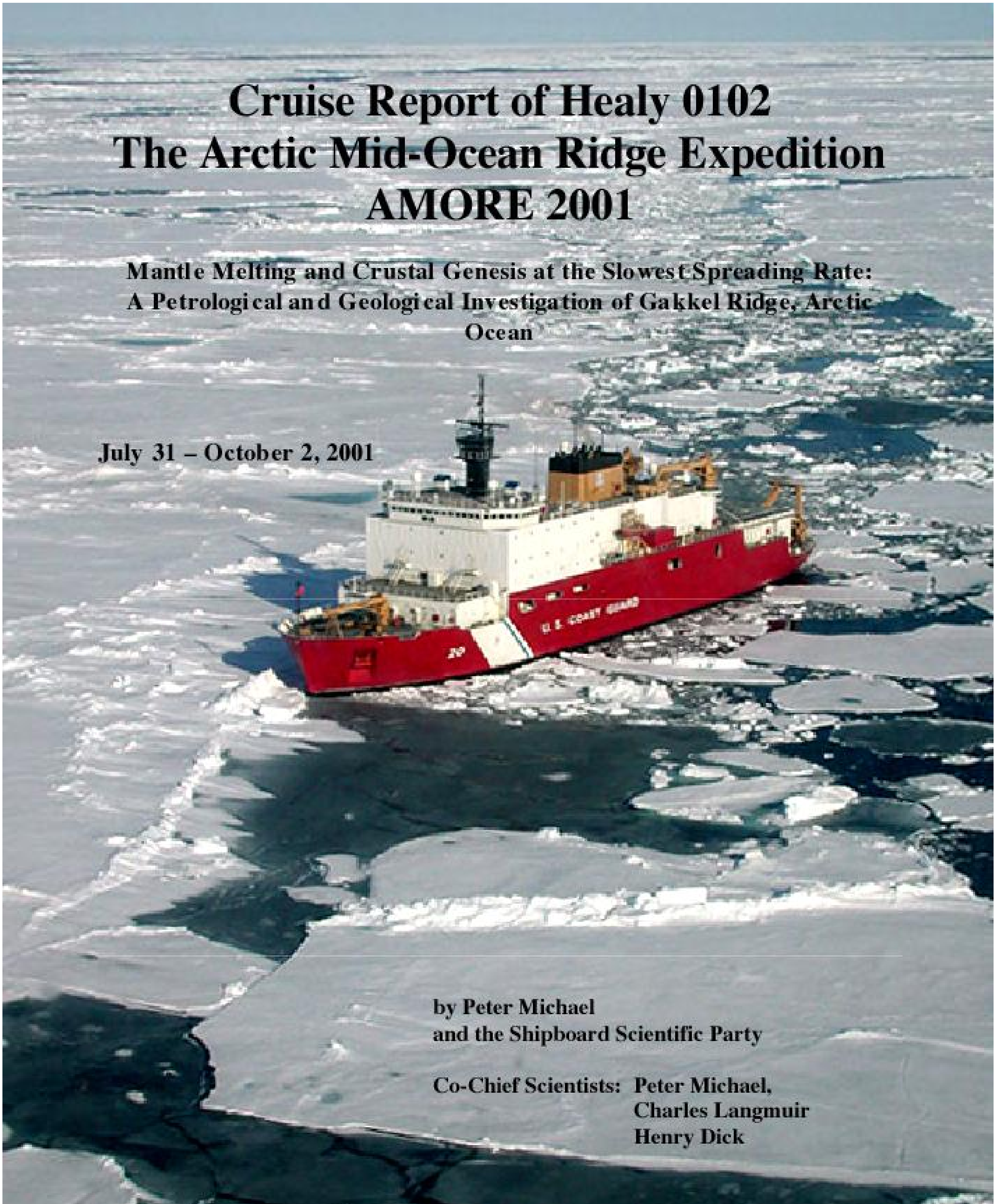

Cruise Report of Healy 0102
The Arctic Mid-Ocean Ridge Expedition
AMORE 2001

Mantle Melting and Crustal Genesis at the Slowest Spreading Rate: A Petrological and Geological Investigation of Gakkel Ridge, Arctic Ocean

July 31 – October 2, 2001

by Peter Michael
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Co-Chief Scientists: Peter Michael,
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1. Introduction

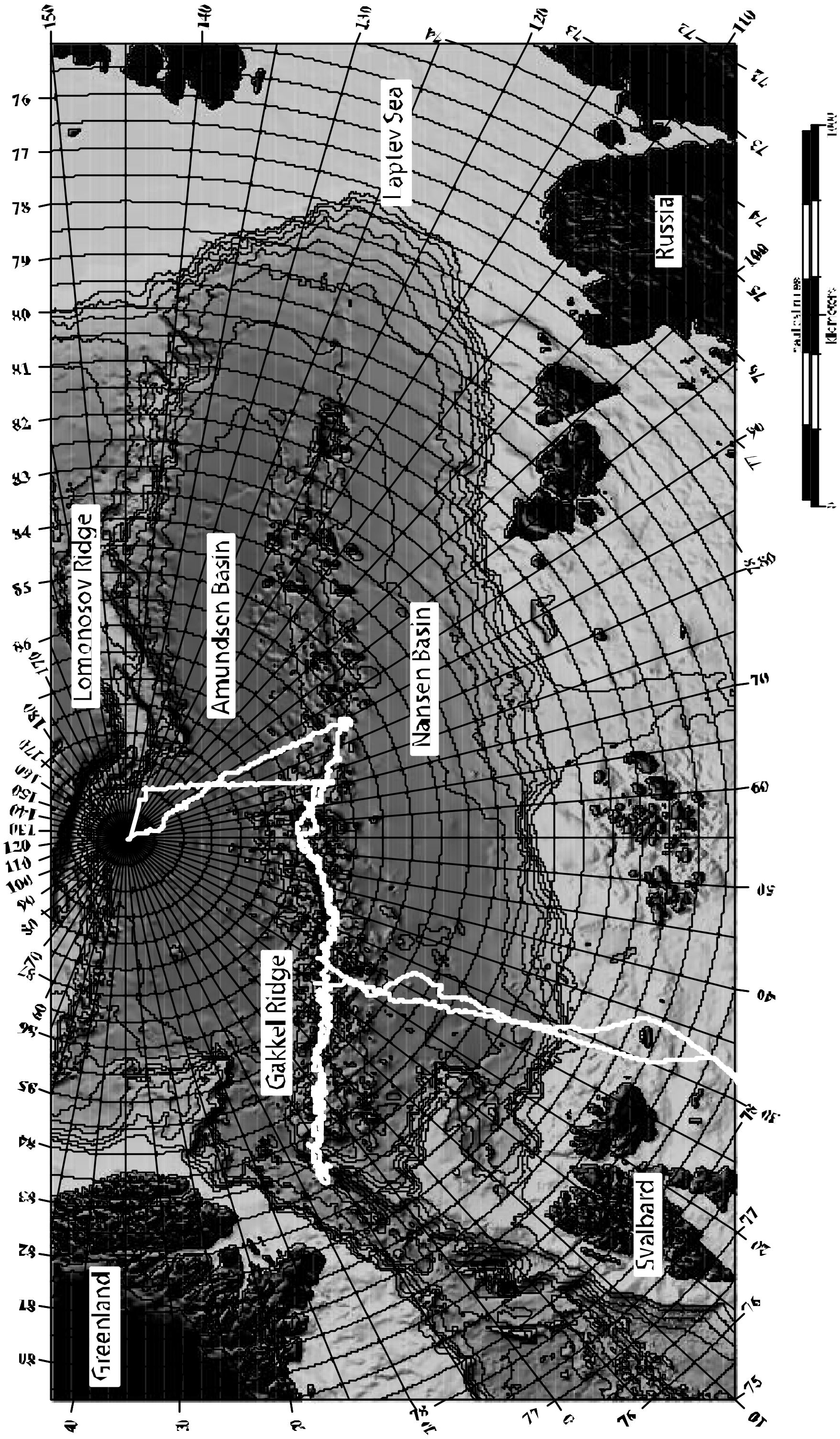
On its maiden scientific voyage, designated "Healy 0102", USCGC Healy left Tromsø, Norway on July 31, 2001 accompanied by the German icebreaker PFS Polarstern. The overall objective of the two-ship Arctic Mid-Ocean Ridge Expedition (AMORE) was to investigate how the mantle melts and how oceanic crust is created at the slowest spreading mid-ocean ridge. Healy's primary mission was to sample rocks from 1100 km along the axis of Gakkel Ridge from 7°W to 85°E (Figure 1) and secondarily, to provide icebreaking support for the seismic surveys of Polarstern. The cruise results far exceeded the original mission plan, making the cruise a resounding success. Rock samples were recovered from many more sites than expected, and Healy's SeaBeam system worked far better than expected in the ice leading to a stunning map of 1100 km of the Gakkel Ridge. There were serendipitous discoveries as well: abundant hydrothermal activity was discovered and sampled and new species of biota were collected. USCGC Healy, her Captain and her crew more than lived up to their motto: "Promise and Deliver". The hard work and dedication of the superb scientific party on Healy (Table 1; end of text) were also instrumental to the success of AMORE

1.1 Cruise synopsis

During the approach to Gakkel Ridge from east of Spitzbergen at about 15°E, Healy led Polarstern through the ice while the Polarstern conducted a seismic refraction survey with a towed streamer. We first joined Gakkel Ridge at 15°E after the seismic survey (Figure 1). From here both ships traveled westward along the axis to 8°W. During this leg, bathymetric mapping and reconnaissance sampling were carried out from both ships and Polarstern carried out a series of seismic reflection and refraction experiments. The ships then sampled the rift axis and walls intensively as they returned eastward to the entry point on the ridge, operating somewhat independently because of favorable ice conditions. The northern and southern walls of the rift valley were mapped during this return. The ships rejoined around 20°E. Healy led Polarstern once again as reconnaissance sampling, bathymetric surveying, and the seismic studies were resumed for the long journey eastward along the axis of Gakkel Ridge.

Healy next broke ice for Polarstern as the latter ship carried out a seismic study of the Amundsen Basin crust as far as Lomonosov Ridge (Figure 1). The primary geographical objective was a long transect perpendicular to the ridge at 85°E on the northern side of the Gakkel Ridge axis but the transect took place at 72°E instead because of ice conditions. At the end of the survey, Healy led Polarstern the short distance to the North Pole, where a brief celebration was held. USCGC Healy returned alone 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, which involved intensive sampling and more bathymetric mapping. Ice and fog conditions worsened around September 11, so sampling became more difficult and some targets were forsaken. Still, Healy and Polarstern

Figure 1 –Arctic Ocean bathymetry and cruise track of Healy and Polarstern, AMORE 2001. After Jakobsson et al., 2000; IBCAO chart.



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.

2. Scientific Objectives and Rationale

Gakkel Ridge in the Arctic Ocean occupies a unique and important place within the global system of mid-ocean ridges. It offers a unique combination of the "forcing functions" that control the creation of oceanic crust. It is the slowest spreading significant length of ridge; it is the deepest ocean ridge and appears to be the ridge above the coldest upper mantle; it is the sole region where polar mantle compositions can be sampled directly; it has a unique tectonic setting surrounded by continental lithosphere in close proximity; and its strike is perpendicular to spreading direction which results in very few transform offsets. This combination of characteristics permits a large number of hypotheses of ocean crust formation to be tested. In particular:

- Do global correlations between axial ridge depth and chemistry of basalts and peridotites result from differences in mantle temperature (Klein and Langmuir, 1987; and McKenzie and Bickle, 1988), or from differences in the final depth of melting (Shen and Forsyth, 1995), or both? Correlations among the mean chemical compositions of ocean ridge basalts, the compositions of abyssal peridotites the regional depth of the ridge, and crustal thickness (Figure 2) (Klein and Langmuir, 1987: Langmuir et al, 1992; Dick et al, 1984; Michael and Bonatti, 1985) are some of the primary global observations that serve as benchmarks for various models of mantle melting and crust creation. The Gakkel Ridge is the deepest significant length of ridge, and therefore provides a test of the robustness of these relationships, and may provide increased dynamic range in the most interesting part of the signal where the extents of melting are potentially the smallest and the crust the thinnest.
- Do differences in the amplitude and wavelength of geochemical variability along mid-ocean ridges reflect different spreading rates or intrinsic regional differences in mantle heterogeneity that are related to mantle plumes? For currently studied ridges, there is an inverse correlation between the standard deviation of the chemical composition and the spreading rate. MORB from the slow spreading MAR and super-slow spreading SWIR, for Figure 1 –Arctic Ocean bathymetry and cruise track of Healy and Polarstern, AMORE 2001. After Jakobsson et al., 2000; IBCAO chart.
- example, display extreme isotopic variability compared to the fast spreading East Pacific Rise, (EPR) (Allegre et al., 1984; Batiza, 1984). What is the cause of this relationship? Gakkel Ridge provides unique constraints because it is relatively homogenous in depth and morphology along its entire length, similar to the EPR, yet it spreads very slowly. If geochemical variability along Gakkel Ridge resembles EPR, then spreading rate is not the major control on variability in ridge basalts. If it resembles the MAR, then spreading rate must be the most important factor.

- What are the relative roles of ridge obliquity, lithospheric structure and melting instabilities in generating segmentation and determining the lengths of segments along mid-ocean ridges? The ultimate cause of ridge segmentation is not clearly understood. On one hand, magmatic segmentation may be imposed by variations in lithospheric thickness that are associated with transform offsets that focus magma or mantle upwelling to segment centers (Magde and Sparks, 1997). The offsets themselves are a consequence of the obliquity of the strike of the ridge to the spreading direction. On the other hand, segmentation may reflect melting instabilities that originate in the asthenosphere as a result of active upwelling Whitehead et al., 1984; Kuo and Forsyth, 1988; Lin and Phipps Morgan, 1992.
- Is the local trend in Na_8 vs. Fe_8 of MORB (Figure 2) related to large scale, inter-ocean mantle heterogeneity or to spreading rate (Niu and Hekinian, 1997)? In addition to the global systematics of MORB melting that were established using regionally averaged chemistry (Klein and Langmuir, 1987), there are large local variations in the chemistry of individual samples from a single ridge segment, after compositions have been corrected for shallow-level crystal fractionation. Attempts to explain the local vector by pooling of melts from different parts of the melting regime (Klein and Langmuir, 1989) do not match the local vectors (Langmuir et al., 1992). Niu and Batiza (1993) suggested there is a relationship between the slope of the local chemical variations and spreading rate. They proposed that the local vector on slow spreading ridges reflects melt-rock reaction in a rising diapir and that diapirs are common on slow-spreading ridges, but not on fast-spreading ridges. The EPR and MAR have very different spreading rates, but they also are in different ocean basins with very different tectonic histories and possibly different styles of major element heterogeneity. Are the local variations controlled exclusively by spreading rate, or are there important differences related to regional location and mantle composition?
- What is the composition of the MORB source mantle? The Gakkel Ridge promises to have basalts derived by the lowest extents of melting of any ocean ridge. In places we may have come close to directly sampling the unmelted mantle source of MORB where peridotites are emplaced in the absence of a basaltic cover. These least depleted peridotites in the oceans may provide important new constraints on the nature of the MORB source mantle.
- Is Gakkel Ridge hydrothermally active? Earlier studies suggested that the frequency of hydrothermal venting is positively correlated with spreading rate, because the latter is an indicator of magma supply (Baker ET al., 1995). Recent evidence (Dick, pers. Comm.) suggests hydrothermal deposits are common on SWIR. The hydrothermal activity we found on Gakkel Ridge confirms that there is no simple relation with spreading rate. Moreover, it paves the way for future studies of hydrothermal activity and biota in a very remote portion of the global mid-ocean ridge system. A critical question that could be answered by our discovery and initial exploration of vent fields along the Gakkel Ridge is whether Arctic vent fauna have evolved independently due to their remoteness and hydrographic isolation.
- The Gakkel Ridge is a fundamental component of the Arctic system: it is the most active geological feature, and created some 30% of the Arctic seafloor. The architecture and

lithology of this ocean crust is poorly known, in part because there are no other ridges that are appropriate analogues to the Arctic. Existing seismic and gravity data suggest very thin crust (Figure 3), but gravity models of thin crust are not unique (Coakley and Cochran, 1998) and cannot discriminate between a 2-km layer of basalt atop peridotite vs. a thicker layer of interlayered basalts and peridotites (Cannat, 1996). Aeromagnetic maps suggest there are significant lateral variations in crustal lithology along Gakkel Ridge (Vogt et al., 1979). The types and proportions of rocks that make up the crust will determine the chemical changes that occur to Arctic seawater as it circulates through the oceanic crust.

- Does the polar mantle differ from the mantle elsewhere? The Arctic mantle has adjacent continental lithosphere all around it, which may lead to both thermal and compositional effects. There are in addition a number of important regional questions. Schilling et al (1999) speculated that the geochemical scatter exhibited by the Knipovich compared to Kolbeinsey, and Mohns Ridges arose from melting of schlieren of continental lithospheric mantle that had been incorporated by shearing caused by highly oblique spreading near Spitzbergen, and were still present in the asthenospheric mantle because rifting was relatively recent (<35 Ma). If this interpretation is correct, then similar isotopic compositions and geochemical scatter should <u>not</u> be present on Gakkel Ridge, since it started spreading earlier (55-65 Ma: Vogt et al., 1979) and spreads orthogonally. Alternatively, the data could be showing a regional gradient in mantle composition, in which case the Gakkel Ridge may also exhibit the complex characteristics of the Knipovich Ridge.
- The northern MAR has distinctive geochemical traits that might continue into the Arctic. Both depleted and enriched MORB from the MAR from 30°N to the northernmost samples at 77.5°N have anomalously high ratios of H_2O to incompatible elements (e.g., H_2O/Ce) compared to MORB from elsewhere (Michael, 1995). The high-H_2O/Ce "province" encompasses the MAR affected by the Azores, Iceland and Jan Mayen plumes. Its northern boundary is unknown, and its origin is poorly understood, but may be related to sampling of rapidly subducted materials by plumes and mid-ocean ridges (Michael, 1995). If low ("normal") H_2O/Ce ratios are present in the MORB we recovered from Gakkel Ridge, it would suggest that the Arctic mantle has been isolated from the influence of both the Iceland plume and the North Atlantic mantle.

Despite these compelling scientific reasons, Gakkel Ridge was virtually unsampled petrologically before the Arctic Mid-Ocean Ridge Expedition (AMORE). The problems were largely logistical. The ice cover of the Arctic Ocean makes geophysical data difficult to obtain. The perennial ice over the Gakkel Ridge favored an expedition using two icebreakers working in tandem.

Two developments made AMORE both timely and possible in 2001. 1) The new US research icebreaker, USCGC Healy, was completed and was ready for science operations. 2) The U.S. SCICEX bathymetry, sidescan and gravity data collected from a submarine provided the background data to plan a good sampling program. German colleagues, in response to

InterRIDGE planning efforts, provided the other ice breaker, the Polarstern, for the two-ship, 63-day international expedition: the first major sampling effort devoted to Gakkel Ridge.

Detailed geochemical study of these rocks will be combined with geophysical estimates of crustal and lithospheric thickness to generate quantitative models of oceanic crust formation under ultra-slow spreading conditions. AMORE's reconnaissance hydrothermal survey using MAPR devices attached to the dredging (or coring) wire and rosettes/CTD laid the groundwork for future hydrothermal and related biological studies along Gakkel Ridge.

3. Geology and Geophysics of Gakkel Ridge

3.1. Seafloor spreading

Gakkel Ridge stretches 1800 km across the Eurasian Basin of the Arctic Ocean (Figure 1). Its western end is connected to the Knipovich Ridge, the most northern part of the MAR, at the Spitzbergen Fracture Zone and Lena Trough. Its eastern end runs into the continental margin of the Laptev Sea, where rifting continues based on gravity and magnetic lineations (Grachev, 1982; Drachev et al., 1996; 1998; Sekretov et al., 1998). Global plate motion solutions (Nuvel 4: DeMets et al., 1990) show that 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. These rates are consistent with the excellent aeromagnetic surveys and compilations (e.g.Vogt et al., 1979; Kovacks et al., 1985; Roest et al., 1996) that show clear marine magnetic anomalies throughout the basin. The magnetic anomaly data show that spreading is nearly orthogonal to the strike of the ridge and that there is only one major offset in the ridge axis at about ≈60°E.

3.2. Bathymetry, gravity, crustal thickness and ridge segmentation

Knowledge of Gakkel Ridge’s bathymetry and morphology expanded considerably with the advent of the U.S. SCICEX program in which nuclear submarines were modified to obtain geophysical and oceanographic data. Swath bathymetry, side-scan sonar and single channel sub-bottom data were collected over large parts of Gakkel Ridge by the SCAMP equipment on SCICEX in 1998 and 1999, and were available (in paper copy only) for this cruise a few weeks before departure. After completion of the 1999 program, nearly the entire ridge crest west of 100°E had been mapped with swath bathymetry, sidescan and gravity data, most of it out to 50 km from the axis. An important exception was 150 NM of the ridge between 7°E and 7°W, which was carefully mapped for the first time during AMORE.

The western part of Gakkel Ridge has a deep, continuous axial valley 15-20 km wide and 4600-4800 m deep, which is 1500-1800 m deeper than the rift flanks at 3200 m deep (Figure 3a) (Coakley and Cochran, 1998). The axial and flank depths are greater than those of the MAR, making Gakkel the deepest mid-ocean ridge in an overall sense. Troughs and ridges can be traced for long distances, showing an abyssal ridge bathymetry with scarps of 1400 m common on both rift walls and ridge flanks. Free water gravity anomalies reflect the bathymetry (Figure 3). Gravity anomalies over the rift valley have 85-150 mGal peak to peak amplitudes, which are 1.5-

2 times greater than gravity anomalies over similar relief on the MAR. The deep bathymetry and high amplitude gravity can be modeled successfully only by very thin crust (2-4 km thick: substantially thinner than similar models of the MAR) or anomalously dense crust (Figure 3b) (Coakley and Cochran, 1998). The model of thin crust is consistent with seismic investigations of the western part of the Eurasian Basin that suggest a 2-4 km thick crust (Reid and Jackson, 1981). Large along-axis variations of the amplitude of the central anomaly magnetic high (CAMH) from the aeromagnetic surveys suggest that magnetic susceptibility or thickness of the magnetized layer (or both) varies along axis (Vogt et al., 1979). In particular, the amplitudes of the CAMH are anomalously low along the deeper parts of the axis.

Up to AMORE, there had been no systematic sampling of rocks to determine if the differences in geophysical characteristics represent variations in crustal lithology or thickness. It is possible that much of the seafloor consists of peridotites. Further to the east (east of 60°E), limited crossings showed the rift valley mountains at 3800 m water depth, 600 m deeper than the western Gakkel Ridge. Sediments there have filled the rift valley to a depth of 4300 m and have greatly subdued the relief in the rift valley mountains. The preliminary descriptions of the 1998 and 1999 SCAMP bathymetry data (Coakley et al, 1999) suggest that the ridge axis west of 60°E is characterized by a deep rift valley that is segmented at 50-100 km intervals by non-transform discontinuities of less than 20 km offset. The rift valleys seem to be asymmetric: compared to outside corner highs, inside corner highs have steeper slopes and much higher relief, reaching shallower depths. Similar features on the MAR have been interpreted as large megamullions on which ultramafic rocks are widely exposed (Tucholke et al., 1998).

3.3. Rock samples

Two small samples of rocks were recovered from the western and central parts of Gakkel Ridge (30° and 60°E, respectively) by Polarstern in 1991 and 1994 (Mühe et al., 1991; 1993; 1997). They provided a very limited but tantalizing glimpse of the magmatism along this ridge. Basalts from both stations have high $Na_{8.0}$ and low $Fe_{8.0}$ (Na_2O and FeO after correction to 8% MgO for fractional crystallization). They plot at the extreme of the global trend of axial depth versus chemistry, suggesting they formed by smaller extents of melting than almost all other MORB. Based on trace element compositions, the basalts are transitional between enriched (E-MORB) and depleted (N-MORB) mid-ocean ridge basalts (Mühe et al., 1991; 1993; 1997). Their Pb, Nd and Sr isotopic compositions plot on the boundary between the MAR/EPR and Indian Ocean ridges, and are similar to some samples from Knipovich Ridge (Schilling et al., 1999). The two Gakkel basalts recovered to date appear to have a significant "DUPAL" component based on their $^{208}Pb/^{206}Pb$ ratios (Mühe et al., 1993). Mühe et al. (1997) further speculated that there might be an isotopic boundary in the Arctic region, because $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios are significantly lower in the more eastern sample.

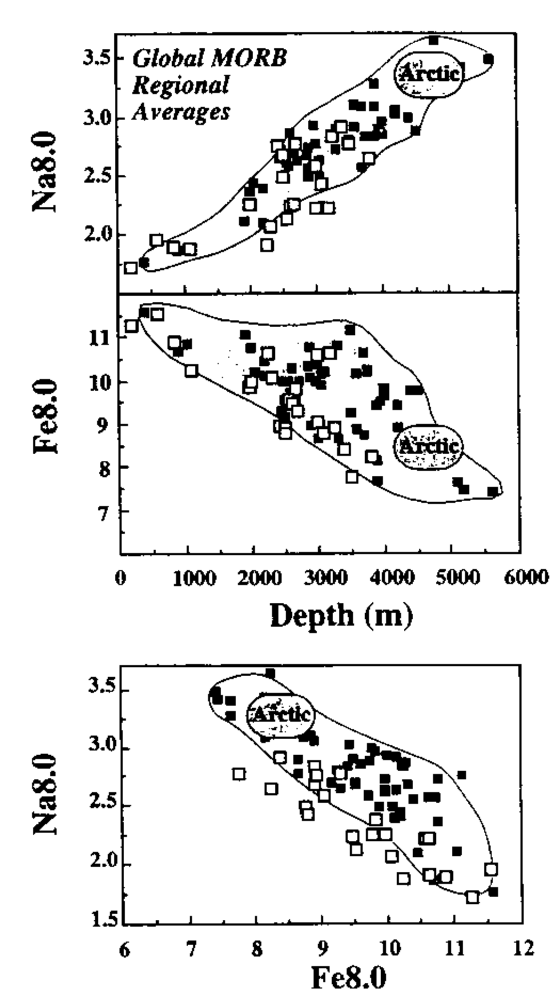


Figure 2: Plot of regional averages from the global system of ocean ridges. Each regional average represents on the order of 100 km of ridge length. Dark squares are averages for "normal ocean ridges well-removed from hotspots. Data from the centers of hotspots are not shown. The Arctic average is comprised of two data points from the Gakkel Ridge (Mühe et al., 1993) which provide an initial estimate of the composition, and show that it plots at the extreme of the global distribution. Figure modified from Langmuir et al (1992).

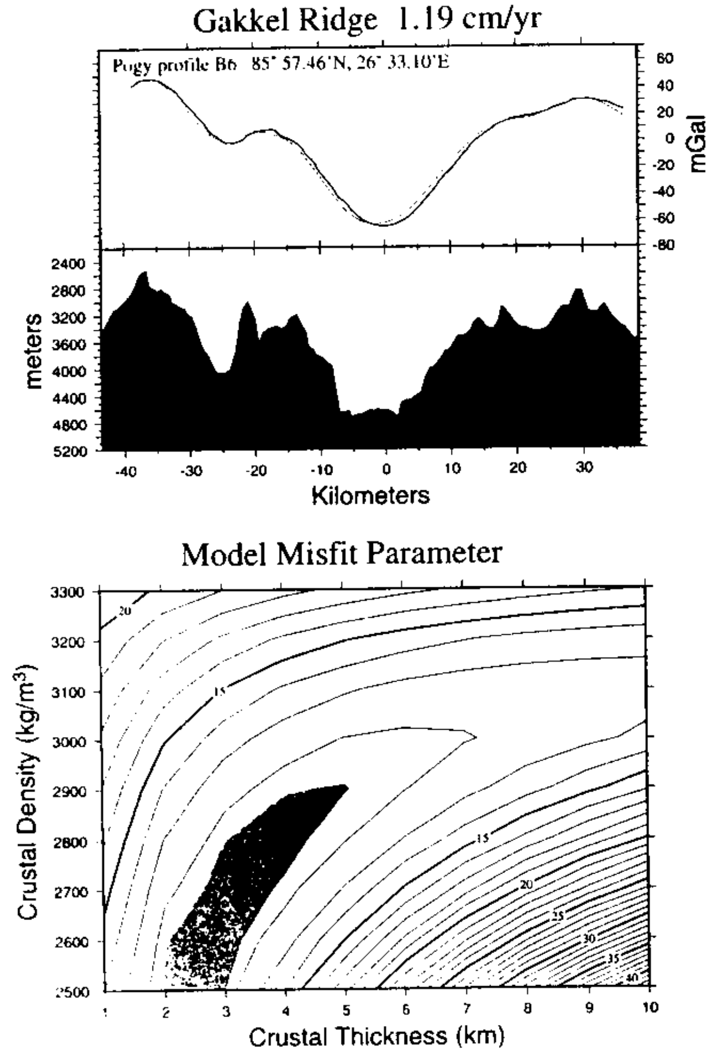


Figure 3: From Coakley and Cochran, (1998). Upper Representative bathymetry and free-water gravity profile across the Gakkel ridge crest from SCICEX 96. The profile is projected perpendicular to the local trend of the ridge with north to the left.

Lower. Results of 2-D modeling to determine the range of crustal thickness and average crustal density pairs, which best explain observed gravity anomalies on profile above. The profile is best fit by crustal densities of 2650-2850 kg/m3 and crustal thicknesses of 2-4 km: thinner than found at faster spreading ridges, but consistent with limited seismic refraction data from the Eurasian Basin.

4. Cruise Narrative

July 31, 2001 - left Tromsø at about 21:00. After several hours of travel in the protected inner passage, we entered the North Atlantic with 40 knot winds and 9-meter seas. We transited north toward a meeting with Polarstern.

August 1, 2001 - Transit continued northward. The winds and waves started strong and subsided later in the day.

August 2, 2001 - We continued the transit northward, passing within view of the island Kvitøya, a glorious sight when illuminated by the low sun. Walruses were spotted near the ship.

August 3, 2001 - USCGC Healy and PFS Polarstern meet at sea. Passage into the ice commences. Ice is light and sparse at first. Polarstern starts shooting airgun and towing seismic streamer as USCGC Healy leads through the ice.

August 4, 2001 - Polarstern's survey continues as Healy leads into heavier ice.

August 5, 2001 - Gakkel Ridge is encountered. The seismic survey continues.

August 6, 2001 - Seismic survey ends and ships move to their first sampling site. The first dredge is attempted, but the wire breaks because the winch is not set up correctly by MST. About 3400 meters of 9/16" wire plus MAPR, pinger and dredge are lost.

August 7, 2001 - The ships move rapidly westward doing a seismic survey with Polarstern towing a streamer. The axis is dredged around 15°E and 9°E.

August 8 - 12, 2001 - The ships continue their rapid trip to the west with seismic survey by Polarstern and reconnaissance sampling from both ships. Hydrothermal sulfides were recovered in D8 on August 12, near Lena Trough.

August 13 - The seismic survey is finished. Dredge 10 is lost along with another 3400 meters of wire plus a MAPR and pinger. The cause was a large piece of ice that pinched the wire against the hull.

August 14 - 21 - The ships sample volcanic centers and peridotite walls more carefully as they move from 5°W to 7°E.

August 22, 2001 - We continued the sampling and bathymetric surveying from 7°E to 11°E on the north side of the axial valley within Gakkel Ridge. We continued sampling wall sites for peridotites and axial sites for fresh young basalts

August 23, 2001 - Dredging was finished in the early morning hours. We then transited to the meeting point with Oden and Polarstern at 85°30'N 15°E. Gangplanks were opened so that personnel could walk on the ice between ships. The senior scientists and masters of all three vessels met and celebrated the occasion, which was commemorated by signing of letters to heads of state of Sweden, Germany and the U.S. The ships were opened for tours and the ships' stores and post offices were also opened. A celebration that included a barbecue feast on Healy followed. There was a soccer tournament and other games as well. Plans for the next portion of the cruise were discussed briefly on Healy.

August 24, 2001 - Healy returned to the Gakkel Ridge axis at about 11°E and continued to sample the axis while Polarstern traveled east and surveyed the high area at 17-21°E.

August 25, 2001 - Healy continued sampling the Gakkel Ridge axis and walls from about 13°E to 17°E while Polarstern surveyed and sampled the high area at 17-21°E.

August 26, 2001 - Healy sampled the axis from 17°-24°°E. Polarstern traveled eastward.

August 27, 2001 - Healy and Polarstern join up again. From here until September 3, Polarstern sets up remote "Reftek" hydrophone stations and records teleseismic events plus airgun shots. The hydrophone stations are "leapfrogged" by Polarstern's helicopters so that they are in front of and behind the ships as they transit between magmatic centers. Both ships also sampled the axis around 24°E to 30°E.

August 28, 2001 - Healy and Polarstern dredged around 30°-32°E and departed around 22:00 for the next waypoint east along the axis. Four dredges and a rock core were recovered on Healy, with fresh basalt in most.

August 29, 2001 - The magnetic high point at 38° is a well-formed volcano. Healy and Polarstern dredged around 38°E then departed around 22:00 for the next waypoint east along the axis. One dredge and two rock cores were recovered on Healy, with fresh basalt only in the dredge. Hydrothermal anomalies were encountered on the dredge attempt and the last rock core, both on the volcano.

August 30, 2001 - We arrived at about 42°E after steaming until 09:00. Healy extricated Polarstern from the ice at 02:30 after she got stuck in the previously cut lead. We discovered that the magnetic high point at about 43°E on the Naval Research Lab map is a well-formed volcano, with reasonably fresh basalts. Finished second dredge and met with Polarstern to continue transiting to 49°E.

August 31, 2001 - Healy and Polarstern arrive at 49°E on Gakkel Ridge and carry out a dredging program.

September 1, 2001 - Healy and Polarstern arrive at 60°E on Gakkel Ridge and carry out a dredging program.

September 2, 2001 - Healy and Polarstern travel to 67°E- 72°E and sample axis.

September 3, 2001 - A geophysical transect across Amundsen Basin from Gakkel Ridge at 72°E to Lomonosov Ridge at 89°N, 130°E begins in the afternoon. This location is chosen for the transect because ice conditions further east are deemed much worse. Polarstern tows a streamer and shoots an airgun as Healy breaks ice.

September 4, 2001 - The geophysical transect from Gakkel Ridge at 72°E to Lomonosov Ridge at 89°N, 130°E continues.

September 5, 2001 - The geophysical transect to Lomonosov Ridge at 89°N, 130°E ends in the afternoon. A transect to 90°N begins, recording bathymetric data.

September 6, 2001 - The traverse from the end of the geophysical transect to the North Pole is completed. A celebration and barbecue with Polarstern is held at the North Pole. Healy departs southward four hours later, following a course to Gakkel Ridge that is around 90°E. Polarstern stays longer and surveys bathymetrically around the North Pole.

September 7, 2001 - Healy continues the return trip to Gakkel Ridge at about 87°E.

September 8, 2001 - Healy continues the return trip to Gakkel Ridge at about 87°E.

September 9, 2001 - We continue the return trip to Gakkel Ridge at about 87°E. We arrive at Gakkel Ridge, 85°E at about 18:00 and start a two-day sampling campaign in this area of the axis.

September 10, 2001 - Intensive sampling continues on the recent lava flows at 85°E. The dredges are very successful. Polarstern is returning with difficulty along the original transect at around 70°E, occupying heat flow stations along the traverse.

September 11, 2001 - Intensive sampling continues at 85°E, but the wind velocity increases so that further sampling is thwarted by ice. Healy transits westward to the 70°E volcano. Polarstern decides to remain at 70°E, finishing a heat flow study.

September 12, 2001 - Healy continues to transit westward and arrives 17:00 at 72°E for the beginning of the dredging campaign back to 30°E. Extremely fresh basalts are sampled from the western limb of the volcano at 70°E. Healy and Polarstern are back together for the first time since the meeting at the North Pole.

September 13, 2001 - Continuing westward, Healy samples walls on north side of axial valley, finishing sampling at 67°E, then travelling to 64°E.

September 14, 2001 - Sampling the area around 65°E. Started sampling "Langseth Ridge" summit at 60°E. Captain is anxious about weather and ice so some targets are not attempted.

September 15, 2001 - Finished sampling the upper slopes of the large "Langseth Ridge". Continued westward, sampling volcanic targets on the large constructional edifice at 59°E. Serviced North Pole weather Station in afternoon by adding buoy #8056 with helicopter operation.

September 16, 2001 - Transited back to the location of the very sharp and strong MAPR anomaly for a CTD. After CTD, we sampled the small feature at 54°E (just south of the large edifice) before continuing westward to the north wall of the ridge at 53°E. Low pressure and bad visibility.

September 17, 2001 - Sampling of walls and volcanic center around 48°E. Cold weather and high pressure prevails.

September 18, 2001 - Continue sampling around 45°-40°E, especially eastern side of volcanic center at 43°E. Strong MAPR anomaly at summit of 43°E volcanic center initiates a CTD. Pressure drops and snowstorm starts.

September 19, 2001 - Finish CTD and sampling of volcanic center at 43°E (western side). Low pressure and stormy weather continue. Start sampling southern wall near 40°E.

September 20, 2001 - Dredging around 39°E.

September 21, 2001 - Dredging around 37°E, moving quickly westward to avoid bad ice conditions.

September 22, 2001 - Dredging the seamount and wall near 30°E. Michael, Langmuir and Dick travel to Polarstern and are stranded there because of helicopter mechanical problems and then icing conditions. Goldstein returns from Polarstern.

September 23, 2001 - Michael, Langmuir and Dick return to Healy. Dredging north wall west of 31°E. Some confusion with Polarstern concerning which ship should sample which wall.

September 24, 2001 - More dredging west of 30°E. Dredge 101 comes up with only one small shrimp. CTD started.

September 25, 2001 - Finish CTD from the previous evening with some difficulty because of 45 kt winds from the east pushing ship and ice. Attempt Dredge #102, but we abort in the morning before putting the wire in the water because of 0-visiblilty and high winds. Polarstern is stuck in the ice. Meeting point with Polarstern is revised westward to 22° E. long.

September 26, 2001 - Start the initiation for Blue Noses with a slave auction in the morning. Rock curation activities throughout the day. Blue Nose skits in the evening.

September 27, 2001 - Polar Bear Day! Blue Noses are initiated starting at 05:00. Healy P.I.s + Edmonds meet with Thiede, Jokat and Snow to discuss publications and post-cruise meeting. Ice liberty 13:00-17:00. Healy leads Polarstern through the ice for seismic study. The ships part ways at about 23:00. Science party secures for sea that night.

September 28, 2001 - We have left the ice completely and are travelling south past Spitzbergen toward Tromsø. The science party is working on subsampling and cataloging the Polarstern dredges and the last Healy dredges.

September 29 - October 2 - Travel past Svalbard to Tromsø. We are working hard on processing Polarstern dredges and the final Healy dredges.

5. Operations and Systems aboard USCGC Healy

This section of the cruise report is a record of the methods that were employed for various operations in the ice and with two ships, the problems that were encountered and the ways they were solved (or left unsolved). It is meant to serve as a documentary of the cruise and also to help future Healy scientists to plan and work as effectively and efficiently as possible. Because this was USCGC Healy's first major scientific cruise, some additional opinions are offered on the ship's operation. For certain subjects, the easiest way to convey these observations is by comparisons with UNOLS vessels and with our partner in the expedition, PFS Polarstern.

5.1. Ship's culture

The ship's officers and crew maintained extremely positive attitude and a very high degree of professionalism throughout this long expedition. Whenever problems with equipment or various systems were encountered, they were analyzed and then solved with determination and perseverance. The crew certainly lived up to Healy's motto: "Promise and deliver". Their attitude was always "Can do". Complaints were rarely heard, even when the demands of the science party seemed inconsistent. Captain Visneski always tried to offer a realistic view of what was possible, and was almost always willing to do whatever was possible, even when it was difficult. A few times, he was reluctant to have the ship encounter tough ice conditions near some targets. Science operations were never restricted because of a lack of personnel or expertise, or because they would tax the ship's systems.

5.2. Healy's Icebreaking and ice-working capabilities

Healy passed her icebreaking trials last year, but the U.S. and international scientific communities still had some questions as to how well she would perform on an extended scientific mission to the high Arctic. In fact, during this cruise Healy proved herself to be an excellent icebreaker. Certainly, the expertise at the helm also played a role in the ship's ability to break ice. Captain Visneski and Cdr. Segalla's use of satellite imagery and helicopter reconnaissance also helped Healy to choose better routes, which saved time, fuel and aggravation.

Healy's propulsion system seemed to be very dependable, with few if any interruptions in service. The bridge was able to bring up additional diesel engines quickly when needed for tougher ice, or to turn them off to save fuel. Healy's 30,000 shaft horsepower were sufficient for breaking almost all of the ice we encountered. Almost as important, the twin opposable screws and twin rudders made Healy extremely maneuverable so she was able to follow curved leads and to go around floes. The maneuverability was also beneficial for science operations (setting up a dredge: see below) and station keeping.

It was clear after working with Polarstern that Healy was significantly better at breaking ice than her partner was. During the geophysical surveying when Healy broke a lead and Polarstern followed, Polarstern became stuck in the lead several times and Healy had to return and break her out. Several times when Healy was leading Polarstern, the bridge of Polarstern requested the Healy bridge to make wider turns because Polarstern was not as maneuverable. During the cruise, Healy functioned on one or two engines for most of the time, using a third engine infrequently when the ice became more packed. As a result of this careful marshalling of power, fuel consumption was surprisingly moderate.

The bow wash system never worked properly because of a design flaw. It was apparent in September when the ice became snow-covered, that the snow on the surface of the ice sapped energy through friction and slowed the ship's progress. Healy could do an even better job of breaking ice if the bow wash system worked. A cost-benefit analysis of reconfiguring the plumbing of the bow wash system (suggested by Captain Visneski) is encouraged.

It is important for science operations that take place in ice-covered waters to be protected from ice interference with the wire or device. Healy's wide stern is an important design feature that enabled us to dredge in the ice. It is likely that dredging from Healy is much easier than from USCGC Polar Sea and USCGC Polar Star, which have sterns that taper to a point. Healy's wide stern deflects large ice chunks outwards, rather than aft into the wire. Bridge personnel were able to keep the area around the wire fairly ice free by judicious use of the props to "blow" it away.

5.3. Integration of Bridge Personnel and Science activities

Bridge personnel, especially the Officers of the Deck (O.D.s) played important roles in the success of both the geophysical program from Polarstern and all of the operations (e.g., bathymetric mapping, sampling) from Healy. They showed a great deal of interest in the scientific activities. Compared to UNOLS bridge watchstanders (Captain, 1st Mate, 2nd Mate etc), the USCG officers are younger and less experienced, but they are intelligent and motivated. The level of expertise in handling the ship and integrating science activities increased greatly as the cruise proceeded. We think this is partly due to the culture within the USCG and the duties of personnel: junior officers see themselves as students and are eager to learn and advance. Senior officers are willing to teach and encourage junior officers. It seemed that almost everyone on Healy was training and increasing their skills throughout the cruise.

5.4. Marine Science Technicians

Healy's MSTs contributed a great deal to the success of AMORE. There was always a MST available during our cruise. Compared to UNOLS vessels, where some of the senior MSTs have 20+ years of experience, the MSTs were less experienced. But several of Healy's MSTs had trained on UNOLS vessels, and they had in turn trained their fellow MSTs. (The same training atmosphere on the bridge carried over to the MSTs). There was a sufficient number of MSTs, whereas UNOLS vessels are sometimes deficient. The MSTs were well trained in all of the operations we carried out. They were highly motivated and maintained a regular watch schedule so that science operations were truly 24/7. Rock dredging and coring and CTDs were more continuous on Healy than on Polarstern because the MSTs were cross-trained in multiple operations. On Polarstern, it was necessary to program various operations around the sleep schedule of a particular technical specialist. In summary, the motivation, training and versatility of the MSTs contributed a great deal to the success of this cruise.

5.5. SeaBeam 2112 and bathymetric mapping

5.5.1. SeaBeam system description

(adapted from Peter Lemmond in H. Dick's cruise report of Knorr 162 Legs VII-IX) The SEABEAM Series 2100, Model 2112 installed aboard USCGC Healy is a multibeam bathymetric sonar system that operates at a frequency of 12 kHz. The sonar signal is generated in the transmitter subsystem and is projected as a single narrow beam across a swath under the ship. Eighty hydrophones mounted athwart-ship (and perpendicular to the transmitter array) receive the reflected sonar signal, convert the sound to electrical signals, which are then digitally processed to form multiple beams. Both transmit and receive beam widths are 2 degrees, with athwart-ship beam spacing of 1 degree. This configuration allows the system to measure a cross section of the ocean floor roughly perpendicular to the direction of the ship's heading for each ping cycle.

In addition to the sonar signal processing, the SEABEAM receives navigation input (via P-code GPS), heading input (via ship's gyro or Ashtec GPS), and speed input (via Doppler speed log). The surface sound velocity is input based on measurements of surface temperature and salinity. An additional input is a precise time signal, needed to synchronize all data streams to UTC. All data inputs are made at 1 Hz. Periodic updates are made to the SEABEAM sound velocity profile, needed to correct for ray path distortions. These profiles are derived from XBT-based temperature profiles, and historical data (Levitus database).

The principal digital output of the SEABEAM system is sonar record files. These files contain data from each sonar ping, along with various system configuration information. Of primary interest in the sonar record files are the beam-angle and travel time measurements, derived bathymetric information, co-located mean beam amplitude data, and swath sidescan. Under most conditions, the system produces 120 beams, resulting in a swath width of approximately 3.4 times the water depth.

5.5.2. SeaBeam performance in ice

The quality of SeaBeam data while Healy was breaking ice far exceeded our expectations and allowed the production of a remarkable bathymetric map of Gakkel Ridge. We anticipated that the noise of ice on the hull would allow multibeam sonars to work in the ice only when a lead ship had broken a channel for the surveying ship. In fact, Healy almost never had a previously broken lead, yet her Seabeam worked well most of the time. Real-time SeaBeam was extremely useful for reconnoitering dredge targets and preparing custom charts for use by scientists and O.D.s to set up dredges. The quality of Seabeam is related strongly but not perfectly to the thickness and % cover of the ice. It is also related to the speed at which the ship breaks ice, and to the presence of ice beneath the ship (a speed of <7 kts is required for travel in the ice anyway). It was almost always possible to design a survey to get at least some good bathymetric data. If bathymetric data are really critical, then clearing a channel by breaking ice, followed by surveying, should work. If the ice is not too bad, simply slowing down may help. A good reference with which to understand the data quality is the map of Gakkel Ridge and Amundsen Basin on the way to the North Pole made after September 1. Healy was in the lead for this entire trip which took place through fairly hard ice conditions of 9/10 - 10/10 ice cover (Appendix 1).

In ice-free water (and up to 6/10 ice coverage) data coverage is 2 - 3X water depths with no gaps. Some editing of the outer beams is required. An example of the quality of SeaBeam 2112 data that were collected in 9/10 - 10/10 ice at about 2-4 knots is given in Appendix 1. When the ship is using 2 engines hard or 3 engines to break into the middles of heavy multiyear flows, most of the bathymetric data are lost but there is still some useful information. When the ice coverage is 8/10 and the ship is slicing off corners of flows and moving easily between leads (but still breaking some serious ice), there are very few gaps in the data. In between these conditions, at 9/10 ice, 20-70% of the data are lost, but useful bathymetric data are still obtained. The ship's speed in the ice also seems to affect SeaBeam performance. Slower progress results in better quality (but a slower survey). Faster cruising results in a greater percentage of lost data.

5.5.3. Twisting the ship –

A useful way to generate a large area of good bathymetric data was to find a pool of relatively ice-free water and slowly "spin" or "twist" the ship in place. The Healy Bridge twisted the ship mostly with the rear props and rudders and without the bow thruster, since the thruster encountered problems early in the cruise and was "babied" as a result. We are not sure how well SeaBeam works when the bow thruster is powered up. The ship must twist slowly enough (five minutes per 360°) so that the coverage on the outer part of the circle is not lost. It is better to take time and do it right. Because we functioned in ice-covered waters, where the pitch and roll were imperceptible, these corrections during twisting should be negligible.

5.5.4. Ice under the transducer –

Occasionally, after breaking heavy ice, the SeaBeam data did not return as normal, even after re-entering ice-free leads. This was seen mostly as the loss of one side of beams. In these cases, we think that ice may have been caught under the hull or transducer. It was sometimes possible to clear the ice by stopping to twist the ship, or by backing then moving forward.

5.5.5. SeaBeam Processing(by Greg Kurras)

. Seabeam data were output in standard MBSystem Format #41 [D. Caress and D. Chayes] and separated into hour files named with Julian day and UTC time stamp. These ping files were then run through a series of automatic and interactive filtering and processing techniques to produce geographically referenced latitude, longitude, and depth values weighted as an inversion function of beam distance from ship nadir. These geographical depth data were then processed using the Hawai'i Mapping Research Group (HMRG) processing techniques to filter and smooth the bathymetry before gridding with Generic Mapping Tools (GMT) [P. Wessel] software.

The use of these automated processing techniques greatly reduced the personnel time needed for post-processing. The interconnectivity of the Healy's Seabeam system, SGI system(s), and Science Data Network (SDN) allowed for the creation of c-shell Unix scripts which automated data transfers, backups, processing, and charting. All real time charts were produced using automatically processed data. Interactive ping editing was done; however, data quality was good enough that it really was not necessary except in a few instances of Seabeam problems. These few cases, a total of five SeaBeam system malfunctions, and the need to occasionally hand edit navigation due to Ashtech GPS heading and P-Code GPS position problems (see below) were the only data requiring human intervention.

The use of automated processing techniques made SeaBeam watch standing even more critical. Watch standers worked 24/7 to insure good quality data acquisition by continuously monitoring and adjusting the sonar. The varying ice cover meant adjusting ping gain and width, occasionally switching to manual bottom tracking, and always checking the Surface Sound Velocity system (SSV).

5.5.6 Heading problems (by Greg Kurras).

During the later half of the AMORE cruise the Ashtech GPS system began having problems calculating the ship's heading. This problem occurred at a regular interval for a two-week period and is believed to be the result of shipboard electronic interference. Numerous attempts were made to track the problem down; however, nothing was ever shown to be the direct cause of the problem. The SeaBeam system must take heading from the Ashtech system as the ship Gyro has an inconsistent drift in the northern latitudes; therefore, during times of Ashtech problems, Seabeam data were unusable. Fortunately the problems lasted only small periods of time (~5-10 min), with the exception of a few 30 – 90 min errors.

Recommendation: Replace the AshTec heading system that supplies the heading with a unit that performs better at high latitudes.

5.6. Navigation

The Seabeam system used P-Code GPS to determine position of bathymetric data. System performance was excellent with only one day of problems. On September 20th, the GPS systems for BOTH Healy and Polarstern had large positioning errors. Because both ships experienced the interference, the cause has been ascribed to atmospheric interference. The heading problem described above was the biggest problem we encountered.

We worked out a shift of the SCICEX maps by matching distinctive geologic features. For most of the 1998 survey, the correction was about 30-40 minutes of longitude (SCICEX maps read too high) which at these latitudes is only about 3 km. A correction of 1 minute of latitude (SCICEX readings are too low) was also needed.

5.7. Sample recovery: dredging and rock coring

5.7.1. Overall strategy

We planned a "double isochron" strategy based on the bathymetry, gravity and magnetic data. This involved parallel sampling of the rift valley axis and walls at corresponding spots. This double isochron method had two advantages. First, peridotites were sampled more often, which will allow comparison of mantle and basalt compositions along certain parts of the ridge axis. Second, the basalts we collected should be more representative of the ridge as a whole, since hidden sections in the volcanic stratigraphy in the rift valley, or off-axis flows may be missed by axial sampling, but recovered from the adjacent walls. Also, any correlation between axial basalts, segmentation pattern and the gravity structure should be repeated directly off-axis if it is robust rather than fortuitous.

Recognizable volcanic segments were sampled at their midpoints, at their ends and at points in between. Our objective was to obtain a representative sampling of the ridge, and a detailed sampling of a few individual volcanic centers.

For this type of regional study, highly specific sampling sites were often not required. Therefore, leads in the ice usually dictated where we would collect a sample within a given area on the map. Having some flexibility in sample locations within a given area was more often a key to success. We also obtained volcanic samples from prominent constructional features by rock (wax) coring. This process required less time than dredging and could be done where there were no leads present. Wax coring was usually successful in acquiring enough sample material for analysis. Our strategy was to first map the ridge and to sample and at a regional scale and to then carry out more detailed sampling as time warranted during the return west or east. DC Plasma analyses of the regional samples and new multibeam bathymetric data helped to guide this detailed sampling. For the most part, the two ships were able to sample independently because of moderate ice conditions. The final sample density is even denser than the reconnaissance spacing recommended by InterRidge and vastly better than we anticipated.

5.7.2. Finding dredge targets using maps.

We expected that the ice would prevent use of the two ships' multibeam bathymetric systems to identify and map dredge targets. Therefore, we planned to use the unpublished SCICEX bathymetric maps to identify dredge targets. These maps were poorly navigated however because they were collected by a submarine that relied on inertial navigation. Our initial plan was to identify specific distinctive bathymetric features using the ships' multibeam systems and then calculate a local correction vector that could be applied to the SCICEX charts. We were surprised to learn that even when USCGC Healy was breaking ice in front of Polarstern, her SeaBeam 2112 system worked very well and was able to make good maps of the seafloor as wide as 2.5X water depth, with very little loss of data because of ice noise. The maps we could make using the SeaBeam system (plus the narrower swath width from Polarstern's Hydrosweep system) had much better navigation AND much better resolution than the SCICEX maps, so were much better for choosing dredge targets. Our strategy quickly changed to make use of these beautiful maps. The SeaBeam 2112 system was used in "flashlight mode" as we went along the axis the first time doing reconnaissance. On the second pass along the axis, the charts from both ships were used to choose targets. In the end, SCICEX bathymetric maps were used only as a rough guide to the position of the axis, and to see farther out on the walls to locate some peridotite targets. The SCICEX sidescan charts were more useful for choosing dredge targets. Dark (i.e., high backscatter) areas were typically fresh lavas, so the area of volcanic activity could be outlined. Unpublished aeromagnetic charts kindly supplied by Dr. John Brozena were also very useful in locating fresh lavas along the axis. Along-axis magnetic high zones were typically places of the most recent eruptions and freshest lavas. Magnetic low zones were often amagmatic. The unpublished aerogravity chart supplied by Dr. Brozena helped us locate the axis west of 7°E, where there were no SCICEX bathymetric or sidescan data.

To locate good basaltic targets, we used aeromagnetic, SCICEX sidescan and multibeam bathymetric charts, in order of increasing detail. In SeaBeam 2112 maps, we looked for cones and irregular constructional bathymetric features. To locate good peridotite targets, we looked for steep smooth continuous walls on the sides of the axial valley at slopes <24°. The success rate of these bathymetric criteria in predicting rock types was only fair. However, this did not severely impact the success of the cruise, since all the rocks are important in understanding the geological processes occurring in this region. Detailed study regions for basalts were selected to have a wide range variety of the mantle geochemical indicator Ba/TiO2, based on shipboard DCP analyses. A detailed study region for peridotites was one in which they were abundantly exposed, as determined by previous dredging.

5.7.3. Dredge equipment -

In order to be able to collect samples effectively under different ice and bottom conditions, we were prepared to deploy several different sampling tools. Dredges were used unless ice conditions were very compressive. They were capable of recovering large samples (e.g., peridotites and lava flow blocks) from steep terrain, but they were relatively time-consuming. All dredge operations (but one) used the standard Woods Hole Oceanographic Institution rock dredge with a welded chain link bag connected to a steel box frame. Most deployments, especially axial dredges and suspected basaltic targets, used a nylon fishnet liner (≈2cm) in the chain link bag. Dredges on the wall were done with a "naked" chain link bag, to prevent recovery of large quantities of mud. Late in the cruise, we noticed that Healy's dredges were consistently recovering rocks that had better-preserved glass compared to the rocks obtained by Polarstern's pipe dredges. We speculate that the pipe dredges rotate while dragging the seafloor and harshly break the glass off the rocks. This factor (plus the net bag) might also be important in Healy's better biological by-catch.

Dredges were connected to the wire rope by two weak links after a ball bearing swivel. The purpose of the weak links is to protect the trawl wire from excessive strain. The links are set to shear before the elastic limit of the wire is reached and is adjustable according to the projected amount of wire-out at a given target. The primary link was connected directly from the swivel to the dredge bail. In theory, if this first link is broken the dredge would be yanked sideways and aft centerline with the intent of dislodging the frame from its hang-up. The secondary link is attached in such a way that any sample captured will retained. If the dredge was still lodged on the seafloor after this tug, the second link would part, resulting in the loss of the dredge.

Most dredges were done using the 9/16" 3x19 torque-balanced trawl wire that is standard on most UNOLS vessels. We lost a total of 6800 meters of this wire early in the cruise (see below), but for most of the cruise, the remaining 5000 meters of trawl wire was of sufficient length to dredge targets of interest. Late in the cruise, when deeper targets were attempted, we were forced to use the 0.680" conductive cable that was longer. This coaxial cable worked surprisingly well for dredging although the continuity of the conductor may have been compromised so should be tested.

5.7.4. Breaking the wire –

We anticipated problems dredging in the ice, so we had 6 pingers, 4 MAPRs, 13 dredges and many weak links on board. It was anticipated that the opportunities for freeing an anchored dredge by maneuvering the ship would be strongly limited by the ice. Thirteen chain link dredges were taken on board, because we anticipated that we would have to free the ship by breaking off the dredge at the weak link. Instead, no weak links were broken throughout the cruise. We were surprised however when on the first dredge attempt, the wire broke at less than 14,000 lbs tension, resulting in the loss of a pinger, dredge and MAPR, as well as 3400 meters of wire. Upon careful inspection, it was discovered that the trawl wire had "jumped" a sheave in the winch room. A flag block, normally free to articulate during operations was inadvertently left "pinned" in place. Comprehensive setup procedures were instituted to prevent recurrence of this. On the tenth dredge station, we lost another suite of equipment and 3400 meters of wire when the dredge was anchored under 15,000 lbs of tension. The ship was backing slowly in an attempt to free the dredge and the wire was pinched against the hull by a piece of ice. We quickly learned the importance of keeping ice away from the wire.

With only 5000 meters of wire left and 95% of the cruise remaining, we considered several options, including taking on 18 mm wire from Polarstern or dredging with the 0.680" conductive cable on Healy. We also adopted a very conservative attitude toward dredging for a while**.** This included 1) Setting the weak links to lower values to minimize the tension that could build in the wire. 2) Minimizing the amount of extra wire laid out compared to bottom depth. 3) Recovering the dredge sooner, after getting a few good bites, since the amount of reward added by additional rocks diminished greatly while the risk of losing gear stayed the same. 4) Decreasing the tension by paying out immediately when ice came near the wire. Easing off on the ship's speed was not fast enough. 5) Keeping even moderate sized pieces of ice away from the wire. The latter is accomplished by judicious use of the props in "forward" mode. Also, we learned that it was important to avoid backing the ship when there was ice nearby.

It was deemed more important to follow these risk reduction procedures, especially 2, 3, 4, and 5 earlier in the cruise than later on, after some success had been attained and the risk of overall failure had diminished. We decided to continue dredging steep walls even though they had a higher risk of getting hung up and needing to be broken off. Once the importance of keeping large pieces of ice from pinching the wire was established, few additional problems were encountered and dredging became more routine, and we relaxed restrictions 1), 2) and 3) above. As time went on, we learned how to keep ice away from the wire and dredged steep slopes more confidently. There were no further losses of equipment after 91 more dredging stations.

5.7.5. Recommendations

1. In hindsight, there should be backup spool of 9/16" trawl wire on board.
2. For future operations in the ice, the 9/16" wire should be replaced with a larger diameter trawl cable, either 5/8" or 3/4" torque balanced wire rope with a greater working load.

5.7.6. Setting up and performing a dredge –

Through a close collaboration between scientists, MSTs, bridge personnel and engineers, a successful method for dredging in ice-covered waters was developed after a few dredging attempts. This was one of the most satisfying aspects of our work with USCG personnel. Scientists would select a region or feature that they desired to dredge, and a series of headings that were possible. They would print a map of the target area and bring it to the Aloft Conning Station (Aloft Conn) from where the ship is piloted in the ice. The engineers installed a real-time display of SeaBeam in the Aloft Conn that allowed visualization of the ship's position relative to the bathymetry of the seafloor. An ice drift velocity was then calculated by allowing the ship to drift for a short while with the ice. This is important because a typical target might be 1 mile in extent and/or width. Considering a 1-hour lowering time for a dredge and a 0.5 knot drift, the ship could easily drift completely off target. Working with the OOD in the Aloft Conn, the scientist would scout and estimate the location of leads in the ice pack that would take the ship to a suitable target and in a good heading, taking into account the ice drift. If an important target was covered with ice, or slightly choked, the ship also sometimes steamed back and forth to "clean out" the lead. The importance of the target and the availability of alternative targets or headings would determine whether it was worth the time to "clean the lead". Also, knowledge of ice drift was critical before investing a great deal in a target, since the cleanup of a lead means more time for the lead to drift past the target. It was better to choose a point to dredge "upwind" from the target, and wait for the lead to drift over the target while cleaning the lead and lowering the wire. Occasionally, targets were covered with vast flows or very thick ice. In these cases, the target had to be abandoned without deploying a dredge. We never tried using two ships to dredge one location (the lead ship to break ice, the second ship to dredge in the lead) because it seemed too time consuming to bring the ships together and perhaps too dangerous to operate them closely. There were often alternative targets nearby, that could be obtained more efficiently.

Each dredge deployment had its own unique history of setup and completion, but can be described in general as follows. Once a lead was found or made in a location such that the ship would drift over the dredge target, the dredge would be lowered in the water to 150 meters depth, at which point, a 12 KHz Benthos pinger was attached. A MAPR was attached at 200 meters above the dredge and lowering continued at a rate of 40 meters/min up to 400 meters depth, and then at100 meters/minute until the dredge reached the bottom. (Pinger location was monitored using a Knudson 12 KHz recorder). At this point, the ship started making way slowly while wire was paid out at about 5-10 meters/minute. Once the distance between the pinger and the bottom closed to about 50 meters, the winch was stopped while the ship continued at 0.5-1.0 kt. On occasion, the dredge would "bite" during this phase. The wire was brought in at 5-10 meters/min after a while. Most "bites" occurred during this "power dredging" phase. When the end of the lead was reached, the ship was forced to stop, and wire was brought in, often with "bites" continuing. When the pinger attained >150 meters of separation from the bottom and the dredge was free of the bottom, winch speed was increased to 100 meters/minute for recovery.

Recommendation - We appreciate the willingness of the engineers and the CO to install Seabeam on the bridge and Loft Con, to have readouts of the winch system etc. on the bridge. The flexibility to alter the readouts and controls was very helpful for this cruise. If possible, a higher quality monitor would have been better for visualization. Also, everyone who used the system wished that the SeaBeam monitor displayed a latitude-longitude grid or markings or at least a scale bar. This should be a suggestion to the manufacturer.

5.7.7. Rock (wax) coring (by Charles Langmuir).

We used the rock coring (sometimes called wax coring) technique to recover basalt glass from the rift valley. The rock core is the fastest sampling method and requires only a hydrographic winch. It works best when collecting fresh glass from medium- and fast-spreading ridges, but has also had reasonable success on slow-spreading ridges like SWIR. It recovers relatively small samples that are insufficient for adequately characterizing peridotite and gabbro. AMORE used the Lamont rock core design with a 300 kg weight, a core head with six cores, and a "collar" around the weight with 14 additional cores.

Twenty rock core deployments were carried out. All but one recovered at least some glass. Two thirds recovered enough glass for a complete major element, trace element and isotopic analysis. In general, rock cores deployed on known magmatic features recovered relatively abundant material, particularly in the western Gakkel region. Rock cores deployed in unknown areas or for logistical convenience or necessity were more problematic. Almost every rock core recovered sediment as well as glass. In some cases it was clear that more than a meter of sediment was penetrated, as the entire core barrel was coated in mud. In a few recoveries the only glass recovered was sieved from the sediment.

AMORE demonstrated that rock coring can be a viable tool in the Arctic when deployed on young volcanic terrain. It also has the advantage that in difficult ice and weather conditions it is possible to rock core when it is not possible to dredge, and therefore ship time is not wasted.

There were several drawbacks to rock coring, however, when compared with its use on other ridges and other UNOLS vessels. Healy's CTD and trawl winches have the same wire speed of 90-100 meters/minute in contrast to most UNOLS vessels where the CTD winch operates at 50-100% faster wire speeds than the trawl winch (e.g. 115M/min. vs. 60M/Min on the Melville). This makes the time advantage of rock coring on the Healy less than on other vessels. Rock coring also normally allows much more precise sampling, where very small and specific targets can be sampled as the ship maintains station. But because of ice drift, station-keeping is not possible on the Gakkel Ridge, and therefore while the final location is known precisely, targeted sampling is less possible. In addition, because AMORE's aim was reconnaissance sampling, it was advantageous to recover large amounts of material, and many sample sites were on the rift valley walls, where rock coring is not useful. Rock coring will be a more useful tool for future detailed studies focussed on individual volcanic centers.

5.8. Rock processing and curating (by Henry Dick)

No dredge samples were discarded other than loose gravel which fell onto the deck and may have been contaminated. Due to the heavy terrigeneous component of the marine sediments along the Gakkel Ridge, many dredges came up with the rocks submerged in a mass of thick clayey mud. While samples of this mud were usually taken and washed with seawater to extract the biological components, separating the rocks from the mud required washing the latter overboard. All remaining material was curated, described, and a subset of working samples selected. The rocks were then divided with 50% going to the Alfred Wegener Institute, and thin section chips and slabs were cut for the shipboard investigators (Appendix IIa), while glass was chipped from the basaltic samples. The glass was divided up among the investigators as required for their shore-based studies (Appendix IIb and IIc) after a split was taken for shipboard DCP analysis, with the remaining glass divided between archives at the Woods Hole Oceanographic Institution and the Lamont Doherty Earth Observatory. The remaining rock samples were packed for shipment to the Woods Hole Curatorial Facility, where they will be available for other investigators to sample at the end of the normal proprietary sampling period.

Once the dredge was brought on-board, all the samples were laid out to dry on a sheet of brown paper with the dredge number on it on a large table where they were isolated from other samples being processed in the lab. A rough sort of the material was done on the table by rock type, and then a fully representative sample suite was cut for description. In the case of Mn-coated samples, this entails every sample of reasonable size (fist sized or greater), and a random selection of smaller pieces. In the case of basalt dredge hauls, where samples could be identified without cutting, sawing was kept to a minimum, but still at least some 30 or 40 samples were cut from larger dredge hauls, and all the reasonable sized pieces from smaller dredge hauls were cut. After cutting, a final sort of the samples by lithology was done, and all the reasonable sized samples and cut pieces were labeled, weighed, measured and described, as discussed below. Small samples, or excess material in dredges exceeding 300 kg, were bagged by lithology, weighed and recorded with a collective description.

Rocks from all the dredges were described using an Excel based format description sheet using "*A Field Guide to the Rough Description of Abyssal Dredge Hauls*" by Henry Dick (Appendix III). Systematic numerical estimation of various parameters included:

1. Presence of glass (thickest interval),
2. Vesicle content and average size (using a hand lens as many rocks contain very small vesicles),
3. Phenocryst proportions and average size,
4. Strength of igneous, crystal plastic and brittle deformation fabrics,
5. Total alteration, and
6. alteration percentage by mineral phase and alteration product (phenocryst alteration for basalts and diabase).

Alteration in our descriptions is the product of hydrothermal processes distinct from weathering. Alteration percentages were estimated for coarse grain rocks from the sum of alteration of the individual phases, while total alteration for diabase and basalt was based on qualitative estimates based on appearance. Qualitative estimates of the degree of weathering, sample roundness, and surface character were made, and vein assemblages with the thickest vein width noted for each. The proportions of minerals other than olivine, plagioclase and pyroxene were noted in the "Comments" section. Appendix IV presents all the rock description data tabulated by dredge haul.

Sample weights given were all weighed, except for small samples (<0.2 kg), which were estimated. Where two or more rock types are found in a single sample, these are described on separate lines with the same sample number. In such cases the correct sample number when referring to one type or the other must include the rock name. In addition, since two different rock types in contact with each other cannot be easily weighed, we arbitrarily divide the rock weight by the number of lithologies. Thus a single sample weighing 3 kg, with two lithologies would have arbitrary weights of 1.5 kg for each rock type in the tables.

Beginning with Dredge 21, time permitting, digital photographs of each dredge were taken, with selected photos of representative features in various samples. These photos can be are available from the Chief Scientist as a separate CD-ROM.

On board sampling was done of the basalts, peridotites and gabbros. Sampling of the peridotites was limited to thin section chips and some slabs of a representative working collection of gabbros and peridotites, while a more extensive sampling program of the basalts and basalt glasses was undertaken as described elsewhere in this report.

5.9. DC Plasma analyses of rocks on board Healy by C. Langmuir and K. Lehnert

Major element analyses of basalt samples were performed by DC plasma spectrometry on board the Healy. During transit to the Gakkel Ridge, the plasma was set up and standards were analyzed as a test of data quality. Once on the ridge, fusion of a batch of 11 samples and one standard took place approximately every four days. Analyses from the first pass along the ridge proved invaluable for choosing detailed sampling locations for the second pass.

Prior to the cruise there was some trepidation that vibration during transit through the ice would make high quality analysis impossible. The Healy turned out to be very free from vibration except in difficult ice conditions. The lack of any pitch and roll was advantageous for plasma analysis. Ideal time for instrument operation was when the ship was on station, where the lab was extremely quiet. There were no problems with lab temperature stability or with electrical power. In general, geochemical analysis on board Healy should be superior to what can be attained on other UNOLS vessels.

Techniques for preparing basalt solutions at sea differ somewhat from those used on land. Lithium metaborate flux, standard powders, and "hi" standard powders were pre-weighed at Lamont. Approximately 50 mg of clean basalt chips (50 mg was chosen by comparing the volume of the unknown chips with pre-weighed chips of similar size) were placed on top of 200 mg of flux in a graphite crucible and fused. A crude but effective pan-type balance was constructed on board which aided in weighing of samples. In future expeditions, traditional balances should function quite effectively on Healy because of the lack of pitch and roll. The chips and flux were placed in a muffle furnace at 1100°C for ten to fifteen minutes. The molten material was dissolved in 70 ml of 1N HNO_3. Nine elements were analyzed for each solution, Si, Al, Mg, Fe, Ca, Na, Ti, Sr, and Ba.

Data reduction is based on normalizing emission counts to a known solution, referred to as a "hi" standard. During AMORE we used K1919, an internal Lamont basalt standard from the 1919 flow at Kilauea, which is the source of the BHVO standard, as our "hi". K1919 was run every third or fourth analysis. Each sample was normalized to K1919 to determine the concentration of each element in solution. Corrections were applied for non-linearity of the Na peak. The sum of the concentrations was then normalized to 99.5%. This normalization step was necessary because of the inability of weighing the samples precisely at sea. The un-normalized sum reveals the actual sample weight, which was generally within 5-10 mg of 50 mg. Each sample was analyzed twice for each element, and the two analyses were averaged for the final data. As a test of data quality for each run, one known standard was analyzed with each batch of unknowns. A compilation of the standard analyses is given in Appendix V. Data for most elements have standard deviations from run to run of less than 2%. Twelve batches of basalt solutions provided analyses of 120 samples.

5.10. Basalt Sample Processing for Geochemical Analysis (after sawing for AWI)

Basalt working samples were selected from all dredges. Where there was no glass, the US half of the rock was sawed to make two representative slabs that were sent to Tulsa and to Lamont. Two thin section chips were also cut. A twenty to fifty gram chunk of the least altered portion of the sample was also selected for future geochemical analysis.

Samples with glass had the glass removed using a ball hammer and small chisel, with the sample enclosed in a plywood box to prevent loss of material. A portion of the glass was crushed lightly in a stainless steel mortar and pestle, and sieved into coarse (~3mm) and fine (<3mm) fractions. These fractions were cleaned in an ultrasonic bath until the water remained clean after several minutes of sonification. The cleaned glass fractions were then hand-picked under binocular microscopes for chips for DCP analysis, and for future geochemical work. Glass fractions went to LDEO, The University of Tulsa and Oregon State University (Appendices IIb and IIc).

5.11. Winches

The winches worked well for the cruise, attesting to the fact that the problems with the Alstom control system were ironed out by extensive testing and repairs done earlier. The AMORE science party thanks the USCG, AICC, UNOLS and NSF for their wisdom in arranging and supporting shakedown cruises. The winches ran quickly and reliably throughout most of the cruise. Switching from one type of wire to another was a relatively efficient operation.

Early in the cruise, a problem of electrical interference of the CTD by the Oceanographic winch was discovered and repaired. The CTD functioned reliably after this, but the oceanographic winch tripped off twice during subsequent CTD/rosette runs. *Recommendation* - Alstom should do additional diagnostic and repair work on the O2 winch so that it functions reliably.

5.12. MAPRs (by Henrietta Edmonds)

5.12.1. General

An opportunistic program of reconnaissance for hydrothermal plumes was conducted using Miniature Autonomous Plume Recorders (MAPRs) developed at NOAA PMEL in Seattle (Baker and Milburn, 1997). Each MAPR is a self-contained, internally recording instrument comprising a pressure sensor, temperature sensor, and light scattering sensor (Seapoint Turbidity Meter). Hydrothermal plumes are primarily detected as layers of increased light scattering (increased concentration of suspended particulate material), although occasional small temperature anomalies are observed as well.

Four MAPRs were ordered and purchased (1/2 by NSF, 1/2 by NOAA PMEL) for use by Healy scientists on the AMORE cruise in anticipation of equipment failure and possible loss during an extended expedition with the additional hazards of operating in the ice. (Four more were procured for Polarstern scientists: 1/3 NSF, 1/3 NOAA PMEL, 1/3 German). These MAPRs were modified from the original design for use in the Arctic. The primary modification was replacement of the SeaTech Light Scattering Sensor, which plugged into the end cap of the MAPR and was attached to the frame of the instrument with cable ties, with an integrated or "bulkhead" sensor. This sensor was located within a protective cage at the top of the instrument along with the temperature and pressure sensors, and thus was protected from damage by surface ice during deployment and recovery. While this modification was a success, the MAPR temperature sensors were not adequately prepared for use in the Arctic, in that each had a minimum temperature below which it would not read. In all cases this temperature was above the temperature of Arctic surface waters (which were not of interest anyway), and in some cases was above the temperatures of deep waters, seriously limiting the use of the MAPRs for discerning temperature anomalies associated with hydrothermal plumes. This limitation became apparent early in the cruise and was communicated to Ed Baker and Sharon Walker at NOAA/PMEL. Due to the expertise of the USCGC ETs and EMs, and the availability of parts and calibration equipment on board, a fix was possible, but ultimately was not attempted due to additional problems (see below).

5.12.2. MAPR Deployment

MAPRs were deployed on almost every dredge and rock core deployment, and every CTD cast (see below) during the cruise. For dredge operations, the MAPR was attached to the 9/16" wire (or 0.680" cable later in the cruise) 25 meters above the pinger, and therefore typically 175 m above the dredge. For deployment on the 0.680" cable, because we had no inserts for the MAPR clamp that would fit the cable, electrical tape was wrapped around the cable at 175 m wire out and the MAPR was clamped directly to the tape. On rock core deployments, the MAPR was routinely attached to the 3/8" wire 50 meters above the rock core, although we began the cruise at a more conservative 75 meters above. At CTD stations 5-9 the MAPR was attached to the conducting cable 30 m above the rosette, while at station 4 it was attached 10 m above the rosette.

On the first dredge attempt, (Dredge HLY 0102 D01), MAPR #11 was lost along with the dredge and pinger when the wire parted (see above). MAPR #13 was deployed at the next sampling station, Rock core HLY 0102 RC01. We discovered that the temperature sensor did not read below –0.29694 ˚C. Thereafter, MAPR #10 was deployed on dredges and MAPR 12 on rock cores (each being fitted with clamps of the correct size for the relevant wire), until the loss of MAPR #10 on Dredge HLY 0102 D10. MAPR #12 was then used for all subsequent deployments. An intermittent communication problem with this MAPR first surfaced on August 13. The problem was thought to lie with the battery board, and after resoldering a connector (by ET1 R. Retzlaff and EM1 B. Bixler) the MAPR performed fine until September 1 (Dredge HLY 0102 D55). After this point the battery board from MAPR #13 (with the useless temperature sensor) was used in MAPR #12 for all remaining deployments. This switch occurred just before we received instructions on how to fix the problem with MAPR #13's temperature sensor, but due to problem with MAPR #12's battery board, we chose not to proceed with fixing MAPR #13.

MAPRs were deployed a total of 123 times from Healy. No MAPR was deployed on Dredges HLY 0102 D13, D16, or D17, due to concerns about further losses following Dredge HLY 0102 D10, on Dredge HLY 0102 D72 because it was on a shallow seamount, nor on Rock core HLY 0102 RC05 for an unknown reason. Two deployments ended in loss of the MAPR as described above. On Rock core HLY 0102 RC04 and Dredge HLY 0102 D55, MAPR #12 returned bad data and no data, respectively. Both MAPR #12 and MAPR #13 were deployed on Dredge HLY 0102 D12, on which MAPR #12 returned no data. Deployment number 92 was an aborted dredge (HLY 0102 D77a) and therefore no useful data were obtained. We thus have data from 118 deployments. Note that two of these deployments were of MAPR #13 and thus do not include useful temperature data.

5.12.3. MAPR Configuration, Data Reduction and Interpretation

Communication with the MAPRs for configuration and for downloading the data was accomplished using the application "MAPR Terminal" (provided by Baker and Walker of NOAA/PMEL) installed on a PC running Windows NT. MAPRs were always deployed with a 5-second sampling interval for maximum resolution. Data were downloaded as soon as possible following each deployment. Processing and visualization of the data were done using Microsoft Excel, utilizing the mapr files macro provided by Baker and Walker at NOAA/PMEL. Pressures (and thus depths) were corrected for a relatively constant offset of between –10 and –15 dbar on deck. Data acquired at the surface before and after recovery were removed before initially plotting light scattering (as instrument reading in volts) and temperature versus depth. A second step in data processing involved pulling out the time during which the primary instrument was on the bottom, which was generally quite noisy in terms of light scattering (particularly over muddy bottoms) and separating the upcast and downcast data. All data were fully analyzed within 9 hours of instrument recovery (most often within 1 hour). These analyses were used throughout the cruise to target sites for CTD/Rosette casts.

5.13. CTD/Rosette Casts (by Henrietta Edmonds)

Six successful CTD/Rosette stations were occupied in response to MAPR data indicating the presence of hydrothermal plumes. A total of ten casts were attempted during the cruise. On August 4 we attempted a routine test cast as we first encountered deep water on the continental shelf. The purpose of the cast was to test the instrumentation and deployment operations/procedures, and to fill all of the bottles with deep seawater in order to clean and condition them for trace metal sampling. In preparation for this test cast the 0.322”conducting cable was reterminated on August 3. The instrument tested fine when connected to the cable in the starboard staging area. When the instrument was taken out on deck (starboard A-frame) and the slack taken up on the winch, the deck unit was turned on again and an error alarm was received. Several MST’s, ET’s and Dr. Edmonds worked to troubleshoot the electrical problem, and discovered that one of the connector leads was not making a solid connection. The cable was reterminated and the connector lead replaced, but the time window for the test cast had elapsed and no further test was attempted.

On August 12 during Dredge HLY 0102 D8, fresh hydrothermal sulfides were recovered and a MAPR signal observed. This was considered a prime opportunity for a CTD cast and preparations were begun. Because the vent field was known to lie along the line of the dredge, we planned to conduct a “tow-yo” of the CTD rather than a traditional station cast, in order to try to pinpoint the site of venting. Therefore preparations were made to deploy the CTD/Rosette system off the stern of the ship rather than the traditional starboard side. This involved re-routing the 0.322 cable and moving the instrument from the starboard staging area to the aft working deck. The latter was accomplished by placing the rosette on a standard wood palette and transporting it using a palette jack. The bottles were cocked in the aft staging area and communications with the instrument through the cable and deck unit were tested successfully. The instrument was carted to the stern and the cast (CTD01) was begun. When the CTD was in the water the deck unit was turned on and an error alarm received. Again, Healy’s MST’s, ET’s and EM’s worked diligently to troubleshoot and fix the problem, testing and reterminating the cable (a fault in the cable was discovered 10 meters above the rosette), but in the interim the station had to be abandoned.

Eventually, through the troubleshooting efforts of the Healy crew, it was discovered that the error occurred when the winch was on, while communications were fine when the winch was off. Thus, some kind of interference from the winch system was causing a noise signal to ride along the signal cable. Major modifications were made to shielding and grounding of the winch systems, swivel, and cable. CTD02 was a test cast on August 16, during which the system worked as long as the winch speed was less than 10 meters/minute. Further electrical modifications were made in the winch room. On

August 17, the MAPR on Dredge 21 revealed a large hydrothermal plume, with signals in temperature as well as light scattering. Dredge HLY0102 D20 and Rock Core HLY0102 RC07, in the same area, had smaller light scattering peaks at the same depth. CTD03 was a test cast (to ~200 m) to determine if the system would work, prior to deciding to steam back to the site of Dredge HLY0102 D21 for a hydrocast. The instrument performed well at winch speeds up to and exceeding the normal operating speed of 60 m/min. All bottles were fired, but only 5 closed, perhaps due to the haste at which they were fired but also indicative of a general problem we had with the bottles. The lanyards were loosened for all subsequent deployments.

CTD stations 04 through 09 were made in six separate locations in response to hydrothermal signals observed with the MAPRs, including one at the site of Dredge HLY 0102 D21 following the successful test at HLY 0102 CTD03. Locations and bottle samples for these 6 stations are summarized in Appendix VI. A MAPR was deployed on CTD casts in order to provide a direct like-for-like comparison of the characteristics of the hydrothermal plume between the stations used to target the CTD and the CTD cast itself. In addition, MAPR data could be plotted up quickly with minimal processing after the cast. Note that one advantage of the old MAPR design is that the light scattering sensor from the MAPR could be plugged directly into the CTD and the data visualized real-time.

While the six sample casts were largely successful, noisy data was still a problem and resulted from two known sources. First, several wild data points occurred in each cast. In some cases we believe these to have resulted from the wire rubbing against the hull of the ship, but others may be due to residual problems with noise from the winch system.: This issue must be thoroughly investigated (along with the mechanical problems noted earlier in the winch section) well in advance of any future hydrographic cruise. In addition, deployment off the stern means passing the conducting cable through blocks of the wrong size, which were damaging the cable and may further have contributed to deterioration of the data. Second, deployment of the CTD/rosette off the stern often meant that the pumps and sensors froze during transportation to and setup on the aft working deck. As a result, the pumps did not turn on until the system could be lowered into (and allowed to sit in) the warmer Atlantic Water layer below ~100 m. For this reason, the sensors often did not give reliable data for several hundred meters or more (over 2000 m in the case of CTD09). While this was not critical to our investigations of deep hydrothermal plumes, data were lost, and it will be absolutely critical to address this for any future physical and chemical oceanographic work.

With regard to deployment off the stern, we initially continued this practice following the aborted station CTD01 to save the trouble of re-routing the cable. We hoped to return to working off the starboard A-frame for CTD09, and in fact had re-routed the cable prior to that, but the bridge asked that it be moved to the stern again due to worries about ice pinning the wire against the hull on the starboard side. We must stress that it will be very important in the future to develop a standard operating procedure for deploying the rosette in ice off the starboard side. First, it is time consuming to move the system to the stern and back to the starboard staging area for sampling. Second, the cable can be damaged (which is expensive and may result in data loss) by using blocks of the wrong size. Third, the pumps and sensors freeze and result in loss of data as noted above – this would not occur if the CTD were deployed straight from the starboard staging area as intended. Fourth, relying on stern prop wash to clear ice away from the wire will also result in bad data for surface waters. Finally and perhaps most important, danger to personnel results from wheeling the rosette (nearly 1000 pounds) around on a small palette jack on an icy deck. This problem worsened considerably later in the cruise as weather conditions deteriorated, and in fact the CTD tipped off the palette prior to deployment of CTD09.

Finally, we must note that we were extremely pleased with the dedication and perseverance of all the members of the Healy crew who worked to troubleshoot and solve the difficulties with the CTD and winch.

5.14. Recovery and processing of biological samples (by Linda Kuhnz)

The primary biology project goal was to collect and describe organisms found in geological sampling equipment. Linda Kuhnz of Moss Landing Marine Laboratories performed the collections.

As the contents of USCGC Healy dredges were emptied, they were searched for organisms, mud, and sediment. Fossils, shells, rocks with animals or fossils attached, and all other evidence of biological activity were collected. Wax from several rock cores also yielded samples. Animals were recovered from the benthos and the water column.

We immediately placed live specimens in containers with cold seawater and a waterproof label documenting dredge number, date, and sample number. Polarstern samples were handled in a similar manner. To document the natural color of animals, we took detailed photographs of specimens prior to processing them. The presence of severely damaged or unrecoverable organisms was noted. When more than one specimen of an animal was recovered, we used multiple preservation techniques.

For most samples, formaldehyde was added to seawater to make a 4% solution (=10% formalin), which fixed the organisms (Appendix VII). Each sample was thoroughly mixed in the solution to ensure proper and fast fixation; the amount of time allowed for fixation varied according to taxonomic group (e.g. sponges 8-12 hr, decapods ≥ 4 days). Later, formaldehyde was poured off samples, the sample rinsed in fresh water and then stored in 70% isopropyl alcohol. Nemertean worms were stored strictly in 4% formaldehyde. Some specimens were stored directly in 70% isopropyl alcohol, while others were frozen at –85 °C or refrigerated at 4°C. Some mud and all foram/sponge spicule mat samples were washed through a 0.5 mm mesh sieve by placing small amounts of material on the screen. The sieve was partially immersed and the sample rinsed in seawater within a large plastic container. Other mud samples were preserved without sieving.

The samples will be archived and chain of custody will be maintained at Moss Landing Marine Laboratories. Pending funding, complete taxonomic sorting of samples and species identifications will be conducted. New species will be fully described.

5.15. Communications

5.15.1. Email and Internet-

Satellite communications were limited by the very high latitudes at which we operated. The unreliability of email was a source of frustration for a good part of the cruise. The TDRSS system from NASA was useful and fast some of the time, but it took a lot of effort on the part of the radio operators to keep it aimed properly and running reliably. Nevertheless, it was definitely worth having aboard. Some large files like photographs took time to transmit. The earlier problems that we had with email were due to a computer virus that came aboard with the science party. Once it was found and eradicated, email worked reasonably well more than half the time. There was some discussion about problems with the ground link in White Sands, NM early in the cruise. These did not seem to be an issue during much of the cruise possibly because it was solved on land in August. For the last ten days of the cruise, there was no email from the TDRSS system. We never received a satisfactory explanation for this, and perhaps neither did the USCG. The InMarsat connection to the science network did not work either when it became in range for the last three days of the cruise. We were told that this was because of the SDN router being down. Apparently, this router was at least partly responsible for the TDRSS connection not working earlier

The Microsoft Outlook program was used for email. Despite the fact that most of the scientific party was accustomed to using Macintosh computers with Eudora, the Outlook program was deemed acceptable for light email activities.

Recommendations - 1. An automated aiming system would improve the reliability of the TDRSS link. 2. A more reliable router (or a back up router) is needed onboard for the science network. 3. A more reliable series of ground links should be established. The use of TDRSS for communications at high latitude should be formalized and perfected. If a USCG ground link is used, it should be changed to be more reliable. 4. The ship's command should keep the scientists better informed of the status of email and the reasons for problems.

5.15.2. Voice communications –

Inmarsat was used only at the very beginning and end of the cruise because we were out of range. A portable Iridium telephone provided by the science party was used for voice communications, but it had to be operated outdoors. A Sailor Telephone (Iridium) that had been installed by the US Coast Guard was also available in the Chief Scientist's Conference Room. Iridium communications were acceptable about 50% of the time. About 50% of the time, signal strength was insufficient to establish or maintain a connection. Iridium was never set up for data or email communications during our cruise.

VHF and HF radio voice communications provided the easiest and most important link between the ships. Communications between the ships was occasionally lost, but was mostly good.

5.15.3. Ship-ship datalink –

We thank the USCG for procuring the ship-ship data link. It was very useful and important in allowing transfer of data files between the two ships. The data transfers were useful for operational and planning issues and also for helping the expedition to act more coherently, rather than as two separate ships. Multibeam bathymetry data, geochemical data, sampling plans and other communications were transferred between ships. Files were transferred via the IBM PC and the UNIX instruments.

5.16. Shipboard computers and the Science Data Network

There was an adequate number of desktop computers on board: both Macintosh and PCs. These computers were reasonably current in terms of hardware and software. The Macintosh computers were not integrated very well into the ship's Science Data Network (SDN), nor could the personal Macintosh computers brought on board by scientists be integrated into the SDN. They were also unable to access all of the printers. Transferring files between any Macintosh and the SDN could have been accomplished via removable media like Zip disks, but the PC computers lacked Zip drives, except for the external Zip drives supplied by the science party.

The ship's Science Data Network was used for storing shared files.

Recommendations - 1. Printers should be identified better on the network. Several printers were designated with similar names. 2. Macintosh computers should be better integrated with PCs into the network. A wired network is much preferred. At the very least, each PC should have a 100 MB Zip drive, which is currently the best medium that can be transferred between Macs and PCs. 3. More training or support is needed for the MST who is in charge off the SDN. He was normally spread too thinly.

5.17. Weather and Ice information from satellites

The weather and ice information received on the ship was helpful some of the time. The Radarsat images were excellent for seeing ice conditions even in cloudy or foggy weather, but we sometimes went for days without getting an image, or images did not cover the area of operations. The Visible satellite images were excellent because they could be printed at a scale that was useful for navigation and planning. But it was impossible to use these images most of the time because of the persistent cloud cover in the high Arctic. The Radarsat images were valuable for planning operations and movements. It would help any science program in the high Arctic if their delivery was more dependable and they were tailored for the region of operations.

Recommendation - If possible, NSF or the USCG should negotiate a more active agreement with the supplier of the Radarsat images.

It would have been nice to have a dedicated meteorologist on board Healy. Polarstern had a professional meteorologist on board who gave 24-hr, 48-hr and advanced weather forecasts each day that were useful for planning, including helicopter flights. These were somewhat more detailed than those supplied by the MSTs on Healy. Perhaps future expeditions should try to get a self-funded meteorologist to participate on their expedition. Their role could be as independent arctic researcher as well as weather forecaster.

5.18. Helicopter Operations

Helicopters could have benefited the science program more if they had been easier to use and less time consuming to launch and recover. There was a strong contrast between Healy's and Polarstern's helicopter operations. Helicopters' launch and recovery on Healy required a lot of time and tended to interfere with science operations and consumed science time because of the many support personnel needed and because of the rules for a stationary ship. We quickly learned that it was important to carefully schedule helicopter operations during dredging or CTD operations when the ship was stopped anyway. This was true even for operations involving Polarstern's helicopters landing on Healy. Well-timed and planned operations tended to minimize the loss of science time. In contrast, Polarstern's helicopters required much less time and fewer personnel to launch and recover. Polarstern was able to have helicopters arriving and departing all day without severely interrupting science operations, and they used their helicopters much more.

The size and type of helicopters on Healy also seemed to make operations more difficult. Polarstern's helicopters were smaller so they were much more nimble and able to operate on a small ship-based pad, and actually had a longer range and similar payload as the HH-65A helicopters on Healy. The pilots on Healy might also have preferred the smaller helicopters and should be consulted.

5.19. Shipboard Laboratories

The laboratory space aboard USCGC Healy was quite sufficient for our expedition. The layout was acceptable and was similar to some UNOLS vessels but was not as large or efficient as that on the German icebreaker Polarstern which has exceptional lab space. Polarstern's layout of many dedicated small laboratories reflects the tendency for that ship to carry out expeditionary science, where many different measurement programs are supported each year simultaneously. The UNOLS-like layout on Healy contains fewer but larger spaces that are designed to be molded to suit the main purpose for a particular cruise. It reflects the way science is organized in the U.S.: focused by disciplinary or topical cruises that are supported by peer-reviewed grant proposals.

There were no drawers for storage when we arrived. The addition of a storage shelf above each table was a big improvement, but not a long-term solution. Lighting above the laboratory benches was also insufficient. The addition of movable lighting units that were on stands and could be wheeled into position was a big improvement, but these limited traffic in the lab and would not be safe in open seas.

Recommendations: **1)** Laboratory benches should be made more usable by adding drawers to some or all of the benches in the main lab. Since the benches are movable and changeable, the drawers should also be movable. **2)** Some type of intense lighting should be purchased for the benches in the main lab. These should also be moveable. **3)** It was difficult to gain access to the sinks in the main laboratory. If possible, these should be moved, or things around them should be moved so they are more accessible.
The electrical service to the laboratories was sufficient for our purposes.

5.20. Deck and Hangar and crane layout (by James Broda)

The deck arrangements on board USCGC Healy are flexible and conducive to efficient operations. During AMORE station work, we were able to lead different wires to the aft A-frame which for ice reasons was the location for the overboarding of equipment. The Aft Conning station (Aft Con) lends a clear and protected view for winch and A-frame control and many video angles can be telecast in the control room to monitor all aspects critical to the station operations. The hangars provide sheltered work areas with easy access to the main deck, and were used extensively during the cruise for equipment preparation and sample handling and processing. We secured a 20' shipping container on the fantail for the storage of the 15 tons of material we eventually collected. Positioning the container on the installed pads is complicated by the overhead helicopter deck and by the large tow bit located on the centerline of the fantail. The concept of making the tow bit removable is under discussion in the U.S.C.G. We support consideration of the project to free valuable deck space and to simplify van installation and use.

5.21. Meetings between ship's officers and crew

Evening meetings were held between the Chief Scientist, Captain, Engineering Officer, Operations Officer, Science Officer, Aviation commander, Master Chief and senior MST. Meetings were frequent but not daily and often involved other scientists as well. Each section, (including scientists) gave brief reports on the status of their operations and the intended operations for the next day or so. Problems were discussed and action items determined. Ship-wide announcements were sometimes disseminated to the science party in this way. The meetings worked well for keeping the science party informed about the ship’s systems and happenings as long as the Chief Scientist was not remiss in communicating questions and answers from other members of the science party. In many respects, the communication level on this cruise was better than on some of the UNOLS cruises in which we have participated.

5.22 Medical, dental and other personnel issues

We were very fortunate that no one in the science party developed any serious medical, dental or emotional problems that required treatment that was unavailable on Healy. Nor did anyone sustain serious injury while working or living onboard. We were glad to have a medical officer onboard. The medical forms that we submitted suggested that everyone in the science party were in excellent health, but certainly a problem could have developed. Because we were so far from medical support (even further in terms of time and possibility of evacuation than Antarctic research programs) a serious medical problem could have jeopardized the entire expedition. For this reason, expeditions like this one to the remote high Arctic (as opposed to those in shelf areas near land or within helicopter range) should consider medical exams for scientific personnel. Naturally, we also support similar requirements for USCG personnel. Whether or not to require medical examinations could be determined separately for each expedition, or NSF could develop guidelines for the scale of expedition that would justify the

5.23. Integration with Polarstern

Cruise "Healy 0102" was only one half of the AMORE. Healy's partner ship in the AMORE was the German scientific icebreaker: PFS Polarstern. The activities, responsibilities and scientific returns for the ships and scientists on both sides are laid out in some detail in a Memorandum of Understanding (MOU) that was begun in October 2000 in Bremerhaven and signed in July, 2001 in Tromsø after extensive discussion and revision. The MOU is included as Appendix VIII.

5.23.1. Benefits of a two-ship operation

When AMORE was conceived, there were several perceived benefits of a two-ship expedition.

1) More science was possible by using two ships, especially if the ice conditions were severe. The transits between stations were necessary anyway, so when Healy led Polarstern during seismic traverses and then both ships sampled the seafloor, more science could be done: roughly 1.5 times as many sampling stations could be occupied. Also, Polarstern's seismic program would have been impossible or very difficult without Healy breaking a lead. The seismic program will generate data and models that are complementary to the rock data from both ships.

2) It was thought that multibeam sonar maps or even views of the seafloor were possible only if a ship was following in the lead cut by another ship. In fact, we learned that Healy's SeaBeam system was capable of charting the seafloor even when she was in the lead and actively breaking ice. Polarstern's system also performed well. The resulting map was produced about 75% from Healy's SeaBeam system, so there was some benefit from having the two ships work together.

3) There is some safety benefit from having two ships together, since it is possible that one ship may get beset in the ice and need to be broken out by the other. Although Healy was never beset in the ice herself, she freed Polarstern several times.

4) There are benefits to saving fuel and having a longer expedition possible if two ships work together. In fact, Healy either worked alone or led Polarstern during the entire cruise. Healy derived no fuel savings whatsoever from working with Polarstern, although Polarstern did benefit somewhat. Healy could have completed the cruise easily as a single ship in terms of fuel.
5) Ships can provide technical and material support to each other, especially when there are failures of systems lacking redundancy. For example, Polarstern's machinists fashioned a replacement component for Healy's bow thruster that could not be made on Healy. Also, there was some discussion about transferring trawl wire from Polarstern to Healy after Healy lost 6800 meters. This option was at least available, although it was not pursued.
6) The two-ship operation was seen as an insurance policy for both ships, but especially for Healy because she was untried as an icebreaker and scientific research platform. If Healy was unable to fulfill her icebreaking and scientific missions, U.S. scientists would at least have access to the samples collected by Polarstern. AMORE was Healy's first major scientific cruise, and as such, a trial. How well would she break ice? How dependable was her propulsion system? How well would her winches work? How well could she do science operations? There were some tense moments in the early part of the cruise, but Healy proved her capabilities in every way. She is even better at breaking ice than Polarstern. Her propulsion system never failed in 63 days at sea. The winches worked well and sample recovery was much greater than expected.

We originally thought that severe ice conditions would force us to use two ships sampling as a unit (one ship breaks ice while the other ship dredges). It would have been logistically more difficult to sample this way, so we never attempted this method, and there was no benefit derived from having two ships present. Instead, we either sampled independently in good ice conditions or each ship abandoned their sample sites that were too inaccessible.

5.23.2. Scheduling a two-ship operation

Not having control over the start and end date of the expedition was one of the most difficult aspects of being involved with another ship. There was a little discussion about timing, but in the end, Healy's schedule was adjusted to fit Polarstern's schedule, which was dictated by their cruise earlier in the summer. Polarstern also desired a longer expedition than originally envisioned by the American P.I.s. Taken together, these factors meant that the ships were in the high Arctic up to the last possible day. The weather window was closing rapidly behind us as we left the ice in late September. The lateness of AMORE also increased the hardship for the following cruise on Healy. A departure from Tromsø on July 15 instead of July 31 would have allowed the cruise to conclude within a better weather window, although there is some question about the ice conditions in early or mid-July being too tough. Improved long range planning, especially for expeditions involving two ships, was not possible in this case, since

Polarstern sets her schedule two years in advance. The fact that Healy is now a proven platform in the Arctic should allow her planners to have a much stronger position when negotiating the start and end dates of expeditions involving two ships. Earlier planning would also help.

5.23.3. Sharing of samples and data –

Another difficult aspect of the two-ship operation was the fact that there were additional petrologists on Polarstern who wished to analyze the same samples for the same chemical parameters as Healy scientists. These conflicting goals were worked out in the MOU, but required compromise from all parties, and were a continuing source of tension between the ships and scientists.

5.23.4. Was a two-ship operation necessary?

It is possible that USCGC Healy could have carried out the parts of the AMORE that were in the interests of her scientific party on her own. For scientists on Healy, the main benefit that was derived from the two-ship expedition was that more sampling stations were occupied since transits were shared. Scientists on Polarstern shared this benefit, but more significantly for them, were able to conduct a major seismic study as well. As mentioned above, having two ships provided more security in terms of ice breaking and sampling success.

5.23.5. Coordination of scientific and seagoing activities

Science activities between the two ships were coordinated for the short term mostly by radio communications that took place several times a day. Two or three times, the ships were separated by too many miles to be in easy radio contact. This led to some problems in selecting target areas and in preventing duplication of sampling. The different time base for the two ships (purely GMT for Healy, closer to local time for Polarstern) presented problems for communication when the offset exceeded three hours. Sometimes, scientists on either ship had to be awakened for radio calls.

For the medium term, science activities were coordinated mostly by personal meetings that required helicopter travel for the P.I.s between ships. This was usually very helpful in setting longer term goals, and would have happened more frequently, but for two reasons. On several occasions, weather prevented these meetings. We were also reluctant to disrupt sampling activities to launch and recover helicopters on Healy. Longer duration visits to the other ships by individual P.I.s would have helped also, because they would have led to a better understanding of how the other ship functioned scientifically and operationally. Also, we could have detected some shortcomings in Polarstern's sampling methods earlier in the cruise: the damage that their pipe dredge inflicted on glassy samples. The data link between the ships also provided an important means of coordinating activities. Files including previous and future sampling activities were transferred along with notes between P.I.s.

Daily and weekly planning required compromises by different scientific groups on both ships. Sometimes it was difficult to integrate the daily schedules, routes and locations of the two ships, especially during the seismic operations that required the two ships to travel together. There was less time for sampling operations because Healy was often leading Polarstern during these seismic traverses. Sometimes these traverses ended in locations that were not optimal for sampling, or excellent sampling sites were bypassed. Sometimes the sampling went too fast for seismic stations to be placed at good locations, thus compromising the seismic results.

5.24. Education and outreach during AMORE

Recognizing the need to keep the public informed and involved in NSF-funded research, NSF OPP developed the TEA program (Teachers Experiencing the Arctic and Antarctic). Ms. Michele Adams from Musselman Middle School in Berkeley County, WV participated in AMORE as a TEA. Ms. Adams primary goal was to maintain a journal of her activities, observations and impressions which was broadcast daily (or as frequently as TDRSS would allow) over the WWW. The journal was concise and interesting and included images from the ship and the Arctic. Interested science classes, individual students and other persons were able to follow the expedition and even ask questions and receive answers from Ms. Adams. Judging by responses from people who followed the website, from the number of questions and by the number of “hits” on the website, Ms. Adams endeavor was a huge success. Hundreds or thousands of students and interested people were engaged by AMORE through her website. They learned about the scientific goals of the expedition, what the Arctic environment was like, what kind of work was being done onboard, and what shipboard life was like. Ms. Adams also participated fully in the scientific work of the expedition, including sample preparation and archiving, and the making of the SeaBeam charts. She was a valuable member of the scientific party.

In addition to Ms. Adams website, Columbia University’s Earthscape also maintained a website about the expedition which included images, short movies and discussion contributed by scientists and other expedition members. It provided viewers with different information and outlook

6. Scientific Results

6.1. Bathymetric Map

The bathymetric map that was produced using data from Healy's SeaBeam system and Polarstern's Hydrosweep system was an unexpected and highly significant result of AMORE. It shows regularly spaced volcanic centers in the absence of axial offsets. It shows an abrupt change in the nature of the ridge that coincides with changes in the magnetic character of the ridge and with a change in basalt chemistry. Further details are given in the abstracts by Dick et al. And Kurras et al. in Appendix XIII.

6.2. Rock recoveries -

Dredge operations were carried out from 6°W to 87°E on the axis, walls and adjacent seamounts of Gakkel Ridge. There were 101 dredge attempts, of which 2 dredges were lost, and **seven** came up empty or containing only mud or mud stone. The locations and a brief description of the amounts and contents of each dredge and rock core are given in Appendix IX. Photographs of each dredge are available from the Chief Scientist. Station information including time, date and depth on and of bottom are given in Appendix X. A map of each dredge site, along with a tension log is given in Appendix XI. Tension logs were not generated for the dredges that were done using the 0.680" conducting cable. A plot of the latitude and longitude of dredge and rock core recovery sites is shown in Figure 4. Polarstern's station log is given in Appendix XII.

Some of the early observations are presented in Appendix XIII which are abstracts that were submitted about half way through the cruise to the Fall 2001 Annual Meeting of the American Geophysical Union.

6.3. MAPR and CTD results (by Henrietta Edmonds)

6.3.1. MAPRs

As discussed earlier (operations), data were returned from 118 MAPR deployments. Of these, an astounding 96, or 81 percent, show layers of increased light scattering consistent with hydrothermal plumes. Many of these are quite small (circa 10 mV above background) but are consistent in a given area of ridge crest, i.e. the same signal was detected multiple times in a region and at varying strengths suggesting proximity to or distance from a vent source. Seventeen of the observed plumes are very large (>40 mV above background); nine of these seventeen are in the area of the purported 1999 eruption and thus represent a single source. Most of the observed plumes were between 3000 and 3500 m water depth, but many were also observed at around 2500 (± 300) m. The MAPR data from each deployment may be found in Edmonds et al., 2002). On board analysis and interpretation of the MAPR data were used to target CTD deployments.

6.3.2. CTDs

CTD data and water samples were collected at six stations along the Gakkel Ridge in response to signals observed in the MAPR data. The first cast, CTD04, was in response to Dredge HLY 0102 D21 (and smaller signals in Dredge HLY 0102 D20 and Rock Core HLY 0102 D7) near 2˚W. The remaining five casts were conducted during the return leg west from 85˚E to 24˚E. The site of CTD05, at the site of the 1999 seismic event near 85˚E (Edwards et al., 2001), was chosen based on MAPR information from five dredges and two rock cores. CTD06 was conducted near 55˚E in response to a very large plume observed on Dredge HLY 0102 D74, but ice conditions prevented us from reaching our target station and the plume observed on the CTD cast was quite small. CTD07 was conducted near 55°E in response to a very large (150 mV light scattering sensor) plume observed on Rock core HLY 0102 RC18. CTD08 was conducted near the sites of Dredge HLY 0102 D50 and Rock core HLY 0102 RC14, which had been occupied on the eastbound leg of the cruise. CTD 09 was specifically designed to target one of the smaller MAPR signals, rather than one of the large, obvious plumes. Such signals were observed over much of the ridge, but were generally not large enough to have associated temperature anomalies. Because the amount of hydrothermal activity suggested by the MAPR deployments is surprisingly high,

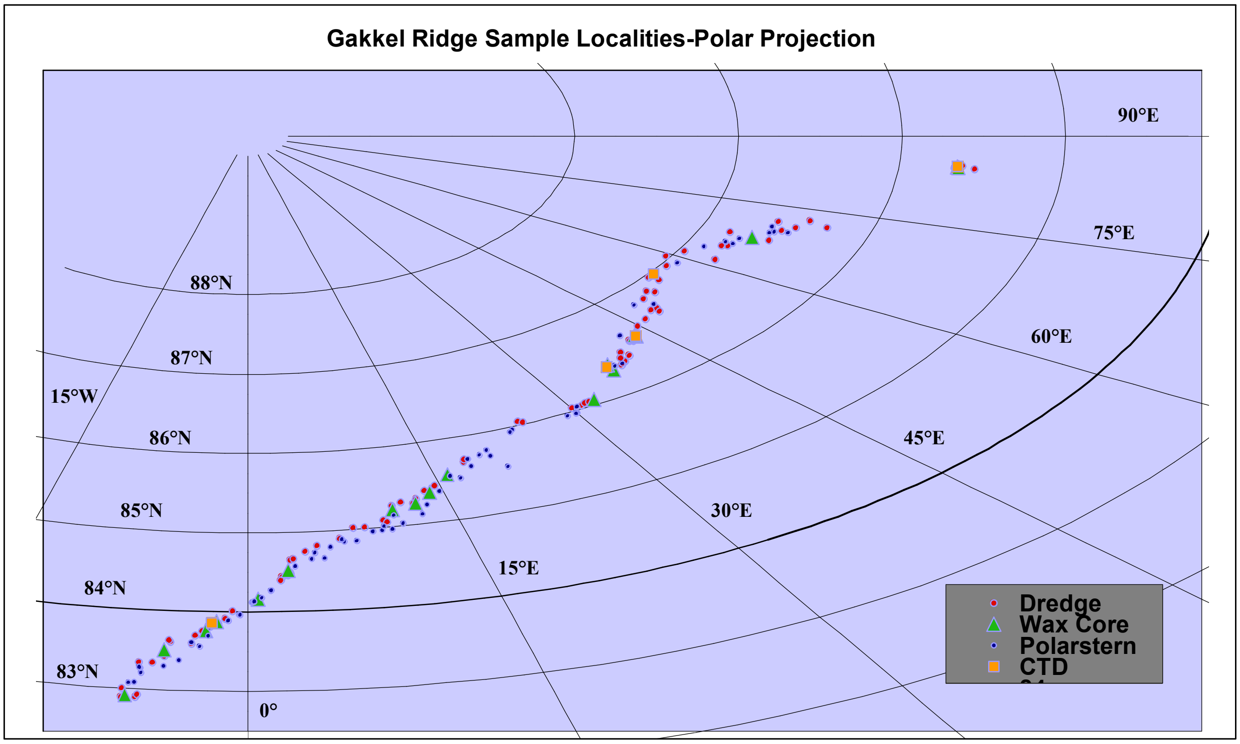


Figure 4 – sample recovery by Arctic Mid-Ocean Ridge Expedition (AMORE 2001)

it is particularly important to acquire chemical data to verify the hydrothermal nature of the
light scattering peaks.

Samples were collected from all six casts for helium isotopes, methane, and manganese, the "big three" dissolved chemical tracers for hydrothermal plumes. In addition, samples were collected for salinity measurements from all bottles. Nutrient samples were collected from casts 4, 7, 8, and 9. Samples for biological investigation were taken for Linda Kuhnz from particularly plume-rich samples. Several additional samples were collected for ancillary non-hydrothermal investigations, but these were lost when a -80°C freezer became too warm. At stations 5, 7, and 8, water was collected for possible future analysis of ^{129}I, in order to investigate the ventilation rate of Eurasian Basin deep waters from the Barents Sea shelf. From CTD05, five samples were collected for Mukul Sharma of Dartmouth College (requested through Jon Snow) for osmium isotope analysis. Information on bottle samples (depth, samples taken) is summarized in Appendix VI).

Because of problems with noisy data (see earlier section), the CTD data from most of the casts will require lengthy post-processing which was not possible in the time-frame of the cruise. All necessary files and information required for this has been taken to The University of Texas at Austin Marine Science Institute and the work will be completed by November, 2001. Initial analyses of the data show discernible signals in temperature and salinity in addition to light transmission.

6.4. DCP results (by Charles Langmuir and Kerstin Lehnert)

More than 120 basalt glass samples were analyzed on board for major elements, Sr and Ba by direct current plasma spectrometry. Because the cruise track encompasses a double-pass along most of the ridge, the on board 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 predict progressively smaller extents of melting at greater depths eastward along the ridge. Instead, the data conform to the three distinct tectono-magmatic regimes. In the west, basalts exhibit a "slow spreading local trend" of negative correlation between Fe_8 and Si_8 and positive correlation between Na_8 and Fe_8.There is a well-defined geochemical gradient from more enriched incompatible trace element compositions in the west to depleted compositions in the east. At the eastern terminus of this region there are small volcanic cones with chemical compositions rare or unique among MORB. They were most likely derived by very low extents of melting of a depleted source. There is no evidence for an enriched "veined mantle" component at these very low extents of melting. These samples appear to reflect the dying out of the melting regime and a depleted mantle in this region. Proceeding further east, there is an amagmatic region where purely tectonic spreading appears to take place, and where no basalts were recovered. Magmatism then revives at about 10°E, first with highly enriched basalts then with progressively less enriched compositions further east. In the far eastern, slowest spreading portions of the ridge we sampled at 87°E, the magmatism is fresh and abundant, but is focussed at large, slightly elongate volcanic complexes, separated by short sections of tectonized ridge. The mean compositions of Gakkel Ridge basalts correspond with the global depth-chemistry systematics. The deepest and highest Na_8 region is the central Gakkel along the strike of the ridge, even at ultra-slow spreading rates. Mantle composition and possibly mantle temperature clearly play an important role even at ultra-slow spreading rates. The edges of the amagmatic zone provide evidence of the variable compositions of the lowest degree melts that occur in the sub-oceanic mantle.

6.5. Biology

In all 169 samples were collected, many containing multiple species or multiple animals. It is likely that more organisms will be found when sorting of samples is completed. We recovered an abundance of specimens from two relatively shallow dredges at two seamounts (dredges HLY 0102 D72 and D97). Sixty-four of the 98 recovered dredges by USCGC Healy contained biological samples (65.4%). 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.

6.6. Geophysics

Scientist onboard Healy did not gather geophysical data. USCGC Healy participated in the geophysical program by breaking ice for PFS Polarstern while the latter deployed an airgun and/or towed a seismic streamer. The results of this study are described in Appendix XIII, in an abstract by Jokat et al.

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8. List of Appendices (ON CD ROM)

Appendix I – Examples of Seabeam under difficult ice conditions

Appendix II - Rock (slab & chip) and glass distribution to various PIs

Appendix III - Rock description methods by H. Dick

Appendix IV – Rock descriptions

Appendix V DCP emission spectroscopy standards

Appendix VI CTD bottle log

Appendix VII summary of biota recovered

Appendix VIII Memorandum of Understanding

Appendix IX Healy 0102 sample stations and synopsis-

Appendix X Healy 0102 Sampling activity: time and navigation

Appendix XI Individual station maps

Appendix XII Polarstern sampling log

Appendix XIII American Geophysical Union abstracts, Fall 2001.


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