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Magmatic and Hydrothermal Activity in Lena Trough, Arctic Ocean

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The nature of magma generation, crustal construction and hydrothermalism beneath ocean ridges at extremely low spreading rates is a hot topic currently in marine earth sciences. Partial melting (10-20%) and magma mixing experienced by most mid-ocean ridge basalts hampers our understanding of the mantle and melting processes. This is because the lowest-degree partial melts (containing essentially all the incompatible trace elements) and their still-fertile peridotite residues are never observed – their compositions can only be inferred. Thermal models predict a sharp drop in partial melting at spreading rates significantly under 16 mm/yr (full rate) [*Reid and Jackson*, 1981]. The ultimate slow spreading ridges have remained relatively unstudied, however. These ocean ridges are located at high latitudes beneath the arctic ice cap, and include the northern end of the Mid-Atlantic ridge system at Knipovitch Ridge, Molloy Deep, the entry into the Arctic Ocean via Lena Trough, and Gakkel Ridge beneath the Arctic Ocean. The few samples available from these regions [*Hellebrand et al.*, 2001b; *Mühe et al.*, 1997; *Mühe et al.*, 1993] confirm very low degrees of partial melting. For this reason, mapping and sampling of arctic ridges has a strong priority in the international Ridge community, as codified in the InterRidge project plan “Mapping and Sampling the Arctic Ridges” [*InterRidge-Arctic-Working-Group*, 1998].

A major obstacle to testing hypotheses related to very slow spreading and to low-degree partial melting is posed by previous lack of success in recovering basement samples in the high arctic. Indeed, the few basement samples extant from Gakkel Ridge were sampled unintentionally by sediment corers; until now there has been no successful dredging north of Molloy Deep. Some of the first high-arctic basement samples were recently recovered from Lena Trough in Fram Straight northwest of Spitzbergen by the German icebreaker POLARSTERN. The recovered basalt, peridotite and massive sulfide ore deposits paint a striking picture of mantle melting, magmatism and hydrothermal activity on the world’s slowest-spreading mid-ocean ridge system, and demonstrate the feasibility of high-arctic sampling. These results pave the way for future geologic mapping and sampling on spreading ridges in the high arctic.

Geologic Setting

The Lena Trough is an enigmatic linear deep in the Arctic Ocean. It extends from the westernmost end of Gakkel Ridge to the Spitzbergen Fracture Zone (Figure 2), a distance of 300km, at an axial depth of around 4000m, and is largely filled with sediment. It represents the westernmost and southernmost portion of the arctic ridge system. One very puzzling aspect of its makeup is its obliquity to the regional spreading direction. The azimuth to the spreading pole between the North American and European plates is approximately 030 here, and the axis of the deep trends 345, implying an obliquity of about 45 degrees. Given the slowness of the spreading rate (~14 mm/yr full rate) and this apparent obliquity, it is not at all clear what type of magmatic construction might occur there, if any. Possible spreading geometries include a highly stepped transfer zone similar to the 12-15 °E region on the SW Indian Ridge, a transtensional fracture zone, possibly leaky, or some kind of as-yet unknown oblique spreading type.

Operations

Ice conditions encountered by POLARSTERN Cruise ARK XV/2 in the summer of 1999 were particularly bad. Frequent pack-ice conditions (Figure 1) and formation of pressure ridges meant that transit progress in ice was quite poor, so that large portions of the geophysical program had to be abandoned. Frequent fog also precluded large parts of the planned aeromagnetic survey. Nonetheless, the three days of dredging originally planned were not shortened, and several targets on slopes near the center of the Lena Trough structure could be carried out, as shown in Figure 2. The technique used to accomplish the dredging was to locate a long enough lead (0.5-2km) that crossed the feature to be sampled. The dredge was put into the water as close to the base of the slope as possible, and cable was paid out as the ship steamed to the opposite end of the lead. Then the dredge was reeled in a single time. Hang-ups were not experienced, and no dredges were lost. This may have been due to the 18mm cable and dredge tackle used, which has almost double the working strength of standard US 9/16” geo wire. The Woods Hole-designed weak links could thus be set at their maximum breaking strength of 13 metric tons at all times. Average time per dredge haul not including transit was 6 hours. Five total hard rock dredge deployments on this cruise included 4 in ice, and all contained significant amounts of rock. All those in Lena Trough were on its flank of near the center of the structure.

Petrography

Massive sulfide: Ocean floor massive sulfide ore deposits are the spectacular expression of deep-seated hydrothermal circulation within the ocean crust. Dredge Station 088 brought up ~30 kg of hydrothermal sulfide deposits, related alteration products and hydrothermal sediments. The largest piece is a solid boulder comprised of 100% massive hydrothermal pyrite weighing 18kg (Figure 3). The fine-grained texture of the pyrite indicates its relative freshness and lack of recrystallization typical of recent black smoker deposits. Oxidized porous material resembling chimney pieces were also recovered. Cores of some of the samples appear to show relicts of fine and coarse grained igneous rocks. The dredge haul also contained fragments of fibrous massive asbestiform serpentinite and peridotite, suggesting that ultramafic rocks hosted the hydrothermal deposit. Because the discovery of this field was not preceded by water column measurements or television survey and was thus completely fortuitous we decided to name it the “Lucky B” field, a deliberate reference to the also fortuitous Lucky Strike field further south.

Peridotites: Abyssal peridotites are the mantle residues of the melting that produces MORB. Peridotite was present in all Lena Trough dredge hauls, and Dredge 089 consisted primarily of this rock type (78 kg). The precursor rock was a plagioclase-free spinel harzburgite. The peridotites appear strongly tectonized and altered in hand sample, but in thin section contain abundant relict olivine,

Fig. 1: Dredging operations in pack ice.

orthopyroxene, clinopyroxene and spinel. Many of the samples are cut by late carbonate veins, a common feature of ocean floor peridotites. Spinel grains in the peridotite samples are either clear (nearly Cr-free) or dark (Cr-rich) in color suggesting different populations of Cr content and thus melting degree in rocks sampled by the relatively small region of the dredge haul. At least some of these (the Cr-poor ones) are likely to be the product of very low degrees of mantle partial melting. Spinel clasts in carbonate-cemented monomict peridotite breccias also show two populations of spinel color, some being pale (i.e., nearly chrome-free) and some being quite dark (indicating a normal chrome content).

Basalts: The oceanic crust is constructed primarily via the intrusion and extrusion of basaltic magmas. Glassy basalt pillow fragments were recovered in dredge 090, along with altered peridotite. The basalts appear petrographically primitive, with clear idiomorphic olivine as the dominant phenocryst phase. Two samples also contained spinel as a phenocryst phase and one contained plagioclase. Unusually for mid-ocean ridge basalts, these samples are 5-10% vesicular. Since the basalts were recovered from a depth of 3000m, this implies either improbably large vertical displacements or, more likely, a high volatile content of the MORB liquid. Another indication of high volatile contents are abundant 2-phase fluid inclusions trapped within the olivines. Otherwise the textures are typical of a relatively primitive MORB.

Preliminary Geochemistry

The geochemistry of both basalt and peridotite samples reflects the melting mechanisms operating in Lena Trough. Despite their obvious tectonic and petrographic similarity to MORB, the recovered basalt samples are decidedly unlike MORB chemically. Preliminary electron microprobe results on the glasses show indications of low degrees of partial melting [R. Mühe, unpublished data;*Hellebrand et al.*, 1999]. The glasses are hawaiites (Figure 4a) with an average of 1.7 wt. % K_2O, 3.8% Na_2O in moderately differentiated rocks with average MgO contents of 5.8%. High alumina ~17% suggest that despite the apparently evolved nature of the rocks, significant fractionation of plagioclase had not occurred. This was probably the result of the high water content in the melt during fractionation, although high-pressure fractionation also suppresses plagioclase crystallization. A low degree of partial melting is indicated.

Spinel composition is an important indicator of peridotite melting history [*Dick and Bullen*, 1984], and allows a quantitative estimation of the degree of partial melting a peridotite has experienced [*Hellebrand et al.*, 2001a]. The peridotite spinels show, as was suggested by their color, a nearly bimodal distribution of Cr-number, Cr/(Cr+Al), as shown in Figure 4b (E. Hellebrand, unpublished data). The lower cluster indicates a degree of partial melting (1-5%) as low as any ever measured in the oceans. It is a significantly more fertile composition than the single sample measured from Gakkel Ridge [*Hellebrand et al.*, 2001b]. The next group at a Cr-number of 0.35 (12-14% partial melting) is more depleted than the Gakkel Ridge sample, and is about the same as spinels from near the center (and most depleted) region of the MARK area on the Mid-Atlantic Ridge (Ref). One sample had a very high Cr-number, indicating about 18% partial melting, as high as the samples from Hess Deep in the Pacific ocean.

Discussion

The petrographic types encountered at Lena Trough are clearly the result of magmatic and amagmatic construction at a mid-ocean ridge spreading center. This means that magmatic activity can exist despite the extremes of obliquity and slow spreading rate present in Lena Trough. The combination of primitive and highly vesicular basalt lithologies suggests low-degree partial melting of a relatively fertile (i.e., volatile-rich) source.

The juxtaposition of basalt and peridotite in a single dredge haul is a typical feature of magmatically starved spreading regimes such as the ends of spreading segments near fracture zones. These samples however, were not dredged from the end of the spreading segment, but near the central and shallowest part of the Lena Trough structure, suggesting that the distal ends of Lena Trough produce little or no magma at all. This is born out by dredging results in Molloy Deep, on the other side of the Spitzbergen Fracture Zone. A total of 7 successful dredge hauls carried out there (including one on this cruise) over the years have not returned a single sample of basalt or gabbro, only peridotite.

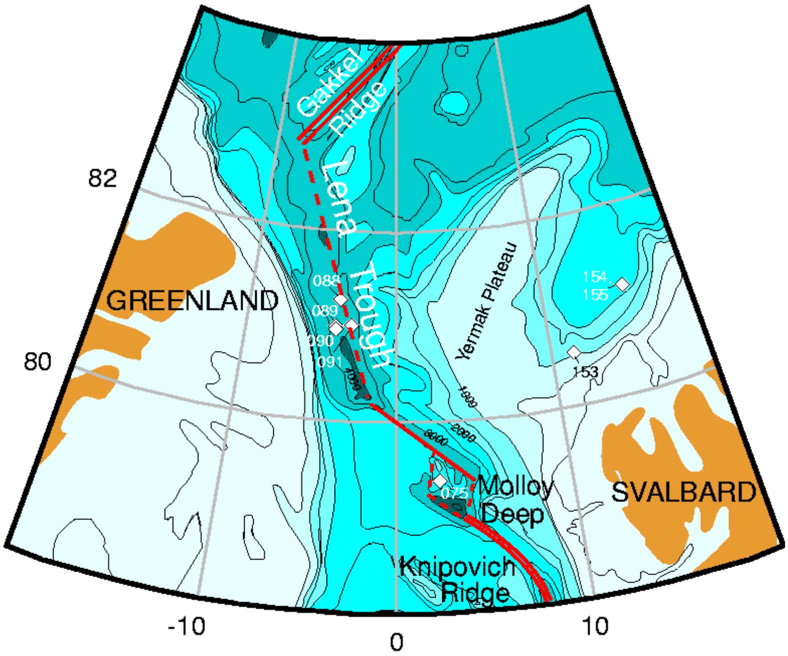

Figure 2: Sample locations from cruise ARK XV/2 of FS POLARSTERN. Locations of spreading axes are marked in red.

them. Another possibility is that the region has not experienced a consistent degree of partial melting. In particular the most refractory sample is difficult to explain in the context of an oblique very slowly spreading ridge segment. It is possible that melting becomes more focussed at very slow spreading rates, thus leading to localized high degrees of melt extraction even though generally the degree of melting is low.

The hydrothermal materials are truly remarkable, since there is general agreement that hydrothermal activity is uncommon on slowly spreading ridges. There are only 6 other hydrothermal deposits known from the entire Mid-Atlantic Ridge and only one other peridotite-hosted hydrothermal deposit [*Fouquet et al.*, 1997]. It is possible that hydrothermal activity is more common than expected on slowly spreading peridotitic crust due to the exothermic nature of the serpentinization reaction. Such deposits are significant, as they represent a vector of direct chemical exchange between mantle and seawater that has as yet received little study.

The basalt geochemistry is very unusual for MORB, in particular their highly alkalic nature; these are some of the most alkalic basalts ever dredged from the ocean floor. At the same time, their $Na_{8.0}$ at an average 3.05 is at the high end of the range of MORB and is similar to that observed for basalts from Gakkel Ridge (average 3.13$\pm$.3) [*Mühe et al.*, 1997; *Mühe et al.*, 1993]. It is the K content that makes these rocks truly remarkable, and which boosts their total alkali contents well beyond the range of MORB. For example the K_2O/TiO_2 ratio at an average 0.79$\pm$.03 is nearly 5 times the MORB average of .17$\pm$.16. Similar rocks have only been recovered from a highly oblique portion of the very slowly spreading SW Indian Ridge [*le Roex et al.*, 1992]. Ironically, these too were recovered by POLARSTERN. After complete geochemical analysis, it was concluded that the SW Indian Ridge basalts were *not* merely the products of low degrees of partial melting of an otherwise homogeneous mantle source, but contained components from a discrete long-term enriched mantle source. The fact that both sample sets are derived from locations where an already low spreading rate is compounded by significant obliquity suggests that such ubiquitous components are preferentially melted at low melting degrees.

The range of Cr-number in the peridotites is unusually large for what is essentially a single locality. In other regions, such as the Leg 153 drill holes in the MARK area on the Mid-Atlantic Ridge, spinels from a single location cluster very tightly over length scales of many hundreds of meters. The Lena Trough spinels by contrast exhibit the entire range of Cr-numbers observed in abyssal peridotites. It would be possible for such a signal to be "inherited" in a region that has not experienced extensive melting. That is, high Cr-numbers from an ancient melting event would be preserved because the magmatic budget is not sufficient to re-equilibrate

Conclusions

Lena Trough lies on the southern and western end of the Arctic ridge system. It spreads at the slowest spreading rate yet sampled at a mid-ocean ridge, with the exception of three essentially accidental samples of Gakkel Ridge. The recovery of these samples dramatically increases the total sample set

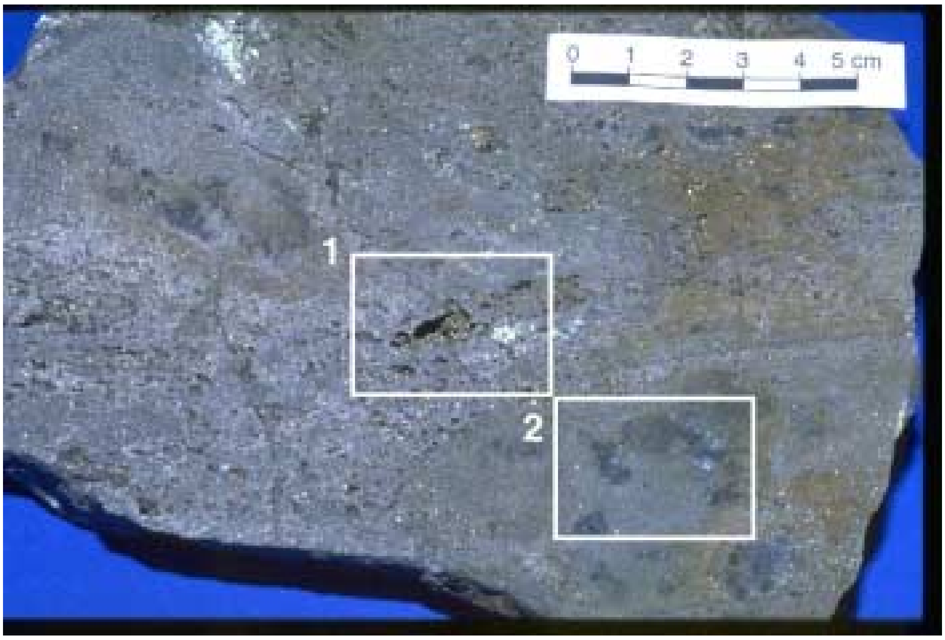

Figure 3: Massive sulfide from Lena Trough. Such ores and associated hydrothermal sediments document the existence of a relatively young hydrothermal field, which we have named the "Lucky B" field. Box 1 shows a porous region that accommodated primary flow, box 2 shows a dark unrecrystallized region indicative of recent activity.

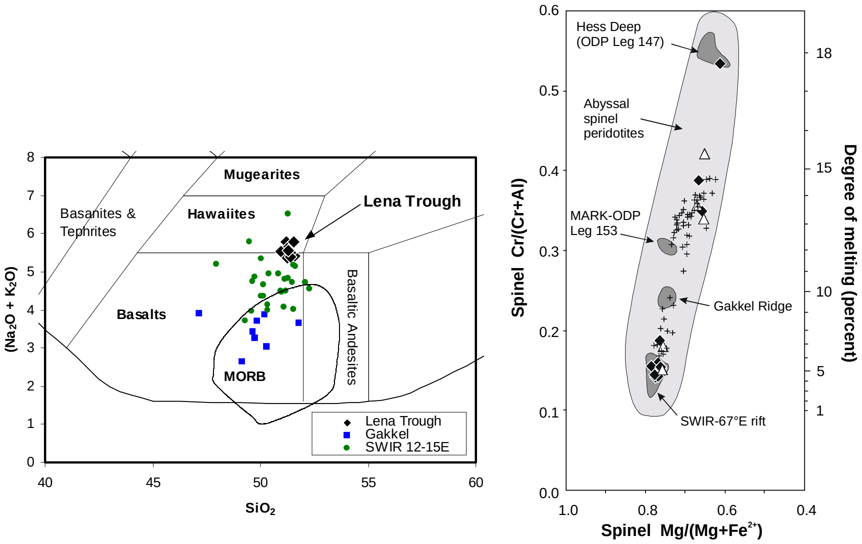

Figure 4: Preliminary basalt and peridotite geochemistry. 4a) Total alkalis versus silica for Lena Trough basalts [R. Mühe, unpublished data;*Hellebrand et al.*, 1999; *le Roex et al.*, 1992] 4b) Cr/(Cr+Al) vs. Mg/(Mg+Fe) in Lena Trough peridotite spinels (E. Hellebrand, unpublished data). Crosses indicate individual analyses in peridotite breccia, closed symbols are sample averages. High alkalis and K_2O/TiO_2 in basalts suggest a combination of low degree melting and enriched mantle components. Spinel chemistry covers the entire range observed for residual abyssal peridotites (discussed in text).

from arctic ridges and shows the feasibility of conducting dredging operations in the high arctic ice, even under difficult ice conditions.

Observations made thus far on the rocks recovered point to active magmatic construction in Lena Trough, with a well-developed hydrothermal activity. Despite this, a general magmatic starvation is suggested by the variety of rock types observed, though admittedly the sampling is very sparse. The petrographic and geochemical evidence is consistent with very low degrees of partial melting generally for the Lena spreading center, even near it shallowest point at the middle. This is very likely the result both of the very slow spreading rate and the high obliquity of the Lena Trough structure. However, long term enriched mantle sources and locally very concentrated melting appear to have played a role in the petrogenesis of these rocks.

These results, both operational and scientific, show the promise for extracting meaningful information about the mantle in general and very slowly spreading mantle in particular from Gakkel Ridge further north and east. The interplay between obliquity, spreading rate mantle temperature and mantle heterogeneity in the even slower spreading portions of that ridge are very likely to bring significant advances in our understanding of mantle composition and dynamics. Sampling there is currently scheduled as part of an InterRidge cooperation by the new US Coast Guard Icebreaker HEALY and the German FS POLARSTERN in a two-ship operation in the summer of 2001.

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