have been recovered from the entire 1800 km length of the Gakkel Ridge (Figure 1). Because the Gakkel Ridge is the slowest-spreading ridge on the planet and is located very close to the Earth's pole, it is essential that a systematic, first-order sampling of basalts and peridotites from this feature be carried out as soon as possible. Such a major operation is possible only with the combined resources of several nations and is completely consistent with InterRidge's global objectives.

3.2 State of knowledge

Over the last 15 years, reconnaissance sampling of the spreading axes north of Iceland has begun in earnest (Figure 1), and has yielded several discoveries important for our ideas on how axial magmatic systems function. The low spreading rate and the presence of ocean islands either on (Iceland) or near to (Jan Mayen) the ridge axis have made the Arctic Atlantic an ideal testing ground for models of magma generation from mantle of varying composition. In general, the intensity of sampling has decreased with the distance north from Iceland, and much of the work to date has been concentrated on the Kolbeinsey Ridge (Figure 1).

Basalts from the Kolbeinsey Ridge are extremely depleted in mantle-incompatible elements (Schilling et al., 1983; Devey et al., 1994) and have been produced by the highest degrees of partial melting found anywhere in the world's oceans (Klein and Langmuir, 1987). This high degree of melting is probably related to the proximity of the thermal anomaly associated with the Iceland mantle plume. Isotopic studies of Kolbeinsey Ridge magmas (Mertz et al., 1991) have shown that they are not contaminated by material from the plume (in contrast to basalts from the Reykjanes Ridge south of Iceland) and have supported ideas based on global mass balance arguments (Chase, 1979) for a southerly flow in the North Atlantic asthenosphere. Despite the high degrees of melting, variations in the relative enrichments of mantle-incompatible elements (e.g. La/Sm, Schilling et al., 1983) have shown the dominating influence of melts formed at the beginning of melting, deep in the mantle, in controlling the trace element budget of ridge magmas (Devey et al., 1994).

The Mohns Ridge and Knipovich Ridge have been less intensively sampled (Figure 1), and show large variations in the degrees of mantle incompatible element enrichment along the ridge, with shallow ridge regions such as the Jan Mayen Platform apparently being associated with the highest degrees of enrichment (Figure 2; Schilling et al., 1983; Neumann and Schilling, 1984; Waggoner, 1989).

North of Knipovich Ridge, in the permanently ice-covered Arctic Ocean, very little is known about the petrology of MOR lavas. Only two dredges have been recovered so far from the Gakkel Ridge (Mühe et al., 1993; Figure 1) and they have shown no sign of an ultra-depleted chemical signature as was proposed in mantle circulation models (Hart, 1988). They give a clear indication of the importance of samples from this high-latitude, ultra-slow spreading ridge for testing global models of mantle melting processes. Sampling station KAL 11/370-5 at 86°N, 23°E yielded crystalline basalt and serpentinites. The other Gakkel Ridge sample (GKG 2167-2) comprises epiclastic glass material from 87°N and about 60°E (Figure 1). The serpentinites in KAL 11/370-5 are texturally identical to residual mantle spinel peridotites dredged and analyzed from many locations along slow-spreading axes (e.g. Bonatti and Hamlyn, 1980). The basalts from both locations are primitive MORB (Mg#>70, MgO > 9 wt.-%) that are slightly enriched in incompatible elements ((La/Sm)N (1). The basalts have high Na8.0 values of 3.3 (Figure 2) suggesting some of the lowest degrees of partial melting observed on the global ridge system. One has spinifex textures and evidence for incomplete magma mixing (MŸhe et al., 1991). These basalts provide the first insight into the composition of the magma mixing (MŸhe et al., 1991). These basalts provide the first insight into the composition of the mantle around the North Pole. Sr and Pb isotopic data show the source region of the Arctic basalts to be similar to Kolbeinsey basalts and to possess traces of an enrichment similar to the DUPAL signature (Figure 3; Hart, 1984). This is remarkable since so far the DUPAL signature is believed to be present only in the Indian but not in the Atlantic or Pacific asthenosphere. These results can also be used to argue against a model of whole mantle convection (Hart, 1988) in which upwelling of enriched material at the equator is balanced by downwelling of depleted material at the Poles.

3.3 Critical petrological and geochemical questions

Two special characteristics of the Gakkel Ridge make it the best location to test several hypotheses that are critical to understanding melt generation and mantle composition for the entire global spreading system. Firstly, the location of the Gakkel Ridge (Figure 1) provides the only opportunity to study the mantle composition beneath the Earth's pole and to test hypotheses of global mantle convection. Secondly, Gakkel Ridge is the slowest spreading ridge on the planet, and varies considerably in its spreading-rate along axis, from 0.85 cm/a at the eastern end to 1.7 cm/a at the western end. It is the only ridge whose spreading rate is below the critical 1 cm/a threshold at which melt generation is thought to become dependent upon spreading rate (Reid and Jackson, 1981). Moreover, the apparent lack of major transform offsets means that melting is probably not complicated by cold edge effects. For all of these reasons, the Gakkel Ridge is an essential laboratory in which to study mantle melting processes.

3.4 Questions related to spreading rate

3.4.1 Gakkel Ridge provides the opportunity to test the global systematics of ocean ridges, and models for mantle melting and mantle temperature variations

The correlation between the mean chemistry of ocean ridge basalts, corrected for low-pressure fractionation, and the regional depth of the ridge or height of the residual geoid where they are erupted (Figure 4; Klein and Langmuir, 1987; Langmuir et al., 1992; Dick et al., 1984), serves as a primary constraint on models of mantle temperature and melting processes beneath ocean ridges. It is also used to map mantle temperature, and hence large scale mantle convection, using basalt compositions. This correlation is controlled in large part by the rare deep and shallow ridges. The Gakkel Ridge occupies an important place in the global ridge spectrum, because it is close to 2000 km of spreading center with the deepest axial depths known. The chemistry of basalts erupted at the Gakkel Ridge can be used to test the generality and validity of the depth-chemistry observation without the complications presented by large-offset transforms such as occur along the Southwest Indian Ridge.

Mantle peridotites also provide information about mantle temperature and melting processes, and there is a close connection between peridotite and basalt chemistry (Dick et al., 1984; Michael and Bonatti, 1985; Johnson et al., 1990). Because the Gakkel Ridge spreads so slowly, it is likely that many peridotites will also be recovered. This will allow a further evaluation of the connections between basalt and peridotite compositions. Peridotite compositions can be predicted on the basis of existing data and models, and these predictions can be tested.

The existence of the Gakkel Ridge as an end member also provides the opportunity to test competing models for the origin of the global correlations between depth and chemistry of basalt and peridotites. Klein and Langmuir (1987) and McKenzie and Bickle (1988) suggested that these correlations resulted from differences in mantle temperature, with the exception of ridges at super-slow spreading rates, which would also be influenced by surface cooling. Shen and Forsyth (1995), however, have argued that mantle temperature variations are not very significant, and that the global correlations are produced by differences in the final depth of melting, which would be controlled predominantly by the thickness of the lithosphere (Figure 5). These two models have rather different predictions for the compositions of Arctic MORB, because the mean pressure of melting varies greatly between the two. Furthermore, the Gakkel Ridge is at the extreme of slow spreading rates, and hence the lithospheric effect should be maximized. MORB from this region provide the ideal material to test and constrain these competing models.

3.4.2 How does the pattern of mantle flow and melt delivery at ocean ridges change with spreading rate?

Geologic and geophysical observations suggest that mantle flow and melt delivery to the crust are highly focused to the mid-point of segments on slow-spreading ridges (Whitehead et al., 1984; Lin et al., 1990; Dick, 1989), but may be more evenly distributed along the axis of fast-spreading ridges (Lin and Phipps Morgan, 1992; Figure 6). This hypothesis is difficult to test, as the presence of a long magma lens beneath much of the EPR may result in along-axis melt transport, eliminating variations in crustal thickness and melt composition that might otherwise indicate underlying focused 3-D mantle flow.

The full spreading rate of the Gakkel Ridge varies significantly, from 1.5 to 0.85 cm/a from west to east (Southwest Indian Ridge (1.7 cm/a). The large dynamic range and ultra-slow spreading rate of the Gakkel Ridge make it the essential place to test models for mantle flow beneath ridges. Both the rapid thickening of the lithosphere due to cooling close to the ridge, and the very low rates of mantle upwelling, should result in extreme and progressively more focused mantle flow and melt delivery along the ridge from west to east. Also, if MORB form by aggregation of many fractional melts from the base to the top of the melting column of mantle (Johnson et al., 1990), then MORB formed at ultra-slow spreading ridges should be anomalously enriched in incompatible elements due to more focused flow (e.g. Devey et al., 1994). These models also predict that serpentinized mantle peridotites should be abundant at the distal ends of Gakkel Ridge rift segments even where there are no significant ridge offsets or transforms.

3.4.3 Does the degree of mantle melting approach "near zero" conditions and does this produce a chemical discontinuity in erupted basalts?

There is substantial evidence that ocean crust formed at spreading rates of less than 2 cm/a (20 mm/a) full rate becomes progressively thinner (Figure 7; Bown and White, 1994; Reid and Jackson, 1981). This thinning is attributed to a thickened conductive lid on the upwelling mantle column with the overall degree of mantle melting falling off rapidly at very-slow spreading rates (Reid and Jackson, 1981). At the eastern end of the Gakkel Ridge at 0.85 cm/a full spreading rate, near-zero crustal thicknesses may be found. There are two important consequences of this unique situation:

First, in order to explain the local heterogeneity of MORB at many ocean ridges, it is believed that the mantle source region is heterogeneously veined with enriched material (e.g. le Roex et al., 1983). Such veins would melt preferentially to the mantle matrix and produce incompatible element enriched alkali basalts at low degrees of mantle melting. Experiments and numerical models suggest that there is a critical, low melt percentage, below which only melts formed in mantle veins may escape. When the critical melt percentage is exceeded, however, melts formed in the depleted mantle matrix will mix with those formed in the veins. There may be a chemical discontinuity along Gakkel Ridge where the degree of mantle melting drops below the "critical melt percentage" and the erupted magmas become abruptly enriched in alkalis and incompatible elements. Gakkel Ridge is likely to be the only place where such an effect could be directly tested.

Second, mantle peridotites emplaced along Gakkel Ridge should reflect the lowest degrees of mantle melting anywhere in the oceans. If mantle melting falls off to near-zero conditions at the eastern end of the Gakkel Ridge, then we may be able to sample the mantle source of MORB directly where peridotites are emplaced in the absence of a basaltic cover. At present the mantle source composition of MORB can only be inferred.

3.4.4 Gakkel Ridge provides the opportunity to further investigate whether "local" petrological variability and systematics correlate with spreading rate

The global systematics of MORB melting have been established using regionally averaged chemistry (Klein and Langmuir, 1987). There are, in addition, large local variations that can be observed in the chemistry of individual samples from a single ridge segment, after compositions have been corrected for shallow-level crystal fractionation. These local variations are quite different for different ridges (Klein and Langmuir, 1989; Langmuir et al., 1992; Niu and Batiza, 1993). On the Mid-Atlantic and Southwest Indian Ridges (Langmuir et al, 1992; Johnson and Dick, 1992) local petrological variations are orthogonal to the global correlations. In striking contrast, on the East pacific Rise (EPR) the Na and Fe variations are parallel rather than orthogonal to the global correlations (Klein and Langmuir, 1989; Langmuir et al., 1992). Niu and Batiza (1993) suggested that there is a relationship between the slope of the local chemical variations and spreading rate. The East Pacific and Mid-Atlantic Ridges have very different spreading rates, but they also are in different ocean basins with very different tectonic histories. Are these local differences controlled exclusively by spreading rate, or are there important regional differences? The only way to address this question is by investigation of ridges in additional ocean basins. The Gakkel Ridge provides a unique opportunity to study the extreme of the spreading rate spectrum. If the local variations are related to spreading rate, then there may also be changes between slow and very slow spreading ridges. In this case the Gakkel Ridge will provide a valuable comparison to the Mid-Atlantic and Southwest Indian Ridges.

3.4.5 Is the distribution of chemical heterogeneity controlled by spreading rate or regional differences?

The East-Pacific Rise and Mid-Atlantic Ridge also have very different distributions of enriched components as expressed in the basalt compositions. On the Mid-Atlantic Ridge, "normal" ridge segments are homogeneous and depleted, and the ridge is punctuated by large depth and chemical anomalies that result from nearby hot spots. Along the East-Pacific Rise, with the exception of the region near Easter Island, there are no major depth and chemical anomalies, but there is a much greater dispersion in trace element chemistry (Figure 8). Enriched basalts occur sporadically along the entire length of the East-Pacific Rise. One possibility is that small hot spots are disseminated along the East-Pacific Rise by the more rapid mantle processing that occurs there as a result of the rapid spreading rate. Alternatively, the upper mantle could be fundamentally different in the two ocean basins. The Southwest Indian Ridge does not clarify this situation, because it shows even greater variability in trace element compositions on a small scale than does the East-Pacific Rise. The Gakkel Ridge provides an important new perspective on this problem, because it has formed a new ocean basin with no apparent hot spot activity. It will therefore clarify whether spreading rate and geochemical variability are related.

3.5 Questions related to the location of Gakkel Ridge

3.5.1 Is the mantle beneath the Gakkel Ridge similar to Indian Ocean mantle?

In Sr-Nd-Pb isotopic composition, the transitional basalts from Gakkel Ridge with their high Na8.0 resemble those from the Kolbeinsey Ridge (Figure 3) which have extremely depleted incompatible element concentrations and very low Na8.0 and are thought to have formed at some of the highest degrees of partial melting on the global ridge system. Thus it appears that, although both Gakkel and Kolbeinsey Ridge basalts have formed from similar mantle sources, their respective melting histories are the two most extreme observed on Earth so far.
The Kolbeinsey-Gakkel basalts fall close to the unradiogenic end of the northern Atlantic trend, but they have high 87Sr/86Sr for nearly constant 206Pb/204Pb (Figure 3) trending toward Indian Ocean MORB in this plot. However, they lack the significantly higher 207Pb/204Pb and 208Pb/204Pb of the Indian Ocean MORB and do not show the low Ce/Pb observed in Indian ridge lavas (Rehkämper and Hofmann, 1997). Thus, the component in the Indian Ocean mantle that has been attributed to recycled sediments may be absent in the Arctic mantle.

3.5.2 Do the distinctive trace element ratios such as H2O/Ce that characterize the northern Atlantic continue into the Arctic, far from the Atlantic hotspots?

In depleted and enriched MORB world-wide, certain trace element ratios such as Ce/Pb, Nb/U and H2O/Ce are nearly constant (Hofmann et al., 1986). H2O/Ce in normal (N-)MORB and enriched (E-)MORB is nearly constant world-wide except for in the Atlantic north of 30¡N (up to Knipovich at least), where H2O/Ce is significantly higher in both N-MORB and E-MORB (Michael, 1995). It is not clear whether higher H2O/Ce is a characteristic of northern Atlantic hotspots, or is a fundamental characteristic of the mantle in this region. The Gakkel Ridge is distant from northern Atlantic hotspots, so should have "normal" H2O/Ce ratios if this effect is hotspot-related.

3.6 Requirements

The need for basalt and peridotite samples from the 1800 km long Gakkel Ridge is critical. A regional systematic sampling with a 30 - 50 km spacing should be carried out and is a realistic goal in the near term. This sampling could be guided by and accomplished using existing bathymetric data; especially if bathymetric data that are currently classified were released. Higher density sampling will require swath bathymetry of the axial zone to place the sample in the context of regional and local tectonics. Some high density sampling could be carried out along the Gakkel Ridge in the vicinity of the Fram Strait using existing maps. This sampling program would allow many of the scientific problems above to be addressed.

In future phases of petrologic study, intensive sampling of numerous parts of the Gakkel Ridge are anticipated, once multibeam and side-scan maps are available. This sampling would aim to examine detailed relationships between geology and magmatic composition, and would be driven by discoveries made during the earlier phase of petrologic study and mapping.

3.7 Strategy

There are several ways that the sampling goals described above can be carried out. These should be pursued simultaneously because sea-going resources are both limited and have multiple demands which might limit their availability, thus delaying the program. Although one particular option is identified as most likely to lead to success, innovative methods of access and sampling, as well as cooperation with other programs, might enhance one of the other options and provide improved sampling opportunities.

Dredging and box coring to obtain samples can best be carried out in ice-covered regions using a capable icebreaker, preferably a research icebreaker. The German icebreaker RV Polarstern is a tested Arctic research platform and is the best current option for sampling the Gakkel Ridge. Over much of the ridge the RV Polarstern must be escorted by a stronger icebreaker. In 1998 the US Coast Guard will launch the RVIB Healy, which is a larger icebreaker with science capabilities similar to the Polarstern, and would be able to work alone in the Eurasia Basin during the summer period. In order to make best use of an icebreaker which is large and expensive to operate, the sampling program would be carried out in parallel with other programs, preferably on long-duration legs that would allow 20 days of sampling. If cruises are multi-disciplinary, and 20 days are not available for sampling, then the program might be undertaken in two or more cruises, each covering part of the Gakkel Ridge.

The possibility of hiring one of the large Russian icebreakers should also be explored. These ships are capable of functioning alone in the Arctic. Because of the expense, we envision that this would also be a multidisciplinary expedition.

The existing US Coast Guard icebreakers are powerful enough to work singly in the Arctic, however they are based in Seattle and transit to the eastern Arctic would be expensive. If there were other programs en route, for example on other Arctic ridges, or multiple programs near Gakkel Ridge, it would defray the transit costs for the sampling program. This option should also be examined.

Sampling by weighted rock corer or piston corer might be possible by drilling through the ice, and could be accomplished using a small Hovercraft. A Hovercraft could operate alone and cover a limited range, or it could be based on a larger icebreaker, where it would extend the scientific capability of a multi-disciplinary expedition by allowing separate operations to proceed in parallel: e.g. sampling and other operations. The ability of rock drills or piston corers to recover basaltic glass from very slow spreading ridges must be determined. Also, dredging from a large ship would still be required to recover peridotites since they are not obtained by this method.

4. SEDIMENTARY ENVIRONMENT AND PALEONTOLOGY AT ARCTIC RIDGES

4.1 Introduction

Knowledge of sedimentary processes and their effects on the environment along spreading ridges is important for understanding the global system of exchange between crust-ocean-atmosphere. Sedimentary processes at spreading ridges have been studied in the past, generally in the context of hydrothermal exchange between crust and ocean. Metalliferous sediment has been used to evaluate the regional distribution of hydrothermal plumes, the potential of ore genesis and the temporal variability of hydrothermalism. Besides these processes, sedimentation at a spreading axis is quite different from that in ocean basins and continental slopes as revealed by systematic investigations over the past few years. There is a need to establish a scientific program addressing the sedimentary and ecological environment of the Arctic axis.

The principal objectives of the regional studies are:

To investigate primary sedimentary processes (particle supply) at regional and local scales.

To identify secondary sedimentary processes (resuspension, lateral advection, debris flows, turbidity currents).

To determine facies development and distribution due to sedimentology and paleoecology (benthic environment).

Because the different sedimentation processes also influence the distribution of matter supplied to the water column by hydrothermal activity (volatiles, fluids, suspended matter), these processes may affect mass and energy transfer and the diversity of biological activity.

4.2 State of knowledge

The non-carbonate fraction of the sediments in the Arctic region (including the Norwegian-Greenland Sea), generally consists of detrital, continentally-derived material. The pelagic input of biogenic carbonate and silicate depends on the productivity of surface waters and decreases generally northward. The sum of influences derived from the active volcanic spreading axis is only poorly described.

Currently, the Kolbeinsey Ridge is the best described segment of all of the Arctic ridges. It has been extensively cored and the sediments recovered are described in Lackschewitz (1991) and Mienert and Wallrabe-Adams (1992). The sedimentology of the surface samples from the Kolbeinsey Ridge was described in detail by Lackschewitz et al. (1991) and Lackschewitz (1991). On the southern Kolbeinsey Ridge, submarine volcanic activity provides the most important contribution to sedimentary deposition, and the sediment distribution is strongly influenced by hydrodynamic conditions and redeposition processes (Lackschewitz and Wallrabe-Adams, 1991; Oehmig and Wallrabe-Adams, 1993). There is a direct interdependence between the hydrodynamics of deep and bottom waters and sedimentary environments on the one hand and the structure of benthic assemblages on the other (Brandt, 1993; Piepenburg and Juterzenka, 1994).

According to Lackschewitz et al. (1994a), sediments of the active, southern Kolbeinsey Ridge, which are rich in volcanic particles, reflect changing fragmentation mechanisms due to increasing sea level during the last deglaciation. Generally, the ridge crest contains only thin and patchy sedimentary deposits, whereas an increase in sediment cover is observed from the flanks to the adjacent basins (Neben, 1992). High compositional gradients in sediments along the Kolbeinsey Ridge result from a variability in sedimentary sources of different geographic regions. Bulk chemical composition in surface sediments and normative sediment analysis have been used to quantify the volcanic, terrigenous and biogenic components (Lackschewitz et al., 1994b).

North of the Spar Offset (ca. 69¡N), the large supply of coarse terrigenous material reflects enhanced deposition of ice-rafted detritus (IRD), indicating that extensive melting of ice occurred in this area (Baumann et al., 1993).

The first geochemical and sedimentological data from the Gakkel Ridge were published by Bohrmann (1991). In addition, cores from the Norwegian-Greenland Sea, including Mohns Ridge, were studied by Paetsch (1991), who showed variations in abundance of some elements with depth. However, with the exception of the Kolbeinsey Ridge, none of these studies have been concerned in detail with the sedimentary processes that are now active on the Arctic ridge system.

4.3 Critical scientific questions

Mid-ocean ridges are important geological and morphological features in the world's oceans. Interactions between the oceanic lithosphere, created at the spreading axes, the biosphere and the hydrosphere affect climate and ocean chemistry. Deep water circulation is influenced when ridges present topographic barriers to flow and hence control circulation directions and velocities. Processes at the ridges such as volcanism and hydrothermalism contribute to the exchange of lithogenic matter between mantle, ocean and atmosphere. Many hydrothermal sites provide food for benthic organisms independent of marine phototrophic productivity. Hydrodynamic conditions influence the distribution patterns of benthic communities. The sedimentary record of lithogenic and biogenic matter on ridges provides an opportunity to reconstruct these processes in time and space.

General questions of interest are:

- How and in what proportion do ridge-related processes contribute to the composition of ridge sediments?
- How does ridge topography control bottom current direction and velocity, and how can we scale the variability of hydrodynamic conditions?
- How do variable hydrodynamic conditions control the sedimentary and benthic environment and how do they affect the sedimentary facies?

Specific questions of interest at the Arctic ridge system are:-

- Do hydrothermal processes play an important role on very slow spreading ridges?
- To what extent do benthic Arctic ridge assemblages depend on lateral advection of food, and thus directly on local hydrodynamics and sediment composition?
- To what extent are benthic Arctic ridge assemblages linked to intense (vents) or low level (diffuse hydrothermal flux of pore waters) food sources other than vertical pelagic fluxes?
- Are there species that survive on low level, hydrothermally induced chemical gradients by utilizing symbiotic bacteria? This question can be answered best in areas where 'background noise' from other food sources is lowest as at the Gakkel Ridge, which is under perennial sea-ice cover and is far from sediment input from shelf areas.

Many parts of the Gakkel Ridge are not affected by mass flows from surrounding shelf areas as are large parts of the Knipovich and Mohns Ridges. Thus, trophic adaptations of benthic organisms should pinpoint most clearly the influence of food sources derived from low level hydrothermalism and lateral advection.

4.4 Main objectives

The main objective in the coming decade will be to explore and describe the sedimentary environment along the spreading axis between Iceland and the Laptev Shelf in order to quantify and understand the inter-relationship between volcanism, tectonism, hydrothermalism, oceanography, hydrodynamic conditions, sedimentation processes and benthic environment in the individual ridge segments.

4.5 Methodology, techniques and tools

Detailed bathymetric and seismic surveying and high density sampling from the ridge crest down to the basins is necessary to obtain information on the variability of the sedimentary environments. High density sampling implies 10 to 20 sites per 10 km (along the ridge), depending on ridge topography, using such devices as box corers and gravity corers.
To characterize the sedimentary environment, intensive sedimentological and petrographical investigations are necessary. Experimental work on sediments at the sediment-water interface must be performed to evaluate the recent hydrodynamic conditions. Information on environmental changes through time can be investigated using long sediment cores.
Further investigations are needed along the western Gakkel Ridge. Initial investigations sugget that this ridge segment is volcanically and possibly hydrothermally active (Bohrmann, 1991; Fütterer, 1992). Therefore, this part of the spreading system seems to be suitable for describing and quantifying metalliferous sediments on an ultra-slow spreading ridge which is highly relevant to developing a model of global hydrothermal fluxes. The extreme topography of the Gakkel Ridge provides special conditions of deep-sea circulation patterns.

5. HYDROTHERMAL OBJECTIVES AT ARCTIC RIDGES

The characterization of hydrothermal phenomena at Arctic ridges is a major objective. Our understanding of hydrothermal circulation in ridges world-wide is still at a rudimentary level. Most attention has been focused on the neovolcanic zone at the axis of spreading centers, where high-temperature (350 - 400°C) venting of fluids occurs. Several sections of ridge have been studied in detail, primarily on the East Pacific Rise where the occurrence of vents is most frequent; more isolated sites of venting have been found on the Mid-Atlantic Ridge (Rona, 1987) and backarc basin settings in the Okinawa Trough and Marianna Trough. The distribution and character of high-temperature vents at the Arctic ridges is unknown except for a field of moderately hot vents ((180°C) in shallow water on the shelf just north of Iceland (Fricke et al., 1989), however, some hydrothermal sediments have been recovered from the Gakkel Ridge.

5.1 Critical questions concerning axial hydrothermal activity

5.1.1 What is the total energy flux from the Arctic ridge segments and its variation from Iceland to the Laptev Sea?

The rate of heat loss in the neovolcanic zones of spreading axes is closely tied to spreading rate, melt generation and mantle plumes. The Arctic ridges provide an excellent laboratory to study these relationships for a number of reasons. First, as discussed above, exploration of the Arctic ridges will provide important new data at the extreme, low end of the spreading rate spectrum. Arctic ridge segments occupy topographically enclosed basins which increases the residence time of effluents associated with hydrothermal activity at the axis. Third, the complex kinematics of spreading in the Norwegian-Greenland Sea and the ultra-slow spreading of the Gakkel Ridge could lead to deep seated fracturing of the oceanic crust and consequently deeper reaching hydrothermal circulation than is typical for the global ridge system.

5.1.2 What is the depth and geometry of subseafloor hydrothermal circulation at the axis, and its interaction with magma chambers?
High temperature, black-smoker vents require a magma chamber at depth to provide sufficient heat to raise water temperatures to 350 to 400°C. However, we do not understand how heat is transferred from the magma chamber to fluids circulating in the axial systems. We suspect that, in the slowest spreading ridges, deep reaching faults and smaller amounts of magmatic activity will lead to deeper circulation into the crust.

5.1.3 To what extent does hydrothermal circulation control the depths of magma chambers or even the existence of magma chambers?
The generation of magma in the mantle and its migration upward into the crust is a complex interplay of spreading rate, mantle temperature, mantle composition, and the pressure of the magma system. Whether the magma will form a reservoir in the crust (at the top of layer 3) depends on these parameters as well as on the rate of loss of heat to the ocean, primarily through hydrothermal circulation. At slow spreading axes the magma chamber is likely to be transitory unless supported by a mantle plume as in the case of Iceland. There is a question whether magma chambers can form at all in ultra-slow spreading environments, or, if they do form, whether they are so local and transitory that they can not support vent communities and the likelihood of detection at any one time is remote. Exploration of the Arctic ridges provides a unique opportunity to see if there is a threshold in magma chamber and black smoker formation.

5.1.4 Have massive sulfide bodies formed in the Arctic ridge system?
If so, what is their distribution and chemistry? The ultra-slow spreading centers in the Arctic region may provide an interesting end member to the spectrum of massive sulfide body chemistries and setting. The northern end of the Knipovich Ridge and the Laptev Sea end of the Gakkel Ridge are inundated with sediments from adjacent shelves. Sedimented ridges provide an environment in which massive sulfide accumulations form and are preserved (Davis et al., 1987).

5.2 Low-temperature hydrothermal phenomena
Low-temperature hydrothermal circulation on the flanks of spreading ridges has been studied in a number of areas. The most extensive studies have been made on the eastern flank of the Juan de Fuca Ridge (Davis et al., 1989), and the flanks of the Galapagos Spreading Center (Langseth et al., 1988). These studies indicate that hydrothermal flux is most intense where igneous basement rocks are exposed at the seafloor. The relatively high permeability of the basement rocks relative to the sediments make the upper part of the igneous basement a good conduit for hydrothermal flow. The rates of flow are low compared to the axial hydrothermal system, typical rates are about 1 m/a (Langseth et al., 1984). However, low-temperature circulation of sea water through oceanic basement is important because of the sheer volume of the flux through the basement as a result of the large area of the ridges over which such flux occurs.

5.3 Principal questions relative to low-temperature hydrothermal regimes
5.3.1 What is the extent of hydrothermal circulation on the ridge flanks?

5.3.2 What is the geometry of the circulation; the depth of circulation and the lateral range of horizontal flow?
It has been conjectured that the circulation is deeper in slow spreading ridge segments than in faster spreading segments because of the more rigid lithosphere and greater likelihood of deeply incised conduits along fault planes.

5.3.3 What chemistry is associated with this circulation?

Deeper penetrating circulation could have an impact on the water-rock chemistry in Arctic ridges. The fact that deeper reaches of the Eurasian basin form a closed basin make it a good reservoir for venting products.

5.4 Methods for study of geothermal heat flow and hydrothermal activity

To determine the total heat flux from a ridge axis it is necessary to determine the distribution of vents, vent temperatures and venting rates. This can be done by examining representative stretches of ridge and vent fields and does not require that every vent field be documented. Alternatively, proxies of the total heat flux, such as the 3He flux, can be used to estimate this important quantity.

The tools for study of axial vents are deep-diving or deep-towed surveying tools such as the Argo-Jason system, towed video and camera tows; and, for detail work, submersibles and, more recently, ROVs have been used. Special instruments to measure the very high temperatures, collect venting fluids and measure the flux rate at the vents have been developed for use from submersibles and ROVs. In the ice-covered seas it is essential to have a capable icebreaker from which to operate deep-towed vehicles. The principal tools for studying low-temperature hydrothermal flow on ridge flanks are seafloor measurements of thermal, chemical and pore pressure gradients in the sediments; measurements of temperature, pressure and porewater chemistry in deep sea boreholes; and in situ measurements of permeability and fluid flow. Of the Arctic ridges, only the Knipovich Ridge has been well surveyed. Crane et al. (1988) have made several closely-spaced lines of heat flow measurements across the ridge and on the Norwegian Margin, otherwise there are only scattered measurements of thermal gradients (Langseth et al., 1984). These measurements indicate the existence of hydrothermal circulation over the flanks of the Arctic ridges, but the data are too sparse to provide information on the scale or amplitude of the heat flow.

6. BIOLOGICAL OBJECTIVES AT ARCTIC RIDGES

6.1 State of knowledge

Recent high resolution mapping of the Mohns (see section 9.2), Knipovich and Kolbeinsey Ridges (Crane and Solheim, 1995; see section 9.2) and side-scan imaging of Knipovich Ridge (Crane and Solheim, 1995; see sections 9.2; Vogt, personal communication) help define plausible regions for water column prospecting of hydrothermal properties (e.g. temperature and light transmission anomalies).

The only documented biological community associated with hydrothermal venting north of Iceland is the Kolbeinsey site visited by the GEO (Fricke et al., 1989) and JAGO (Stoffers, 1997 pers. comm.) submersibles. Descriptions of the site, while superficial, demonstrate the presence of a modified benthic community at the vents. The dominant fauna is comprised of a subset of the surrounding invertebrate fauna and is principally sponges and coelenterates, a condition not usual for deep-sea hydrothermal systems, but similar to the situation at shallow vents in a caldera of the Kurile-Kamchatka region (Tarasov et al., 1990). The nature of the Kolbeinsey vent fauna raises the question of at what depth, if any, a vent-specific vent fauna might be discovered in the Arctic.

Evidence for hydrothermal venting on the Mohns Ridge, based on photographic and side-scan imaging and temperature anomalies, exists, but active venting and associated biological communities have not been observed (Schwab et al., 1992). Recognition of oblique spreading cells within the axial rift valley of the Mohns Ridge based on recent multibeam data (see section 9.2) suggests a more reasonable survey strategy for the Mohns Ridge. Hydrothermal indications in ODP cores were reported for recent drill holes near the Gakkel Ridge. Details remain to be determined (Myhre et al., 1995). A tentative indication of (fossil) hydrothermal activity is reported by the participants of ARK-IX-4 RV Polarstern 1993 (Rachor, personal communication) based on the collection of 'dead bivalves' at a station located at 77(41.7'N, 125(51.3'E (north end of the Gakkel Ridge, 1981 m) but no further elaboration on this find is available at present.

6.2 Critical scientific questions

6.2.1 Has the vent fauna of Arctic ridges evolved independently of the rest of the global ridge fauna? If so, what kinds of parallel evolution can be observed?

This kind of observation could provide insight into the relative importance of selective pressures in hydrothermal vent communities. With exploration of Pacific and Atlantic vent sites, biologists now recognize that vent species are, in general, not cosmopolitan. At least five biogeographic provinces are recognized, corresponding to geographically disjunct ridge crest systems. This situation leads to the expectation that exploration of remote ridge systems will lead to the discovery of novel vent faunas. Of the hydrothermally unexplored ridges, the Arctic ridges are the most remote. Furthermore, north of Iceland, bottom waters of the Norwegian-Greenland Sea and Arctic basins have been isolated from the rest of the Atlantic by the Scotland-Iceland and Iceland-Greenland sills. These sills may well have served as barriers to dispersal of Atlantic vent species as the ridge system propagated north of Iceland.

If, on the other hand, Arctic faunas are derived from Atlantic faunas, the opportunity then exists to study phylogenetic relationships and to evaluate models of dispersal along ridge crests. Regardless of the origin of Arctic deep-sea vent faunas, the possibility exists for novel adaptations of significance comparable to, for example, the symbiotic relationship between invertebrates and bacteria (e.g. Cavanaugh et al., 1981) or the modified eye of vent shrimp (Van Dover et al., 1989).

The primary biological measurements to be made on any newly discovered deep-sea vent community in an Arctic setting are an assessment of the taxonomic composition (requiring photographic documentation and collection of voucher specimens) and clarification of the primary producer - invertebrate trophic interactions.

6.2.2 What is the geochemical nature and distribution of hydrothermal vents on a very slow spreading center? Is there evidence of high T reactions (greater reaction depth) in fluid chemistries and mineralogies?

The spacing of vents is a critical parameter in models of vent biogeography. Greater distances between vents (e.g. as on the slow-spreading Mid-Atlantic Ridge) leads to isolation and speciation and the potential for a greater number of biogeographic provinces per unit length of ridge.

6.2.3 What is the source of the missing carbon in the central Arctic? Could it be chemosynthetic?

Arctic primary photosynthetic production at > 83(N is low, at 10 g organic C per sq. m per year versus 90 g in the Norwegian-Greenland Sea. Benthic turnover rate in the Arctic is 2 - 3 times higher than supply can sustain. The Gakkel Ridge may be an area where primary photosynthetic production is low and the contribution of chemosynthetic production to the surrounding benthos correspondingly gains in significance. Thus the Gakkel Ridge may be an ideal place to examine the 'productivity shadow' of chemosynthetic production, where the photosynthetic noise is lowest. Carbon stable isotope analyses of bulk invertebrate tissues might resolve this issue.

6.2.4 How does the taxonomic and trophic structure of vent communities change with depth?

The Kolbeinsey vents provide the shallow end-member of the depth gradient. To what extent is the 'non-vent' nature of the Kolbeinsey fauna a function of depth? What is the relative importance of chemosynthetic versus photosynthetic energy within a hydrothermal system in the euphotic zone? These kinds of questions might be addressed in other areas where vents are found along depth gradients (e.g. Azores), but the Kolbeinsey system should not be excluded from this kind of analysis, especially given the intensely seasonal nature of primary photosynthetic productivity north of Iceland.

6.2.5 What are the details of the Kolbeinsey hydrothermal systems?

The Kolbeinsey vents are accessible and of interest to international (especially Icelandic and German) scientists. Detailed work on the microbiology, fluid chemistry, ecology and physiology are timely. Preliminary microbial analyses and culture experiments showed evidence for exciting, novel hyperthermophilic archaea and bacteria as part of unknown high-temperature communities (Huber et al., 1989, 1992). In order to investigate this microbiology further, samples of hot water, rocks and sediments from the site should be analyzed by gene probes and cultured for novel micro-organisms (Burggraf et al., 1994). A cruise with the shallow-water submersible JAGO supported by the German research vessel *Poseidon* has undertaken a detailed study of these vents in June 1997.

6.2.6 What is the distribution of viable cells of hyperthermophilic and psychrophilic archaea in Arctic Ocean water?

Submarine hydrothermal systems at different locations harbor many hyperthermophilic anaerobic species which are closely related to each other (Huber et al., 1990). The modes of dispersion are unknown. First results from K. Stetter's laboratory showed that cold Beaufort Sea water harbors viable cells of hyperthermophiles (Stetter et al., 1993). In addition, a recent paper of DeLong et al. (1994) demonstrates that cold Antarctic seawater contains unknown archaea in high abundance, probably thriving there and so far uncultivated. To determine concentrations of hyperthermophiles and archaeal psychrophiles in Arctic seawater, Stetter's lab proposes to take water samples (between 10 and 1000 liters) and perform ultrafiltration and cultivation experiments on board a research vessel.

6.2.7 Are there special adaptations of benthic foraminfera in extreme environments?

Recent studies have shown that benthic foraminfera are among the most successful organisms in extreme environments (e.g. oxygen-depleted regions). Hydrothermal vents, belonging to extreme environments, have been little studied for benthic foraminifera. From eutrophic to oligotrophic and from well-oxygenated to nearly anoxic conditions, benthic forams occupy a large spectrum of environmental conditions. Within the benthic community they can make up an important part of the benthic biomass and exceed macro- and micro-fauna in their physiological turn-over rates.

At hydrothermal vents, it is thus of interest to investigate the spatial distribution of foraminifera in order to:

detect differences in assemblages near to and at greater distances from hydrothermal sources.

detect adaptations of presumably infaunal species to food sources near vents (i.e. chemosynthetic bacteria).

determine if such adaptations are correlated with specific structures or arrangements in the cytoplasm (peroxisomes, symbiotic bacteria, etc.) or in the test morphology (vent tracers of presumably fossilizable potential).

7. ACCESS TO THE ARCTIC OCEAN

7.1 Current and future research platforms for the exploration of the Arctic Ocean

Ice-capable research ships, typified by the *RV Polarstern*, can carry large sophisticated laboratories and large multi-disciplinary scientific crews, support large scale ice operations, take long sediment cores, operate ROVs, do deep hydrographic and biological probing and sampling, and study air/sea/ice interactions. Research icebreakers can also work in shelf areas where other vehicles such as a submarine can not operate safely. In shelf areas research ships with significant ice-breaking capability can be used for deep seismic sounding or close to shore for pollution studies.

7.2 US icebreakers and polar research vessels - current and pending

The Coast Guard Polar Class icebreakers, *Polar Sea* and *Polar Star*, are the only US surface ships that are capable of operating in the Arctic's icy seas at the present time. The icebreakers, built in 1976 and 1978, were not designed for oceanographic research, but recently the Coast Guard has made modifications and added equipment to provide limited oceanographic capability. These improvements include 1200 sq. ft of laboratory space, installation of hydrographic and trawl winches and clearing an area on the main deck aft for over-the-side work and towing.

The recently-refitted Canadian icebreaker *Louis St. Laurent* participated in the Arctic '94 expedition and proved that it could successfully operate in the very high Arctic with moderate fuel consumption.

The US Coast Guard, which is responsible for Arctic operations in the US, is building a research icebreaker, the US Coast Guard Icebreaker Healy which is scheduled to be launched in 1998.

The projected scientific capabilities of the Healy and ARV are patterned after that of the new AGOR-23 class research vessels, except for additional capability in areas that are specific to studies in an ice-covered ocean. They will have a similar amounts of space devoted to laboratories, the same types of laboratories, roughly the same amount of open deck space and space for scientific stores. The projected major characteristics and scientific capability (existing or projected) are summarized in Tables 1a and 1b.

Table 1a. Characteristics of the ARV, Healy and Polar Class Icebreakers

	ARV	Healy	Polar Class

Displacement (LTWS)	11,500	16,300	13,400
Length (feet)	340	420	399
Beam (feet)	76	82	84
Endurance (days)	90	65	60
Power (BHP)	18,000	30,000	18,000/60,000
Ice Capability (3 kts)	4.5	4.5	6
Crew26	75	130	
Launch date	[2000]	1998	1976/78

Table 1b. Comparison of major scientific capabilities of the ARV, Healy and Polar Class Icebreakers

	ARV	Healy	Polar Class
Science Complement	36	35/50	35
Total Lab space (sq. ft)	6,100	3,800	1,200
Working deck (sq. ft)	4,400	3,000	Small
Sci. Storage (cu. ft)	22,200	20,000	Unknown
Vans	4	8	7
Helicopter	Visit only	2	2
Full Compliment of winches	Yes	Yes	No

Table 2. Principal characteristics of a US Navy Sturgeon Class submarine equipped for science. (Note: The Sturgeon Class are especially strengthened for operations in the ice.)

Speed	Up to 25 kts
Depth of operation	0 to 800'
Practical endurance	90 days
Range	unlimited, but normal operations restricted to areas with water depths > 100 m.
Laboratory space	ca. 1000 sq. ft.
Science berths	20 - 25
Operating crew	ca. 70

Table 3. Outfitting a scientific submarine
Hydrography
Recording CTD.
Up-looking and down-looking ADCP.
Enhanced sub-launchable expendable probes for temperature, salinity, oxygen and current shear profiling
Chemical oceanography
An uncontaminated seawater sampling system while submerged.
Capability to sample the shallow water column at discrete depths (ROV or AUV). Underway ship-mounted chemical sensors.
Geophysics
Swath bathymetry.
Gravimeter.
Magnetic gradiometer.
High resolution subseafloor profiler (e.g. parasound or chirp sonar).
High resolution vertical incidence seismic profiling.
Cryology
Up-looking swath mapper of the ice bottom.
Video imaging of the ice.
Biological oceanography
Submerged sampling capability.
Mid-water acoustic imaging capability.
Underway ship mounted color and turbity sensors.

General
A computer-based integrated data management, quality control and display system. Refrigerated space for storage of biological samples.

7.3 Nuclear-Powered Submarines

The capabilities that a scientifically-outfitted nuclear-powered submarine (SSN) brings to oceanographic research in the Arctic are distinct and unique (Table 2). The principal attribute of the SSNs is that their operation is completely independent of surface conditions, whether it is ice or rough seas. They offer a swift, quiet and stable platform of great endurance that is ideal for underway charting operations. For this purpose SSNs are efficient in terms of data quality, time and cost. In the Arctic Ocean, the SSNs can accomplish comprehensive geophysical and hydrographic surveying that is usually done from surface ships in open water, and do it far more cost effectively than ice-capable surface ships (see Tables 2 and 3).
The US Navy is currently decommissioning its fleet of Sturgeon Class attack submarines. These submarines are ice-strengthened to the extent that they can safely surface through 0.5 to 0.75 m of ice, and they have been used successfully in the recent past to carry out scientific cruises to the Arctic Ocean. The most effective use of one of these vessels, that has a 5 to 6 year supply of fuel left in its reactor, would be as a dedicated ship used in a "closed-end program". During such a program, a scientifically equipped SSN could comprehensively map a wide range of parameters in the Arctic Ocean.
A complete, high resolution swath map of the Arctic basins deeper than 100 m.
A complete geophysical map of the Arctic basins (magnetics, gravity, high resolution seismics).
A comprehensive map of hydrographic parameters (temperature, oxygen and salinity) at submerged depths (50 - 240 m); plus closely spaced vertical profiles of the upper 1000 m using expendable profiling devices.
A synoptic seasonal chart of current directions and speeds in the upper waters of the Arctic Ocean.
Basin-wide synoptic surveys of the chemistry of the upper 200 m of the water column.
A 5-year inventory of ice volume in the Arctic Ocean, and time series data on ice deformation and movement as well as ice growth and shrinkage over large areas of the Arctic.
An ocean-wide, year-round inventory of fauna and flora in the upper waters of the Arctic.

The cost of such a program, (estimated at US$250M to US$350M including conversion and equipping costs) is comparable to other oceanographic field programs of the same duration.

7.4 Arktos

Arktos is an amphibious marine transportation vehicle, that can travel across ice and through water, carried by the icebreaker Louis St. Laurent. It consists of two articulated units that weigh about 17 tons. The vehicle is propelled by tracks and a water jet. It can climb out of the water over the freeboard of the ice and climb over pressure ridges. It has been used in the Beaufort Sea as a vehicle to collect high resolution seismic reflection data. It can carry fuel, people and equipment across the ice at a speed of 2 - 3 knots. It could run transects parallel to the ship's track. It would be a valuable means of transporting equipment such as seismometers on the ice.

7.5 Hovercraft

Hovercraft were first tested under Arctic conditions in the Beaufort Sea nearly three decades ago, but have been used only sporadically since. Advances in craft design and the use of diesel power units, instead of gas turbines, have greatly reduced operating costs. A medium-sized craft today has more than three times the payload at half the engine power compared to the unit tested in 1966 by the Canadian Coast Guard.
Sea ice in the Transpolar Current traverses the Eurasia Basin and exits through the Fram Strait without obstruction of major land masses. Laser altimetry shows that the height of pressure ridges in this area is generally lower than ridges of the older sea ice in the central Arctic Ocean and areas north of the Canadian Archipelago and Greenland. The available information on sea ice roughness suggests that a Hovercraft with a hoverheight of 1.5 m may be an efficient and realistic logistic alternative for geoscientific experiments. Such a craft may carry a scientific payload of 2 tons to a maximum range of 700 km with 25% reserve fuel capacity. A cabin area of >40 m2 will provide accommodation and laboratory space for several

scientists on cruises of duration of one week or more. A craft of this type might operate from a land base or an icebreaker expedition into the central Arctic Ocean. Such a logistic facility is currently being considered for Svalbard.

8. INNOVATIVE TECHNIQUES OF DATA ACQUISITION IN THE ARCTIC

8.1 Passive seismic experiments on drifting ice

The Arctic ice cover inhibits the recovery of OBSs conventionally used to collect seismic refraction data, which provide critical information on the crustal structure and the depth to mantle. Permanent ice cover presents a unique opportunity to study the oceanic lithosphere using seismological techniques developed and routinely applied in continental regions. Specifically, an array of broad-band self-contained seismic receivers may be deployed over the ridge for a time period of up to a year. Such an array will maintain its general shape during the observation period, and will be carried by the drift of the ice roughly along the strike of the ridge. Each node of the array will contain a broad-band geophone, a broad-band hydrophone, a depthsounder (pinger), a portable data collection system (REFTEK), a GPS clock and an ARGOS transmitter. Most components of this system already exist and would require minimal modification for use in the Arctic. Observations of body (P, PKP) and surface (Rayleigh) waves from teleseisic sources will facilitate tomographic imaging of both the compressional and shear seismic velocity structures. Results of such imaging will then be interpreted in the context of melt distribution under the ridge and the pattern of the mantle upwelling. Local and regional earthquakes recorded by the array will provide data for crustal thickness and structure studies, which may be done repetitively as the array drifts along the ridge. Accurate locations of the ridge microearthquakes will help in defining the position of the spreading axis, as well as in establishing the ridge's segmentation.

8.2 Ocean bottom seismometers (OBS)

OBS that monitor microearthquake activity permit uniform mapping of the present day activity of spreading axes. Microearthquake activity along ridges can be observed accurately only by the use of dense OBS arrays, with 20 - 50 OBSs, and cannot be done by traditional teleseismic observations, which are, in most cases, thousands of km apart. Figures 9 and 10 show the results of such observations. The microearthquake focal depths are an important indicator of the brittle thickness of the crust in the ridge area, which at the same time is related to the speed of spreading of the ridge.

Seismic refraction experiments, using OBS arrays in combination with air-guns, have shown that OBS are powerful tools for elucidating the crust and upper mantle structure down to 30 - 40 km depth. The use of three component geophone observations at the sea bottom has demonstrated the advantage of obtaining S-wave structures, which are more sensitive to temperature, rock composition, anelasticity, anisotropy, etc. and thus increase our knowledge of the crust and mantle structures. Furthermore, in the case of microearthquake surveys, identifications of S-waves are essential for the accurate location of foci.

We propose extensive use of OBS at the Arctic ridges to define the present day activity of the spreading centers as well as to study the structure of the whole crust and upper mantle. Current OBS may need some modifications to be used in Arctic conditions, however, it is possible to use the current models in the open sea in the Arctic.

The deployment and recovery of OBS requires neither special equipment on the ship, nor much ship time. Deployment normally takes less than half an hour, and recovery can take from half to several hours, depending on the water depth. The recording period of current OBS is up to two months, experience has shown, however, that one month is in most cases enough to complete a microearthquake survey. A prototype OBS which records continuously for a year has been successfully tested in the Hokkaido Sea. Such an OBS may be useful for seismological observations at the bottom of the Arctic sea in the near future, where the service period of one year is valuable. Longer period recording is valuable for tomographic seismological imaging since numerous earthquakes can be captured.

8.3 Side-scan sonar from drifting ice or ice island

Side-scan and swath-imaging techniques provide a powerful means for inferring volcanic, sedimentary and structural features and processes on the seafloor, and they have been widely and successfully used on spreading axes. Side-scan sonar will be an effective reconnaissance tool when deployed from drifting ice. It is capable of imaging a wide swath of

seafloor over which the ice drifts, and is especially important as a means for establishing the regional context and significance of other geophysical and geological data.
A long-range, shallow-towed side-scan system is the instrument of choice for deployment from the ice. Compared to deep-tow systems, shallow-towed instruments are designed to insonify wide swaths that are appropriate to this sort of reconnaissance mission. Shallow-towed systems such as HAWAII MR-1 (operated by University of Hawaii/Hawaiian Institue of Geophysics) and GLORIA-B (operated by Southhampton Oceanography Centre) provide the additional capability of simultaneously acquiring swath bathymetry, resulting in better value for money. This sort of system could be operated by as few as two people, an engineer and a data processor. Necessary physical resources for data acquisition include an appropriate power supply, a winch, hardware for deployment and recovery, and GPS navigation. Transportation to and from the ice could be accomplished using a large cargo plane, icebreaker or Hovercraft.

9. DATA SYNTHESIS FOR ARCTIC RIDGES

9.1 Compilation and synthesis of existing data

An interdisciplinary synthesis of geoscientific data (DSDP/ODP drill data, bathymetry, side-scan, seismics, gravity, magnetics, heat flow, geology and petrology) from the mid ocean ridges of the Atlantic Ocean (north of 50¡N), the Norwegian - Greenland Sea and the Arctic has been initiated by German working groups. An outline of this synthesis is shown in Figure 11 and Table 4. The program plan envisions the following steps:
Locating data:
Obtain an overview of which research cruises have taken place, which methods have been applied, what has already been published, how were data processed, where have data been archived, whether data are freely accessible or, if not, how access is possible.
Data inventory:
Establish maps of data coverage (for each discipline / data type), and evaluate data quality.
Synthesis / Interpretation:
Data synthesis and integrated interpretation with focus on evaluation of relationships between different data types from identical areas.
Develop strategy for further research:
Development of internationally coordinated program plan (a) to complete acquisition of datasets which are needed to evaluate key parameters of ridge dynamic processes and (b) to stimulate advanced projects such as installation of seafloor observatories (including biology), quantification of mass budgets, and detailed numerical modeling of mantle dynamics.

9.2 The seafloor atlas of the northern Norwegian-Greenland Sea

Kathleen Crane
A new atlas of the Norwegian-Greenland seafloor was published in 1995 by the Norwegian Polar Institute (K. Crane and A. Solheim, editors). Revised compilations of regional bathymetry, gravity, magnetics, seafloor echo character, sediment core locations and heat flow have been prepared by individuals from the Norwegian Polar Institute, the University of Oslo, the University of Bergen, Lamont Doherty Earth Observatory, the Naval Reasearch Laboratory and GEOMAR.
However, the main goal of the atlas is to present seafloor swath mapping imagery (bathymetry and side-looking sonar data) collected by the SeaMARC II, SeaBeam, Hydrosweep and GLORIA systems. These data are presented for regions along the Mohns, Knipovich and Molloy Ridges, the Vesteris Seamount and the eastern margin of Greenland.
Publication of the atlas was funded by the Norwegian Polar Institute and the Joint Oceanographic institutions and it is available from the Norwegian Polar Institute. Interested parties should contact:
Annemor Brekke, Information Officer, Norwegian Polar Institute, P.O. Box 5072, Majorstua, N-0301 Oslo, Norway; Phone 47-22-95-95-20; fax 47-22-95-95-01; Brekke@npolar.no

9.3 Russian data from the Arctic Ocean

Vladimir Glebovsky
Aeromagnetic data over the deep Arctic Ocean and marine magnetic data from the Norwegian-Greenland Sea (magnetic anomaly profile maps of different scales) have been collected by VNIIOkeangeologia, St. Petersburg and the Russian Navy (see Figures 12 and 13). These data will complement existing western results and can be used in individual

projects to improve coverage or accuracy, and for geological interpretation. We plan to integrate the resulting gridded data into existing (e.g. AGC) or future international compilations. Preliminary processing of these data (digitizing, adjustment) requires some financial support defined by the actual volume of data used and the manpower needed.

Initial and gridded gravity information in the deep Arctic Ocean may at present be used for internal interpretation only. Results of gravity modeling and some transformed gravity data (residual, isostatic, mantle Bouguer anomalies) may be available for public discussion and analysis.

10. REPORTS ON RECENT RESULTS

10.1 Composition and origin of sediments on Kolbeinsey Ridge

K.S. Lackschewitz, H.-J. Wallrabe-Adams and J. Thiede

In order to reconstruct the sedimentation processes active in the vicinity of the Kolbeinsey Ridge, we focused on the distribution patterns of distinct sedimentary facies and on the chronological order of facies types, including their genetic processes. Of pronounced interest was the relation between morphology, oceanography and particle supply and the resulting sedimentary deposits. Sedimentological and geochemical data proved to be useful for quantifying the composition and distribution of sediment components from the ridge to document the different sedimentation processes (Lackschewitz, 1991). Dating and correlation of sediment layers allowed us to reconstruct changing depositional processes in space and time. The area of investigation was the Kolbeinsey Ridge north of Iceland, where the geotectonic-structural character, as well as the oceanographic and climatic processes, are highly important inter-regional factors influencing the depositional processes. Its southern part is a single, narrow ridge approximately 20 km wide. The ridge descends northward from the Icelandic shelf to water depths of about 1400 m near the Spar Offset. The northern part of the ridge is divided into parallel highs and deeps with an axial rift valley. The spreading velocity is approximately 2 cm/a (Vogt, 1983).

Today, the Iceland Sea is characterized by strong meridional gradients due to the different surface water masses. The modern surface current system in the area studied is characterized by the East Greenland Current, which carries cold Polar water southward along the East Greenland shelf, and the East Icelandic Current, fed by cold Polar and warm Atlantic waters (Hopkins, 1988). Deep water penetration from east to west across the ridge may influence near bottom flows on the Kolbeinsey Ridge, Figure 14.

Most of the sediments studied were collected by box coring during *RV Poseidon* cruise 158 (Puteanus and Werner, 1990), *RV Poseidon* cruise 175 (Mienert and Wallrabe-Adams, 1992), *RV Polarstern* cruise ARK V/lb (Spindler, 1989), *RV Polarstern* cruise ARK VII/l (Thiede and Hempel, 1991) and *RV Meteor* cruise 21/5 (Pfannkuche et al., 1993).

Surface sediments from the northern ridge, and from the basin west and east of Kolbeinsey Ridge, generally consist of brownish sandy silty clay (Figure 14). The sand fraction of these sediments is mainly composed of terrigenous particles, but east of the ridge, sediments are characterized by sandy silty clay with relatively high amounts of planktic foraminifers. On the southern Kolbeinsey Ridge sediments show an increase in volcanic sand.

Sediments from the northern ridge area show characteristic records of glacial/interglacial deposits with intercalated subaerial volcanic ashes, opening a window on the geological and climatic history of the western Iceland Sea (Baumann et al., 1993). On the basis of oxygen isotope stratigraphy, we have reconstructed the changes in the depositional processes during the last 250,000 years. The sediment cores are generally characterized by low calcium carbonate values. In glacial sediments of oxygen isotope stages 6, 4 and 2 the carbonate content usually decreases to values of less than 10 weight-%. The highest calcium carbonate contents are measured in oxygen isotope substage 5.5 suggesting that warm Atlantic water reached the western Iceland Sea. The sediments are rich in coarse terrigenous material throughout. Previous studies of marine sediments from high latitudes have shown that coarse lithogenic particles (>63 (m) can be interpreted as ice-rafted detritus, if other transport mechanisms (e.g. gravity flows, boundary currents) can be excluded (Ruddiman, 1977; Heinrich, 1988; Spielhagen, 1991; Bond et al., 1992). Together with low but constant calcium carbonate values, this documents a relatively stable environment in this area over the last 250,000 years, strongly influenced by polar conditions such as sea ice cover, glaciers and cold surface water masses. A distinct ash layer with typical subaerial glasses matches a widespread ash in oxygen isotope stage 7. Another ash layer near the Holocene/Pleistocene boundary consists of volcanic glass of basic and acidic composition, which can be correlated to the Vedde Ash originating from Iceland.

The southern Kolbeinsey Ridge is characterized by a symmetric ridge partly with a narrow central valley. It is volcanically active and hydrothermal processes occur in the southernmost region near the Icelandic shelf (Fricke et al., 1989). Little sediment has accumulated on the ridge crest area whereas a gradual increase in sediment cover is observed from the flanks to the adjacent basins. Primarily in situ produced volcanic glass particles and low amounts of biogenic and terrigenous components characterize the ridge crest. These glasses range in shape and texture from blocky, non-vesicular shards to crenate, highly vesicular types. These basaltic volcanic particles document submarine eruptions along the southern volcanically active zone. Only one type of colorless shard representing the walls of adjacent volcanic gas bubbles shows a more silicic composition and probably originated from a subaerial eruption on Iceland.

With increasing water depth and distance from the ridge crest, the sediments become generally more clayey and silty. However, along the eastern ridge flank, sediments are more sandy, whereas on the western flank, the rise in the silt and clay fraction indicates a higher deposition of fine particles, suggesting that bottom currents incorporate fine material and transport it westward to the western flank and adjacent basin. Sediment cores from the western flank show sedimentation rates of 20 to 50 cm/ka, reflecting the high accumulation of fine volcaniclastic material. In contrast, pelagic sediments of cores from the eastern flank of the Kolbeinsey Ridge show sedimentation rates lower than 10 cm/ka.

These results indicate that spreading axes in the Arctic are a highly complex sedimentary environment with strong changes in depositional processes. In contrast to the unique and widespread facies types of the deep-sea basin sediments in the Norwegian-Greenland Sea, deposits of the mid-oceanic Kolbeinsey Ridge are highly influenced by polar conditions, ridge topography, submarine volcanism and regional bottom current systems (Figure 15).

10.2 State of knowledge of the ridges in the Norwegian-Greenland Sea

Kathy Crane

Compared to other oceans, the ridges in the Norwegian-Greenland Sea have been well surveyed by multi-beam swath mapping systems. Systems that have been used to image the Norwegian-Greenland seafloor are shown in Table 5.

In detail, the ridge axes are unbroken by transform faults, are characterized by en echelon faults (Figures 16, 17 and 18), oriented highly obliquely to both their rift valley walls and to faults located on the rise axis flanks. The detailed regional imagery should provide adequate base maps for future sampling programs strategically located in the rise axes.

Some of the rock sampling effort in this region can be seen on Fig. 1 and Fig. 11d. V. Renard from IFREMER reports that there have been at least three successful dredges on the Mohns Ridge and a few samples have been successfully retrieved from the Molloy Ridge by E. Bonatti, J.-G. Schilling and C. Devey. Many of the difficulties experienced by individuals attempting to dredge the Knipovich Ridge can be explained by the large amount of sediment which has accumulated there. However, with the SeaMARC II imagery in hand, dredging into sediment can be, to a large extent, avoided.

In addition, new ocean-wide compilations of gravity, magnetics and heat flow have been constructed. However, it is quite apparent that very few heat flow stations have been taken south of Svalbard, leaving much room for future surveys.

Seismic reflection and refraction data over the Mohns and Knipovich Ridges have been collected by numerous Norwegian, German and Russian institutions. Many of these data are available through technical reports and in the Seismic Atlas Of Western Svalbard also available from the Norwegian Polar Institute. However, much work remains to compile the existing lines further to the south along the Mohns and Kolbeinsey Ridges. For more information about other data collected over these ridges see Table 5.

Table 5: Data and data sources for ridges in the Norwegian-Greenland Sea

Region	Mapping System	Data type	Organization
Kolbeinsey Ridge	Sea Map	side-looking sonar and bathymetry	NRL, University of Hawaii
Aegir Ridge	SeaMARC II	side-looking sonar and bathymetry	NRL, University of Hawaii

Mohns Ridge	Argo	video, temperature, side-looking sonar	Woods Hole, USGS
Mohns Ridge	SeaBeam	bathymetry, mag., grav., seismics	IFREMER
Mohns Ridge	SeaMARC II	side-looking sonar, bathy., mag., grav.	NRL, LDEO, University of Bergen
Knipovich Ridge	SeaMARC II	side-looking sonar, bathy., mag., grav.	NRL, LDEO, University of Bergen
Molloy Ridge	SeaMARC II	side-looking sonar, bathy., mag., grav.	NRL, LDEO, University of Bergen
Molloy Ridge	Hydrosweep	bathymetry	Alfred Wegener Inst., GEOMAR

10.3 Geophysical investigation on the ice supported by aircraft

M. Sorokin

The success of any geophysical research expedition in hostile and remote zones, such as the polar area of the Arctic Ocean, particularly if it is necessary to use light aircraft for surveying, depends on choosing the right organizational scheme for all stages of the fieldwork.

These organizational problems were solved by the Polar Marine Geosurvey Expedition (PMGE) during field work in 1989-92. The main objective of the work under the special scientific program, TRANSARCTIKA, was to obtain reliable data about the thickness and structure of the crust and sedimentary layers of the central Arctic basin floor (Lomonosov and Mendeleev-Alpha ridges, Makarov and Podvodnikov basins).

The field work was executed along submeridial (1200 km) and sublatitudinal (500 km) research lines (profiles) which used the following geophysical methods:

Deep Seismic Sounding (DSZ) to estimate thickness and structure of crust including "M"-surface.

Surveying by seismic reflection to estimate thickness and structure of sedimentary layers.

Gravity surveying for reconstruction of crustal density model.

Aeromagnetic surveying in zones of 100 km along the research line to obtain magnetic crust properties.

Taking into account previous experience of Arctic research we chose the seasonal aircraft organizational scheme for executing this work.

The main features of this scheme are:

All field work is executed from special ice drift stations organized at certain points in the Arctic basin. All scientific staff and assistant personnel, 2-3 helicopters and 2 light aircraft are based at the station. The station works for a period of three months each year (March - May).

All necessary expendables, including light aircraft fuel, are delivered to the station by four-engined planes (AN-12) from the nearest airports (1000-1500 km) - 30-40 trips per season.

For successful field activity it is necessary to build 2-3 spare ice-runways on the drift station.

The first delivery of bulldozers to build and maintain a runway of sufficient length (1600 m) to serve AN-12 aircraft, is dropped by parachute.

This scheme allows us to obtain scientific data along a 500 km part of the research profile during each field period. The polar expedition (PMGE) has successfully applied this organizational scheme and have obtained reliable geophysical data along the described surveying profiles.

Preliminary results:

In the middle parts of Podvodnikov and Makarov Basins, the crust thickness is 11-19 km, and the thickness of the sedimentary layer is 5-7 km.

In the ocean slope zone (south part of Podvodnikov Basin), the thickness of the sedimentary layer increases up to 12 km.

In the Lomonosov Ridge area, the subcontinental crust is about 25-30 km thick; westward the crust thickness decreases to 9 km (Amundsen Basin ocean crust).

The crust in the Podvodnikov Basin is similar to that of the Lomovosov Ridge, but not so thick.

PMGE is still working on co-interpretation problems of the multidisciplinary geophysical data and wishes to continue such field research along the east side of the latitude profile (Mendeleev-Alpha Ridge).

10.4 Seismic Profiles across Lomonosov and Gakkel Ridges

In summer 1991, the German *RV Polarstern* and the Swedish icebreaker *Oden* penetrated the pack ice across the Eurasian Basin. Continuous gravity measurements and multichannel seismic reflection measurements were carried out on board. Additionally, seismic refraction data were acquired using sonobuoys and recording stations on ice floes. The recorded seismic profiles have a total length of 1500 km. The location of this data is shown in Figure 21.

Two seismic reflection profiles across Lomonosov Ridge show that the ridge is slightly tilted towards the Amundsen Basin and covered by undisturbed flat-lying layers, as shown in Figure 22. The seismic refraction measurements provide low P-wave velocities of 1.7 - 2.3 km/s for these layers and a total thickness of 500 m. The layers are interpreted as marine sediments, deposited on the ridge crest after its subsidence below sea level.

Below this sediment cover, a number of weak reflection signals can be observed. They represent horizontal layers which are bounded by faults and halfgrabens on the Amundsen Basin side. This documents the rifting and extension when Lomonosov Ridge separated from the Barents-Kara Shelf.

The evaluation of the refraction measurements provide P-wave velocities of 4.0 to 5.8 km/s and a total thickness of 1800 m for these sequences. They are presumed to be highly consolidated Mesozoic sediments of terrigenous origin deposited before the ridge split from the Barents-Kara Shelf.

Towards the Makarov Basin the ridge is covered by prograding sequences, which appear to be deposits of the old continental shelf. An unconformity with the layers above shows that material was eroded when Lomonosov Ridge subsided below sea level. Later this unconformity was covered with marine sediments.

A preliminary gravity model across Lomonosov Ridge shows good correlation with an adapted model of the LOREX expedition. The ridge's sediment cover can be divided into two density packages with mean values of 1.9 and 2.5 g/cm3 and a thickness of 2 km and 5 km respectively. Beneath them the crustal root with a density of 2.85 g/cm3 reaches down to a depth of 28 km.

All seismic reflection profiles across the Amundsen and Nansen Basins show clearly the oceanic basement with increasing roughness towards the Gakkel Ridge, covered by a set of continuous sediment layers. With the help of the magnetic anomalies running parallel to the MOR and crossing the seismic profiles, it is possible to estimate an age for the deposited layers, which we divided into three units (AB-1 to AB-4, AB-5.1 and AB-5.2, AB-6 to AB-8; Figure 23).

Based on this stratigraphic model, the following ideas on the evolution of the Amundsen Basin were established:

The lowest 900 m thick layer (AB-1) of the first unit is composed of eroded terrigenous material from Lomonosov Ridge, deposited when the Eurasian Basin opened 60 Ma ago (synrift sediments).

The overlying layers (AB-2, AB-3 and AB-4) onlap the slope of Lomonosov Ridge and increase in thickness towards the Gakkel Ridge. These sediments are believed to be composed of terrigenous material from the Lomonosov Ridge and shallow marine deposits.

After the subsidence of the Lomonosov Ridge below sea level about 50 Ma ago, the layers are increasingly composed of sediments and turbidites from the surrounding shelves and the Gakkel Ridge. They are covered by the 400 m thick units (AB-5.1 and AB-5.2) that pinch out towards Lomonosov Ridge. This demonstrates that after 45 Ma, Lomonosov Ridge was too deep and had no further influence on the sediment input. The deposited material consists mainly of turbidites of Gakkel Ridge and shelves.

The estimated age and the thickness of the layers allow us to calculate a sedimentation rate of 10-15 cm/ka for the first two units (AB-1 to AB-4, AB-5.1 and AB-5.2). This shows the high input of material into the Amundsen Basin, eroded during the subsidence of Lomonosov Ridge.

The third unit (AB-6 to AB-8) is less than 36 Ma old and covers the Amundsen Basin with a constant thickness of 500 m. The sedimentation rate decreased to just 2 cm/ka.

In the central Amundsen Basin the maximum sediment cover has a thickness of 3200 m, but in its southern part it is just a few 100 m thick. Figure 24 shows a cross section across the southern part of the Eurasian Basin from the Morris Jesup Rise to the Yermak Plateau. This part opened after 34 Ma by seafloor spreading. Therefore, just a thin sediment cover of 500-1000 m is observed, which seems to be influenced by currents. The oceanic basement has a very rough topography, and a deep central valley of Gakkel Ridge can be observed (4000 m average).

Finally we will remark that the successful measurements of the ARCTIC'91 expedition were due to international cooperation. This may encourage further joint projects for investigations in the Arctic.

10.5 Seismic investigations at the extinct Aegir Ridge

I. Grevemeyer, W. Weigel and H.B. Hirschleber (Hamburg); F. Avedik (IFREMER); and R.B. Whitmarsh (SOC)

Of substantial interest to marine geophysicists during recent decades has been the structure of oceanic crust and upper mantle at the locus of plate creation - the mid-ocean ridge. The Norway Basin contains a rare example of an abandoned mid-ocean ridge where active spreading ceased about 30 Ma ago. This extinct spreading center, called the Aegir Ridge, had a spreading rate that is within the range of that of ultra-slow spreading centers.

In 1987 and 1989 the Institute of Geophysics, University of Hamburg carried out two seismic surveys at the extinct Aegir Ridge aboard the German RV Valdivia (Figure 25). Using an array of 3 airguns (total 5.7 l), 8 multi-channel seismic reflection profiles (24 channels, active streamer length 600 m) with a total length of about 350 km were obtained. Seismic refraction data were collected in co-operation with IFREMER and IOS along two lines: profile V along the axis and profile IV crossing it orthogonally. As sound source we used three 16.4 l Bolt airguns and chemical charges (Figure 26). The velocity structure was modeled using 2-D ray tracing of P wave travel times. The results reveal major variations in crustal thickness and velocity along and perpendicular to the axis. Crust within the extinct spreading center was found to be about 1 km thinner when compared with the crustal structure about 100 km distant from the ridge axis (Figure 27). Additionally, in the extinct spreading center, velocities were found to be lower than those in "normal" oceanic crust found elsewhere in the Atlantic Ocean. These low crustal velocities within the ridge axis may be due to the fact that the supply of partial melt decreased and the degree of tectonism increased before spreading ceased, causing pervasive fracturing of the entire crust and hydrothermal alteration which lowered seismic P-wave velocities of the basaltic and gabbroic section.

10.6 Mohns Ridge: a detailed geophysical survey

Vincent Renard

Mohns Ridge, in the Norwegian-Greenland Sea, extends more than 500 km from Jan Mayen Island north-eastward to the Knipovich Ridge. In order to study the accretionary processes along the Mohns Ridge, and the crustal evolution towards the continental margin of Norway, a two ship project was carried out in the summer of 1988.

RV Jean Charcot conducted a Seabeam, gravity, magnetic and seismic reflection survey of a cross-shaped area along the ridge axis that was 250 km long parallel to the axis and 170 km wide.

RV Le Suroit followed, conducting a seismic reflection and refraction survey that consisted of:

1700 km of single channel reflection seismics.

Eight profiles of combined refraction/reflection parallel to the ridge axis for a total length of about 500 km, which were recorded with three ocean bottom hydrophones at each profile.

One 60 km long, seismic refraction profile along the ridge axis was recorded with five ocean bottom hydrophones.

Two experiments of seismic tomography recorded by four ocean bottom hydrophones and one ocean bottom vertical seismic array.

Results from these two cruises:

Structure

The rift floor is characterized by en echelon ridges regularly spaced along the axis and.separated by non-transform discontinuities (Dauteuil and Brun, 1993); these ridges trend 30(obliquely to the general rift trend. They are bordered by deep flat-floored depressions.

Central valley walls display non-linear, zigzag escarpments which reach several hundred meters relief, and are asymmetric (the north-western wall is several hundred meters higher than the south-eastern wall).

Absent were fracture zones, as well as long, continuous, normal faults parallel to the ridge, both of which are typical of the MAR.

Magnetics

Sharp positive magnetic anomalies are centered over these inner ridges and correspond, according to 3D modeling analysis, to strong source and rock magnetization.

Magnetic anomalies away from the axis are patchy and not as linear or continuous as normally found along the MAR.

Gravity

Gravity anomalies (3D Bouguer) indicate the presence of a low density body within the crust and low density masses in the upper crust matching the inner ridges. Long wavelength gravity anomalies are compatible with a low density layer below the axis deepening away from the axis as the lithosphere cools.

Seismic refraction

Seismic refraction data indicate the presence of a 6 km thick crust (layers 2A, 2B and 3) overlying a normal mantle except along the ridge axis. The tomographic experiment indicated that the structure at the ridge is consistent with injection of low velocity material in the upper crust from an underlying low density anomalous body (Géli et al., 1994).

Interpretation

Oblique spreading is suggested as the active mechanism which best explains the observations. The en echelon oblique fault system may provide pathways for the extrusion of rising low density material. Gravity and magnetics suggest that the en echelon ridges are made of eruptive volcanic material, and are the surficial expression of active spreading cells. Three rock samples dredged from one of the inner ridges display fresh basaltic glass. The morphology of the inner ridge is also typical of a volcanic extrusive area with numerous circular eruptive centers.

Analog tectonic modeling of oblique spreading reveals a fault pattern similar to the one observed in the central valley, where oblique ridges would correspond to tectonic horsts, however the model predictions are not confirmed by our observations.

Oceanic crust away from the axis is characterized by a lack of aligned structures away from the ridge axis, which could reflect the zigzag trend of the inner walls faulting as it translates laterally.

The Jan Mayen Fracture Zone trend is perpendicular to the inner rift ridges and not to the general trend of the rift and implies that oblique spreading has been active at least since anomaly 5. No major change in the spreading characteristics can be detected within the last 10 Ma.

No mantle seems to be exposed in the central rift area, but is found well away from the axis on the flanks revealing the narrowness of the zone of crustal formation. Detailed crustal models will be derived from the analysis of the seismic refraction and gravity data. Detailed seismicity investigations would be most beneficial as they would help to resolve the mechanism of crustal accretion in an oblique spreading context.

10.7 Paleoceanography of the deep Arctic Ocean: research history and a short review of results

Robert F. Spielhagen and Jörn Thiede

While paleoceanographic research in most parts of the world's oceans has made strong progress in recent years, similar investigations in the Arctic Ocean proper were impeded due to the hostile environment and the perennial ice cover. The only available sea floor samples from the deep Eastern Arctic stemmed from the Fram drift (Böggild, 1906). Early Russian research activities on icebreakers remained inaccessible to the scientific community in the West. It was only in the 1960's that American scientists started to unravel the paleoceanographic history of the Arctic Ocean. Approximately 600 short sediment cores were obtained from Ice Island T-3 between 1963 and 1973, during its 34-year drift in the Amerasian Basin (Figure 28). In essence, two working groups in Madison, Wisconsin (USA) and Seattle, Washington (USA) performed most of the sedimentological and micropaleontological analyses on these cores. The results of each group were published as a large number of research papers and are summarized in Clark (1971), Clark et al. (1980), Herman (1974) and Herman et al. (1989).

In exceptional cases, the T-3 sediment cores contained Upper Cretaceous or Paleogene sediments rich in organic material or marine microfossils (Figure 29). These sediments indicate that the Arctic Ocean was probably not ice-covered and allowed high bioproduction until some time in the Tertiary. Unfortunately, no sediments of post-Eocene to pre-upper Miocene have been recovered yet from the central Arctic Ocean, so that it remains an open question as to when the ice cover developed in this area. Recent results from ODP Leg 151 on the Yermak Plateau place the onset of glaciation within this interval (see Myhre et al., 1995).

The stratigraphy of the Upper Cenozoic sediment cores from T-3 is mainly based on paleomagnetic investigations, which revealed very low sedimentation rates in the Amerasian Basin. Average values range from 0.55 to 2.92 mm/ka in the Brunhes chron and from 0.3 to 1 mm/ka in sediments of the Matuyama, Gauss and Gilbert chrons (Clark et al., 1980). These low rates make it virtually impossible to perform high-resolution studies on millennial or lesser time scales. However, significant changes in the sediment composition indicate related paleoenvironmental changes. The most important feature of all hemipelagic sediments in the cores is the occurrence of coarse terrigenic material, interpreted as IRD. It suggests the presence of an ice cover for the entire Late Cenozoic and no evidence has been found yet for true ice-free time intervals. While coarse-grained IRD has probably been transported by icebergs, much of the fine-grained fraction may have been rafted by floating sea ice. Silty and sandy units are interbedded and often contain well-preserved fossil assemblages of planktic foraminifers, calcareous and arenacous benthic foraminifers, coccoliths, dinoflagellates, and ostracods, in strongly variable amounts (Herman, 1974; Herman et al., 1989). Lithostratigraphic units were defined by their grain-size distribution and fossil content (Clark et al., 1980) and can be traced on all morphological highs throughout the entire Amerasian Basin. Fine-grained units, which may contain planktic microfossils, are interpreted as mostly sea ice deposition during interglacials or even longer intervals of milder climates, while the coarser units should result from sea ice and iceberg transported sediment and represent glaciations or deglaciation events (Herman, 1974; Clark and Hanson, 1983). In the deeper parts, especially of the Canada Basin, hemipelagic sedimentation was often interrupted by turbiditic events (Goldstein, 1983).

Several years after ice island T-3 had been abandoned, further sediment cores were obtained from ice camps. The Canadian CESAR and LOREX expeditions to the Alpha and Lomonosov Ridges (Jackson et al., 1985; Morris et al., 1985) and expeditions on the FRAM-I and FRAM IV ice islands in the Eurasian Basin north of the Fram Strait (Kristoffersen, 1979) obtained new material from previously unexplored parts of the Arctic Ocean (Figure 28) and allowed the first high-resolution studies of the Arctic Ocean paleoceanography during the last deglaciation (Markussen et al., 1985; Zahn et al., 1985). A summary of the state of knowledge in the late 1980s about the paleoceanographic history of the Arctic Ocean is given in Thiede et al. (1990).

Research possibilities in the Arctic Ocean were strongly improved by the use of icebreakers adapted to research tasks (Figure 28). Starting in 1980 with the Swedish Ymer-80 expedition in the waters north of Svalbard (Boström and Thiede, 1984), icebreakers allowed the deployment of heavy coring equipment for long, large-diameter cores along the ship's cruise track. The German RV Polarstern crossed the entire Nansen Basin in the summer of 1987 and reached the active-spreading Gakkel Ridge at 85°N, 25°E during expedition ARK IV/3 (Thiede, 1988; Spielhagen et al., 1988). Sediment cores from this morphological high were dated by radiometric methods (Mienert et al., 1990; Bohrmann, 1991; Eisenhauer et al., 1994). They document a dominantly fine-grained sedimentation from sea ice throughout the last 125 ka with very little evidence for the presence of icebergs (Figure 30). In contrast, sediments from the previous glaciation (oxygen isotope stage 6) are coarse-grained and contain coal particles, probably derived from Northern Siberia, indicating a strong continental glaciation in this area (Spielhagen and Thiede, 1994). One core from Gakkel Ridge valley contained altered basalts (Mühe et al., 1991) and geochemical results from various sediment cores from this area indicate a hydrothermal influence at least during the last 130 ka (Bohrmann, 1991). A special issue of "Deep Sea Research" (Pfirman and Thiede, 1992) contains various papers with results from material obtained during ARK IV/3.

American expeditions with Polar Star to the Northwind Ridge and the Beaufort Sea were conducted in 1988 and 1992 (Philips et al., 1992; 1992 Arctic Summer West Scientific Party, 1993) and revealed low sedimentation rates of 3 - 5 mm/ka. Foraminifer-rich layers are interpreted as representing the interglacial periods of the Brunhes magnetic chronozone, when seasonally open waters may have allowed enhanced bioproduction along the basin margins in this area (Poore et al., 1993). In 1993, sediment cores were obtained by Polarstern along the Northern Eurasian continental margin in the Barents and Laptev seas (Fütterer, 1994).

In the 1990's, two expeditions with conventional icebreakers reached the North Pole (Figure 38). During ARCTIC'91, the Swedish Oden together with Polarstern performed multidisciplinary research along their way from Svalbard to the Pole (Anderson and Carlsson, 1991; Fütterer, 1992). Sediment cores of excellent qualities were obtained by Polarstern along track and allowed high-resolution analyses of the Quaternary paleoceanographic history of the eastern and central Arctic Ocean. Results have revealed four phases of enhanced iceberg concentrations in the central Arctic Ocean during the last 650 ka, all of them corresponding to strong continental glaciations in Northern Siberia. Surface water masses experienced significant influence from continental sources by meltwater influx from decaying ice sheets (Stein et al., 1994) and changes in the deeper water masses corresponded to the surface water development (Cronin et al., 1995). A special issue of "Marine Geology" (Thiede et al., 1994) contains various papers with results from material obtained during ARCTIC'91.

Finally in 1994, the transect across the Arctic Ocean from the Fram Strait to the Bering Strait was completed during the US-Canadian expedition Arctic Ocean Section Cruise 1994 of icebreakers Louis Saint-Laurent and Polar Sea, when scientists obtained various sediment cores from north of Alaska across the Amerasian Basin to the North Pole. With this excellent material in their hands, paleoceanographers are optimistic that they will be able to solve many secrets of the Late Cenozoic history of this planet's least explored ocean.

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Abbreviations Used

ADCP	Acoustic Doppler Current Profiler
AGC	Atlantic Geoscience Centre
ARV	Arctic Research Vessel
AUV	Autonomous Underwater Vehicle
CTD	Conductivity, Temperature, Depth
DSZ	Deep Seismic Sounding
EPR	East Pacific Rise
GIN	Greenland-Iceland-Norwegian
IOS	Institute of Oceanographic Studies
IRD	Ice-Rafted Detritus
LDEO	Lamont-Doherty Earth Observatory
MAR	Mid-Atlantic Ridge
MCS	Multi-Channel Seismics
MOR	Mid-Ocean Ridge
MORB	Mid-Ocean Ridge Basalts
NRL	Naval Research Laboratory
OBH	Ocean Bottom Hydrophones
OBS	Ocean Bottom Seismometer
OBVSA	Ocean Bottom Vertical Seismic Array
ODP	Ocean Drilling Program
PMGE	Polar Marine Geosurvey Expedition
ROV	Remotely Operated Vehicle
RV	Research Vessel
SCS	Single Channel Seismics
SSN	Nuclear-powered submarine
SWIR	South West Indian Ridge
UH/HIG	University of Hawaii/Hawaii Institute of Geophysics
USGS	United States Geological Survey

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Meeting Presentations
Talks
Global ridge objectives, *C. H. Langmuir*
Paleoceanography of the Arctic, *R. Spielhagen*
Arctic Gateways (ODP Leg 151) - Development of the Arctic Basins, *A. Myhre*
Hydrothermal vent communities at the shallow subpolar Mid Atlantic Ridge, *O. Giere*
Drifting sea ice as a platform for marine geophysical experiments, *Y. Kristoffersen*
Arctic research vessel logistics, *W. Jokat*
Nuclear Submarines for Arctic Science, *M. Langseth*
A new Seafloor Atlas of the Norwegian-Greenland Sea, *K. Crane*
MCS surveys at Kolbeinsey and Aegir Ridge, *F. Theilen*
Composition and origin of sediments on the Mid-Atlantic Ridge north and south of Iceland, K. Lackschewitz, *H.-J. Wallrabe-Adams, and J. Thiede*
Geochemistry of Kolbeinsey Ridge basalts, C. Devey
Seismic Investigation at the extinct Aegir Ridge, *I. Grevemeyer, W. Weigel, H. Hirschleber, F. Avedik, and R.B. Whitmarsh*
Ocean bottom seismographs as a tool to study Arctic Ridges, *H. Shimamura*
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Russian magnetic and gravity datasets in the deep Arctic Ocean and Greenland-Norwegian Basin - the possible ways of compilation and interpretation, *V. Glebovsky*
Geophysical investigations in the Central Arctic Ocean crust, *M. Sorokin*
Seismic profiles across Gakkel and Lomonosov Ridges, *E. Weigelt*
Petrology of Nansen-Gakkel Ridge, *R. MŸhe*
Aerogeophysical data from the Arctic, *J. Brozena*
Plans for a synthesis of Arctic data, *R. Rihm*
Video on Knipovich Ridge to Molloy transform and Deep, *K. Crane*
Perspectives of Ocean Drilling in the Arctic and discussion on researchstrategies, *H. Dick*
Nansen Arctic drilling, *Y. Kristoffersen*

Posters

Sediment facies and geochemical characteristics of Late Quaternary deposits between Iceland and Jan Mayen Fracture Zone, *K. S. Lackschewitz and H.-J. Wallrabe-Adams*
Sea MARC II investigations along the accreting/transform boundary in the Greenland Sea - Fram Strait area, *E. Sundvor*
The magnetic compilation of the Arctic and North Atlantic, *Verhoef, Macnab et al.*
A transect of the Arctic Ocean: Alaska to Norway, *R. Jackson, Sweeney et al.*
Refraction and reflection data from the Canada Basin, *R. Jackson, Grantz et al.*
Cretaceous magmatism in the Canadian Arctic: A possible link with the opening of the Amerasia Basin, *Williamson*
Aerogeophysical data from the Arctic, *J. Brozena*

Workshop Discipline Groups

Geology and geophysics: O. Eldholm (chair), B. Menke (rapporteur) and 17 participants
Biology and hydrogeology: O. Giere (chair), C. Van Dover (rapporteur) and 5 participants
Petrology and volcanology: P. Michael (chair), J. O'Connor (rapporteur) and 8 participants
Sedimentology and paleontology: H.-J. Wallrabe (chair), K. Lackschewitw (rapporteur) and 4 participants