Results of the Arctic Mid-Ocean Ridge Expedition - AMORE 2001 - Seafloor Spreading at the Top of the World

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Overview

The Arctic Mid-Ocean Ridge Expedition (AMORE 2001) returned in early October 2001 after an incredibly successful nine-week study of Gakkel Ridge and its surrounding basins in the high Arctic. AMORE 2001 was an international effort involving two icebreakers: PFS Polarstern, from the Alfred Wegener Institute in Bremerhaven, Germany, and the new U.S. icebreaker, USCGC Healy. It was Healy's maiden scientific voyage, and she proved to be an excellent icebreaker and scientific platform. This historic and highly successful expedition far exceeded anyone's expectations and went well beyond the goals set forth by InterRidge in charting and sampling Gakkel Ridge. Some of the highlights of the expedition are:

- Basalts and peridotites were recovered from over 200 sites within and near the axis of Gakkel Ridge, about three times as many sites as were planned.
- Hydrothermal plumes were discovered and sampled along this ultraslow spreading ridge.
- A high-resolution, well-navigated map of the ridge was unexpectedly produced using the hull-mounted multibeam sonar systems, which worked far better in the ice than anticipated.
- Successful seismic measurements showed that crustal thickness varies strongly along the axis of Gakkel Ridge, most likely according to distinct volcanic centers.
- The crustal thickness in the Nansen Basin does not follow theoretical models, which predict thin crust at slow spreading rates. The crust thickens towards the Gakkel Ridge.

Introduction

Gakkel Ridge is an end-member of the global spectrum of mid-ocean ridges in many respects, and offers a unique combination of characteristics (e.g. spreading rate, geographical location, obliquity, segmentation) which may control the composition of the erupted magmas, the crustal thickness and the presence of hydrothermal activity. Its spreading rate is by far the slowest of any mid-ocean ridge and varies by a factor of two along its length. AMORE 2001 has thus greatly extended the range of values over which we can investigate the relationships between ridge properties and spreading rate. Gakkel Ridge has an exceptionally deep rift valley, and the thinnest known crust for a normal ridge (<4 km). It has no large offsets, so it allows examination of the roles of ridge obliquity (transform faults) versus mantle upwelling in causing ridge segmentation. Gakkel Ridge is far from the Indian Ocean, and therefore allows separation of the effects of spreading rate from the anomalous Indian Ocean mantle source in the geochemistry of basalts. Analysis of a few small basalt and peridotite samples from Gakkel Ridge suggests the extents of melting may be very low (Mühe et al., 1997; Hellebrand et al., in press). This has implications for the ratio of peridotite to basaltic crust that may be present in the ridge axis.

While so far there is little doubt on the existence of thin crust in the rift valley, the situation off-axis is different. Past observations and a recent study (Weigelt & Jokat, 2001) indicate that there might be no simple relation between spreading velocity and crustal thickness away from the Gakkel rift valley. Although spreading velocity decreases, sparse seismic refraction data and gravity modeling suggest a thickening of the oceanic crust. It is not clear whether this observation is typical or if it represents only local variations in the composition of the oceanic crust. In any case it challenges currently accepted theoretical models. May be Gakkel Ridge represents a

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threshold spreading environment, where existing global models fail in general.

How the mantle beneath the Arctic Ocean is related to the mantle beneath the northernmost Atlantic Ocean and the rest of the planet, and how it may have been influenced by the nearby continents are additional basic questions that will be addressed by geochemical study of the igneous rocks. Gakkel Ridge is our sole opportunity to sample this portion of the earth's interior.

Gakkel Ridge

Gakkel Ridge stretches 1800 km across the Eurasian Basin of the Arctic Ocean, all of it beneath Arctic sea ice (Fig. 1). It is the most remote and slowest spreading portion of the global mid-ocean ridge system. To the west it passes via Lena Trough and the Molloy Fracture Zone into Knipovich Ridge, the most northern part of the MAR. Its eastern end runs into the continental margin of the Laptev Sea, where rifting continues (Drachev et al., 1998). Spreading rates decrease from 1.33 cm/yr (full rate) at the western end to 0.63 cm/yr at the eastern end in the Laptev Sea. Spreading is nearly orthogonal to the strike of the ridge and there is only one major offset in the ridge axis at about 60°E (Kovacs et. al., 1985).

Cruise Operation

The ships left Tromsø July 31 and approached Gakkel Ridge from east of Svalbard at about 15°E (Fig. 1). The ships first joined Gakkel Ridge at 20°E after the seismic reflection survey crossing the entire Nansen Basin. Both ships then traveled westward along the axis to 8°W performing bathymetric mapping and sampling and acquiring seismic refraction data along axis between the sampling stations. The ships then sampled the rift axis and walls intensively as they returned eastward to 20°E, operating somewhat independently because of favorable ice conditions. The northern and southern walls of the rift valley were mapped during this return. During all seismic reflection experiments in the Nansen and Amundsen basins as well as the seismic refraction profiles along the Gakkel Ridge, both ships operated jointly. Here, Healy led the convoy to break ice for Polarstern that towed the streamer and the airguns (Fig. 1). For both transects in the Nansen and Amundsen basins this setup was critical for the excellent data quality achieved. Because of ice conditions, the latter transect took place at 72°E instead of the primary geographical objective which was to have been a long transect perpendicular to the ridge at 85°E. At the end of the survey, both ships visited the North Pole, where a brief celebration was held. USCGC Healy returned to Gakkel Ridge at 87°E for intensive sampling of a recent lava flow (Edwards et al., 2001) while Polarstern returned to Gakkel Ridge along the seismic survey's path to the west and occupied heat flow stations in the basin. The ships rejoined on Gakkel Ridge at 72°E for the return trip westward along the ridge that involved intensive sampling and more bathymetric mapping, with a wide angle seismic study carried out concurrently. Ice and fog conditions worsened around September 11, so sampling became more difficult and some targets were forsaken. Still, Healy and Polarstern sampled and mapped somewhat independently but in a coordinated program until the time at which they left the ice around 24°E on September 27, 2001. USCGC Healy returned to Tromsø on October 2, 2001

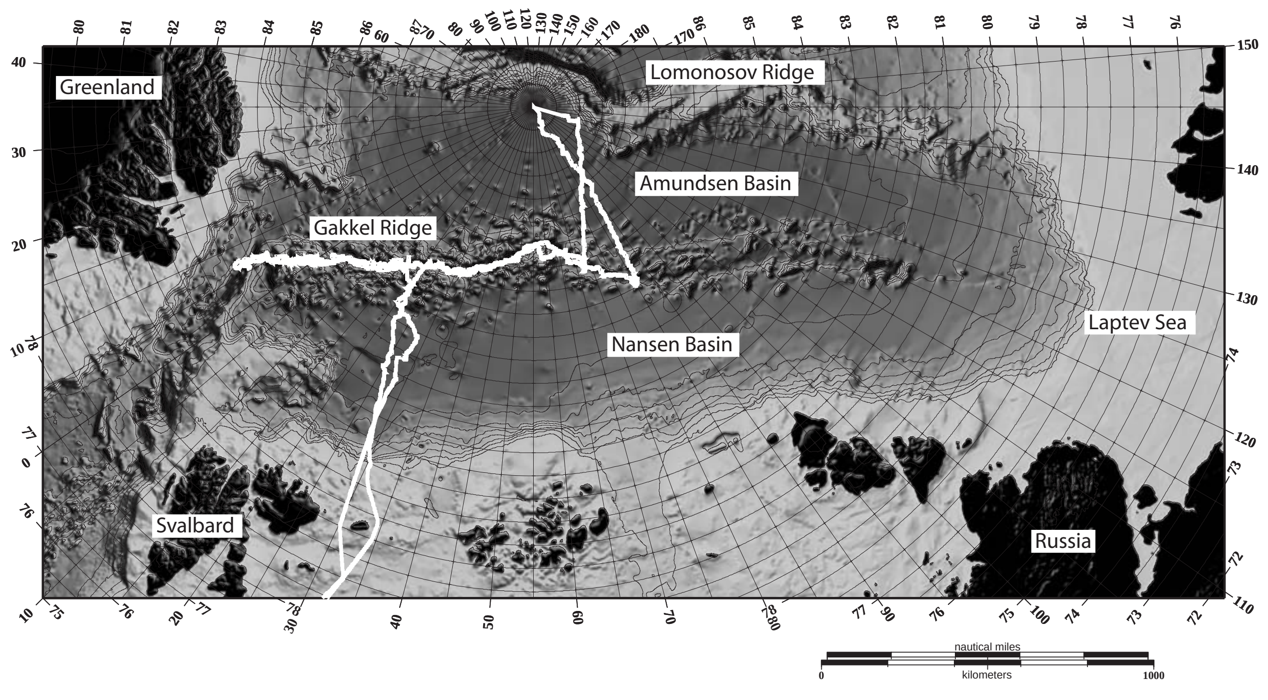

Figure 1. Map of the seafloor of the Arctic Ocean showing the cruise tracks of USCGC Healy and PFS Polarstern during the AMORE 2001 expedition.

while Polarstern went to Bremerhaven on October 7.

New bathymetric map of Gakkel Ridge produced

Surprisingly, the ships' bottom mapping sonar systems (Seabeam 2112 on Healy and Hydrosweep on Polarstern) were able to generate superb maps of the seafloor even while the ships were breaking ice. The bathymetric results far exceeded our expectations. The total surveyed region covers ~1000 km of the axis from 8°W (Lena Trough) to 88°E, providing the first data for the western Gakkel Ridge. The resolution of these data is significantly better than previously existing bathymetry from SCICEX (Cochran et al., in prep.) and reveals geologic detail critical to understanding the segmentation and volcanic and tectonic processes of this ultra-slow spreading MOR. The new bathymetry data show three distinct magmatic-tectonic regions within the area mapped.

Rock recoveries

There was some doubt about whether we would be able to dredge in ice covered waters. After a steep learning curve, the success rate for dredging was fairly high. Flexibility in choosing targets was important, and in a few cases, large ice floes kept us away from entire regions. Each dredge operation had to be carefully set up and planned, using leads through the ice pack and taking into account ice drift velocities. In addition to dredges on both ships, USCGC Healy employed wax cores to recover glass and PFS Polarstern had a TV-Grab. These methods required less open water to succeed. Rock samples were recovered from more than 200 sites along the axis and flanks of Gakkel Ridge, mostly by dredging.

More than 120 basalt glass samples were analyzed on board USCGC Healy for major elements, Sr and Ba by direct current plasma spectrometry. Because the cruise track encompassed a double-pass along most of the ridge, the onboard data permitted testing of hypotheses formulated on the first pass by further sampling on the second pass. Models for the effect of decreasing spreading rate on melt composition that predicted progressively smaller extents of melting at greater depths eastward along the ridge will be tested using these data.

Forty-six thin sections and hundreds of hand samples of mantle peridotites were examined during the course of the expedition. Most of these peridotites are altered 60-90%, like most abyssal peridotites. Some however are stunningly fresh, containing no detectable serpentine in thin section. The distribution of mantle rock types is similar to that from other mid-ocean ridges, but peridotites from Gakkel Ridge seem to have undergone low degrees of partial melting in accordance with theoretical predictions.

Hydrothermal activity along Gakkel Ridge

Miniature Autonomous Plume Recorders from Ed Baker of NOAA PMEL were used on dredges and rock cores to identify sites of hydrothermal venting through light scattering and temperature anomalies associated with hydrothermal plumes. In all, there were 118 MAPR deployments from Healy and 19 from Polarstern. Several plumes were found, and several had corresponding temperature anomalies. Onboard analysis and interpretation of the MAPR data were used to target CTD/rosette deployments, which were collected from Healy at six stations along the Gakkel Ridge. Plume water samples were collected for Mn, methane, and ^{3}He to confirm the hydrothermal nature of the light scattering anomalies and provide some estimate of source strength. Unweathered hydrothermal sulfide chimneys were dredged at one site. In addition, a potential fossil hydrothermal upflow zone as evidenced by abundant epidosite rocks was also dredged from a tectonically uplifted portion of the ridge flank.

Biological specimens

Many of the 98 recovered dredges by USCGC Healy contained biological samples from the benthos and water column. Animals, mollusk shells, fossils, associated rocks, and all other evidence of biological activity were collected. Organisms were preserved using multiple methods for planned morphological and genetic studies. A surprising number of dredges yielded sponges and shrimp. Though the sampling was not biologically targeted, the recovered animals are uniquely valuable to science. Sessile species hold clues to the minimum age of recent lava flows and sulfide deposits. If the organisms are hydrothermally associated, their distributions will indicate or confirm active venting areas along the ridge, and could extend biogeographic inferences into another ocean basin. Pending funding, complete taxonomic sorting of samples and species identifications will be conducted, new species will be fully described, and correlations between biological distributions and extant venting will be investigated.

Geophysical Experiments

To provide a consistent geophysical/petrological model for the super-slow Gakkel Ridge, sufficient information on the crustal thickness and the composition of the upper mantle beneath the rift valley and its flanks is required. Several different geophysical methods were applied to meet these objectives. Both conventional ship-based experiments like seismic reflection experiments as well as measurements located on drifting ice floes were conducted. The results are briefly reviewed here.

Seismic Reflection Experiments. To determine the crustal structure of the Eurasian Basin north and south of Gakkel Ridge, two long seismic transects in Amundsen and Nansen basins were acquired. A 24 l airgun cluster in combination with a 300 m long streamer (48 channels, 6.25 m group spacing) was used. In addition, 36 sonobuoys were deployed in order to provide information on sediment and crustal velocities for a depth conversion of the seismic data. All three profiles provided excellent data and most of the oceanic basement was clearly imaged after processing. The sonobuoys provided signals from even deeper levels of the oceanic crust and in a few cases, signals from the Moho are visible. This allowed a minimum estimate of the crustal thickness. Gravity modeling of the transects will provide more reliable crustal models than in the past.

Seismic Refraction Experiments. To investigate the crustal thickness along the rift valley of Gakkel Ridge both ships had to work together. For this type of reconnaissance survey, only a few stations were deployed along each profile. In case of reverse shooting at maximum two seismic data acquisition units were deployed on ice floes to record the airgun signals. During profiling, USGCC Healy led the convoy, while RV Polarstern towed an airgun array (in total 24-l) to generate the acoustic signals. Crustal thickness was measured at 18 different locations. All stations worked without problems. Most of the record sections show clear Pn arrivals from the crust/mantle boundaries with velocities between 7.8 and 7.9 km/s. The crustal thickness along the rift valley varies between 2 and 6 km.

Gravity measurements. A fixed mounted gravity meter KSS31 onboard the FS POLARSTERN gathered gravity data during the entire cruise. The instrument worked without any problems during the entire cruise. Harbor values were taken in Tromsø and Bremerhaven.

Helicopter based Magnetics. This program intended to fly a detailed magnetic survey across the rift valley of Gakkel Ridge. Unfortunately most of the planned survey could not be conducted, due to constantly foggy weather conditions. Measurements were performed during only 14 days of the cruise. Magnetic data were gathered for a total flight time of 56 hours (4480 nm) with a line spacing of 2 km across the ridge. The data are of good quality and were flown across prominent bathymetric features, so a contribution towards better understanding of spreading processes along the Gakkel Ridge can be expected.

Heat Flow measurements. Thirty eight heat flow measurements were made at fourteen heat flow stations along the rift valley of Gakkel Ridge, and seven along an off-axis seismic transect into the Amundsen Basin. Here, good control for the sediment thickness was provided by the seismic reflection data acquired on the way to Lomonosov Ridge. In the rift valley, it was difficult to find sediment patches of a sufficient extent to perform the measurements. The Parasound data clearly showed that small volcanoes covered most of the seafloor with only a few sediments in between.

Remote Magnetotelluric Experiments and Seismological Array. The deployment of the seismological and magnetotelluric stations on the ice faced two problems. The constantly bad flight conditions in the beginning of the cruise in combination with the relatively fast sampling of the petrology program did not allow the stations to be deployed a reasonable distance to the ship. The risk involved in finding the stations after several days of deployment and with flight distances of more than 50 NM was too large. Secondly, the time of 3 hours plus limited flight windows needed to construct one MT station restricted the number of instruments.

Five MT-experiments were conducted along Gakkel Ridge to investigate the conductivity of the earth's crust and the mantle below this mid-ocean ridge. The stations were recovered after 3 - 9 days. Critical to the interpretation of these data is the rotation of the ice floe on which the instruments are located. Although the floes showed significant drift paths, their rotation was not so strong. So the instruments acquired reasonable data for most of the deployment periods.

While the crustal thickness along Gakkel Ridge was determined by seismic refraction experiments, seismological data are necessary to probe the upper mantle. For this experiment a mobile network consisting of 3-4 stations was deployed on an ice floe. The deployment of the array was mostly finished in three hours. The RefTek recording units had almost no failures during their deployment on the floes. A first view of the seismological data showed that teleseismic as well as local events were recorded. The most spectacular quakes were recorded from the Pacific-Antarctic ridge with sufficient S/N ratio. A careful data analysis will show to which extend local seismicity along the ridge was recorded.

References

Coakley, B.J., and J.R. Cochran. Gravity Evidence of very thin crust at the Gakkel Ridge (Arctic Ocean). Earth Planet. Sci. Lett., 162, 81-95, 1998.

Drachev, S. The Laptev Sea rifted continental margin: Modern knowledge and unsolved questions. Int'l. Conf. Arctic Margins (ICAM III) Abstracts, Celle, Germany (abstract). 48-49, 1998.

Edwards, M.H., G.J. Kurras, M. Tolstoy, D.R. Bohnenstiehl, B.J. Coakley, and J.R. Cochran. Evidence of recent volcanic activity on the ultraslow-spreading Gakkel Ridge. Nature 409, 808-811, 2001.

Hellebrand, E., R. Mühe, and J.E. Snow. Mantle melting beneath Gakkel Ridge (Arctic Ocean): Abyssal peridotite spinel compositions. (in preparation, Chemical Geology)

Jakobsson, M., Cherkis, N., Woodward, J., Coakley, B.J. and Macnab, R., A new grid of Arctic bathymetry: A significant resource for scientists and mapmakers. EOS Trans Am. Geophys. Union, vol. 81, pp. 89-96, 2000.

Kovacks, L.C., C. Bernero, G.L. Johnson, R.H. Pilger, S.P. Srivastava, P.T. Taylor, G.E. Vink, and P.R. Vogt. Residual magnetic anomaly chart of the Arctic Ocean region. Geological Society of America, Map and Chart Series, MC 53, scale 1:6,000,000. 1985.

Mühe, R.K., H. Bohrmann, D. Garbe-Schönberg and H. Kassens. E-MORB glasses from the Gakkel Ridge (Arctic Ocean) at 87°N: evidence for the Earth's most northerly volcanic activity. Earth Planet. Sci. Lett. 152, 1-9, 1997.

Weigelt, E. and Jokat, W. (2001). Peculiarities of roughness and crustal thickness of oceanic crust in the Eurasian Basin, Arctic Ocean, Geophys. J. Int., 145, 505-516.