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Long-lived, cold burial of Baltica to 200 km depth

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ABSTRACT

The collision of two continents causes subduction of one of the continental margins temporarily below the other into the diamond stability field (>3.8 GPa or >120 km depth), coeval ultra-high pressure (*UHP*) metamorphism of the continental crust followed by exhumation of *UHP* metamorphic terrains. Recent thermo-mechanical models propose that this subduction–exhumation cycle is short-lived (<15 Ma), contradicting the range in metamorphic ages observed in several high pressure/*UHP* metamorphic terrains. Here we use microstructures, mineral chemistry, Sm–Nd geochronology and Nd–Sr isotope systematics to show that the micro-diamond bearing Western Gneiss Region in the Scandinavian Caledonides of western Norway was subjected to *UHP* conditions for c. 30 Ma during a long-lived cycle of subduction and exhumation related to the Scandian phase of the Caledonian orogeny. Orogenic peridotite bodies on Otrøy and Flemsøy islands are interpreted as mantle wedge fragments tectonically emplaced into Baltic continental crust during the prograde continental subduction of Baltica underneath Laurentia after c. 438 Ma. Subduction related deformation and associated strain-induced recrystallization of the mantle fragments partially to completely destroyed pyroxene exsolution microstructures in cm-scale garnet within layers of garnet–pyroxenite that have a Palaeoarchaean origin (3.33 ± 0.19 Ga, 2σ, 5 point whole rock). Millimeter scale recrystallized orthopyroxene in garnet–websterite has low Al cores ($\geq$0.10 wt.% Al_2O_3) showing recrystallization conditions at *UHP*, 6.3 ± 0.2 GPa, and at sub-geotherm temperatures of Archaean areas, 870 ± 50 °C. Three mineral isochrons of 2 to 5 points from recrystallized mineral assemblages of garnet–pyroxenite indicate overlapping, early Scandian ages (429.5 ± 3.1 Ma, 2σ, weighted mean) showing that the Archaean mantle fragments record the prograde subduction of Baltica to 200 km depth underneath Laurentia in c. 8 Ma (25 mm a^{-1} vertical subduction rate). Contrasting $^{87}Sr/^{86}Sr$ in recrystallized clinopyroxene from Otrøy and Flemsøy (0.7016–0.7023 and 0.7131, respectively) indicates strain-induced recrystallization occurred partly at dry (fluid absent) conditions. Subsequent metamorphic conditions during peridotite retrogression record exhumation through c. 120 km depth (3.8 GPa), overlapping maximum metamorphic conditions recorded in regional country-rock eclogites dated at c. 400 Ma. A slow average vertical exhumation rate of 3.6 mm a^{-1} is implied for the diamond phase stability. Most external eclogites crystallized or re-equilibrated, probably triggered by deformation and fluids, during crustal exhumation c. 30 Ma after the peridotites crystallized early Scandian garnets. Crustal micro-diamond — formed by long-lived but cold *UHP* metamorphism, and found almost exclusively in Phanerozoic orogens — suggests a change in the nature of collisional tectonics within a cooling earth.

1. Introduction

Ancient exhumed continent–continent collision zones preserve evidence for the temporarily burial, down to mantle depth >120 km, of one continental margin below the other. Evidence includes metamorphic pressure (*P*) and temperature (*T*) gradients normal to the collision front (Krogh, 1977; Griffin et al., 1985), metamorphic index minerals like coesite (Coe) and micro-diamond (Dia; other mineral abbreviations after Kretz, 1983) within the subducted continental crust (Sobolev and Shatsky, 1990; Dobrzhinetskaya et al., 1995) and orogenic (mantle and crustal) peridotites embedded in the subducted continental crust (Brueckner and Medaris, 2000; Liou et al., 2007). In addition, parts of the cycle of burial (subduction), reversal and exhumation of positively buoyant continental lithosphere have successfully been modelled in thermo-mechanical/thermo-tectonic numerical studies (Ranalli et al., 2000; Warren et al., 2008). The first part of the cycle, the subduction of continental lithosphere, transforms

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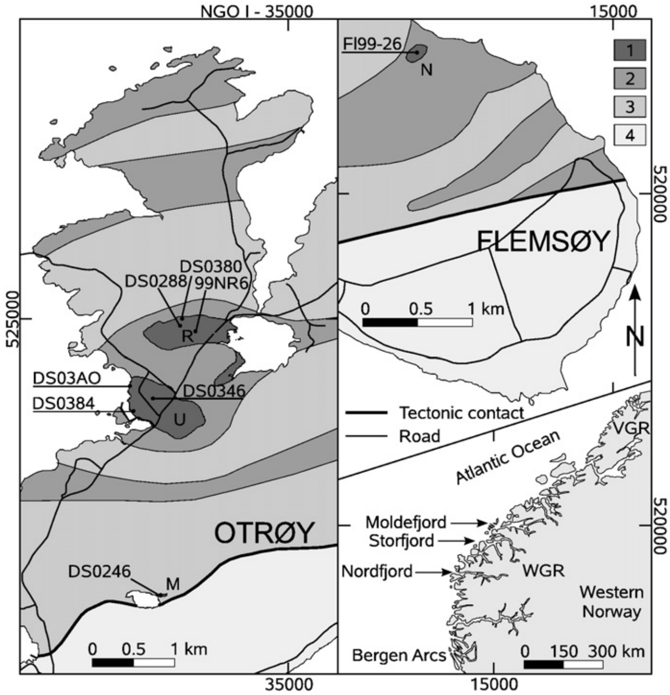

Fig. 1. Simplified geological maps of western Otrøy (Carswell et al., 2006) and eastern Flemsøy (Terry et al., 2000b) showing the position of analyzed samples and of orogenic Grt-peridotite bodies (1; M — Midsundvatnet, N — Nogvadalen, R — Raudhaugene, U — Ugelvik) embedded in gneiss (2 — banded dioritic gneiss with abundant eclogite, 3 — migmatitic or augen gneiss with minor eclogite, 4 — granitoid gneiss and metasediment). WGR, Western Gneiss Region; VGR, Vestranden Gneiss Region.

near-surface low pressure (*LP*) rocks to high pressure (*HP*) and ultra-high pressure (*UHP*) metamorphic crustal rocks. These include eclogite (Eskola, 1915), Coe bearing gneiss (Chopin, 1984; Smith, 1984) and micro-Dia bearing gneiss (Sobolev and Shatsky, 1990; Dobrzhinetskaya et al., 1995), which are believed to preserve the maximum depth of plate burial. The third stage, the exhumation, is generally assumed to overprint to varying degrees the *HP*/*UHP* mineral assemblages. The duration of both the first and third part of the cycle is constrained indirectly by palaeomagnetic and numerical models and directly by combined isotope and mineral chemical studies that all suggest fast rates for both continental plate subduction and crustal exhumation. Reported rates for vertical plate movement range from 7 to more than 80 mm a^{-1} in a single orogen (Torsvik et al., 1996; Terry et al., 2000a; Root et al., 2004; Camacho et al., 2005; Kylander-Clark et al., 2008) that all would lead to estimates for the total burial time of less than 15 Ma.

Evidence for the duration of the intermediate stage two, i.e. the integrated mantle residence time between early subduction (1) and late exhumation (3) is sparse. The reversal of crustal rock movement is generally believed to occur rapidly as the buoyancy contrast between crustal and mantle lithologies increases with depth. Eclogites preserve large age ranges that suggest a larger duration of eclogite-facies conditions of up to 25 Ma (Griffin and Brueckner, 1985; Mattinson et al., 2006; Kylander-Clark et al., 2007). In addition, micro-Dia bearing *UHP* metamorphic terrains commonly enclose orogenic Grt-peridotite bodies that record systematically higher peak *P* and *T* conditions (Hirajima and Nakamura, 2003) than do eclogites and thus suggest deeper subduction. It follows that chronological data from crustal rocks may also systematically underestimate the time of peak metamorphism, and therefore the residence time at mantle conditions. Here we show that orogenic peridotite enclosed in Baltica basement gneiss at Otrøy and Flemsøy islands in western Norway (Fig. 1) records the prograde subduction and early retrograde exhumation history of the Baltica plate margin, indicating that this margin resided in the Dia stability field for c. 25 Ma, in the Coe stability for c. 30 Ma, much longer than generally accepted for any exhumed *UHP* metamorphic terrain.

2. Geological setting and sample description

The Caledonides in Scandinavia formed as a result of the Palaeozoic continent–continent collision between Laurentia and Baltica and consists of a pile of tectonic nappes translated eastwards onto the Baltica continental margin (Roberts and Gee, 1985). The Western Gneiss Region (WGR) of Norway hosts a tectonic window through this nappe pile and exposes at the lowest tectonostratigraphic position a large segment of the former craton of Baltica that is dominated by Palaeo- to Mesoproterozoic, mainly felsic intrusives with minor mafic rocks, which are often converted to high-grade gneiss and eclogite (Tucker et al., 2004). This Baltica basement gneiss encloses minor orogenic peridotite bodies. Many of them are interpreted to be incorporated from the overlaying mantle wedge into the subducting continental crust (Brueckner and Medaris, 2000) during the final, Late Silurian to Early Devonian, stage of contraction, called the Scandian phase (or Scanidan orogeny) of the Caledonian orogeny in Scandinavia (Roberts, 2003; Brueckner and Van Roermund, 2004).

Orogenic peridotites on Otrøy and Flemsøy are melt depleted, serpentinized Grt- and Spl-harzburgite and -dunite (Fig. 1; Carswell, 1968) that are compositionally banded at mm–m scale. Layers and lenses of Grt-pyroxenite and garnetite (Fig. 2a) at mm–dm scale parallel the compositional banding (Carswell, 1973; Van Roermund and Drury, 1998) and form the focus of this study. Two types of Grt-pyroxenite occur: bi-mineralic Grt(red)-clinopyroxenite and tri-mineralic Grt(purple)-websterite. Minor components in both types of pyroxenite are Amp, Ol, Ilm and Rt. The layering of peridotite and pyroxenite is tightly to isoclinally folded, with fold wavelengths at cm–m scale (Fig. 2a) and an axial plane foliation.

It is essential to distinguish between pre-subduction (M_1 and M_2) and subduction-related (M_3) mineral assemblages to demonstrate that Grt-pyroxenite records a prograde subduction history. Eight samples were collected (Fig. 1, Table S5) from bi- (99NR6, DS0380, DS0384) and

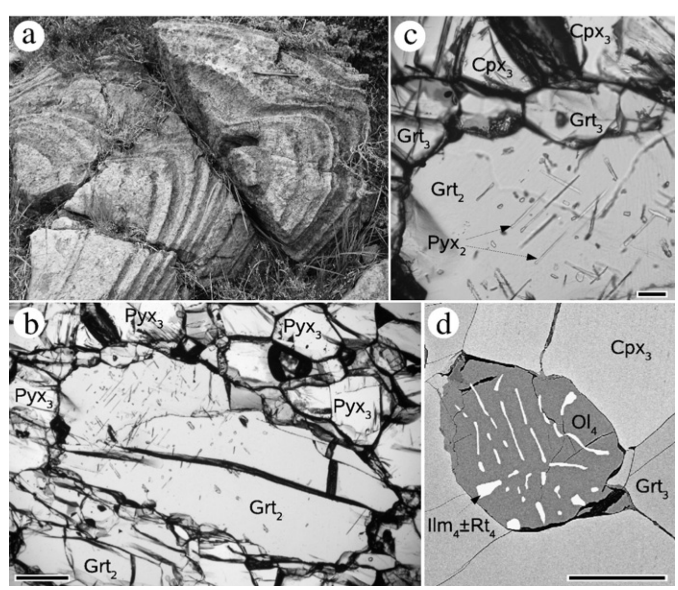

Fig. 2. Meso- and microstructures of Grt-pyroxenite. a) Field image of a tight fold hinge of alternating peridotite and pyroxenite (pen = 15 cm). b, c) Optical light micrographs showing oriented lamellae of M_2 Pyx in porphyroclastic M_2 Grt and lamellae-free recrystallized M_3 Grt and Cpx in pyroxenite DS0288 (c = subset of b). d) Back-scattered electron image of recrystallized M_3 grains with M_4 symplectite of Ol + Ilm ± Rt inferred to be after M_3 Ti-Chu in pyroxenite 99NR6. Scale bars: 500 µm (b) and 100 µm (c, d).