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Monazite trace-element and isotopic signatures of (ultra)high-pressure metamorphism: Examples from the Western Gneiss Region, Norway

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Monazite U–Pb and trace-element data were gathered from six high- to ultrahigh-pressure (UHP) samples from the Western Gneiss Region, Norway, using LASS (laser-ablation split-stream ICP-MS) to investigate variations in monazite composition during high-pressure metamorphism. The UHP monazites were found to contain up to 7600 ppm Sr, 110 ppm non-radiogenic Pb, relatively weak negative Eu anomalies, and Y concentrations as low as 500 ppm. Amphibolite-facies monazite that rims the UHP monazite in one sample contains Y concentrations up to 1.6 wt.%, Sr as low as 13 ppm, and no detectable non-radiogenic Pb. The UHP monazite composition (high Sr–Pb) is interpreted to result from growth in the absence of feldspar, possibly aided by increased compatibility of Sr–Pb–Eu^{2+} in the monazite crystal structure at high pressure. Sr in monazite as a proxy for feldspar stability may be a useful tool not only in studying high-pressure metamorphism, but also in determining timescales of melting and crystallization, when the amount of feldspar changes over time.

1. Introduction

The development and application of in situ analytical techniques (laser-ablation ICP-MS, ion microprobe, and electron microprobe) for U/Th–Pb dating has resulted in dramatic progress in our ability to understand and unravel the complexity of mineral histories chiefly because these techniques allow us to quantify trace-element compositions and U/Th–Pb dates from the same volume of material. Attempts to tie radiometric dates to petrologic conditions (i.e., "petrochronology") have been both quantitative and qualitative.

For monazite, quantitative approaches include monazite–quartz oxygen-isotope thermometry (Breecker and Sharp, 2007; Rubatto et al., 2014) and monazite–xenotime and monazite–garnet thermometry (Gratz and Heinrich, 1997; Heinrich et al., 1997; Pyle et al., 2001; Seydoux-Guillaume et al., 2002; McFarlane et al., 2005; Krenn and Finger, 2010). However, difficulty in assessing equilibrium (e.g., Berger et al., 2005) and poorly understood activity–composition relations due to the many end-member compositions of monazite solid solutions, often necessitate qualitative approaches. These approaches use trace-element patterns along with in situ mineral relationships (particularly inclusion relationships) to tie the time of accessory-phase (re)crystallization to the presence/absence or mode of other minerals. For monazite dating, the most-common approach is to interpret Y and heavy rare-earth element (HREE) depletion as reflecting (re)crystallization in the presence of garnet (e.g., Zhu and O'Nions, 1999; Foster et al., 2000; Foster et al., 2002; Rubatto et al., 2013; Stearns et al., 2013). The Eu anomaly in monazite has been suggested as a qualitative monitor of rock feldspar content (Nagy et al., 2002; Rubatto et al., 2013) although this interpretation is complicated by the sensitivity of Eu^{2+}/Eu^{3+} ratios to f_{O2} (Wilke and Behrens, 1999; Aigner-Torres et al., 2007).

Only two studies have discussed the composition of demonstrably high-pressure monazite (Vaggelli et al., 2006; Finger and Krenn, 2007). This study aims to further understand the relationship between trace elements in monazite and the petrologic conditions at which monazite may (re)crystallize, by examining monazite from ultrahigh-pressure rocks (2.5–3.5 GPa) in the Western Gneiss region, Norway. This is an ideal place to examine the influence of high-pressure metamorphism on monazite composition, because both the timing and spatial extent of UHP metamorphism have been well documented (Fig. 1). We argue that high-Sr and common-Pb concentrations in monazite are indicative of (re)crystallization at (U)HP.

2. The Western Gneiss region, Norway

The Western Gneiss region (WGR: Fig. 1) is part of the Scandinavian Caledonides, an orogenic belt that formed from the collision of Baltica and Laurentia between 500 and 375 Ma (e.g., Corfu et al., 2014 and references therein). The terrane contains rare but widespread

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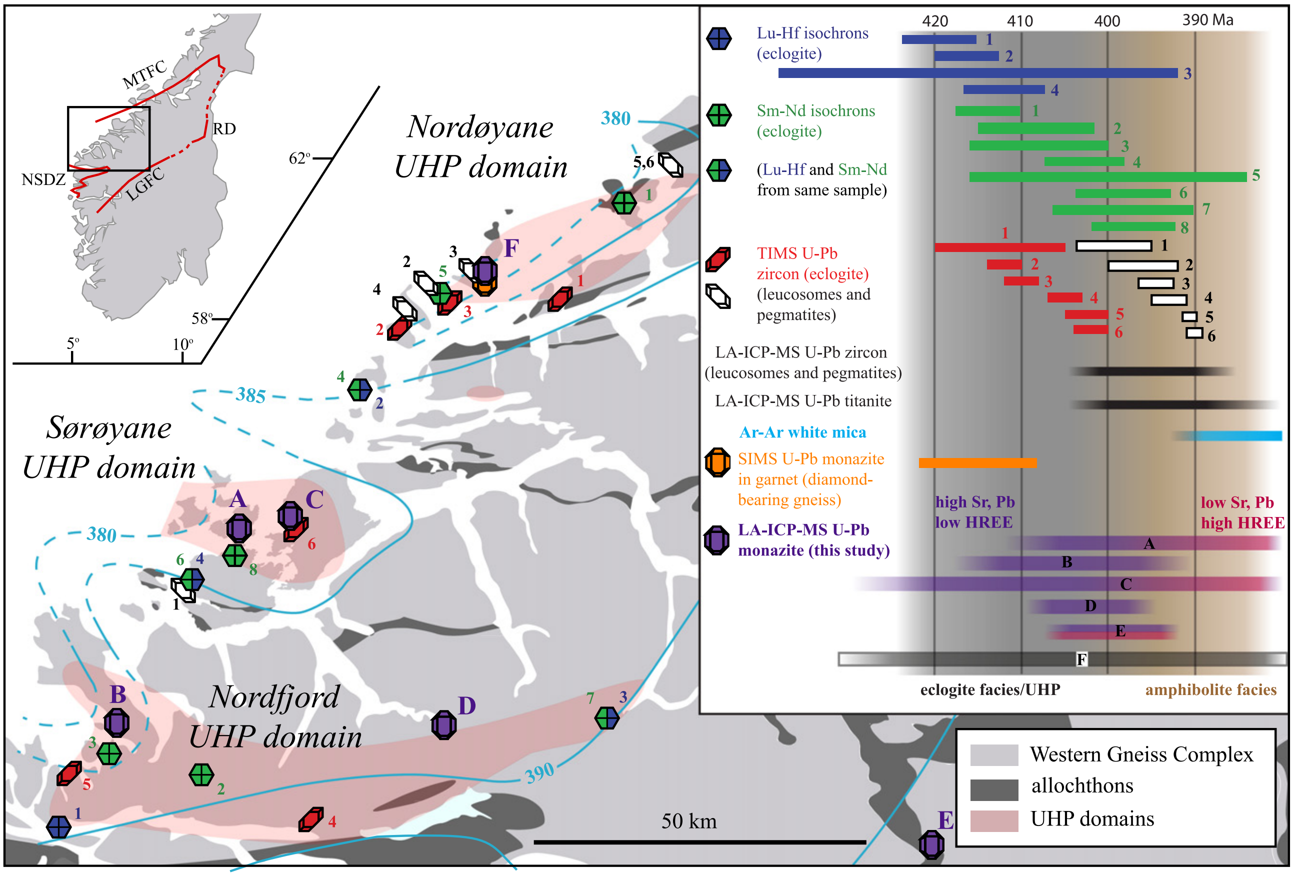

Fig. 1. Simplified geologic map and summary of geochronology used to constrain the timing of eclogite-facies/UHP metamorphism (420–400 Ma) and amphibolite-facies metamorphism (400–380 Ma). The monazites in this study with high Sr and non-radiogenic Pb have U–Pb dates compatible with UHP metamorphism. Lu–Hf isochrons are from Kylander-Clark et al. (2007, 2009). Sm–Nd isochrons from Mørk and Mearns (1986), Mearns (1986), Carswell et al. (2003b), and Kylander-Clark et al. (2007, 2009). TIMS U–Pb zircon dates from eclogites from Carswell et al. (2003a), Root et al. (2004), Young et al. (2007), and Krogh et al. (2011). TIMS U–Pb zircon dates from leucosomes and pegmatites from Krogh et al. (2011), Vrijmoed et al. (2013), and Kylander-Clark and Hacker (2014). LA–ICP-MS U–Pb zircon dates from leucosomes and pegmatites from Gordon et al. (2013) and Kylander-Clark and Hacker (2014). LA–ICP-MS U–Pb titanite dates from Spencer et al. (2013). Ar–Ar white-mica dates and contours from Root et al. (2004), Hacker et al. (2010), and Walsh et al. (2013). SIMS U–Pb monazite date from Terry et al. (2000b). Inset abbreviations: LGFC: the Lærdal–Gjende Fault Complex; MTFZ: Møre–Trøndelag Fault Complex; NSDZ: Nordfjord–Sogn Detachment Zone; RD: Røragen Detachment. Modified from Kylander-Clark and Hacker (2014).

eclogite-facies metamorphic rock and preserves three to four discrete domains that show evidence for UHP (coesite-stable) peak metamorphic conditions of 2.5–3.2 GPa and 650–800 °C (e.g., Cuthbert et al., 2000; Terry et al., 2000a; Root et al., 2004; Hacker, 2006). The onset of continental subduction in the WGR occurred around 430 Ma (e.g., Andersen et al., 1990; Kylander-Clark et al., 2009), and led to the subduction of the Baltica margin to mantle depths (Andersen et al., 1991; Hacker and Gans, 2005). The timing and duration of eclogite-facies metamorphism has been constrained to 425–400 Ma by Lu–Hf isochrons (Kylander-Clark et al., 2007; 2009) and TIMS U–Pb zircon dates from eclogites across the region (Carswell et al., 2003a; Root et al., 2004; Young et al., 2007; Krogh et al., 2011). Exhumation of the UHP rocks to mid-crustal levels occurred shortly after 400 Ma as determined by TIMS and LA–ICP-MS U–Pb zircon from discordant leucosomes and pegmatites (Krogh et al., 2011; Vrijmoed et al., 2013; Gordon et al., 2013; Kylander-Clark and Hacker, 2014), LA–ICP-MS U–Pb titanite from Western Gneiss Complex and hornblende–plagioclase leucosomes (Spencer et al., 2013), and Ar–Ar white-mica dates (Root et al., 2004; Hacker et al., 2010; Walsh et al., 2013).

3. Analytical methods

3.1. Electron-beam methods

Monazite grains were identified through back-scattered electron microscopy and energy-dispersive spectroscopy on a FEI Q400f FEG scanning electron microscope at the University of California, Santa Barbara (UCSB). X-ray maps of the grains were produced on a Cameca SX-100 electron microprobe at UCSB. Quantitative analyses of sample A grain 1 and of all major phases in samples A and B were also conducted on the microprobe. Details of these analyses are described in Appendix 1 and the data is reported in the Supplementary material.

3.2. Pseudosection modeling

Pseudosections of samples A and B were calculated using Perple_X (Connoly and Petrini, 2002) and the internally consistent thermodynamic database of Holland and Powell (2011), to assess which minerals may have been present during (U)HP monazite recrystallization. Details of this procedure are outlined in Appendix 2.

3.3. Laser-ablation split-stream (LASS) petrochronology

All grains were dated using by LASS (laser-ablation split-stream inductively coupled plasma mass spectrometry) using the Nu *Plasma HR* multi-collector and either the Nu *AttoM* high-resolution single-collector or the Agilent *7700S* quadrupole ICP-MS at UCSB. Details of this method are described by Kylander-Clark et al. (2013). Specifics of the analyses in this study are described in Appendix 3 and the data are located in the Supplementary material.