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U–Pb dates and trace-element geochemistry of zircon from migmatite, Western Gneiss Region, Norway: Significance for history of partial melting in continental subduction

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ABSTRACT

The Western Gneiss Region (WGR), Norway, is dominated by migmatitic gneiss that contains inclusions of eclogite, some of which contain evidence for ultrahigh-pressure metamorphism. To evaluate geochemical and age relationships between host migmatite and eclogite, we obtained LA–ICP–MS U–Pb dates and trace-element analyses for zircon from a variety of textural types of leucosome, from layer-parallel to crosscutting. Zircon textures (euhedral, oscillatory- and sector-zone grains) indicate a likely magmatic origin of the leucosomes. Caledonian U–Pb zircon dates from zircon rim and near-rim regions are as old as 410–406 Ma, coeval with previously determined ages of high- and ultrahigh-pressure metamorphism of WGR eclogite. Trace-element analyses obtained simultaneously with U–Pb dates indicate crystallization of zircon under garnet-present conditions in the majority of leucosomes. Other zircons, including those from crosscutting pegmatite, yield younger ages (as young as 385 Ma), coinciding with dates determined for amphibolite-facies retrogression of eclogite; trace-element analyses suggest that these zircons grew under plagioclase-present (garnet-absent) conditions. Combined age and trace-element data for leucosome zircons record the transition from high-pressure (garnet-present, plagioclase-absent) crystallization to lower-pressure (plagioclase-present) crystallization. If the euhedral zircons that yield ages coeval with peak or near-peak UHP metamorphism represent crystallization from anatectic leucosomes, these results, combined with field and petrographic observations of eclogite–migmatite relationships, are consistent with the presence of partially molten crust in at least part of the WGR during continental subduction. The decreased viscosity and increased buoyancy and strain weakening associated with partial melting may have assisted the rapid ascent of rocks from mantle to crustal depths.

1. Introduction

Exhumed ultrahigh-pressure (UHP) terranes document the subduction of crustal material to mantle depths and its return to the Earth's surface (e.g., Chopin, 1984; Hacker, 2006; Liou et al., 2000; Rubatto and Hermann, 2001). One of the main modes of occurrence of UHP rocks is as eclogite (metabasalt and metagabbro) inclusions in migmatitic gneiss (Group B eclogites of Coleman et al., 1965). Although evidence for UHP metamorphism in the gneiss is rare (Dobrzhinetskaya et al., 1995), it is likely that both eclogite and gneiss were metamorphosed at UHP conditions (e.g., Cuthbert et al., 2000; Hacker, 2006; Wain, 1997). However, the relationship of migmatization of the gneiss—specifically, partial melting—to UHP metamorphism (Labrousse et al., 2011) is not well established.

Important questions are whether partial melting of the gneiss occurred during an orogenic episode that pre-dated UHP eclogite metamorphism (and therefore the gneiss remained at subsolidus conditions during UHP metamorphism) or whether migmatization occurred during the same metamorphic event that produced the UHP eclogite. In the latter case, it is important to determine the conditions of migmatization, and in particular, whether partial melting occurred at high or ultrahigh pressures and/or at much lower pressures related to decompression to mid-crustal (amphibolite-facies) levels (Fig. 1).

These questions are significant because the presence or absence of partial melt during continental subduction affects the rheology of the subducted crust, and therefore the mechanism and rate of exhumation. Field, experimental, and modeling studies suggest that partial melting may occur under the UHP conditions of continental subduction (Auzanneau et al., 2006; Brueckner, 2009; Hermann, 2002; Lang and Gilotti, 2007; Liu et al., 2012; Wallis et al., 2005; Whitney et al., 2004, 2009; Zhang et al., 2009). If present, partial melt (with melt fraction > 10–15%) will dramatically decrease viscosity (Rosenberg and

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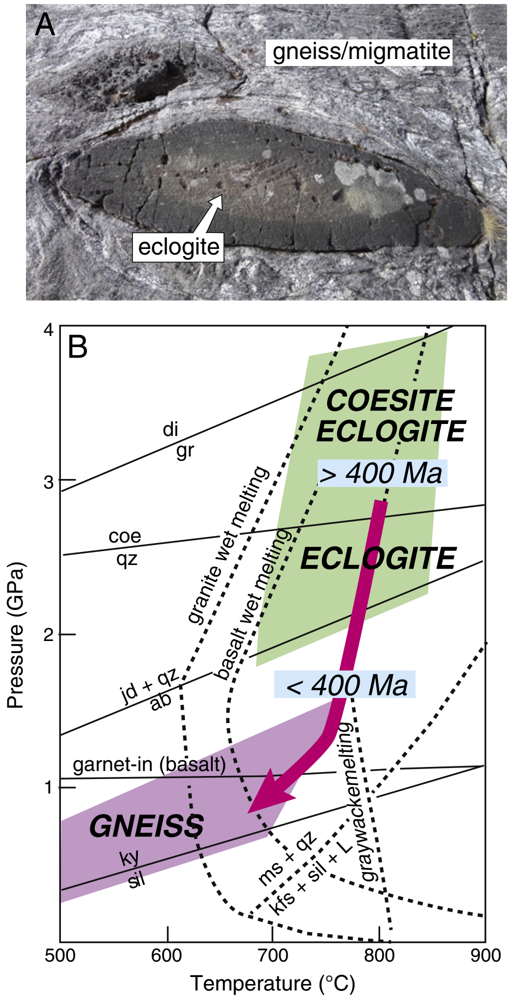

Fig. 1. (A) Outcrop photographs showing meter-scale eclogite lens in migmatitic gneiss, northern UHP domain (WGR, Norway). (B) P–T diagram showing the relationship of WGR metamorphic conditions recorded by eclogite and gneiss and various solidi for meta-igneous and metasedimentary rocks (solidi from Prouteau et al., 2001; Auzanneau et al., 2006; Labrousse et al., 2011; and references therein). Note that although both eclogite and gneiss likely experienced UHP conditions, the gneiss equilibrated at much lower P–T conditions during decompression. Timing of "peak" UHP and lower-P metamorphism from Hacker et al. (2010) and references therein.

Handy, 2005), thus changing the overall deformation regime of the subducted crustal material and potentially of the orogen developing in the overriding plate.

In the Western Gneiss Region (WGR) of Norway (Fig. 2), evidence for (U)HP metamorphism is primarily preserved in eclogite included in gneiss (Carswell et al., 1999; Smith, 1984), although microdiamond has been reported from metapelitic gneiss in the region (Dobrzhinetskaya et al., 1995). Owing to its spectacular exposure and preservation of UHP metamorphism, WGR eclogite has been the focus of much petrological, geochemical, and geochronological research to determine the pressure–temperature–time (P–T–t) history of metamorphism. Studies using a variety of isotopic systems have thoroughly documented Late Silurian to Early Devonian (~425–400 Ma) metamorphism of the Scandian phase of the Caledonian orogeny (Carswell et al., 2003a; Krogh et al., 2011; Kylander-Clark et al., 2007, 2008; Root et al., 2004; Walsh et al., 2007). Studies of gneiss hosting eclogite inclusions in the WGR have documented Precambrian metamorphism (Gorbatschev, 1985; Kullerud et al., 1986; Skår and Pedersen, 2003; Tucker et al., 1990), as well as Caledonian ages for some migmatitic gneiss and pegmatite (Krogh et al., 2004, 2011; Kylander-Clark et al., 2008; Schärer and Labrousse, 2003; this study).

The record of Caledonian migmatization is of particular interest for evaluating relationships between host migmatite and eclogite inclusions in the WGR. Comparison of the P–T paths of Caledonian eclogite with melting and dehydration reactions (Fig. 1), and investigation of the composition and textural locations of leucosomes (Fig. 3) suggests that partial melting may have begun at the high-pressure conditions recorded by WGR eclogite (Labrousse et al., 2011). High-pressure migmatization is further supported by isotopic and inclusion studies that indicate interaction of eclogite and peridotite with the surrounding migmatitic gneiss at near-peak conditions (Griffin and Brueckner, 1985; Vrijmoed et al., 2009).

In this paper, we contribute to ongoing discussion of the occurrence, conditions, and consequences of partial melting in continental subduction by presenting new geochronological and geochemical data for migmatites that host (U)HP eclogite in the WGR. Migmatites in the WGR exhibit a range of textures that may indicate the involvement of melt during metamorphism and deformation (Fig. 3), but the timing of migmatization has not previously been systematically determined for different textural varieties of crystallized melt bodies spatially associated with eclogite. Some previous geochronology studies have focused on texturally late leucosomes (e.g., Krogh et al., 2011) or have dated leucosome minerals using techniques that yield cooling ages, not crystallization ages (e.g., U–Pb titanite; Schärer and Labrousse, 2003). In this study, we focused on a range of migmatite textures, from layer-parallel leucosomes to crosscutting dikes, in order to evaluate migmatite–eclogite relationships from (U)HP to lower-P conditions.

2. Brief overview of the Western Gneiss Region

The WGR is one of the largest and best-exposed ultrahigh-pressure terranes on Earth. UHP conditions are primarily recorded in eclogite pods within migmatite that records polyphase metamorphism (Tucker et al., 1990). The WGR has been the site of many studies of UHP metamorphism, including investigations that focused on the petrology of crustal and mantle rocks (Butler et al., 2013; Carswell and van Roermund, 2005; Carswell et al., 1999, 2003b; Cuthbert et al., 2000; Dobrzhinetskaya et al., 1995; Scambelluri et al., 2008; Smith, 1984; van Roermund et al., 2001, 2002; Vrijmoed et al., 2006; Wain et al., 2000, 2001), the timing of (U)HP metamorphism and exhumation (Carswell et al., 2003a, 2006; Hacker, 2007; Hollocher et al., 2007; Krogh et al., 2011; Kylander-Clark et al., 2007, 2008; Root et al., 2004; Spengler et al., 2009; Walsh et al., 2007), and the structural history and regional tectonic evolution (Brueckner and van Roermund, 2004; Engvik et al., 2007; Foreman et al., 2005; Fossen, 2010; Hacker and Gans, 2005; Hacker et al., 2003, 2010; Johnston et al., 2007; Kylander-Clark et al., 2009; Root et al., 2005; Terry and Robinson, 2003, 2004; Terry et al., 2000a, 2000b; Walsh and Hacker, 2004).

UHP rocks are exposed in three domains in the WGR: south, central, and north (Fig. 2). Many workers have proposed a SE to NW increase in P–T conditions, from 700 °C, ~2.8 GPa in the southern UHP domain to 850 °C, 3.2–3.6 GPa in the north (Cuthbert et al., 2000; Hacker, 2006; Ravna and Terry, 2004). Moreover, maximum P–T conditions may have been as high as 7 GPa and 1000 °C, based on the occurrence of majoritic garnet in websterite (Scambelluri et al., 2008). Leucosomes containing hornblende and Caledonian titanite increase in abundance from southeast to northwest, and the greatest melt fractions in migmatite occur in the northwestern WGR, consistent with the proposal that these rocks achieved the highest Caledonian P–T conditions (Hacker et al., 2010). A possible exception to this trend is a southern-domain eclogite in which microdiamond inclusions in garnet have been identified, indicating a minimum pressure of 3.5 GPa (Smith and Godard, 2013).

Previous WGR geochronology studies have established the timing of Caledonian (Scandian) UHP metamorphism at 425–400 Ma, and have determined the timing (400–385 Ma) of a lower pressure, amphibolite-facies (1.5–0.5 GPa) overprint at similar or slightly higher