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Slow exhumation of UHP terranes: Titanite and rutile ages of the Western Gneiss Region, Norway

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ABSTRACT

U–Pb ages of titanite and rutile were obtained from the central Western Gneiss Region, Norway, to assess the style and timing of exhumation and cooling of the Western Gneiss UHP terrane. Approximately half of the titanite ages are concordant, the majority of which yield a limited age range from 393 to 390 Ma. The other titanite data are discordant, and define discordia arrays with upper intercept ages of either ~938 Ma or ~1.6 Ga, and a lower intercept of ~389 Ma. Concordant rutile analyses range from 385 to 392 Ma. Both titanite *and* rutile ages young WNW toward the core of the orogen and are ~4 Ma older than $^{40}Ar/^{39}Ar$ muscovite ages, corresponding to a cooling rate of ~90 °C/Ma. A well-defined boundary between concordant and discordant titanite ages, in combination with the WNW-increasing *P–T* gradient and the similarity between muscovite cooling ages in the east and eclogite ages in the west, suggests that the WGR remained coherent throughout its exhumation history, and was progressively unroofed from east to west. A 390.2 ± 0.8 Ma titanite in the Sørøyane UHP domain indicates that exhumation occurred at a vertical rate of ~7 mm/yr for ~12 Ma. These rates are slower than estimates from smaller UHP terranes, but similar to other large UHP terranes, suggesting that there may be fundamental differences in the mechanisms controlling the evolution of large UHP terranes that undergo protracted subduction and exhumation, and smaller UHP terranes that undergo rapid subduction and exhumation.

1. Introduction

The Western Gneiss Region (WGR) of western Norway has long been a primary location for the study of geodynamic processes associated with ultrahigh-pressure (UHP) tectonics as it contains one of the largest (>60,000 km^2) and best-exposed HP terranes on the planet. Much of our understanding of some of the world's most enigmatic processes has been deduced from the inferred history of the WGR, but a large part of its history remains unresolved.

The WGR is composed of crystalline basement of primarily granodioritic to tonalitic composition (the Western Gneiss Complex, WGC), and a series of overlying allochthons emplaced during the initial stages of the Caledonian orogeny (~435–400 Ma, Roberts and Gee, 1985; Hacker and Gans, 2005). Peak pressures and temperatures increase westward, reflecting down-to-the-west subduction of the western edge of the Baltica craton (WGC) beneath Laurentia during the late stages of orogenesis (e.g., Griffin et al., 1985). The western portion of the WGR contains three distinct UHP regions (Fig. 1, Root et al., 2005), the northernmost of which records peak pressures >3.4 GPa (Dobrzhinetskaya et al., 1995; van Roermund and Drury, 1998; Terry et al., 2000b; van Roermund et al., 2001; Carswell et al., 2006). Peak temperatures are ~700–800 °C across the three UHP regions, but decrease south of Nordfjord to ~600–650 °C (Fig. 1, Cuthbert et al., 2000; Labrousse et al., 2004; Walsh and Hacker, 2004; Hacker and Gans, 2005; Carswell et al., 2006; Hacker, 2006; Young et al., 2007). The post-(U)HP exhumation of the WGR was nearly isothermal, with metamorphic minerals recording passage through amphibolite-facies conditions down to pressures as low as 0.6 GPa at 750 °C (Fig. 2, summary in Hacker, 2007).

Exhumation of the WGR imprinted a pervasive, westward-increasing E–W horizontal stretch during decompression-related retrograde amphibolite-facies metamorphism (e.g., Andersen, 1998) and caused local *in situ* melting (Labrousse et al., 2002). Such intrusive bodies form important time and strain markers for studying the exhumation process, but they are similar in appearance and difficult to distinguish from older Phanerozoic and Proterozoic intrusions (Lundmark and Corfu, 2007). Determining the ages of intrusive bodies across the WGR is therefore important to constraining the exhumation mechanism.

Several of the best-studied UHP terranes worldwide are known to have undergone rapid exhumation. The exhumation rate of the WGR is known in general terms (e.g., Root et al., 2005; Hacker, 2007), but it is constrained mostly by peak metamorphic ages locked in at mantle depths and by $^{40}Ar/^{39}Ar$ cooling ages frozen in at mid-crustal levels. The history of the intervening 300 °C of cooling is poorly known, and this

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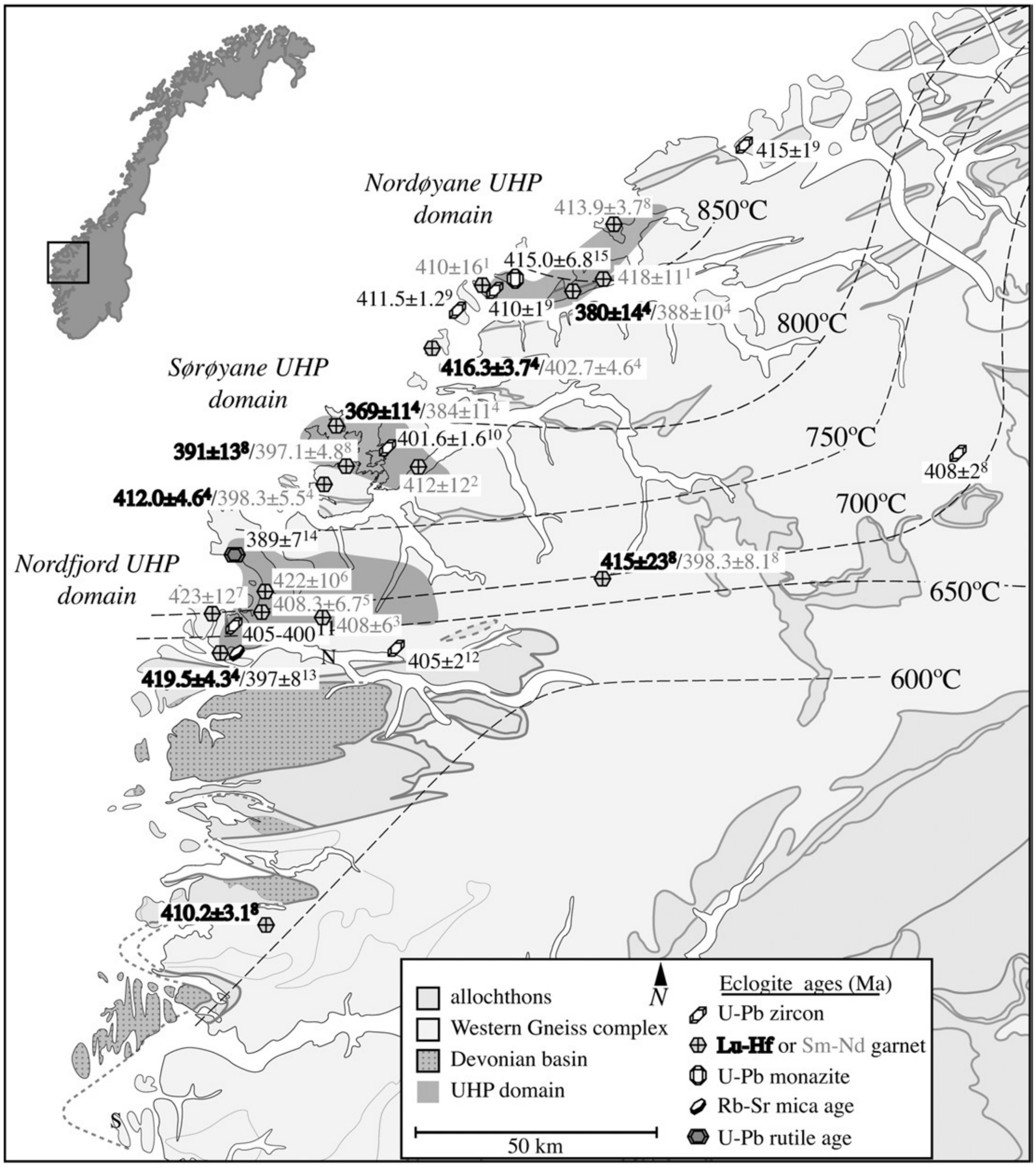

Fig. 1. Western Gneiss Region, western Norway, showing approximate peak temperatures and the following eclogite ages: 1) Mørk and Mearns (1986), 2) Jamtveit et al. (1991), 3) Mearns (1986), 4) Kylander-Clark et al. (2007b), 5) Carswell et al. (2003a), 6) Brueckner (personal comm.), 7) Griffin and Brueckner (1980), 8) Kylander-Clark et al. (2007a), 9) Krogh et al. (2004), 10) Carswell et al. (2003b), 11) Root et al. (2004), 12) Young (2007), 13) Griffin and Brueckner (1985), 14) Schärer and Labrousse (2003), 15) Terry et al. (2000). S = sample location for titanite not shown in Fig. 3; N = Nordfjord.

limits our ability to understand the exhumation mechanism. Understanding the exhumation mechanism requires comprehensive measurements of the cooling rate and its spatial variation throughout the WGR.

Continent-subduction models make predictions of the style and rate at which tectonic processes occur. In particular, the timing and magnitude of melting, and the rates of exhumation and cooling—and their temporal and spatial variation—can be used to distinguish among tectonic models for the formation and exhumation of UHP terranes. These models are best tested through field observations, and can be improved with more accurate input parameters. For the case of Norway, defining how exhumation, melting, and cooling varied spatially from the core of the orogen to the hinterland allows one to discriminate among several models that predict different aspects of the retrograde evolution of the region: 1) Was the WGR exhumed as one coherent body, a few large bodies, or was it well mixed/disrupted (e.g., Wain, 1997; Wain et al., 2000)? 2) Did the WGR stall and flatten at the Moho (Walsh and Hacker, 2004) or was it progressively exhumed at constant rates? 3) Did the slab rise as a diapir through the mantle or was it extruded as a slab (Hacker, 2007; Young et al., 2007)? 4) Was it thick (Root et al., 2005) or thin (e.g., Ernst and Peacock, 1996)? 5) Did the bulk of the crust transform to high-pressure phases or was the transformation limited to mafic material (e.g., Ernst, 2006)? A successful model must predict the deformational structures and the *P*–*T*–*t* path observed for the WGR. The purpose of this study is to address the timing and rates of exhumation, cooling, and melting of the WGR through the geochronology of phases associated with the amphibolite-facies overprint of the WGR.

1.1. Geochronology of sphene and rutile

To be well suited for dating a post-(U)HP amphibolite-facies overprint, a mineral must either i) have an amphibolite-facies closure