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Highly depleted cratonic mantle in West Greenland extending into diamond stability field in the Proterozoic

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ABSTRACT

This study presents electron microprobe data for dunite xenoliths from a lamprophyre dyke located on the island of Qeqertaa, West Greenland. The minimum age of this dyke is Palaeoproterozoic and it experienced amphibolite facies metamorphism and deformation during that era. The samples consist of nearly 200 xenoliths with a size range of 0.5-8 cm. These dunite xenoliths have olivine Mg#, that range from 80.3 to 94.6 ($n = 579$) with a mean of 92.6. Orthopyroxene is found in three xenoliths and garnet in five others. The latter suggests the depth of the Qeqertaa xenolith suite to be near the diamond stability-field, which is substantiated by the finding of diamonds in bulk samples of the Qeqertaa dyke. This further indicates the presence of a lithospheric mantle domain dominated by high-Mg# dunite to this depth in Palaeoproterozoic time. Cr-rich spinel, in the 0.1–0.2 mm size range, is found within and between olivine grains in individual xenoliths. These Cr-spinels yield Fe–Mg exchange temperatures of 400–600 °C. However, the presence of intermediate spinel compositions spanning the lower temperature solvus suggests that equilibration temperatures were >550 °C. Fe^{3+}#, expressed as $100 \times Fe^{3+}/(Fe^{3+} + Al + Cr)$, is shown to be a useful parameter in order to screen for altered spinel ($Fe^{3+}\# > 10$) with disturbed Mg# and Cr#. The screened spinel data ($Fe^{3+}\# < 10$) show a distinctly different trend in terms of spinel Cr# versus Mg#, compared to unmetamorphosed xenoliths in Tertiary lavas and dikes from Ubekendt Ejland and Wiedemann Fjord, respectively, also located within the North Atlantic craton. This difference likely reflects amphibolite facies metamorphic resetting of the Qeqertaa xenolith suite by Fe–Mg exchange. Given the similarity of the Qeqertaa xenolith suite with the Ubekendt and Wiedemann suites, in terms of their olivine Mg# and spinel Cr# distribution, high-Mg# dunite is likely to be an important component of the subcontinental lithospheric mantle beneath the North Atlantic craton and appears to have spanned a vertical distance of at least 150 km in this region, even during the Palaeoproterozoic.

1. Introduction

Determining the composition of the subcontinental lithospheric mantle (SCLM) has implications for our understanding of the crust–mantle system and its evolution through time. Previous studies on SCLM xenoliths from Greenland have shown the occurrence of nearly monomineralic dunites consisting of remarkably refractory olivine with molar $Mg/(Mg + Fe^{2+})$, or Mg#, averaging about 92.8 (e.g. Bernstein et al., 1998, 2006; Bizzarro and Stevenson, 2003; Garrit, 2000; Wittig et al., 2008). The Qeqertaa xenolith suite presented in this study shows equally refractory olivine compositions. This growing body of data on cratonic mantle xenoliths from Greenland suggests that such olivine-rich mantle is common here, and perhaps comprises a large proportion of the lithospheric mantle beneath substantial parts of Greenland.

High and consistent Mg# in olivine is thought to reflect partial melting of the mantle to the point of exhaustion of orthopyroxene (Bernstein et al., 2007). The implied high degree of melting (37–45%; Bernstein et al., 1998; Herzberg, 2004) is not achieved in any current geological environment and is thus thought to reflect a hotter mantle during the formation of cratonic SCLM. This is in agreement with the generally Archaean Re-depletion ages of cratonic SCLM xenoliths (e.g. Hanghøj et al., 2001; Pearson et al., 2003; Shirey and Walker, 1998; Wittig et al., 2010) and the inferred hotter mantle at that time (Herzberg et al., 2010). However, the exact formation environment is still debated with one model proposing a single-stage process in a polybaric melting column either in a spreading ridge or plume environment (e.g. Aulbach et al., 2011; Bernstein et al., 1998, 2006; Griffin et al., 2009; Herzberg et al., 2010; Kelemen et al., 1998), whereas another model proposes flux melting of previously depleted harzburgite in a subduction zone setting (e.g. Canil, 2004; Lee, 2006; Wittig et al., 2008).

In addition to documenting the composition of the Palaeoproterozoic xenolith suite at Qeqertaa this study also shows that although parameters such as Mg#, and molar $Cr/(Cr + Al)$, or Cr#, may at first appear

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to retain information of the primary composition of a mantle xenolith suite, examination of molar $Fe^{3+}/(Cr + Al + Fe^{3+})$, or Fe^{3+}#, in associated spinels reveals a history of alteration that strongly modified both Mg# and Cr# so that even visually unaltered spinel had its chemistry overprinted during amphibolite facies metamorphism. Thus, spinel compositions, which are widely thought to be reliable indicators of primary igneous conditions in metamorphic intrusive rocks (e.g. Barnes, 2000) may reflect re-equilibration during metamorphic events (Evans and Frost, 1975; Sack and Ghiorso, 1991).

2. Geology

The Qeqertaa xenolith suite is hosted by an up to 6 m wide vertical dyke of ultramafic lamprophyric affinity, which crops out on the small island Qeqertaa, some 50 km north of Ilulissat at 69°38 N, 50°38 W (Fig. 1). The dyke is one of many that cut late Archaean gneisses and supracrustal rocks in the Ataa area, eastern Disko Bay (Garde and Steenfelt, 1999; Larsen and Rex, 1992; Marker and Knudsen, 1989). The Qeqertaa dyke has not been dated, but similar intrusions in the Ataa area have yielded K–Ar ages of 1782 Ma and 1743 Ma, both ±70 Ma (Larsen and Rex, 1992). Because the dykes have been affected both by metamorphism and deformation linked to the Palaeoproterozoic Rinkian–Nagsoqtuqidian orogeny, these ages could represent metamorphic overprinting and thus represent minimum ages, as pointed out by Larsen and Rex (1992). Structural interpretation suggests that the Ataa region can be divided into a series of crustal blocks with distinct tectono-magmatic history (Garde and Steenfelt, 1999) and the Qeqertaa dyke is situated in the border zone between the Ataa domain to the north and the Rodebay domain to the south.

The Qeqertaa xenoliths are rounded to subangular, with a size range of 0.5 cm to 8 cm in the longest dimension. In several places along the dyke, the xenoliths are so abundant as to make a clast-supported network. The dyke has brecciated contacts with tonalitic gneisses, and is deformed with pinch and swell structures. Apophyses are often sheared into tight isoclinal folds. Deformation mainly affected the matrix, which often shows carbonate crystallization in pressure shadows of the xenoliths and matrix foliation wrapping around individual xenoliths (Fig. 2). Matrix mineralogy is dominated by tremolite, mica, carbonate, ilmenite and iron oxides. Of these minerals, only mica and ilmenite are thought to remain from the primary mineralogy of the dyke matrix, although even these minerals show evidence of alteration and recrystallization, manifested as oxide exsolution along cleavage planes in mica, and exsolution lamellae and oxidized microcrystalline overgrowth zones on ilmenite.

A collection of nearly 200 xenolith samples forms the basis of this study. Individual xenoliths larger than about 3 cm were cut into several slices 5–8 mm thick and all xenoliths were inspected visually before a subset of 119 xenoliths of varying size was prepared for standard polished thin sections and analyzed by electron microprobe. The xenolith suite as a whole appeared very homogeneous in terms of mineral mode, texture and grain size. The xenoliths are all dunites with only a few samples containing spinel, garnet, mica or orthopyroxene (see below). A few xenoliths are completely serpentinized, while others are relatively fresh peridotite with only local alteration along minor cracks and veins. However, as shown below, all studied xenoliths have experienced some degree of chemical modification of their primary minerals even though they at a first glance appear nearly unaltered. Typically, in standard thin sections olivine grain margins are yellowish to light brown, in some samples more dusty brown (Figs. 2 and 3). Such margins can be relatively wide (1–2 mm), but are mostly in the order of 0.2–0.6 mm, such as in the example of xenolith sample qq-2 in Fig. 3. Spinel is often oxidized, with irregular grain margins and is opaque in standard thin sections. In rare cases, the spinel has retained a brownish translucent core. Secondary oxide, mainly magnetite, is common along veins and cracks within olivine grains and at the rim of individual xenoliths (Fig. 3). Some examples of xenoliths and their textures are given in Fig. 2a–d.

All xenoliths are coarse protogranular, following the terminology of Mercier and Nicolas (1975). Grain size varies from 1 to 2 mm to

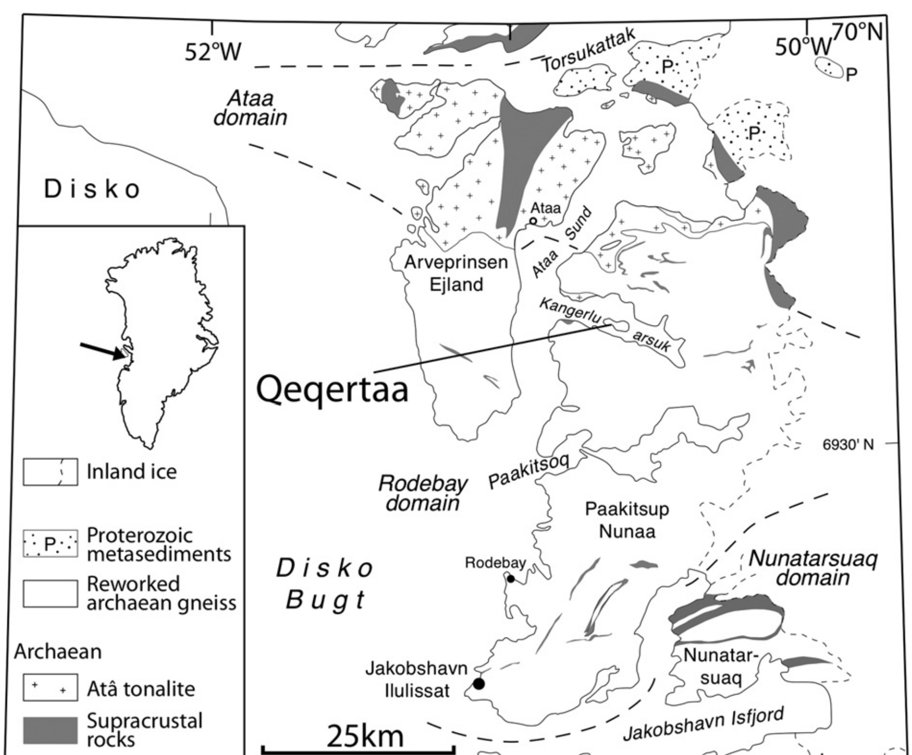

Fig. 1. Simplified geological map over the north-eastern Disko Bay region, showing the location of the island Qeqertaa in the northern Rodebay domain. Qeqertaa is situated a few kilometers south of the border of the Atâ tonalite. After Garde and Steenfelt (1999).