Continental exhumation triggered by partial melting at ultrahigh pressure

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Abstract

Partial melting textures, observed in most continental crust buried in ultrahigh-pressure (UHP) conditions, have mostly been related to their retrograde evolution during exhumation in collisional orogens. Analysis of leucosomes from the Western Gneiss Region (WGR, Norway) UHP and HP domains in the Caledonides show a wide scatter of their chemistries, from early ones close to trondhjemites restricted to UHP domains, to granites in late occurrences or associated with HP domains. Nearly trondhjemitic compositions compare with hydrous melts produced in felsic systems at high pressure (>2 GPa) and moderate temperature (<900 °C). Partial melting experiments at higher temperatures or in dry conditions produce granitic glasses similar to late leucosomes from the WGR. Comparison of pressure-temperature paths for Caledonian eclogites with melting and dehydration reactions for the surrounding gneiss suggest that (1) the continental crust remained partially hydrated during its subduction to ultrahigh pressure, and (2) partial melting reactions producing the trondhjemitic melts started as soon as the WGR rocks reached their hydrated solidus, at the peak pressure recorded by the eclogites. The limited partial melting degree at the peak conditions induced weakening of the continental crust, decoupling from the lithospheric root, and initiation of exhumation.

INTRODUCTION

Partial melting of the continental crust, coeval with thermal re-equilibration, is inferred to induce ductile flow of orogens (Teyssier and Whitney, 2002). To evaluate the rheological impact of partial melting on the continental crust during burial and exhumation, the timing of partial melting initiation needs to be constrained, since the softening effect of partial melting is efficient for very low melt contents (Rosenberg and Handy, 2005). Attempts to date partial melting via accessory mineral dating in leucosomes only provided constraints on crystallization stages (Kylander-Clark et al., 2008). This study intends to correlate the natural diversity of leucosomes in the high-pressure (HP) and ultrahigh-pressure (UHP) domains in the Western Gneiss Region (WGR, Norway) with their timing relative to the metamorphic and tectonic evolution of the eclogites and surrounding gneiss. The composition of leucosomes is compared with published experimental data and new experiments performed on a natural sample from the WGR. We conclude that the initiation of partial melting coincides with maximum burial of the Baltica continent, and we discuss the impact of partial melting on continental subduction.

PARTIAL MELTING AT ULTRAHIGH-PRESSURE CONDITIONS

Natural Evidence from Ultrahigh-Pressure Domains

Migmatites have been described in different large-size UHP continental crust units in Dabie Shan (China; Faure et al., 2003), Kokchetav (Russia; Hermann et al., 2001), or Caledonides (Labrousse et al., 2004; Lang and Gilotti, 2007). In the Hercynides, trondhjemites and leucogranulites have also been interpreted as the result of partial melting of crust in HP conditions (Nicollet and Leyreloup, 1978; Kotkova and Harley, 2010). Comparison of *P-T* paths for UHP units with undersaturated solidus for continental crust material (Auzanneau et al., 2006) shows partial melting evidence associated with decompression. Nevertheless, indirect evidence attests that silicate melts can be present at peak conditions. In Dabie Shan, zircon ages from granite dikes overlap with the age for peak metamorphism (Wallis et al., 2005). In Kokchetav, zircons grown from Zr-saturated melts present at UHP conditions (Hermann et al., 2001) were found in K, Na, Si, and light rare earth element–poor gneiss possibly affected by melt extraction. In the WGR, high initial Sr signatures in the Opx-bearing eclogites (Griffin and Brueckner, 1985) were interpreted as due to interaction with the surrounding gneiss at peak conditions. In addition, polyphase solid-inclusions, Sm-Nd, and Sr data from a peridotite body, in the northern WGR, suggest that it was infiltrated by crustal-derived melts at pressures above 3.4 GPa and temperature ∼800 °C (Vrijmoed et al., 2009). The above evidence therefore suggests that partial melting of buried crustal units can occur at their peak pressure.

Constraints for the Western Gneiss Region Pressure-Temperature History

A wealth of experiments have explored the melting behavior of felsic rocks at crustal to mantle pressures (Auzanneau et al., 2006; Hermann and Spandler, 2008; Huang and Wyllie, 1981; Schmidt et al., 2004). Melting curves determined from these experiments can be compared to the *P-T* paths for the WGR (Fig. 1). Low-pressure eclogites from the Sunnfjord area (Labrousse et al., 2004), where rare partial melting textures were described, yield peak conditions in the subsolidus domain. Nordfjord eclogites (Carswell et al., 2000; Hacker, 2007; Labrousse et al., 2004), included in the southernmost migmatites, equilibrated at conditions overlapping the different experimental estimates of the wet solidus curve for continental rocks. Peak conditions estimates for the northernmost UHP eclogites (Hacker et al., 2010; Terry et al., 2000) are bracketed by the wet solidus curves and the undersaturated curve for metapelites. It seems therefore possible that gneiss surrounding the eclogites did melt at UHP conditions if the water budget allowed them for fluid-present partial melting.

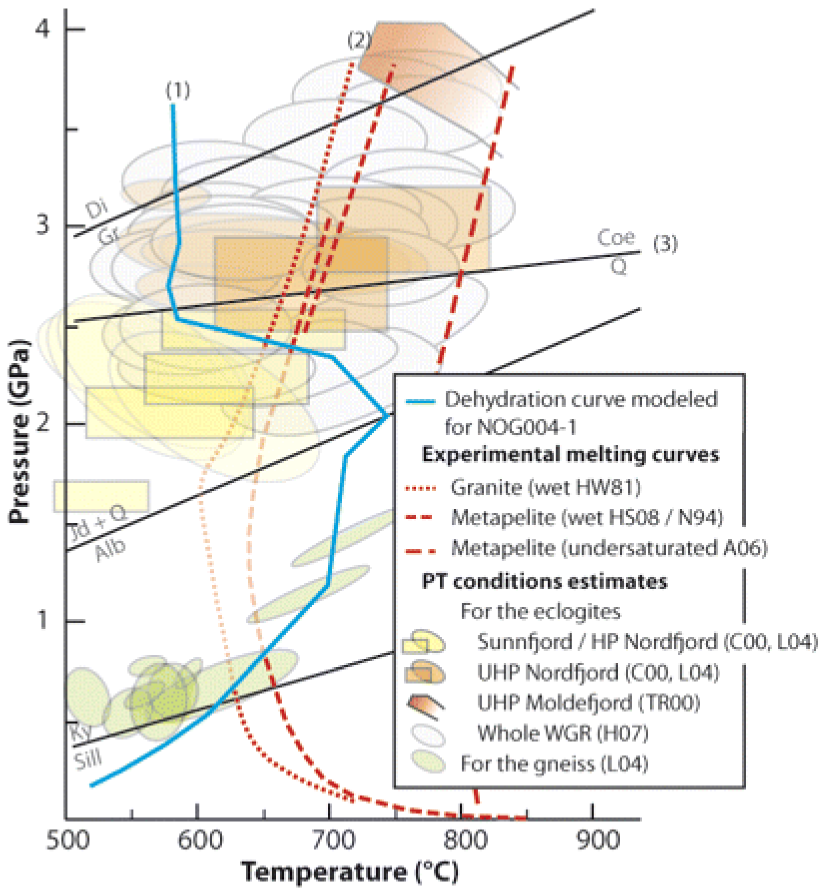

Figure 1.

Pressure-temperature diagram for the Western Gneiss Region (WGR) ultrahigh-pressure (UHP) and high-pressure (HP) domains (CC00: .Carswell et al., 2000; L04: Labrousse et al., 2004; TR00: Terry et al., 2000; H07: Hacker, 2007) compared to hydrated solidus for granites (HW81: Huang and Wyllie, 1981) and metapelites (HS08: Hermann and Spandler, 2008; N94: Nichols et al., 1994; A06: Auzanneau et al., 2006). Computed dehydration curves for our starting material: Domino software (de Capitani and Petrakakis, 2010), Holland and Powell (1998) database. Curves labeled 1–3 are presented in Figure 3.

LEUCOSOMES IN THE WGR AND THEIR CHRONOLOGY

Nine natural leucosomes were collected throughout the eclogite province in the WGR from Nordfjord to Bud (location of sampling and complete chemical analysis is available in Table DR2 in the GSA Data Repository[1]). Samples were selected in association with HP eclogites (sample NO10-16) or UHP eclogites (all others) and with all the possible relative chronologies with regard to the deformation in the gneiss. All samples come from gneiss wrapping the eclogite lenses, and therefore crystallized during or after the Caledonian HP event. Leucosomes transposed in the gneiss foliation are considered as early; leucosomes occurring in patches or veins crosscutting the foliation are considered as late and coeval with retrogression in the amphibolite facies. In an An-Ab-Or projection (Fig. 2A), their compositions define a remarkable trend parallel to the Ab-Or join from nearly trondhjemitic to granitic compositions. Among leucosomes associated with UHP eclogites, trondhjemitic compositions are found in the northernmost UHP localities (Svartberget), and early leucosomes are systematically richer in albite than their late counterparts, on the same outcrop. The leucosome associated with HP eclogites (NO10-16) is close to the latest and southernmost sample associated with UHP eclogites (NO10-27). One noteworthy sample (NO10-51) collected in the crystallization shadow of a meter-scale mafic lens in the Svartberget UHP locality shows a unique tonalitic composition out of the regional trend, with MgO + FeO up to 7.9 wt%. This tonalite is clearly distinct from other leucosomes and probably derived from a different source. The linear trend in granitic compositions, unprobably connected to any sampling bias, could result from variation of the partial melting conditions of a unique source. To test this hypothesis, these leucosome compositions are compared to published experimental data and results from new experiments performed in a pertinent system.

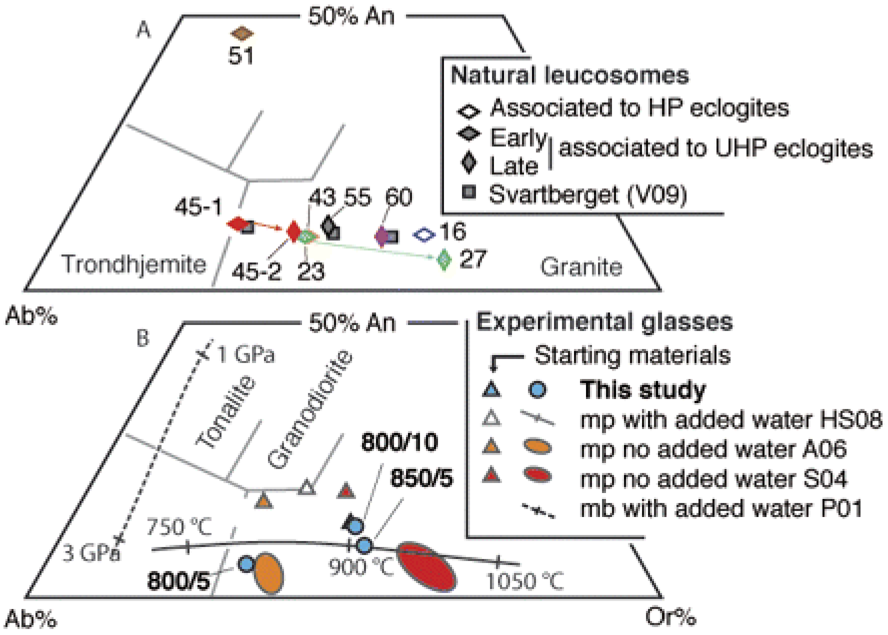

Figure 2.

Anorthite-albite-orthoclase normative triangle showing the Western Gneiss Region leucosomes compositions (A) and the experimental glass compositions (B). A: Numbers XX refer to NO10-XX samples in Table DR2 (see footnote 1). UHP—ultrahigh-pressure; HP—high-pressure. B: Temperature and wt% water added in our experiments (e.g., 800/5 denotes 800 °C and 5 wt% added water). Experimental melt compositions produced in hydrous metapelitic system with (Hermann and Spandler, 2008) or without (Schmidt et al., 2004; Auzanneau et al., 2006) added water. Dashed line represents the evolution with pressure of melts produced from partial melting of hydrous basalt (Prouteau et al., 2001). mp—metapelite; mb—metabasalt.

EXPERIMENTAL CONSTRAINTS

Literature Data

When plotted in the An-Ab-Or projection (Fig. 2B), experimental melt compositions produced in metasedimentary systems in the pressure range 2.2–4.5 GPa and temperature range 750–1050 °C (Auzanneau et al., 2006; Hermann and Spandler, 2008; Schmidt et al., 2004) evolve from trondhjemitic to granitic with An contents not exceeding 10 wt%. Experiments without added water (Auzanneau et al., 2006; Schmidt et al., 2004) cluster in the granitic field, while melts produced in hydrated conditions (H_2O <6 wt%) define a trend parallel to the Ab-Or join (Hermann and Spandler, 2008). This evolution is correlated to increasing melting temperature from 750 °C for trondhjemites to 1050 °C for the potassic end member. This trend is remarkably similar to the natural one, but the temperature range is not realistic in this geological context (Fig. 1). Temperatures exceeding 950 °C, necessary for the production of the more potassic glasses, were not reached in the WGR.

Experiments on a WGR Protolith

In order to estimate the impact of protolith composition and partial melting conditions on melt compositions for the WGR rocks, new piston-cylinder experiments were performed on a natural sample considered as representative of the regional bulk composition (NOG004-1, Table DR1). The starting material NOG004-1, a granitic two-mica gneiss, was reacted at 2.5 GPa with added H_2O at 800 and 850 °C. These experimental conditions (Table DR1) correspond to the maximum temperature reached by the WGR rocks. Hydrous silicate glass (quenched liquid) is present in all experimental charges (Table DR1). Phases identified in addition to glass (Fig. DR1) are mainly garnet, biotite, and kyanite. Plagioclase is also present at 800 °C in the less hydrated run, and orthopyroxene is stable at 850 °C.

The composition of glass produced at 800 °C and 5% added water lies close to the granite-trondhjemite boundary in the An-Ab-Or projection (Fig. 2B), like glasses obtained from metapelites (Auzanneau et al., 2006) in water-undersaturated experiments at comparable *P* and *T*, or derived from wet metapelites at higher pressures and temperatures ~800 °C (Hermann and Spandler, 2008). Glasses produced at higher temperature (850 °C) or higher water content (10 wt%) plot close to the starting material in this projection and compare well with glasses obtained from nearly fluid-absent partial melting experiments on metapelites (Schmidt et al., 2004). They lie in the high-temperature part (>950 °C) of the compositional trend for melts derived from metapelites at HP and hydrated conditions (Hermann and Spandler, 2008). These preliminary results therefore show that the natural trend observed in the WGR leucosomes is similar to the trend in experimental melts from a unique protolith and with realistic temperatures in presence of free water. Limited discrepancies in Mg# and TiO_2 contents between natural and experimental compositions can be explained by a difference in fO_2, which controls Fe-Ti oxides crystallization (Conrad et al., 1988; Prouteau and Scaillet, 2003). The question of what part of the initial melt is actually represented by the final leucosome remains a subject of debate (Kriegsman, 2001). However, the similarity between the compositions of experimental and natural data presented here suggests that leucosomes can preserve their genuine composition along the *P-T* path, with limited interaction with the surrounding gneiss, as opposed to their important metasomatic effect on ultramafic inclusions (Vrijmoed et al., 2009).

Among all experimental results for metapelites, only glasses from experiments at low temperatures (750–800 °C) and pressures above 2.5 GPa in water-present conditions show trondhjemitic compositions (Hermann and Spandler, 2008), suggesting that the nearly trondhjemitic leucosomes observed in the WGR may be produced at temperatures below 800 °C, i.e., close to the peak pressure recorded by the eclogites. This also implies that a significant fraction of free fluid was transported by the continental crust down to UHP conditions. Other evidence suggests free water in the continental crust subducting at mantle depth. If not the result of complex metasomatic reactions with the associated mafic body, the occurrence of a tonalitic leucosome implies that mafic material may have also sporadically melted during the Caledonian burial and exhumation event. Such a tonalitic melt can be produced by fluid-present melting of basalt in the 2–3 GPa range and temperatures below 950 °C (e.g., Prouteau et al., 2001). As temperatures reported along the *P-T* paths for the WGR never exceed 850 °C, a free-fluid phase must have been present in this pressure range. The free water present in the source may come from the breakdown of hydrous phases stable below the wet solidus (Schmidt et al., 2004). Destabilization curves for paragonite, glaucophane, and chloritoid, as computed by Domino software (de Capitani and Petrakakis, 2010) for the NOG004-1 composition limit a free-fluid domain above 700 °C in the amphibolite facies, shifting to 600 °C in the jadeite stability field (Fig. 1). Above 2.5 GPa, the dehydration curve is crossed at lower temperature than the solidus. Therefore, a gneiss subducting along a thermal gradient lower than 8 °C/km would release ∼1% H_2O just before reaching the partial melting field.

DISCUSSION: EVIDENCE FOR PARTIAL MELTING AT ULTRAHIGH PRESSURE AND RHEOLOGICAL IMPLICATIONS

To be subducted to mantle depths, the less dense portions of the continental lithosphere (i.e., the upper crust, with upward buoyancy) must remain coupled to the denser levels (i.e., the lower crust and the lithospheric mantle). In contrast, they must be decoupled to allow exhumation. The peak metamorphism therefore corresponds to the triggering of a decoupling mechanism, such as slab breakoff (von Blanckenburg and Davies, 1995) or metamorphic weakening (Austrheim et al., 1997; Jolivet et al., 2005; Labrousse et al., 2010). Partial melting is considered as a possible weakening mechanism for the continental crust during thermal relaxation of a thickened crust (Vanderhaeghe and Teyssier, 2001) or during decompression of subducted continental slices (Wallis et al., 2005), but rarely mentioned as a mechanism for the very initiation of the exhumation of continental crust at ultrahigh pressure (Hermann et al., 2001). The dehydration curve and the wet solidus for continental crust can be superimposed on the crustal stratigraphy and thermal structure of a collisional orogen (Fig. 3) compatible with *P*-*T* data from the WGR (Fig. 1) deduced from thermal models adapted for the Scandian continental subduction at its paroxysm (Kylander-Clark et al., 2009) and compatible with geometries and *P*-*T* paths predicted for continental subduction from fully coupled thermomechanical modeling with implemented partial melting (Li et al., 2010). Their relative positions suggest that the two boundaries are successively crossed by the upper continental crust between 2.5 and 3.5 GPa. The top of the upper crust evolves from a hydroxyl-bearing mineral state to a partially molten state at 2.3 GPa, while the base of the upper crust dehydrates in the subsolidus domain between 2.5 and 3.5 GPa.

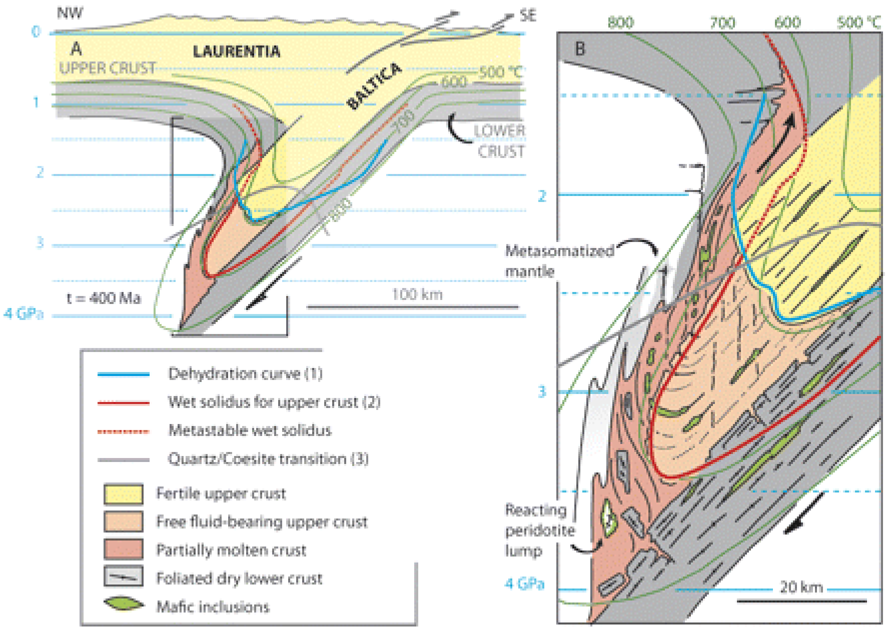

Figure 3.

Conceptual sketch of the Scandian continental subduction at ca. 400 Ma. Dehydration curve (1), wet solidus (2), and quartz/coesite transition (3) from Figure 1. Crustal thicknesses and modeled isotherms from Kylander-Clark et al. (2009).

Even if partial melting at the peak pressure conditions may have remained limited compared to later decompression melting, the first silicate melt may have drastically lowered the effective viscosity of the continental crust (Rosenberg and Handy 2005) and acted as a decoupling mechanism, triggering the exhumation of the upward-buoyant crust. The low-viscosity migmatites can also incorporate lumps of peridotite from meter to kilometer scale (Brueckner and Medaris, 2000) and drag dense eclogite lenses or dry unreacted parts of the lower crust toward the surface without significant temperature change.

The long-term (>10 Ma?) persistence of such a partially molten channel as a steady-state geometry could also explain the scatter of eclogites with contrasted *P-T* records (Fig. 1) as well as the poor correspondence between UHP eclogite occurrences and structures in the gneiss. Indeed, the limits of UHP domains remain diffuse (Hacker et al., 2010).

CONCLUSIONS

The chemical study of natural leucosomes from the WGR displays a linear trend from early trondhjemites to late granites, with occasional tonalite associated with a mafic lens. The products of partial melting experiments performed on a natural sample representative of the WGR gneiss at the maximum temperature recorded during their retrogression partly reproduce the natural trend. We deduce from this and published experiments in a similar system (Hermann and Spandler, 2008) that (1) leucosomes trapped in the gneiss preserved their genuine composition, and (2) first melts nearly trondhjemitic were produced at temperatures as low as 750 °C and pressures higher than 2.5 GPa, i.e., at the peak conditions recorded by eclogites. Onset of water-present partial melting and maximum burial of the continental slab would then be coeval, the release of free water by breakdown of hydroxyl-bearing minerals occurring at pressures as high as 2.5 GPa according to thermochemical modeling. A tonalitic leucosome even testifies to possible limited melting of eclogites themselves in hydrated conditions. Liquids produced by water-present melting at the peak conditions are sufficient to weaken the continental crust, decouple it from the down-going slab, and favor its ascent by buoyancy forces, explaining the apparent coincidence of peak *P-T* conditions recorded by the eclogites and the wet solidus for continental crust

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