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High-pressure Reactive Melt Stagnation Recorded in Abyssal Pyroxenites from the Ultraslow-spreading Lena Trough, Arctic Ocean

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Pyroxenites are an essential component in petrological and geochemical models for melt formation at mid-ocean ridges and ocean islands. Despite their rarity, their origin has been widely discussed and various processes have been invoked for their formation. Here, we present a detailed study of the microtextures and major, minor and trace element compositions of relatively fresh pyroxenites and associated harzburgites from the ultraslow-spreading Lena Trough, Arctic Ocean. Microtextural and geochemical characteristics suggest an origin by magmatic assimilation–fractional crystallization with a high ratio of mass crystallized to mass assimilated. The major element compositions of pyroxenes suggest that this process occurred at high pressures (≥0.7 GPa), although interstitial plagioclase in two of the pyroxenites indicates that melt–rock reaction continued at lower pressures. The parental melt to the pyroxenites was most probably depleted mid-ocean ridge basalt similar to basalts from the North Lena Trough and westernmost Gakkel Ridge; basalts from the Central Lena Trough cannot have functioned as parental melts. The melt was generated close to the garnet–spinel facies transition by variable degrees of partial melting and reacted with the local refractory harzburgite. Pyroxenites from this study provide further evidence, together with plagioclase-bearing and vein-bearing peridotites, for significant melt stagnation below the Lena Trough that occurred over a range of depths, either continuously or stepwise. Comparison with abyssal pyroxenites reveals common characteristics, suggesting that, consistent with results of high-pressure crystallization experiments, they mark the onset of (reactive) crystallization of melts passing through the deeper parts of the mid-ocean ridge plumbing system.

KEY WORDS: Arctic Ocean; major and trace elements; melt–rock reaction; pyroxenite; ultraslow-spreading ridge

INTRODUCTION

Mantle rocks emplaced on the sea floor at mid-ocean ridges (MORs) provide insight into the shallow upwelling mantle and deep-seated melt-related processes, such as
melt generation, percolation and crystallization (e.g. Dick, 1989). Pyroxenites form less than 10% of the subcontinental lithospheric mantle (SCLM) based on their abundance in ultramafic massifs and shallow mantle xenoliths (Downes, 2007), and sampling at MORs suggests even lower amounts for the sub-oceanic mantle. Abyssal pyroxenites have been collected along mid-ocean ridges (Dick et al., 1984, 2010; Fujii, 1998; Juteau et al., 1999; Constantin et al., 1995; Kempton & Stephens, 1997; Hellebrand et al., 2005; Arai & Takemoto, 2007; Dantas et al., 2007; Warren et al., 2009; Seyler et al., 2011), but not all have been studied in great detail. Meanwhile, pyroxenites are an essential component of many models of the petrogenesis of mid-ocean ridge basalts (MORBs) and ocean island basalts (OIBs) (Hirschmann & Stolper, 1996; Salters & Dick, 2002; Hirschmann et al., 2003; Sobolev et al., 2005) and their origin in the Earth's mantle is a matter of debate.

Five principal processes have been invoked to explain the formation of pyroxenites found in mid-ocean ridge settings, as follows.

1. Pyroxenites could represent cumulates from percolating, asthenosphere-derived melts. A fractional or in situ crystallization origin was suggested for pyroxenitic xenoliths and pyroxenites from ultramafic massifs (Wilshire & Shervais, 1975; Frey, 1980; Irving, 1980; Obata, 1980; Loubet & Allegre, 1982). A similar origin has been proposed for pyroxenites from slow and ultraslow-spreading ridges (Dick et al., 1984; Juteau et al., 1990; Kempton & Stephens, 1997; Arai & Takemoto, 2007; Dantas et al., 2007; Warren et al., 2009; Seyler et al., 2011).

2. Pyroxenites could be the products of metamorphic segregation from peridotite by dissolution and precipitation during plastic flow and pressure solution creep (e.g. Dick & Sinton, 1979).

3. Pyroxenites could be solid remnants of subducted oceanic lithosphere, stretched out into thin eclogitic or pyroxene-rich layers during mantle convection and forming a two-component, marble-cake mantle together with the surrounding peridotite (Allègre & Turcotte, 1986). Although some pyroxenites, eclogites or mafic rocks in ultramafic continental mantle massifs and xenoliths have been described as consistent with primary recycled oceanic lithosphere (Allègre & Turcotte, 1986; Pearson et al., 1993; Jacob et al., 1994; Blichert-Toft, 1999; Barth et al., 2000; Morishita et al., 2003, 2004), no evidence for the physical existence of such primary eclogites has thus far been found at MORs.

4. Hybrid pyroxenites formed by melt–rock reaction between eclogite-derived melts and wall-rock peridotites have been invoked (Yaxley & Green, 1998; Yaxley, 2000; Sobolev et al., 2005, 2007). Ultrasonically spreading ridges may be the best places to preserve such mantle heterogeneities, as the degree of partial melting is expected to be low.

5. Pyroxenites could be the products of melt–rock reactions that result in olivine dissolution and the formation of pyroxenes. Similar refertilization reactions are thought to be common in the continental mantle (Kelemen et al., 1996) and also have produced secondary lherzolite after harzburgite (e.g. Le Roux et al., 2007) and pyroxenites (Garrido & Bodinier, 1999; Bodinier et al., 2008) in different orogenic ultramafic massifs. An origin by melt–rock reaction was suggested by Constantin et al. (1995) for a clinopyroxenite from the Terevaka Fracture Zone in the SE Pacific.

Any combination of these formation processes at MORs is possible and would lead to a variety of pyroxenites with particular textural, mineralogical and geochemical characteristics.

In this study, we investigate the origin of a suite of relatively fresh abyssal pyroxenites and associated harzburgites from the ultrasonically spreading Lena Trough, Arctic Ocean.

**GEOLOGICAL SETTING**

The Lena Trough is a 350 km long, oblique, ultrasonically spreading ridge segment situated between Greenland and Spitsbergen in the Arctic Ocean (Fig. 1). Via the Spitsbergen and Molloy Fracture Zones, the Lena Trough connects the Knipovitch Ridge in the south with the Gakkel Ridge in the north (Engen et al., 2008). The depth of the axial valley varies between 3800 and 5000 m, covered with up to 500 m of sediments (Jokat, 1998). The Lena Trough was formed in the final stage of the North American and Eurasian continent separation in Miocene times at around 10 Ma (Crane et al., 2001; Engen et al., 2008). Today, the full spreading rate is about 15 mm a⁻¹ (DeMets et al., 1990), making the Lena Trough, together with the Gakkel Ridge, the slowest spreading ridge system on Earth. Sampling results of the ARK XV/2 expedition in 1999 and ARK XX/2 expedition in 2004 revealed that most of the Lena Trough is composed of peridotite (Snow & Petrology-Group-ARK-XX/2, 2007; Snow et al., 2011, Fig. 1). It has a northern basalt-dominated portion bordering on the Gakkel Ridge (NLT), a central basalt-free, peridotitic portion and a southern basalt-bearing portion (usually referred to as the Central Lena Trough, CLT) (Snow & Petrology-Group-ARK-XX/2, 2007; Nauret et al., 2011). This is typical for ultrasonically spreading ridges, which are generally composed of magmatic and amagmatic accretionary ridge segments (Dick et al., 2003). The central basalt-free portion of the Lena Trough is the longest continuous amagmatic section (as conventionally defined) along the global mid-ocean ridge system and includes the ‘Lucky Ridge’, an irregularly shaped ~130 km long north–south-trending narrow ridge, as well as peridotite outcrops.
Fig. 1. Detailed bathymetric map of Lena Trough. Dredge statistics from the expeditions ARK XV/2 (1999) and ARK XX/2 (2004) are shown as pie charts. Location of dredge PS66-256 is highlighted and total recovered mass is indicated. Projection is polar stereographic with scale 1:500,000. Modified after Snow & Petrology-Group-ARK-XX/2 (2007). Inset shows an overview map of the Arctic and North Atlantic oceans. The Lena Trough (indicated by arrows) is located between Greenland and Spitsbergen and connects the Knipovitch Ridge in the south (not labelled) with the Gakkel Ridge in the north.
on the western side of the rift (Snow et al., 2011). The Lena Trough is not strictly speaking ‘amagmatic’, as peridotites collected in this section are mostly residues of partial melt extraction (Hellebrand et al., 2004). It is likely that some melt production occurred beneath this segment, but that melt extraction was insufficient to produce an overlying basaltic crust (Snow et al., 2011). This is also in agreement with the widespread occurrence of plagioclase-bearing peridotites and other lithologies that show a significant amount of melt entrapment. Deep melt extraction occurred at the Lena Trough, with up to 6% melting in the stability field of garnet and up to 4% in the stability field of spinel (Hellebrand & Snow, 2003). These estimates agree with a deep onset of melting (~80 km depth) and the presence of a thick lithospheric lid that depresses the top of the melting column and limits melt production (e.g. White et al., 2001).

One important question that needs to be addressed is whether peridotites from the Lena Trough represent a part of unroofed SCLM influenced by the proximity to the Spitsbergen and Greenland continental margins. Recent studies of Os-isotopes in Lena Trough peridotites and rare gases from lavas show no contribution of SCLM (Lassiter & Snow, 2009; Nauret et al., 2010), whereas basalts from the CLT have anomalously K-rich enriched (E)-MORB compositions more similar to continental rift environments (Nauret et al., 2011) and western Gakkel Ridge lavas also show a contribution attributable to SCLM (Goldstein et al., 2008). Nevertheless, NLT basalts have an isotopic and trace element signature similar to normal (N)-MORB (Nauret et al., 2011) and the Lena Trough peridotites are similar to other abyssal peridotites, pointing to recent melt generation beneath the ridge (Hellebrand & Snow, 2003; Hellebrand et al., 2004).

**SAMPLING AND ANALYTIC METHODS**

**Sampling and sample selection**

Eight samples were chosen for this study; four of them are pyroxenites and four are harzburgites. All samples were collected in the dredge operation PS66-256 (Fig. 1) during the ARK XX/2 expedition of the RV Polarstern. The rocks were recovered in the central part of the ‘Lucky Ridge’ starting at 81°32’98”N, 3°34’39”W at a depth of 3374 m and ending at 81°32’98”N, 3°39’42”W at a depth of 3017 m.

Dredge PS66-256 recovered 139.3 kg peridotite and 2.2 kg gabbro (Snow & Petrology-Group-ARK-XX/2, 2007). Most of the peridotite samples are highly altered (~95%); only a few peridotites and pyroxenites have lower degrees of alteration. Based on on-board sample description, around 40% of the samples are plagioclase-bearing and around 12% are vein-bearing (gabbro and pyroxenite) peridotites (Snow & Petrology-Group-ARK-XX/2, 2007). Among the plagioclase-free peridotites, harzburgites and enstatite dunites are the dominant lithologies. The pyroxenites PS66-256-6 (plagioclase-bearing olivine websterite), PS66-256-7 (clinopyroxenite), PS66-256-19 (olivine websterite) and PS66-256-93 (orthopyroxenite) were selected for detailed investigation because of their low degree of alteration (~25%) and their representative mineralogy for the spectrum of pyroxenites. The harzburgites PS66-256-14, PS66-256-15, PS66-256-24 and PS66-256-64 were selected for comparison to supplement the data of Lena Trough peridotites from Hellebrand & Snow (2003).

**Modal analyses**

The four pyroxenite samples and the four peridotite samples were point counted to determine mineral modes under an optical microscope using a 200 μm x 200 μm grid. An olivine-free vein in PS66-256-19 was counted separately, as well as fine-grained interstitial areas in PS66-256-6 and PS66-256-93. Usually, if sufficient material was available, thin sections were counted with 5000–7500 points. Alteration was counted separately, but later re-integrated with the primary modes. This was facilitated because of distinctive pseudomorphous alteration textures in peridotitic and pyroxenitic rocks (i.e. serpentine mesh structure after olivine, bastite pseudomorphs after pyroxenes) (see also Hellebrand & Snow, 2003). Additionally, limited alteration that is mostly confined to cracks within the minerals allowed the discrimination between altered orthopyroxene and clinopyroxene.

Mineral modes from point counting were double checked by image analyses, using a Java-based image-processing program (ImageJ). First, sketches of thin sections were drawn showing minerals and grain boundaries from thin-section scans supplemented by back-scattered electron (BSE) images (Fig. 2). The drawing was monitored with simultaneous optical microscopy. Second, minerals in the sketches were color-coded. Third, mineral abundances were determined using ImageJ and a self-built plugin. For areas with small grains, such as interstitial silicate assemblages in PS66-256-6 or PS66-256-93, a mineral ratio was calculated for without limitations and from cracks in the altered minerals allowed the discrimination between altered orthopyroxene and clinopyroxene.

**EPMA, SIMS and LA-ICP-MS analyses**

Major and minor element compositions of silicate phases and spinels were determined in situ by electron probe microanalysis (EPMA) on polished thin sections by wavelength-dispersive spectroscopy using a Cameca SX 100 electron probe microanalyzer at the University of Freiburg and a Jeol Superprobe 8900 at the University of Mainz. For pyroxenes and plagioclase an accelerating voltage of
Fig. 2. Sketches of thin sections of pyroxenites from the Lena Trough. BSE images and thin-section scans (plane-polarized and crossed Nicols) were used as templates. The drawing was monitored with simultaneous microscopy.
were 49% for each element; averages for the pyroxenite samples and orthopyroxene, respectively. Positive secondary ions with an accelerating potential of 12 kV were used. Negative oxygen ions were used as primary ions in a peak jumping mode. Each measurement consisted of a six-cycle routine. For clinopyroxene, REE were measured in each cycle for 60 s, except Er and Yb for 40 s, Sr, Y, Zr and Ti for 15 s, K and Sc for 5 s, and the remaining elements for 1 s. For orthopyroxene, REE were measured for 60 s, Zr, Sr and Y for 20 s, Ti for 15 s, Sc for 5 s, and the remaining elements for 1 s. For plagioclase, REE were measured for 60 s, except Zr and Y for 30 s, Ba for 20 s, Sr and Ti for 15 s, Sc for 5 s, and the remaining elements for 1 s. Si was used as a reference mass, as the SiO₂ concentrations from the corresponding electron microprobe analyses are known (measured at the same spot). To reduce molecular interferences, a high-energy offset of ~80 eV was applied. Two MPI-DING reference glasses (GOR132-G and KL2-G; Jochum et al., 2000) were used as standards to obtain sensitivity factors for the correction of the measurements. Oxide interferences on Eu, Gd, Dy, Er and Yb were corrected offline. More information on the analytical conditions has been given by Hellebrand et al. (2002, 2005).

LA-ICPMS analyses were carried out at the Department of Geosciences, University of Bremen, using a New-Wave UP193ss laser (193 nm wavelength) coupled to a ThermoFinnigan Element2. Analytical conditions included a laser pulse rate of 3 Hz, irradiance of 1 GWcm⁻², and a spot size between 50 and 75 μm. Helium (89 l min⁻¹) was used as sample gas and argon (0.681 min⁻¹) was subsequently added as make-up gas; plasma power was 1200 W. The ThO/Th ratio determined on NIST 612 glass was <0.1%. All isotopes were analysed at low resolution with five samples in a 20% mass window and a total dwell time of 25 ms per isotope. Blanks were measured for 20 s prior to ablation.

For every 8-13 data points the NIST 612 and 610 glasses were analysed as external calibration standards using the values of Jochum et al. (2011). For data quantification the Cetac GeoPro™ software was used with Ca as internal standard for clinopyroxene and plagioclase and Mg for orthopyroxene. Data quality was assessed by BHVO2G glass analysed along with the samples. Analytical precision is better than 5% for most elements and generally <1%; accuracy is better than 10% except for Y (up to 12%) (for standard measurements, see Electronic Appendix C-4).

Trace element concentrations obtained by both methods, SIMS and LA-ICP-MS, show good agreement within analytical errors. Therefore, their combined averages are given for each sample.

PETROGRAPHY

Pyroxenites

The pyroxene-rich samples (PS66-256-6, pyroxenite part of PS66-256-7, PS66-256-19 and PS66-256-93) are all pyroxenites with variable olivine contents and orthopyroxene-clinopyroxene ratios. The degree of alteration extends for all pyroxenites to ~34 vol. %. Owing to the small sample sizes, no contact relationships between pyroxenites and wallrock could be recovered, except for sample
PS66-267-7 where clinopyroxene is in contact with dunite. Sketches of the thin sections are shown in Fig. 2. Modal analyses are shown in Fig. 3 and reported in the Electronic Appendix A. A summary of the mineralogy and important characteristics is given in Table 1.

The plagioclase-bearing olivine websterite PS66-256-6 consists of olivine (ol), orthopyroxene (opx), clinopyroxene (cpx), spinel (sp), plagioclase (pl) and serpentine group minerals, as well as chlorite as a secondary alteration phase. Optically clear ol grains are preserved as small relics surrounded by mesh-textured serpentine and exhibit limited solid-state deformation microstructures (undulose extinction and pronounced deformation bands); they lack any preferred crystallographic orientation (Fig. 4a), similar to ol in the associated harzburgites. Pyroxenes show undulose extinction and exsolution lamellae that can be slightly bent. Coarse-grained clinopyroxenes are irregular, indicating mobilization of grain boundaries and even breakup (Fig. 4b and c). A fine-grained (<300 μm) cpx–opx–pl assemblage in the ratio 43:40:15 occurs across the entire thin section between the coarse-grained crystals (Fig. 4d, e and f). Spinel occurs as up to 1 mm, brown, anhedral crystals and is usually associated with olivine. Commonly spinels have coronae of plagioclase.

The olivine websterite PS66-256-19 shows the lowest degree of alteration compared with the other pyroxenites, thus preserving primary microtextures best. It is composed of ol, opx, cpx, sp and trace levels of sulfides (mostly pentlandite) and comprises an olivine-free websterite vein with a width of ~1 cm, indicating modal heterogeneity on a thin-section scale. However, even areas outside the vein have highly elevated pyroxene contents compared with peridotite samples. Similar to the plagioclase-bearing olivine websterite PS66-256-6 and the harzburgites, optically clean olivine occurs as fine-grained relics surrounded by serpentine-group minerals (Fig. 5a), with deformation bands and undulose extinction present within some of the grains (Fig. 5b). In general, ol is often vermicular in shape and associated with opx or surrounded by interstitial opx and cpx (Fig. 5a, e and f). Opx and cpx both show undulose extinction and exsolution lamellae with kink bands. Grain sizes differ inside and outside the vein, whereby pyroxenes generally tend to be smaller in grain size within the vein (~1–2 mm). Interfingering of opx and cpx as well as lobate grain boundaries are commonly observed within the vein (Fig. 5d). The grain-size distribution outside the vein is bimodal, with large opx and cpx grains (up to 6 mm) and fine-grained areas (as low as 50 μm; Fig. 5c). Spinel is fine-grained and commonly associated with olivine.

Sample PS66-256-7 is composed of clinopyroxenite in contact with dunite. The contact between the two lithologies appears to be sharp in hand specimen. However, a clear boundary cannot be recognized on thin-section scale owing to the advanced degree of alteration. The dunite part is almost entirely composed of mesh-textured serpentine and up to ~1 mm large anhedral spinels. No optically clear, fresh ol grains are present. In the clinopyroxenite, which is composed of cpx, opx and sp, the clinopyroxenes range in size from several micrometers to several millimeters. Grain boundaries of cpx are irregular (Fig. 6a), similar to clinopyroxenes from the plagioclase-bearing olivine websterite PS66-256-6. Smaller cpx grains often occur in clusters, which also show an elevated abundance of spinel. Spinel is brown and anhedral and often contains cpx inclusions. Spinel from dunite and clinopyroxenite do not differ optically and form continuous clusters. Orthopyroxene is rare and forms fine-grained crystals between the clinopyroxenes, as well as exsolution lamellae in cpx (Fig. 6b). Serpentine group minerals, chlorite and calcite are alteration products, and wide calcite veins cut through the whole sample.

The overall modal composition of orthopyroxenite PS66-256-93 makes it formally an olivine norite (IUGS nomenclature) because of the high amount of interstitial plagioclase (more than 5 vol. %). However, a detailed investigation of the textures suggests two different lithologies in this sample, one of them an orthopyroxenite with
orthopyroxene grains of various sizes and shapes. The degree of alteration is moderate (~50%), leading to the formation of a typical mantle fabric characterized by the destruction of olivine and its replacement by serpentine and plagioclase. The large opx grains show undulose extinction and poikilitic pods that resemble reaction textures. The large opx grains show undulose extinction and poikilitic pods that resemble reaction textures. The large opx grains show undulose extinction and poikilitic pods that resemble reaction textures. The large opx grains show undulose extinction and poikilitic pods that resemble reaction textures. The large opx grains show undulose extinction and poikilitic pods that resemble reaction textures. The large opx grains show undulose extinction and poikilitic pods that resemble reaction textures.

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<th>Clinopyroxenite</th>
<th>Olivine websterite</th>
<th>Orthopyroxenite</th>
<th>Harzburgites</th>
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<td>PS66-256-6</td>
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<td>Specific features:</td>
<td>interst. cpx-opx-pl</td>
<td>wallrock: dunite</td>
<td>interst. ol-pl-opx</td>
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**Table 1: Summary of the mineralogy and important characteristics of Lena Trough pyroxenites and harzburgites**

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**Peridotites**

Four harzburgites (PS66-256-14, PS66-256-15, PS66-256-24 and PS66-256-64) from the same dredge were analyzed for comparison. Their degree of alteration extends to ~70 vol. %.

Peridotites from dredge PS66-256 are spinel harzburgites with <2 vol. % cpx and show porphyroclastic textures, similar to other harzburgites dredged from the Lena Trough (Hellebrand & Snow, 2003). Serpentine mesh structure after olivine pervades most of the samples and only a few optically clear olivine grains can be observed. Within these grains, undulose extinction and deformation...
Fig. 4. Plagioclase-bearing olivine websterite (PS66-256-6) microtextures. (a) Olivine grain showing deformation bands. (b) Clinopyroxene with exsolution lamellae indicating breakup in two grains, surrounded by an interstitial cpx-opx-pl assemblage. (c) Clinopyroxenes in the interstitial assemblage. Cpx grains have similar appearance and optical orientation and therefore most probably originated from a coarse-grained clinopyroxene. (d) Orthopyroxene and plagioclase surrounded by clinopyroxene (BSE image). (e, f) Sketches of the interstitial cpx-opx-pl assemblage between coarse-grained clinopyroxenes (dark grey). Plagioclase seems to be the last phase to form after opx (light grey) and cpx (intermediate grey). Sketches were drawn using BSE images as templates. Photomicrographs were taken under crossed Nicols.
Fig. 5. Olivine websterite (PS66-256-19) microtextures. (a) Vermicular olivine between coarse-grained orthopyroxenes and small clinopyroxene ‘drops’. (b) Deformation bands in partly serpentinized olivine. (c) Coarse-grained clinopyroxene surrounded by clino- and orthopyroxene (outside the vein). (d) Typical cumulate texture within the vein with interfingering clino- and orthopyroxene. (e, f) Sketches showing vermicular olivine between orthopyroxene and clinopyroxene. Spinel (black) is commonly associated with olivine. These textures indicate dissolution of olivine. Sketches were drawn using BSE images as templates. Photomicrographs were taken under crossed Nicols.
bands are present, pointing to solid-state deformation. Opx forms porphyroclasts with various sizes up to 7 mm. Cpx is rare and shows undulose extinction. Both pyroxenes show exsolution lamellae of the complementary pyroxene. Light brown holly-leaf shaped spinel is disseminated throughout the harzburgites.

**RESULTS**

**Major elements**

Major and minor element compositions of minerals are reported in Electronic Appendix B (Table B-1: olivine; Table B-2: clinopyroxene; Table B-3: orthopyroxene; Table B-4: spinel; Table B-5: plagioclase). Table 1 summarizes the important major element characteristics.

**Olivine**

Olivine major and minor element compositions show variations between and partly within the pyroxenites (PS66-256-6, PS66-256-19 and PS66-256-93), but variations also exist compared with the harzburgites (PS66-256-14 and PS66-256-64). Olivine in the harzburgites has a high forsterite content ranging from 90·4 to 91·4, whereas the pyroxenites have lower contents ranging from 89·3 to 90·8 (Fig. 7a). NiO and MnO concentrations measured with HCMA are lower or similar for the harzburgites compared with pyroxenites, ranging from 0·374 to 0·404 wt % for NiO and from 0·127 to 0·142 wt % for MnO. For the pyroxenites, NiO ranges from 0·376 to 0·447 wt % and MnO from 0·119 to 0·173 wt %. To directly compare these minor elements and remove the effect of changing partition coefficients for Ni and Mn concentrations with the Mg content of the olivine (Hart & Davis, 1978), we normalized Ni concentrations to the ratio of \((\text{Mg}/\text{Fe}) \times 1000\) (in ppm) and Mn concentrations to \(100 \times \text{Fe}\) (in ppm) of the single measurement (Fig. 7b), similar to Sobolev et al. (2007). In the following discussion, normalized minor elements are designated as element

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**Fig. 6.** Clinopyroxenite PS66-256-7 (a, b) and orthopyroxenite PS66-256-93 (c, d) microtextures. (a) Large clinopyroxene grain with irregular grain boundaries surrounded by fine-grained opx and sp. (b) Orthopyroxene and spinel granular aggregates within large clinopyroxene grain (BSE image). (c) Plagioclase poikilitic pods within large orthopyroxene. (d) Highly altered interstitial ol-pl-opx assemblage in contact with large orthopyroxenes with deeply corroded grain boundaries (highlighted). Photomicrographs were taken under crossed Nicols.
The results reveal higher Ni_{norm} concentrations in the pyroxenites than in the Lena Trough harzburgites, even for olivine websterite PS66-256-19, which has similar absolute NiO concentrations to the harzburgites. In the plagioclase-bearing olivine websterite PS66-256-6, a microstructural link with NiO and MnO concentrations can be observed, indicating higher NiO and lower MnO concentrations in areas with low olivine abundances. This correlation is also observed in olivine websterite PS66-256-19, although much less pronounced.

No correlations between our data and the data from previous studies of abyssal peridotites and pyroxenites are observed in minor elements, but the lack of high-precision minor element data from abyssal peridotites and pyroxenites available to date inhibits direct comparison and correlations might simply not be visible owing to the lower precision of previous measurements.

**Clinopyroxene**

Clinopyroxene was analysed in plagioclase-bearing olivine websterite PS66-256-6, olivine websterite PS66-256-19, clinopyroxenite PS66-256-7 (no cpx was observed in orthopyroxenite PS66-256-93) and in two harzburgites (PS66-256-15 and PS66-256-24). Overall, the pyroxenites and peridotites from the Lena Trough fall within the compositional range of global pyroxenites and peridotites for most major and minor elements (Fig. 7a and b). The notable exception is Na$_2$O, for which the Lena Trough samples show generally elevated concentrations. Sodium in cpx can reach as much as 1.72 wt % in CLT peridotites (not shown; Hellebrand & Snow, 2003), whereas three of the four pyroxenites and the associated harzburgites are in the range of 0.47–0.8 wt % Na$_2$O and pl–ol-websterite 0.29–0.56 wt %.

Clinopyroxenes in pyroxenites show large variation in composition in each sample (e.g. Mg-number in the range of 89.4–93.3), whereas harzburgites show a more restricted composition, but overlap in range (e.g. Mg-number 91–93.5). The same is observed for Al$_2$O$_3$ contents, which show a broad negative correlation with Mg-number on a sample scale (Fig. 8a). No systematic correlation with microtexture is observed in either pyroxenites or harzburgites, with the exception of plagioclase-bearing olivine websterite PS66-256-6. Here, coarse-grained clinopyroxenes show concentric zoning with decreasing concentrations of Al$_2$O$_3$ and Na$_2$O, and increasing Mg-number towards the rims (Fig. 8a and b). TiO$_2$ behaves differently, as it first increases with little change in Cr-number, followed by a decrease during rising Cr-number (not shown). In addition, clinopyroxenes from the interstitial cpx–opx–pl assemblage are compositionally similar to the rims of the coarse-grained clinopyroxenes (Fig. 8a and b).

Clinopyroxene inclusions in spinel from PS66-256-7 have distinctly different major element concentrations relative to coarse-grained clinopyroxenes in this sample. They have higher Mg-numbers ranging from 92.4 to 94.1 (Fig. 8c) and lower Al$_2$O$_3$ (2.2–3.4 wt %) and Na$_2$O concentrations (0.22–0.47 wt %) (Fig. 8d). They also differ in terms of their CaO and SiO$_2$ contents which, together with Na$_2$O, should not be affected by subsolidus equilibration with the host spinel. The cpx inclusions resemble in their major element characteristics those in highly refractory harzburgites.
found at the Mid-Atlantic Ridge (Seyler et al., 2007) (Fig. 8c and d). They also are similar to refractory harzburgites from the CLT, except that these have higher Na$_2$O contents which have been attributed to a late, post-melting, sodic metasomatism event by Hellebrand & Snow (2003).

**Orthopyroxene**

Orthopyroxene was analysed in all the selected pyroxenites and harzburgites from dredge haul PS66-256. Its composition falls within the range of abyssal peridotites and pyroxenites. Whereas harzburgites from the same dredge...
show a narrow range in major element compositions, the pyroxenites are characterized by distinct variations in certain elements similar to what has been observed for clinopyroxene.

The pyroxenites extend to lower Mg-numbers (88-2-910) whereas the harzburgites have Mg-numbers ranging from 90-2 to 914 (Fig. 9a). This range of variation can occur for pyroxenites within a given sample, whereas single harzburgites are more homogeneous. The pyroxenites and harzburgites have low TiO$_2$ concentrations of around 0-40 wt %, with the exception of orthopyroxenite PS66-256-93 where TiO$_2$ can reach as much as 0-29 wt % (Fig. 9a). Cr$_2$O$_3$ is variable for pyroxenites and harzburgites, ranging from 0-29 to 1-08 wt % (Fig. 9b). Pyroxenites show large within-sample variation in Al$_2$O$_3$ that almost spans the range seen in abyssal peridotites, with highest concentrations (up to 6-6 wt %) observed in coarse-grained orthopyroxene cores in PS66-256-6 (Fig. 9b).

Major element concentrations vary systematically within and between coarse- and fine-grained interstitial orthopyroxenes only in orthopyroxenite PS66-256-93 and olivine websterite PS66-256-6. Both samples show core-rim zonation with decreasing Al$_2$O$_3$ in PS66-256-6 towards the rim (Fig. 9c and d) and decreasing Al$_2$O$_3$ and Cr$_2$O$_3$ concentrations in interstitial orthopyroxenes in PS66-256-93 (Fig. 9d).

**Spinel**

Spinel was analysed in all selected pyroxenites and in three harzburgites (PS66-256-15, PS66-256-24 and PS66-256-64) (Fig. 10). Major and minor elements in spinel are highly variable in the Lena Trough pyroxenites, except for olivine websterite (PS66-256-19), which shows little variation and plots generally close to harzburgites from the same dredge and other peridotites from the Lena Trough (Fig. 10a). In general, abyssal pyroxenites are shifted towards lower Mg-number at a given Cr-number relative to peridotites. This is most notable for the plagioclase-bearing pyroxenites at high Mg-number and Cr-number, something that can be also observed in plagioclase-bearing peridotites (Fig. 10a). The harzburgites, on the other hand, have Mg-numbers ranging from 69 to 75, similar to the olivine websterite PS66-256-19 and other peridotites from the Lena Trough (Hellebrand & Snow, 2003).

Two samples appear to contain two populations of spinel. Plagioclase-bearing olivine websterite PS66-256-6 shows two data populations, between which a compositional gap is visible in otherwise continuous trends for major and minor elements, which cannot be related to microtextural features. On the other hand, spinels in clinopyroxenite PS66-256-7 exhibit two compositional trends depending on the lithology in which they occur (dunitic versus clinopyroxenite), although they are optically identical and similar in some minor elements. Differences between the two lithologies are also seen in other elements, especially in ZnO (not shown). TiO$_2$ concentrations are variable except for olivine websterite PS66-256-19, which has concentrations similar to peridotites (Fig. 10b). PS66-256-6 and PS66-256-7 show a broad positive correlation between TiO$_2$ and Cr-number; there is a higher variability at a comparatively more restricted Cr-number in the orthopyroxenite, which also shows highest concentrations (up to 0-38 wt %).

**Plagioclase**

Plagioclase is mostly found as part of a fine-grained ol-pl-opx assemblage in orthopyroxenite PS66-256-93 and also occurs in low abundances in the fine-grained cpx-opx-pl assemblage in plagioclase-bearing olivine websterite PS66-256-6.

PS66-256-93 has a restricted range of calcic plagioclase compositions, ranging from An72 mol % to An82 mol %, with an average around An76 mol %. PS66-256-6 has more Ca-rich plagioclase with an average around An90 mol % and higher FeO$_{tot}$ contents with up to 0-28 wt %. Comparable plagioclase analyses in abyssal pyroxenites are scarce and until now, only Warren et al. (2009) and Dick et al. (2010) have measured plagioclase in abyssal pyroxenite veins. Their An content is variable and ranges from An60 mol. % to An90 mol. %.

**Trace elements**

Trace element concentrations of clinopyroxene, orthopyroxene and plagioclase are reported in Electronic Appendix C (Table C-1: clinopyroxene; Table C-2: orthopyroxene; Table C-3: plagioclase). Sample averages are shown in Table 2.

**Clinopyroxene**

Clinopyroxene trace element concentrations were measured in all cpx-bearing pyroxenites (PS66-256-6, PS66-256-7 and PS66-256-19) and two harzburgites (PS66-256-24 and PS66-256-64). Trace element patterns for the pyroxenites show no variations on a thin-section scale and sample averages are used (Fig. 11a and b). Overall, the Lena Trough pyroxenites show light REE (LREE)-depleted cpx patterns similar to abyssal peridotites; however, only five studies on abyssal pyroxenites to date have reported cpx trace element concentrations (Hellebrand et al., 2005; Arai & Takemoto, 2007; Dantas et al., 2007; Warren et al., 2009; Seyler et al., 2011). The pyroxenites all have cpx REE patterns with depletion in LREE relative to heavy REE (HREE), although absolute concentrations differ. In the following discussion subscript N denotes CI-chondrite normalized concentrations with chondrite values taken from Anders & Grevesse (1989).

Clinopyroxene PS66-256-7 and olivine websterite PS66-256-19 show similar cpx REE and trace element patterns, with slight depletion in LREE [(La/Yb)$_N$ 0.147 at (Yb)$_N$ 6.88 for PS66-256-7; (La/Yb)$_N$ 0.42 at (Yb)$_N$ 7.41 for PS66-256-19] and resemble clinopyroxene in
equilibrium with an N-MORB melt (Klein, 2004). PS66-256-6 is more depleted in LREE with (La/Yb)$_N$ 0.004 at (Yb)$_N$ 10.36, similar to the harzburgites. A negative Sr-anomaly indicates limited reaction with interstitial plagioclase. Harzburgites PS66-256-24 and PS66-256-64 have LREE-depleted cpx patterns with (La/Yb)$_N$ 0.002 at (Yb)$_N$ 6.76 and (La/Yb)$_N$ 0.014 at (Yb)$_N$ 9.15, respectively. All pyroxenites and the harzburgite have negative Ti and Zr anomalies, typical for clinopyroxenes from mantle peridotites (Rampone et al., 1991).

**Orthopyroxene**

Orthopyroxene trace element concentrations were measured in all the studied pyroxenites (PS66-256-6, 256-93, 256-6, and 256-14). Major element composition of orthopyroxene is presented in Figure 9. Orthopyroxenite (PS66-256-93) has high TiO$_2$ relative to other pyroxenites and harzburgites from the Lena Trough. Core of the coarse-grained orthopyroxenes have higher Al$_2$O$_3$ concentrations relative to their rims and cpx in the interstitial cpx-opx-pl assemblage. Compositional variation is common to both plagioclase-bearing samples (PS66-256-6 and PS66-256-93) with the lowest Al$_2$O$_3$ concentrations in the interstitial assemblage and orthopyroxenite (PS66-256-93), with large orthopyroxenes having high Al$_2$O$_3$ concentrations in the cores, decreasing to the rims. Orthopyroxenes from the interstitial ol-pl-opx assemblage have the lowest Al$_2$O$_3$ concentrations. It should be noted that compositional variation is common to both plagioclase-bearing samples (PS66-256-6 and PS66-256-93) with the lowest Al$_2$O$_3$ concentrations in the interstitial assemblage (see Fig. 8). For harzburgites, only sample averages are shown. Compositional fields in grey as in Fig. 8.
PS66-256-7, PS66-256-19 and PS66-256-93) and in two harzburgites (PS66-256-14 and PS66-256-64). As observed for cpx trace element concentrations, no variations on thin-section scale are present in opx and sample averages are shown for illustration (Fig. 11c and d).

Pyroxenites and harzburgites show similar patterns with a weak depletion in LREE and typical positive Ti and Zr anomalies in opx (Rampone et al., 1991). Orthopyroxenite PS66-256-93 has slightly more elevated LREE compared with the other pyroxenites and pronounced negative Sr and Eu anomalies. These anomalies suggest equilibration with plagioclase, which occurs in the interstitial assemblage of the sample.

**Plagioclase**

Plagioclase trace element concentrations were measured in PS66-256-6 and PS66-256-93 (Fig. 11e and f). Plagioclase in orthopyroxenite (PS66-256-93) has higher trace element concentrations compared with plagioclase-bearing olivine websterite (PS66-256-6). Both samples show strong positive Eu and Sr anomalies. Calculated equilibrium melts [partition coefficients for cpx and opx after Kelemen et al. (2004) and pl calculated after Bedard (2006)] indicate no equilibrium between interstitial pl and opx/cpx in PS66-256-6, whereas interstitial pl in PS66-256-93 is in equilibrium with opx. Plagioclase in the latter sample has high LREE concentrations at about 5 × CI, similar to a plagioclase of An80 (mol %) in equilibrium with N-MORB (Klein, 2004).

**DISCUSSION**

**Lena Trough pyroxenites: products of assimilation–fractional crystallization (AFC)**

A combined fractional crystallization and wall-rock assimilation (i.e. melt–rock reaction) formation process successfully accounts for the textural, major, minor and trace element systematics of the Lena Trough pyroxenites. Interaction between migrating melt and wall-rock peridotite has often been described in mid-ocean ridge settings (e.g. Kelemen et al., 1992, 1995a, 1995b, 1997, 1998; Dijkstra et al., 2003), although formation of dunites rather than pyroxenites is commonly observed.

The Lena Trough pyroxenites show several indicators for melt–rock reaction. In particular, microtextures such as undeformed vermicular and interstitial orthopyroxene and/or clinopyroxene in contact with olivine or cpx–opx–sp aggregates have been related to pervasive melt–rock reactions leading to refertilization of peridotites (Kaczmarek & Muntener, 2008; Suhr et al., 2008; Soustelle et al., 2009). Equivalent textures are observed in the olivine websterites (PS66-256-6 and PS66-256-19), where olivine is often vermicular in shape and associated with orthopyroxene or surrounded by interstitial orthopyroxene and clinopyroxene. Narrow deformation bands in olivine, commonly associated with deformation during asthenospheric flow, are indicators for its residual origin, whereas pyroxenes do not show comparable deformation microtextures.
### Table 2: Averages of trace element concentrations for clinopyroxene, orthopyroxene and plagioclase from pyroxenites and harzburgites (in ppm)

<table>
<thead>
<tr>
<th>Sample:</th>
<th>Clinopyroxene</th>
<th>Orthopyroxene</th>
<th>Plagioclase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology:</td>
<td>Ol-web</td>
<td>Cpxite</td>
<td>Ol-web</td>
</tr>
<tr>
<td>n:</td>
<td>16</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>Na</td>
<td>2963</td>
<td>4649</td>
<td>4171</td>
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</tr>
<tr>
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<td>10</td>
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</tr>
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</tr>
<tr>
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<td>0.2</td>
</tr>
<tr>
<td>Ce</td>
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<td>1.2</td>
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</tr>
<tr>
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<td>0.23</td>
</tr>
<tr>
<td>Nd</td>
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</tr>
<tr>
<td>Sm</td>
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<td>0.98</td>
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</tr>
<tr>
<td>Eu</td>
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<td>0.38</td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>Er</td>
<td>1.88</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>1.11</td>
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</tr>
<tr>
<td>Lu</td>
<td>0.32</td>
<td>0.17</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Ol-web, olivine websterite; Cpxite, clinopyroxenite; Opxite, orthopyroxenite. n, number of analyses; n.m., not measured; empty values, below detection limit.
Fig. 11. Chondrite-normalized REE and trace element patterns of clinopyroxene (a, b), orthopyroxene (c, d) and plagioclase (e, f). Patterns for cpx, opx and plagioclase in equilibrium with Mid-Atlantic Ridge N-MORB (Klein, 2004), and cpx and opx in harzburgites from the same location (PS66-256-14, PS66-256-24 and PS66-256-64) are shown for comparison. The compositional field of Lena Trough peridotites (dark grey) is shown [N-shaped pattern from Hellebrand & Snow (2003) and Hellebrand et al. (2004)]. Light grey field is the field of abyssal peridotite (AP) compositions (Johnson et al., 1990). Chondrite normalization values are from Anders & Grevesse (1989).
Frequent occurrence of spinel with olivine and cpx inclusions suggests dominantly a residual origin for spinel as well. Hence, we interpret olivine and spinel as derived from a precursor peridotite. Clinopyroxene inclusions in spinel from clinopyroxenite PS66-256-7 provide important compositional information on this precursor mantle rock (see discussion below). Additionally, relatively lesser deformation and cumulative textures are observed in all pyroxenites. In the websteritic vein in PS66-256-19 clinopyroxene and orthopyroxene of similar size show interfingering grains, indicating simultaneous crystallization of the two pyroxenites. Likewise, clinopyroxene clusters formed in clinopyroxenite PS66-256-7 and orthopyroxene grain sizes (~1 cm) in orthopyroxenite PS66-256-93 support a magmatic origin. Comparable features are not observed in the associated harzburgites. This also precludes the possibility that Lena Trough pyroxenites represent subducted crust, where an equal level of deformation and equilibrated textures would be expected for all mineral phases from their shared tectonic history.

Instead, combined textural observations point to two possible reactions involved in the formation of the Lena Trough pyroxenites:

\[ \text{liq.}1\text{a} + \text{olivine} \rightarrow \text{orthopyroxene} + \text{liq.}2\text{a} \]  
\[ \text{liq.}1\text{b} + \text{olivine} \rightarrow \text{orthopyroxene} + \text{clinopyroxene} + \text{liq.}2\text{b}. \]

The most commonly described type of melt-rock reaction in the shallow oceanic mantle is widely believed to involve dissolution of pyroxene and precipitation of olivine (Kelemen et al., 1997, and references therein), in contrast to reactions (1) and (2). Melt-rock reaction that results in olivine dissolution and formation of orthopyroxene [reaction (1)] has been reported from Archean cratons (Kelemen et al., 1998), whereas production of both ortho- and clinopyroxenes (± aluminous phase) [see reaction (2)] has been described in the subcontinental mantle of various orogenic massifs (Garrido & Bodinier, 1999; Le Roux et al., 2007; Bodinier et al., 2008; Soustelle et al., 2009). In the latter case, pervasive refertilization produced secondary lherzolite after harzburgite and, eventually, pyroxenite during channelized melt flow at pressure and temperature conditions close to the peridotite solidus (Burg et al., 1998; Garrido & Bodinier, 1999; Le Roux et al., 2007; Bodinier et al., 2008; Dantas et al., 2009). Although such pyroxene-forming reactions are more frequently observed in subcontinental mantle, they play an important role in the formation of the Lena Trough pyroxenites.

**Extent of assimilation and composition of the protolith**

The quantification of the melt/rock ratio and the proportion of assimilation to crystallization involves various parameters such as changes in modal abundances or mineral trace element composition. For example, the melt/rock ratio involved in reactions (1) and (2) can be estimated by the abundance of olivine still present (Garrido & Bodinier, 1999). Olivine-rich pyroxenites would indicate a moderate melt/rock ratio, whereas olivine-free websterites represent the final reaction products at high melt/rock ratios. Based on this qualitative observation, the Lena Trough pyroxenites would imply high to very high melt/rock ratios.

In addition to changes in modal composition, changes in Mg-number in olivine and pyroxene are thought to be an indicator for refertilization reactions, as the Mg-number should decrease with increasing refertilization. Bodinier et al. (2008) measured a change in olivine Fo content from 83 to 89 from lherzolites to olivine-free websterites in the orogenic peridotite massif of Roda (southern Spain). Such a decrease in forsterite content suggests that the percolating melt underwent substantial fractional crystallization, oligine dissolution was limited and the melt/rock ratio was high (Bodinier et al., 2008). The Lena Trough pyroxenite samples have only slightly lower Fo contents than harzburgites from the same dredge haul (Fo contents from 89 to 90-4 from the pyroxenites and from 90-4 to 91-4 for the harzburgites). The lack of substantial chemical gradients could indicate reaction with either a primitive melt at variable melt/rock ratios or an evolved melt at very low melt/rock ratios. In addition, buffering of Mg-Fe by the peridotite wall-rock may have played an important role in illuminating contrasts in Mg-number between pyroxenites and mantle rocks (Dick & Bullen, 1984). On the one hand, these divalent cations show fast diffusion in olivine at near-solidus conditions (Ozawa, 1984; Liernier & Ganguly, 2003; Petry et al., 2004) and minerals crystallizing deep in the mantle should have a sufficiently long residence time to equilibrate with the surrounding mantle. On the other hand, equilibrium between melt and refractory mantle may have already occurred during percolation (Vernieres et al., 1997; Suhr et al., 1998). The absence of pronounced gradients in Mg-number between the Lena Trough pyroxenites and harzburgites could be therefore related to any of these processes and this inhibits exploration of the degree of refertilization through this parameter.

Trace or minor element variations may provide a better opportunity to determine the amount of assimilation versus crystallization. Models based on incompatible elements have a low sensitivity to discriminate between AFC and fractional crystallization alone if only olivine is assimilated, as its incompatible trace element concentrations are orders of magnitude lower relative to those of melts (De Hoog et al., 2010). Therefore, the trace element composition of pyroxenes produced by AFC between peridotite and percolating melt will be dominated by the composition of the melt up to a very high assimilation ratio.
Instead, a compatible trace element in olivine such as NiO is expected to react sensitively to olivine assimilation and hence the proportion of crystallization relative to assimilation. Indeed, Kelemen et al. (1998) have shown that Ni in olivine is positively correlated with orthopyroxene and negatively with olivine modal abundances in cratonic peridotites. This led them to conclude that addition of melt SiO$_2$ to harzburgites produces an orthopyroxene-rich mantle rock according to reaction (1). Experimental investigation of the olivine to opx transformation has revealed that a Ni-rich reaction front forms that may result in Ni-rich opx and olivine when substantial SiO$_2$ metasomatism occurs (Milke et al., 2011). In the experiment a two-fold Ni enrichment occurred within a 2 µm wide zone ahead of the replacement front.

To quantify the importance of assimilation in the origin of the Lena Trough pyroxenites we calculated a simple model that explores the effect of replacement of olivine by opx and cpx on olivine Ni content (Fig. 12). This model can be applied to only the olivine websterites (PS66-256-6 and PS66-256-19), as no fresh olivine was present in the clinopyroxenite PS66-256-7 and olivine in the interstitial assemblage in the orthopyroxenite PS66-256-93 is interpreted as late magmatic, as discussed below.

For this model, starting mineral abundances and Ni concentrations in olivine were based on fertile [depleted MORB mantle (DMM) from Workman & Hart (2005)] and representative depleted mantle compositions (harzburgite from the same dredge haul, PS66-256-14) (modeling parameters can be found in Electronic Appendix D). We assumed that replacement of olivine by pyroxene proceeded in equal proportions to explore an end-member case of this process. For this reason, we also assumed that the melt was Ni free. Pathways for both reactions (1) and (2) were calculated, but are very similar because of comparable partition coefficients for Ni in both pyroxenes (Kelemen et al., 2004). Therefore, only reaction (1) is shown in Fig. 12. Reaction (1) was also investigated by Kelemen et al. (1998) by solving a system of non-linear equations with an iterative least-squares minimization routine and a not further specified silica-rich melt composition. Their results are similar to ours.

We can show with our simple model that assimilation with concomitant pyroxene formation would result in increasing Ni contents in residual olivine, as also predicted by previous models and described from cratonic peridotites (Kelemen et al., 1998) and experiments (Milke et al., 2011) (Fig. 12). Regarding the Lena Trough pyroxenites, the most important outcome of this model is that a substantial amount of pyroxene must have formed by crystallization.

Although an adequate match of the model curve with olivine websterite PS66-256-6 can be achieved, this is possible only if a fertile DMM-like peridotite was the starting composition. The olivine websterite PS66-256-19 has an
even lower olivine NiO content and cannot be modelled successfully by this set of parameters.

Despite the match for PS66-256-6, all the evidence points to a rather refractory harzburgite as the most likely precursor; specifically, the dominance of enstatite dunities and harzburgites and the near-absence of lherzolites in the regional geology, as well as the very refractory composition of the spinel inclusions in PS66-256-7. In the latter case, whereas the high Mg-number and low Al₂O₃ content in the clinopyroxene inclusions may reflect their late subsolidus equilibration with the host spinel, their very low Na₂O content is unlikely to be modified by partitioning with spinel. This suggests that the pyroxenite precursor was even more refractory than the associated harzburgites and similar to MARK peridotites (Seyler et al., 2007).

If the observed pyroxenite Ni contents were produced by melt–rock reaction alone from such a refractory harzburgitic protolith, the starting Ni contents must either have been much lower (in the range 2000–2500 ppm, lower than what is observed in the Lena Trough peridotites) or modified during cooling. A different, Ni-containing melt composition would only aggravate this mismatch by further increasing the bulk Ni contents.

Subsolidus modification of the Ni content in olivine through exchange with the pyroxenitic phases would also further increase concentrations relative to their magmatic values (Witt-Eickschen & O'Neill, 2005) because Ni is preferentially partitioned into olivine upon cooling. In addition, we observe qualitatively a variation between local olivine modal abundance and the associated Ni concentration in the olivine websterites (PS66-256-6 and to a lesser extent in PS66-256-19) within each thin section; large clusters of olivine tend to have lower Ni concentrations, whereas less abundant olivine within a pyroxene matrix often shows higher Ni concentrations. This would discount significant subsolidus equilibration with the surrounding harzburgites. Notably, in addition to small-scale correlation with modal mineralogy, Ni contents also vary on a sample scale. Although single NiO concentrations in olivine websterite PS66-256-19 are still similar in their range to those from the harzburgites, Ni₀ norm values are slightly higher compared with the harzburgites. The Ni₀ norm notation is used here to remove the effect of Mg content on Ni partitioning in olivine because of the decrease of the Ni partition coefficient with increasing Mg in the melt (Hart & Davis, 1978; Leeman & Lindstrom, 1978). Therefore, this notation allows for better intercomparability of the samples, which differ slightly in their Mg-number. When taking the Mn/Fe ratio into account, olivine from the orthopyroxenite PS66-256-93 plots toward lower Mn contents, in agreement with a different, most probably more magmatic origin.

A thorough evaluation of the quantitative effect of each of these processes on Ni contents in olivine may be of great interest, but it is beyond the scope of our study, and—together with a lack of chemical gradients and field relationships—rigorous testing is difficult. Overall, we interpret the Ni concentration (relative to harzburgites) at increasing pyroxene abundance in the pyroxenites as evidence of melt–rock reaction in which pyroxene fractionation greatly exceeded olivine dissolution.

**Composition of the melt**

In the previous section we identified one component of the pyroxenites as a local residual harzburgite, with olivine being the only or at least dominant phase assimilated during melt–rock reaction. For the investigation of the melt composition, incompatible trace element systematics are good candidates because their concentrations in olivine are orders of magnitude lower than in the melt. Accordingly, olivine dissolution affects melt composition during melt–rock reaction only at high M₀/Mₑ (mass assimilated/mass crystallized) and the compositions of presumably magmatic pyroxenite phases should be direct reflections of melt composition and liquidus proportions.

Based on this observation, we simplified the model calculating only fractional crystallization (Shaw, 2006) again using partition coefficients from Kelemen et al. (2004). Melt extraction is often not effective enough to remove all the percolating melt from the grain matrix (e.g. Dick & Natland, 1996; Hellebrand et al., 2002) and we also allowed for melt entrapment following the model of Hellebrand et al. (2002). We assumed that all olivine in the samples, with the exception of orthopyroxenite (PS66-256-93), is residual and tried to match phase proportions to the observed mineralogy of the samples. A detailed description of the models including the modeling parameters can be found in Supplementary Data Electronic Appendix D.

Because no basalts were recovered in dredge haul PS66-256 or its vicinity, local melt compositions are generally unconstrained. For modeling purposes, we chose average basalt compositions from the CLT and NLT–WGR (Western Gakkel Ridge) (Nauret et al., 2011) as closest accessible basalts. The two basalt populations differ fundamentally in their trace element patterns, suggesting that at least two distinctive melt sources are present below the Lena Trough with unknown spatial extent. Major and trace element compositions of harzburgites associated with the pyroxenites (PS66-256-24 and PS66-256-64) indicate up to 2% of garnet-field and up to 8% of spinel-field partial melting locally. Accordingly, we added a third melt composition to the model, an average N-MORB from the slow-spreading Mid-Atlantic Ridge (MAR) from Klein (2004), which in our view is a good approximation for a natural melt that would have formed locally. This melt is compositionally more similar to the NLT–WGR basalts than to the CLT basalts, but slightly more depleted in incompatible trace elements.
Figure 13 shows the combined results of fractional crystallization and melt entrapment models. Using Lena Trough melts, either from the C1T or NL1–WGR, yields unsatisfactory results for all pyroxenitic phases (Fig. 13a and c). Notably, LREE contents using CLT are too high whereas HREE contents using NL1–WGR are slightly too high to fit. A fractional crystallization model with limited melt entrapment of a MAR-like melt can, however, best account for the trace element patterns of pyroxene phases in PS66-256-7, PS66-256-19 and PS66-256-93. Only the modeling results with the latter are shown as full REE patterns (Fig. 13b and d) and further discussed below.

The olivine websterite (PS66-256-19) clinopyroxene pattern can be successfully modeled as a cumulate with 5–10% melt entrapment in which orthopyroxene and clinopyroxene crystallize in equal proportions (50:50) (Fig. 13a and b). The clinopyroxenite sample (PS66-256-7) yields a similar result but with a slightly higher amount of melt entrapment (7–10%). Clinopyroxenes from both samples have slightly lower HREE than predicted by the model, which can be explained by a slightly higher degree of garnet-facies melting recorded in the melt. Additionally, modeling of the negative Ti and Zr anomalies yields only approximate results for both samples, with anomalies more pronounced than predicted by the model. Neither application of a more fractionated melt nor one produced by a higher degree of melting can resolve this mismatch. Vannucci et al. (1998) have shown that clinopyroxene partition coefficients can be affected by melt composition, with increasing Si contents strongly affecting $D_{\text{REE, Y, Sr}}^{\text{cpx/liquid}}$ while leaving $D_{\text{Zr, Ti}}^{\text{cpx/liquid}}$ almost unaffected. Therefore, a higher Si content of the melt could result in stronger fractionation of Ti and Zr from the REE. Alternatively, assuming a different melt source composition could also resolve this discrepancy.

The orthopyroxenite (PS66-256-93) can be modeled by fractional crystallization followed by 3–5% melt entrapment with crystallization of plagioclase and olivine in equal proportions (50:50) (Fig. 13c and d). Textures indicate that the interstitial assemblage of olivine and plagioclase was formed relatively later in the orthopyroxenite (see discussion below), which suggests subsolidus equilibration of the phases.

The plagioclase-bearing olivine websterite (PS66-256-6) has clinopyroxene concentrations about one order of magnitude too low for LREE and too high for HREE concentrations to be derived from the same melt that formed the other pyroxenites. Instead, its cpx trace element composition is chemically similar to that of harzburgitic cpx. Plagioclase, present here as part of the interstitial assemblage, has the potential to alter clinopyroxene compositions by subsolidus equilibration (Pun et al., 1997). However, no significant negative Sr and Eu anomalies are present in cpx and both phases are not in trace element equilibrium, which argues against substantial subsolidus modification. Hence, we interpret the strong depletion of LREE in the clinopyroxenes as an expression of the parental melt composition. Such a clinopyroxene pattern can, potentially, be produced by crystallization of an in situ melt (e.g. Ross & Elthon, 1993); however, modal proportions and reactive textures count against such a scenario. Cumulates from such strongly depleted MORB melts have been described from the Mid-Atlantic Ridge (Hodges & Papke, 1976; Ross & Elthon, 1993) and from the Ligurian ophiolites (Piccardo & Guarnieri, 2011). Interaction and equilibration of percolating primitive melts with the surrounding harzburgitic mantle during porous flow result in the acquisition of the refractory trace element signature accompanied by progressive silica saturation (Vernieres et al., 1997; Suhr et al., 1998; Piccardo & Guarnieri, 2011). Fractional crystallization of clinopyroxene and orthopyroxene from such a melt could then account for the mineral compositions of olivine websterite PS66-256-6.

Additionally, participation of a melt component derived from pyroxenite melting (Lambart et al., 2012) may also play a role. However, no evidence for the presence of such melts is seen in our samples and any discussion would involve significant speculation. The detection of mantle domains depleted in ancient melting events observed along mid-ocean ridges (Harvey et al., 2006; Seyler et al., 2007, 2011; Dijkstra et al., 2010), and at the nearby Gakkel Ridge (Liu et al., 2008; Stracke et al., 2011), makes the distribution of mantle heterogeneities at least as important as melt heterogeneity for the understanding of MOR processes.

**Where are the pyroxenites formed?**

At low pressures (≈ 0.01–0.2 GPa), the common crystallization sequence of mid-ocean ridge basalts consists of olivine–plagioclase–clinopyroxene. Hence, low-pressure pyroxenites should reflect an origin from evolved melts saturated in clinopyroxene in their major elements (e.g. low Mg-number, low $\text{Al}_2\text{O}_3$ and $\text{Na}_2\text{O}$ and high $\text{TiO}_2$ concentrations in the pyroxenes). On the other hand, experiments performed at higher pressures, between 0.7 and 10 GPa, show that clinopyroxene starts to crystallize at similar or higher temperatures compared with plagioclase (Villiger et al., 2007, and references therein). This is the result of the expansion of the clinopyroxene and spinel liquidus crystallization fields at higher pressures at the expense of olivine and plagioclase (Herzberg, 2004, and references therein). The experiments of Villiger et al. (2004) showed that (spinel) olivine websterites can be produced at 1 GPa and 1270–1240°C during fractional crystallization and from 1240°C to 1150°C during equilibrium crystallization. The crystallization of olivine-free websterites is achieved only during equilibrium crystallization. At lower temperatures, gabbronorites and/or gabbros form, Villiger et al. (2007) showed in their experiments that crystallization processes within the uppermost mantle below mid-
ocean ridges (~20–35 km) can potentially produce up to 47 wt % of ultramafic cumulates. Unfortunately, no geobarometers exist for garnet-free ultramafic rocks that allow a direct assessment of the pressure conditions of pyroxenite formation. Alternatively, the major element compositions of pyroxenitic phases may serve as suitable pressure indicators. In particular, the Al$_2$O$_3$ concentration in clinopyroxene correlates well with pressures and temperatures during crystallization as seen in experiments; experimental data from Villiger et al. (2004, 2007) indicate an increase of Al$_2$O$_3$ in clinopyroxene with increasing pressure and temperature of crystallization.

Major element compositions of clinopyroxene and orthopyroxene from the plagioclase-free olivine websterite (PS66-256-19), clinopyroxenite (PS66-256-7) and the cores of the minerals in the plagioclase-bearing olivine websterite (PS66-256-6) are similar to those reported by Bender et al. (1978) and Villiger et al. (2007, 2004) for plagioclase-free ultramafic cumulates from crystallization experiments at and above 0.7 GPa. Figure 14a and b compares clinopyroxenes from our pyroxenites with those of high- and low-pressure crystallization experiments. Crystallization at high and low pressures produces distinctively different pyroxene compositions related to their position in the crystallization sequence. Specifically, the Lena Trough

Fig. 13. Modeling of trace element abundances in pyroxenes from pyroxenites. (a, b) Clinopyroxenes from the clinopyroxenite (PS66-256-7) and olivine websterite (PS66-256-19). (c, d) Orthopyroxene from the orthopyroxenite (PS66-256-93). All three pyroxenites can be best modeled by small amounts of melt entrapment (3–10%) between cumulus minerals in equilibrium with N-MORB from Klein (2004) (MAR N-MORB). Basalts from the Northern Lena Trough and Westernmost Gakkel Ridge (NLT–WGR) are compositionally similar to MAR N-MORB and could also be considered as parental melts. In contrast, modeling of entrapment of highly alkaline basalts from the Central Lena Trough (CLT) does not yield trace element concentrations similar to those measured in the pyroxenites. Starting compositions for NLT–WGR and CLT are averages taken from Nauret et al. (2011). Error bars in (a) and (c) represent within-sample variations.
Pyroxenites coincide with high-pressure experimental data for \( \text{Al}_2\text{O}_3 \), \( \text{Na}_2\text{O} \), and \( \text{TiO}_2 \), but show a shift to higher Mg-number. This shift in Mg-number may be related to crystallization in the mantle with concomitant or subsequent equilibration; Mg-numbers in the pyroxenites overlap with peridotitic Mg-numbers, as discussed above. Clinopyroxene \( \text{Na}_2\text{O} \) concentrations extend to slightly higher concentrations in the pyroxenites relative to the global pyroxenites.
experiments (Fig. 14b). However, this may be an effect of the regional setting, as late (i.e. after partial melting) pervasive sodic metasomatism has been described in Lena Trough peridotites (as high as 1.7 wt % Na2O in cpx; Hellebrand & Snow, 2003), and could also have affected the pyroxenites.

We conclude that pyroxenite mineral compositions, as well as modal compositions, agree with a high-pressure origin for the Lena Trough pyroxenites. Based on Al2O3 contents in clinopyroxene, this would translate to pressures of formation exceeding 0.7 GPa, with the highest pressures recorded in the mineral cores of clinopyroxenite PS66-256-6 and the lowest in olivine websterite PS66-256-7. Interstitial plagioclase-bearing assemblages in two of the four pyroxenites most probably represent a later, lower-pressure, stage of melt–rock reaction as discussed below.

**Origin of plagioclase-bearing interstitial assemblages**

Plagioclase in ultramafic rocks can be formed by three processes: subsolidus breakdown of spinel during the transition from spinel- to plagioclase-facies conditions (Hamlyn & Bonatti, 1980; Kornprobst & Tabit, 1988; Vissers et al., 1991; Rampone et al., 1993; Hoogerduijn Strating et al., 1993; Cannat & Seyler, 1995; Canil et al., 2003), crystallization of an in situ formed equilibrium melt (Menzies, 1973; Menzies & Allen, 1974; Boudier & Nicolas, 1985) and crystallization of a transient exotic melt (Dick & Bullen, 1984; Dick, 1989; Barth et al., 2003; Dijkstra et al., 2003; Piccardo et al., 2007).

Two of the pyroxenites contain plagioclase as part of a fine-grained interstitial assemblage, involving: (1) olivine + plagioclase + orthopyroxene in the orthopyroxenite (PS66-256-93); (2) clinopyroxene + orthopyroxene + plagioclase in the olivine-websterite (PS66-256-6).

Subsolidus formation of plagioclase occurs at relatively low pressures (<0.7 GPa; Kushiro & Yoder, 1966; Borghini et al., 2010). The transition from spinel to plagioclase facies can be described in the CMAS system as

\[ CaMgSi2O6 + Mg2Si2O5 + MgAl2O4 \rightarrow CaAl2Si2O8 + 2Mg2SiO4 \]

Hence, subsolidus formation of plagioclase is in contradiction with the observed mineral assemblage in the Lena Trough pyroxenites, where either the expected educt or product assemblage does not comply with reaction (3). In particular, even though the Ca-Tschermak's component in orthopyroxene may contribute to plagioclase formation, and rare occurrences of plagioclase lamellae in orthopyroxene have been described (Ohata, 1980), the lack of clinopyroxene as a source for calcium inhibits the formation of 12 wt % of metamorphic plagioclase in the orthopyroxenite. In the case of the olivine websterite, the absence of olivine in the interstitial assemblage is also inconsistent with a subsolidus origin.

Instead, reaction textures suggest different stages of melt–rock reaction occurring at different depths. The chemical disequilibrium between coarse pyroxene minerals and interstitial plagioclase-bearing phases indicates an additional stage of melt–rock reaction following the formation of the (plagioclase-free) pyroxenites. Textural data for the orthopyroxenite suggest that the interstitial assemblage (1) actually only consists of olivine + plagioclase as newly formed phases, whereas the orthopyroxenes represent undissolved remnants of coarse-grained matrix orthopyroxene. This would suggest a net reaction between the orthopyroxenite and an orthopyroxene-undersaturated melt along grain boundaries in which

\[ \text{orthopyroxene} + \text{liq.} \rightarrow \text{plagioclase} + \text{olivine} + \text{liq.} \]

Nevertheless, the trace element compositions of orthopyroxene and plagioclase appear to be in equilibrium with each other, and both are consistent with precipitation from a MORB melt (see discussion above). Subsolidus equilibration between orthopyroxene and the late plagioclase-bearing assemblage may be partially accountable here, but melt composition was probably not very different in both stages. We suggest that reaction textures and the change from plagioclase-free to plagioclase-bearing assemblages indicate melt–rock reaction operating at lower pressures, reflecting the pressure-dependent change of the liquid line of descent from opx-saturated to opx-undersaturated, but plagioclase-saturated, conditions.

Interstitial assemblage (2) in the olivine websterite PS66-256-6 on the other hand indicates melt–rock reaction, where a clinopyroxene-undersaturated melt reacts with the pyroxenitic clinopyroxene to produce plagioclase and orthopyroxene:

\[ \text{clinopyroxene} + \text{liq.} \rightarrow \text{plagioclase} + \text{orthopyroxene} \pm \text{clinopyroxene} \]

In this case the trace element compositions of clinopyroxene and plagioclase are out of mutual equilibrium, with the REE concentrations consistently lower in plagioclase relative to the equilibrium clinopyroxene composition. Although trace element redistribution during equilibration with plagioclase can modify the clinopyroxene composition, it generally results in a strong decrease in LREE and increase in middle REE (MREE) and HREE concentrations relative to spinel-facies cpx (Papike et al., 1996; Pun et al., 1997). Hence a rotation of the cpx REE pattern would be the result, rather than a relative parallel shift in the pattern as in this case.

Plagioclase major element compositions further corroborate our interpretations. Plagioclase in the orthopyroxenite (PS66-256-93) has An contents (~75 mol %) that are consistent with the An contents of plagioclase from
equilibrium crystallization of MORB melts at low pressures (e.g. Grove et al., 1992). The plagioclase-bearing olivine websterite (PS66-256-6), on the other hand, has an An content of ~90 mol % and the trace element patterns of the plagioclase show a slight depletion in LREE. As discussed above, trace elements in the associated pyroxene are not in equilibrium with those in plagioclase, and carry a refractory melt signature. Such plagioclase patterns are different from those of plagioclase in equilibrium with basaltic melts similar to MAR N-MORB (Klein, 2004). They could probably be produced by involving a refractory melt after a significant amount of pyroxene dissolution. High anorthite contents in plagioclase, ubiquitous in plagioclase peridotites and abyssal gabbros (Elthon et al., 1992; Ross & Elthon, 1993; Natland & Dick, 2001), have been attributed to shallow crystallization of a refractory melt (Cannat et al., 1990; Dijkstra et al., 2003) or crystallization of a hydrous melt (Sisson & Grove, 1993; Panjasawatwong et al., 1995; Takagi et al., 2005). No evidence has been found for the presence of such a hydrous melt and we prefer formation of the interstitial assemblage by melt–rock reaction with a refractory melt. As described above, such a refractory signature of melts can either be derived from low-pressure partial melting of refractory peridotites (e.g. Ross & Elthon, 1993), or be acquired by extensive reaction with depleted peridotites during porous melt flow (Vernieres et al., 1997; Suhr et al., 1998; Dijkstra et al., 2003). Compositionally similar plagioclase associated with corroded clinopyroxene has been described in peridotites from the Internal Ligurides, Corsica and Othris (Ramponne et al., 1997; Piccardo et al., 2002; Dijkstra et al., 2003), as well in gabbronorites from the Ligurian ophiolites (Piccardo & Guarnieri, 2011).

Melting and melt stagnation at Lena Trough

Information on melting conditions in the central portion of the Lena Trough is limited to information gathered from peridotite mineral chemistry. Peridotite compositions from Molloy Deep, in the southern basalt-bearing segment, indicate the onset of partial melting in the garnet stability field followed by limited melting in the spinel stability field (Hellebrand & Snow, 2003). Moreover, basalt compositions from the Lena Trough indicate very different mantle sources to the north and south of the central portion (Nauret et al., 2011). Basalts from the CLT are highly alkaline, ne-normative basalts most probably derived by partial melting of an amphibole- or phlogopite-bearing source (Nauret et al., 2011). Basalts in the Northern Lena Trough are chemically similar to NLT–WGR lavas, exhibiting the characteristics of N-MORB in their major and trace element compositions (Nauret et al., 2011). The characteristic K- and LREE-enriched and HREE-depleted composition of the CLT basalts is not shared by the LREE-depleted pyroxenite compositions studied here, such that CLT-like alkali basalt magmas cannot have participated in pyroxenite formation. The parental melts to the pyroxenites have similar trace element characteristics to the NLT–WGR basalts, except that the latter were formed under slightly different melting conditions. Specifically, the parental melts of the pyroxenites were probably formed at similar conditions to the associated harzburgites, recording melting near the garnet–spinel stability field transition. This indicates that the influence of the CLT basalt mantle source does not extend to the location of the PS66-256 pyroxenites in the central portion of Lena Trough and is probably a localized feature.

Pyroxenites from dredge haul PS66-256 show that the onset of melt stagnation occurred at relatively great depths. The transient MORB-like melts reacted with wall-rock composed of highly refractory harzburgite (as evidenced by clinopyroxene inclusions in spinel) at depths of as much as 25 km (>0.7 GPa) and produced various pyroxenite lithologies. Such a depth is in good agreement with estimates for the onset of conductive cooling and crystallization at slow-spreading ridges (Herzberg, 2004; Montesi & Behn, 2007). In addition, the interstitial plagioclase-bearing assemblages of two pyroxenites record a second, shallower period of melt–rock reaction after the pyroxenites were formed. We suggest therefore that melt impregnation and stagnation occurred over a wide range of depths below the Lena Trough, either continuously or in discrete events.

This study further corroborates the presence of a thick lithospheric lid in the Lena Trough. Melts generated beneath the basalt-free segment probably stagnated in the mantle and never managed to erupt (Snow & Petrology-Group-ARK-XX/2, 2007). Hence, the nonvolcanic nature of the Lena Trough is more the result of efficient melt entrapment rather than absence of melt production.

Pressure of (reactive) crystallization in global comparison

Only a few pyroxenites have been collected among the ultramafic lithologies recovered along slow- and ultraspreading mid-ocean ridges. Their major element mineral compositions show largely the same characteristics as the Lena Trough pyroxenites and lie within the field of high-pressure cumulates. Common to almost all are overall high Al2O3 concentrations in clinopyroxene, ranging between 2.5 and 8.3 wt % (Fig. 14c). Where measured, orthopyroxene major elements are also similar for all pyroxenites, with the notable exception of pyroxenites from the Mid-Atlantic Ridge at the Kane Fracture Zone (MARK area). Spinell major elements are similar for pyroxenites from the South West Indian Ridge (SWIR) and the MARK area and their compositional range is restricted (Mg-numbers 63–76; Cr-numbers 10–35), whereas spinel major element concentrations from the Lena Trough pyroxenites show a broad range (Mg-numbers 63–76; Cr-numbers 10–35).
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48–77; Cr-numbers 6–50). Overall, pyroxenites from this study mostly resemble those from the SWIR Oblique Supersegment, the Atlantis II Fracture Zone and the Gakkel Ridge, all ultraslow-spreading settings like the Lena Trough. Sodium and TiO₂ concentrations in clinopyroxene differ significantly between these and the MARK area pyroxenites (Kane Megamullion included). As Dantas et al. (2007) have already summarized, MARK area pyroxenites have lower TiO₂ and Na₂O concentrations and higher Mg-numbers relative to other pyroxenites. This is further emphasized by our data. Clinopyroxene trace element patterns of abyssal pyroxenites show a broad range in absolute concentrations, but are all depleted in LREE similar to pyroxenites from the Lena Trough. Notably, some pyroxenites from the SWIR Oblique Supersegment have highly depleted clinopyroxene patterns (Dantas et al., 2007), similar to the olivine websterite PS66-256-6 from this study.

SWIR pyroxenites have been interpreted by Dantas et al. (2007) as primitive cumulates from an N-MORB melt. Additionally, Warren et al. (2009) concluded for SWIR pyroxenites from the Oblique Supersegment that their parental melts were influenced by the Bouvet mantle plume and locally reacted with the surrounding mantle. Pyroxenites from the MARK area have been interpreted as originating most probably from in situ crystallization of a trapped partial melt (Juteau et al., 1990; Kempton & Stephens, 1997). The differences between SWIR and MARK area pyroxenites in clinopyroxene compositions (TiO₂ and Na₂O) probably reflect parental melts generated from different mantle sources, as suggested by Dantas et al. (2007). Hence, although the relative proportion of assimilation and (fractional) crystallization does seem to vary during pyroxenite formation in each case, all of the abyssal pyroxenites studied to date exhibit characteristics suggesting recent formation from MORB melts in the lithospheric mantle.

Comparison of the clinopyroxene major element compositions of these abyssal pyroxenites with experimental data reveals that they lie in the compositional field of high-pressure crystallization, as do the Lena Trough pyroxenites (disregarding the low TiO₂ and Na₂O concentrations of the MARK area pyroxenites) (Fig. He and d). A correlation between the onset of crystallization and spreading rate is suggested by the data. Pyroxenites from the SWIR, Lena Trough and Gakkel Ridge, all slow- to ultraslow-spreading ridges, indicate high crystallization pressures, whereas pyroxenites from a fast-spreading setting (SE Pacific; Constantin et al., 1995) indicate low crystallization pressures, based on Al₂O₃ variations in cpx. Nevertheless, the global database of abyssal pyroxenites is still limited and further studies of abyssal pyroxenites will be required to validate our findings, which are consistent with models of conductive cooling and estimated pressures of partial crystallization of MORB (Herzberg, 2004).

SUMMARY AND CONCLUSIONS

We investigated abyssal pyroxenites and associated harzburgites dredged from the basalt-free segment of the ultraslow-spreading Lena Trough, Arctic Ocean. Two olivine websterites, an orthopyroxenite and a clinopyroxenite, all from the same location, were selected for this study. The samples are relatively fresh (<35% alteration), allowing detailed textural investigation, and cover a wide range in pyroxenite mineralogy. The samples show distinct textural and major, minor and trace element features that are consistent with melt–rock reaction processes in the asthenospheric mantle. The following conclusions can be drawn from our investigation.

(1) Peridotites from the same location are harzburgites that are residues of near fractional partial melting close to the garnet–spinel facies transition, similar to the Lena Trough peridotites previously described from further south (e.g. Hellebrand & Snow, 2003).

(2) Microtextures, and major and minor element compositions of pyroxenites are in agreement with an origin by assimilation–fractional crystallization. The microtextures and minor element compositions indicate that olivine and spinel are residual phases derived from the wall-rock peridotite, whereas clinopyroxene and orthopyroxene in the matrix are generally magmatic. Only in the orthopyroxenite do magmatic olivine and spinel occur as part of an interstitial mineral assemblage.

(3) The protolith was a highly refractory harzburgite, at least for the clinopyroxenite, based on clinopyroxene inclusions in spinel that are compositionally distinctly different from matrix clinopyroxenes.

(4) The trace element compositions of pyroxenes and plagioclase in the pyroxenites are dominated by the parental melt composition during melt–rock reaction; LREE-depleted ([La/Yb] = 0.17–0.002) cpx and opx trace element patterns are consistent with an origin by fractional crystallization, limited melt entrainment (3–10%) and limited olivine dissolution.

(5) The parental melts to the pyroxenites were local MORB-like primitive melts that were generated close to the garnet–spinel facies transition and then modified to variable extents by melt–rock reaction during porous flow.

(6) Erupted basalts in the Central Lena Trough, south of the pyroxenite sample location, have characteristic alkaline- and LREE-enriched chemical compositions resulting from melting of continental mantle lithosphere (Nauret et al., 2011) and are not involved in the formation of the pyroxenites. This gives a spatial limit to the extent of this mantle domain.

(7) Petrographic and geochemical characteristics suggest that the pyroxenites formed at high pressures.
(>0.7 GPa), whereas an interstitial plagioclase-bearing assemblage in two of the pyroxenite samples that shows reactive boundaries to the pyroxenite matrix minerals suggests a second, shallower stage of melt-rock reaction.

(8) Pyroxenites from this study provide evidence for a deep onset of melt stagnation below the Lena Trough. Along with abundant plagioclase-bearing peridotites and gabbroic veins they suggest significant melt entrainment over a wide pressure range. The presence of a thick lithospheric lid contributed strongly to the magma-starved nature of the Lena Trough.

(9) Pyroxenites from the Lena Trough are similar in their major and trace element compositions to most global abyssal pyroxenites. Comparison with experimental high- and low-pressure data indicates that a high-pressure magmatic formation may be common for abyssal pyroxenites in general. In addition, with a growing data collection for pyroxenites, a trend emerges that suggests a correlation between the depth of pyroxenite formation and decreasing spreading rate, in agreement with predicted spreading-rate-dependent changes of ridge thermal structure. Crystallization depths >25 km are indicated for pyroxenites at ultra-slow-spreading rates.

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at Journal of Petrology online.

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