

Geophysical and geochemical constraints on crustal accretion at the very-slow spreading Mohns Ridge

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Abstract. The composition of upper mantle and lower crustal material at very-slow spreading centers cannot be reliably determined by seismic studies alone. Since the range of P-wave velocities for serpentinized peridotites and gabbros overlap, additional information provided by the major and rare earth element (REE) content of the basalts is useful to constrain interpretations of seismic data. Refraction seismic data from the very-slow spreading (16 mm/a, full rate) Mohns Ridge in the Norwegian-Greenland Sea yields a highly variable thin crust of 4.0 ± 0.5 km thickness. Analysis of S-waves suggests that Layer 3 is composed primarily of gabbro containing at most a small percentage ($< 20\%$) of mantle material. The Na_2O content of Mohns Ridge basalts suggests a magmatic crustal thickness of 4–5 km. Inversion of the REE concentrations yields a melt thickness of ~ 5 km. This agreement between seismic and geochemical data suggests that neither large quantities of mantle material are found in the lower crust nor is a large volume of basaltic magma frozen in the upper mantle.

Introduction

Some of the main questions regarding crustal accretion at very-slow spreading ridges concern the composition of the lower crust and upper mantle. Combination of geological field observations, petrological data and geophysical evidence (mostly seismic and gravity data) indicates that at very-slow spreading rates the lower crust may not comprise solely magmatic gabbros, but may consist at least partially of serpentinized peridotite [Cannat, 1993]. The upper mantle might be highly serpentinized [Francis, 1981] or contain magma that has been frozen and trapped due to increased cooling resulting from the very slow spreading (Cannat [1996] suggests that the amount of frozen melt in the upper mantle may be as high as 25% down to 10–20 km depth).

For spreading rates lower than 20mm/a, numerical models predict that the crustal thickness decreases with spreading rate [Bown and White, 1994]. This is confirmed by the few seismic refraction studies conducted to date at very slow (< 20 mm/a) spreading centers, all of which have reported reduced crustal thicknesses (e.g. Jackson *et al.* [1982] in the Arctic Ocean; Muller *et al.* [1997] on the South-West Indian Ridge). Since

correlations between seismic velocities and lithology of the crust are non-unique, modeling of geochemical data can provide insight into the crustal composition of mid-ocean ridges.

Because the temperature and flow regime of the mantle influence the extent of partial melting [McKenzie and O'Nions, 1991; Klein and Langmuir, 1987], variations in mid-ocean ridge basalt (MORB) chemistry and crustal thickness should be correlated [Klein and Langmuir, 1987; Niu, 1997]. Consequently, the use of geochemical data may provide valuable constraints on the melting environment and melt thickness [White *et al.*, 1992; Muller *et al.*, 1997]. In this paper we discuss geophysical and geochemical data from the Mohns Ridge, a very-slow, oblique spreading ridge in the Norwegian-Greenland Sea (see Figure 1) [Géli *et al.*, 1994].

Seismic results

Modeling [Zelt and Smith, 1992] of the seismic refraction data from Mohns Ridge yields a thin crust of

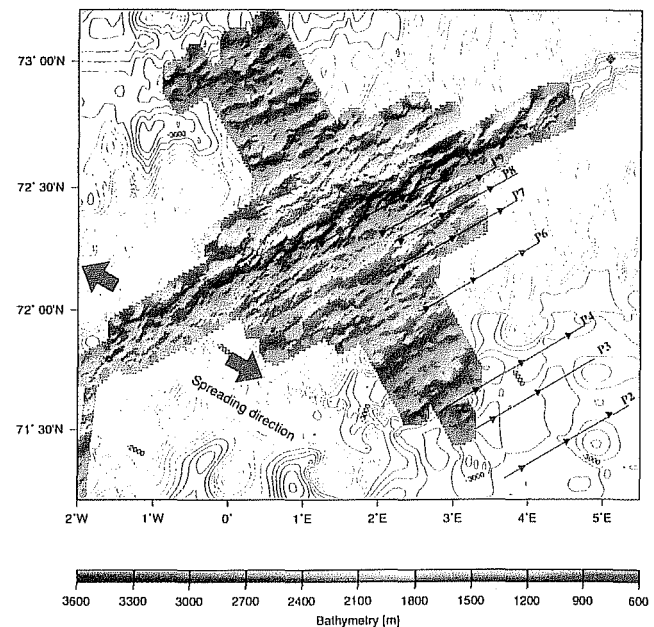


Figure 1. Study area at the very-slow spreading Mohns ridge in the Norwegian-Greenland Sea at 72°N. Seafloor relief from SeaBeam data acquired during the cruise. Refraction profiles and OBH positions are indicated by black lines and inverted triangles, sample locations from F/S Meteor by stars and from R/V Endeavor by diamonds.

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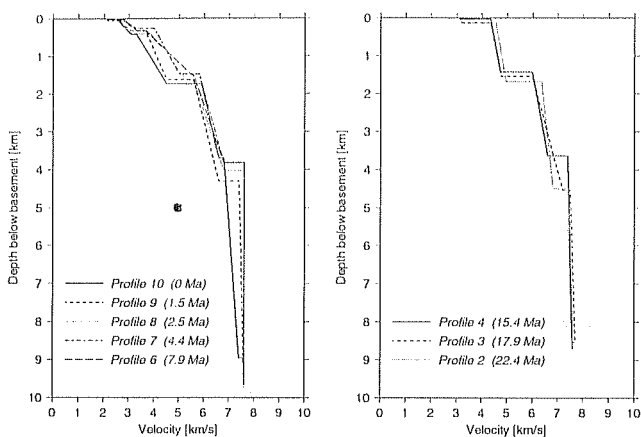


Figure 2. Velocity-depth relationship averaged for gradients and layer thicknesses. Shaded gray areas from White *et al.* [1992] for Atlantic crust 0–127 and 0–7 Ma.

4.0 ± 0.5 km thickness, with a very thin Layer 3 and nearly normal thickness Layers 2A and 2B [Klingelhöfer *et al.*, in press]. Variations of crustal thickness are accommodated by changes in seismic Layer 3, which thickens below topographic highs and thins below local basins. Figure 2 shows velocity-depth curves averaged for gradients and layer thickness from all profiles.

The high quality S-wave arrivals on the off-ridge profiles yield a Poisson's ratio of 0.28 for Layer 3. Compared to experimental measurements of gabbros and serpentinized peridotites from the MARK area [Miller and Christensen, 1997], and from the compilation of Carlson and Miller [1997], the values for Mohns Ridge fall into the gabbroic field (see Figure 3). However, pure gabbros and peridotites with 10–20% serpentinite

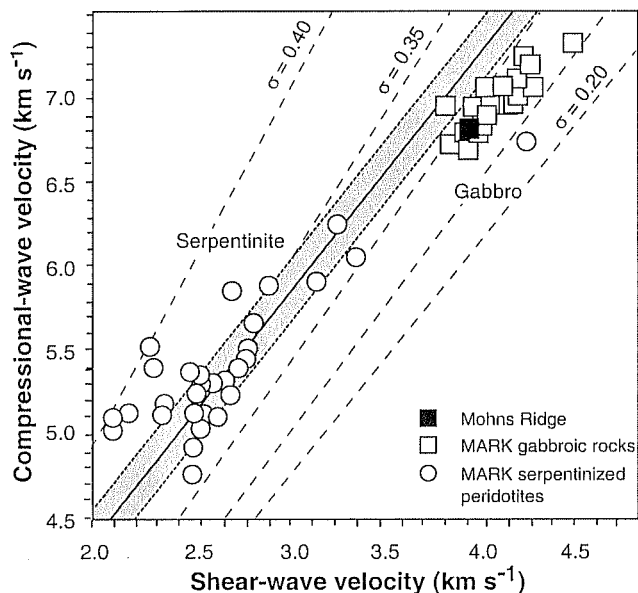


Figure 3. V_p , V_s and Poisson ratio measured on gabbros and serpentinized peridotites from the MARK area and as found from S-wave modeling for Mohns Ridge for comparison. Redrawn after Miller and Christensen [1997]. Shaded line shows serpentinite trend reported by Carlson and Miller [1997].

can exhibit similar Poisson ratios at P-wave velocities of 6.1–7.2 km/s [Horen *et al.*, 1996]. From refraction modeling one can say that Layer 3 consists of gabbro with at most 10–30% serpentine.

The upper mantle velocity is low, around 7.4–7.8 km/s, with the lowest values below the spreading axis. Low mantle velocities are found throughout the northern North Atlantic [Barton and White, 1997; Navin *et al.*, 1998], and may be related to the Iceland mantle plume. A separate plume has been proposed beneath Jan Mayen [Schilling *et al.*, 1983], which potentially could explain the low mantle velocities beneath the Mohns Ridge. However, this is unlikely since there is no plume track and no petrological evidence for excess temperatures underneath Jan Mayen, and a comparison of crustal thickness with a numerical model [Bown and White, 1994] requires no anomalously high mantle temperatures [Klingelhöfer *et al.*, in press]. It appears more likely that the Jan Mayen melting comes from volatile-rich mantle due to the influence of a nearby fracture zone and a propagating rift [Haase *et al.*, 1996]. Two other possible causes for the anomalously low mantle velocity have been proposed: i) melt frozen in veins in the mantle as suggested by observations from ophiolites [Coulton *et al.*, 1995; Cannat, 1996]; and ii) serpentinization of the upper mantle through fluids crossing the thin crust in faults and entering the upper mantle [Francis, 1981]. We use geochemical evidence to address these possibilities.

Geochemical results

We use published geochemical datasets from dredges on the Mohns Ridge obtained from two cruises: the F/S Meteor [Haase *et al.*, 1996] and the R/V Endeavor [Neumann and Schilling, 1984] (dredge sites see Fig. 1).

As Na is a moderately incompatible element it can be used as an indicator of the degree of melting. A high Na

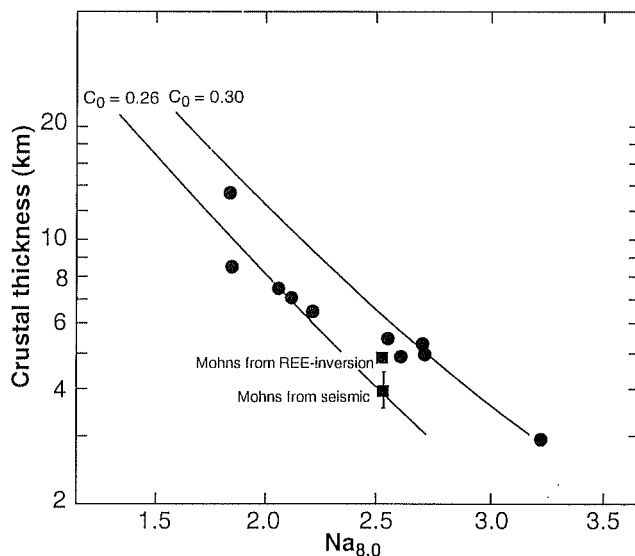


Figure 4. Seismically determined crustal thickness versus $Na_{8,0}$ for different mid-ocean ridges. Curves are theoretical fractional melting calculations for source abundance of $Na_2O = 0.30$ wt% (primitive mantle) and $Na_2O = 0.26$ wt% (slightly depleted mantle). Redrawn after Klein and Langmuir [1987].

content indicates a low degree of melting. To correct the geochemical data for fractionation to $MgO=8$ wt%, the Na_8 content is calculated from the Na_2O content with the formula ($Na_8=Na_2O+0.06MgO-0.48$) derived from the Mohns Ridge data [Haase *et al.*, 1996]. Both data sets have a Na_8 content of 2.64 wt%. Comparison with empirical correlations of crustal thickness versus Na_8 from a global dataset (see Figure 4) indicates that the 2.64 wt% concentration measured on the Mohns Ridge samples corresponds to a crustal thickness of 4 km if the mantle source Na_2O content is 0.26, which is appropriate for depleted mantle [Klein and Langmuir, 1987]. If the Mohns Ridge mantle is more enriched, as appears to be the case from Sm-Nd isotopic measurements [Haase *et al.*, 1996], then the parent mantle Na_2O concentration would be higher and a crustal thickness of about 5 km would be inferred.

We also use the REE concentrations to infer the total amount of melting in the mantle [McKenzie and O'Nions, 1991; White *et al.*, 1992]. We use a depth for the top of the melting column of 25 km, which is appropriate for mantle conductively cooled beneath a very-slow spreading center [Bown and White, 1974]. Spinel is allowed to be stable to depths of 80 km, and garnet is stable only at depths below 60 km. We allow the calculation of melting to extend as deep as 100 km, although only at depths shallower than 80 km does the partial melting exceed 1%, which is consistent with the onset of melting in normal temperature mantle not influenced by mantle plumes [White *et al.*, 1992]. The REE inversion requires the mantle composition to be defined. The Mohns Ridge basalts are enriched in light REE and other incompatible elements (Figure 5). We calculate the ratio of enriched to normal MORB-source mantle by using the observed average ϵ_{Nd} of 7.0 measured on the Mohns Ridge basalts [Haase *et al.*, 1996], although we also show below the range of fits that would result if the mantle source were either of the end-members of depleted or enriched mantle.

Taking data from the two cruises separately, the Haase *et al.* [1996] REE concentrations (Fig. 5a) are, on average, about 30% lower than the Neumann and Schilling [1984] REE concentrations (Fig. 5b). Separate REE inversions for these two datasets yield very different melt thicknesses of 6.6 km for the Haase *et al.* [1996] data and 4.5 km for the Neumann and Schilling [1984] data. However, the two sets of samples appear to have undergone different amounts of fractionation, and after the measured REE concentrations for each sample have been corrected for fractionation using the observed Fe and Mg contents [McKenzie and O'Nions, 1991], the REE distributions for samples from the two cruises are indistinguishable. Melt thicknesses from separate REE inversions of the corrected data are 5.3 and 4.8 km, while inversion of the combined REE dataset yields a thickness of 5.0 km (solid line, Fig. 5c).

REE inversion of the combined dataset, using first depleted MORB source mantle, and then primitive mantle give melt thicknesses of 4.5 and 5.9 km respectively (broken lines, Fig. 5c). The REE fit for the depleted source is worse than the best-fit with $\epsilon_{Nd}=7.0$, but that for a primitive source is much better. However, because the observed ϵ_{Nd} average 7.0, and because there is no other evidence for a mantle plume in this area of the Mohns Ridge, we suggest that the light REE enrichment is due to contamination by small melt fraction wet melts [Haase *et al.*, 1996]. The appropriate melt

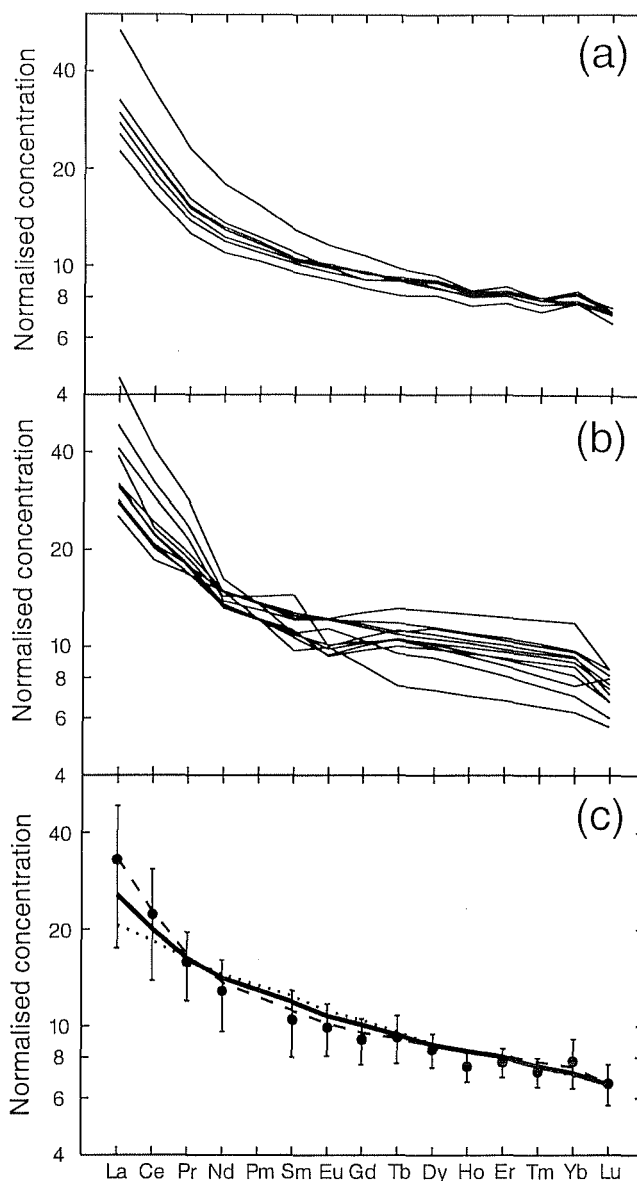


Figure 5. Element concentration ratios with respect to depleted mantle from McKenzie and O'Nions [1991]. (a) Raw data from Haase *et al.* [1996]; (b) Raw data from Neumann and Schilling [1984]; (c) Inversion of combined REE dataset after correction of REE concentrations for fractionation. Filled circles are averages and vertical bars show range of observed values. Solid line is best-fit REE inversion with ϵ_{Nd} of 7.0, giving melt thickness of 5.0 km (see Table 1). Long dashed line is inversion assuming primitive mantle and dotted line assuming depleted MORB-source mantle.

thickness to use is thus 5.0 km, derived assuming dominantly depleted parent mantle with $\epsilon_{Nd}=7.0$ beneath the Mohns Ridge.

Discussion and conclusions

The crustal thickness at Mohns Ridge inferred from geochemical analyses (4–5 km) is similar to the crustal thickness found from seismic refraction data (4.0 ± 0.5 km). A systematic discrepancy between the results of

both methods on the order of 0.5-1 km is observed worldwide, but is on the order of the error margins inherent in each method and thus not considered to be significant [White *et al.*, 1992]. Analysis of S-waves indicates that Layer 3 is composed of gabbros containing at most a small percentage (10-30%) of serpentinized peridotite. These amounts (melt missing seismic layer 3 and difference between melt thickness and crustal thickness) will lead to at most 10% of frozen, trapped melt remaining in the uppermost 15 km of the mantle at Mohns Ridge, a proportion which is insufficient to explain the low mantle velocities. We thus exclude the possibility of having a significant proportion of frozen magma in the upper mantle (even if the obliqueness of spreading is expected to enhance cooling effects resulting from very slow spreading). Instead, we favor the serpentinization of the upper mantle though fluids crossing the thin crust along faults to explain the anomalously low mantle velocities [Francis, 1981]. This suggests that neither large quantities of mantle material are found in the lower crust, as has been reported for the northern Mid-Atlantic Ridge [Cannat, 1993], nor is frozen basaltic magma required in the upper mantle. The seismic Moho corresponds approximately to the boundary between extrusives and mantle material, and is not likely to be an alteration front.

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