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Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision

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A B S T R A C T

Partial melting at continental lithosphere depths plays an important role in generating geochemical variations in igneous rocks. In particular, dehydration melting of ultrahigh-pressure (UHP) metamorphic rocks during continental collision provides a petrological link to intracrustal differentiation with respect to the compositional evolution of continental crust. While island arc magmatism represents one end-member of fluid-induced large-scale melting in the mantle wedge during subduction of the oceanic crust, the partial melting of UHP rocks can be viewed as the other end-member of fluid-induced small-scale anatexis during exhumation of the deeply subducted continental crust. This latter type of melting is also triggered by metamorphic dehydration in response to P–T changes during the continental collision. It results in local occurrences of hydrous melts (even supercritical fluids) as felsic veinlets between boundaries of and multiphase solid inclusions in UHP metamorphic minerals as well as local accumulation of veinlet-like felsic leucosomes in foliated UHP metamorphic rocks and metamorphically grown zircons in orogenic peridotites. Thus, very low-degree melts of UHP rocks provide a window into magmatic processes that operated in continental subduction zones. This article presents a review on available results from experimental petrology concerning the possibility of partial melting under conditions of continental subduction-zone metamorphism, and petrological evidence for the occurrence of dehydration-driven in-situ partial melting in natural UHP rocks during the continental collision. Although the deeply subducted continental crust is characterized by a relative lack of aqueous fluids, the partial melting in UHP rocks commonly takes place during decompression exhumation to result in local in-situ occurrences of felsic melts at small scales. This is caused by the local accumulation of aqueous fluids due to the breakdown of hydrous minerals and the exsolution of structural hydroxyl and molecular water from nominally anhydrous minerals in UHP rocks during the exhumation. The dehydration melting of UHP rocks would not only have bearing on the formation of supercritical fluids during subduction-zone metamorphism, but also contribute to element mobility and ultrapotassic magmatism in continental collision orogens. Therefore, the study of dehydration melting and its effects on element transport in UHP slabs, rocks and minerals is a key to chemical geodynamics of continental subduction zones.

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1. Introduction

Continental collision is defined as a series of tectonic processes that encompass subduction and exhumation of the continental crust with regional metamorphism at low-pressure greenschist facies, high-pressure (HP) blueschist and eclogite facies, to ultrahigh-pressure (UHP) conditions in the stability field of coesite and diamond. Lithosatic pressures are assumed to cause mineralogical reactions and phase changes in the crustal interior, resulting in formation of HP to UHP parageneses and index minerals (e.g., Schreyer, 1995; Liou et al., 1998; Chopin, 2003). The continental collision is associated with intercontinental orogenesis within the framework of plate tectonics theory. Thus, continental collision orogens are categorized into two types, depending on the nature of colliding crustal slabs (Zheng et al., 2009a,b). One is continent–continent collision orogens that are generated by collision between two ancient continents (e.g., Dabie–Sulu of China, Western Gneiss Region of Norway), and the other is arc–continent collision orogens that are produced by collision between a juvenile arc and an ancient continent (e.g., Alps of Western Europe, Himalaya of South Asia). The continental collision takes place within given temporal and spatial frameworks, which can be clearly distinguished from post-collisional processes. However, post-collisional magmatism is very common in the two types of continental collision orogens, often erasing various records of collisional orogenesis.

A prominent progress in Earth sciences is discoveries of coesite and micro-diamond inclusions in metamorphic minerals of supracrustal rocks (e.g., Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990; Xu et al., 1992). It provides mineralogical evidence for burial of crustal rocks to mantle depths of >120 km. This has resulted in recognition of continental deep subduction and UHP metamorphism, leading to dramatic advance in our understanding of the plate tectonics theory. (e.g., Schreyer, 1995; Liou et al., 1998, 2009; Chopin, 2003; Jahn et al., 2003a; Rumble et al., 2003; Zheng et al., 2003a, 2009a; Ernst and Liou, 2008). Some special textures of mineral exsolution were also found in UHP metamorphic rocks (e.g., Dobrzhinetskaya et al., 1996; van Roermund and Drury, 1998; Ye et al., 2000; Ogasawara et al., 2002; Song et al., 2005; Liu et al., 2007a,b), suggesting possible ultradeep metamorphism at depths in excess of 200 to 300 km. These deep processes would not only result in phase changes and mineralogical reactions within UHP slabs, but also bring about crust–mantle interactions during the continental collision.

UHP metamorphic rocks would commonly evolve under nominally anhydrous conditions and thus were examined mainly in terms of phase relationships among crystalline minerals (Poli and Schmidt, 2002; Zheng, 2009). Peak P–T conditions of UHP metamorphism during the continental collision are commonly estimated to be as high as 3.3–4.4 GPa at 700–950 °C. At these conditions, dehydration melting in UHP slabs due to breakdown of hydrous minerals such as mica- and epidote-group minerals is possible (Hermann, 2002a; Schmidt and Poli, 2003; Patiño Douce, 2005; Auzanneau et al., 2006). The generation of hydrous silicate melts by dehydration-driven in-situ partial melting has been increasingly recognized in UHP rocks (e.g., Labrousse et al., 2002; Massonne, 2003; Hwang et al., 2004; Whitney et al., 2004; Perchuk et al., 2005; Korsakov and Hermann, 2006; Lang and Gilotti, 2007; Zhao et al., 2007; Xia et al., 2008; Ragozin et al., 2009; Liu et al., 2010). Partial melting of UHP metamorphic rocks can dramatically affect the rheology of deeply subducted crust and thus play a crucial role in accelerating the exhumation of UHP slabs (Hermann et al., 2001; Labrousse et al., 2002; Chopin, 2003). Thermal–mechanical models support a link among continental subduction, partial melting, and crustal flow in the overriding continental lithosphere and suggest that partial melting may be a significant process in exhumation of UHP rocks and collisional orogenic evolution in general (Whitney et al., 2009).

Partial melting of the lower crustal rocks during HP granulite-facies metamorphism is well established and its genetic links to migmatite and granite have been explored in terms of metamorphic petrology and geochemistry (Clemens, 1990; Brown, 1994; Villaseca et al., 2001; Brown, 2007). Partial melting of thermally mature zones of thickened crust can result in the generation of a layer of low-viscosity rocks, which can significantly affect the rheological behavior of crustal rocks in orogenic belts (e.g., Arzi, 1978; Brown and Solar, 1998; Whitney et al., 2003). This would favor mechanical decoupling between the subducting plate and the overlying thickened orogenic crust (Vanderhaeghe and Teyssier, 2001; Wallis et al., 2005), density-driven intracrustal differentiation at mantle depths (Patiño Douce, 2005), and tectonic collapse of collisional orogens (Rey et al., 2001; Vanderhaeghe and Teyssier, 2001; Skjerlie and Patiño Douce, 2002). The generation, transport and final fate of crustal melts are controlled by tectonic forces (Vanderhaeghe and Teyssier, 2001; Brown, 2007), and thus may have different dynamic and temporal relationships with tectonic events during collisional orogenesis (Keay et al., 2001; Whitney et al., 2003).

However, it is hardly straightforward to demonstrate explicitly that the incipient melting indeed took place in these UHP rocks because most of UHP metamorphic rocks have experienced extensive retrograde reaction and reequilibration during exhumation. This is particularly so for those UHP rocks that experienced amphibilite-facies overprinting. If aqueous fluids were locally present in felsic UHP lithologies to approach water saturation at appropriate P–T conditions, partial melting would take place even under reduced geothermal gradients (e.g., Compagnoni and Rolfo, 1999; Chopin, 2003). Nevertheless, isothermal or heating decompression is generally associated with the initial exhumation of UHP slabs (Carswell and Zhang, 1999; Zong et al., 2007; Liu et al., 2010; Xia et al., 2010; Gao et al., 2011; Janak et al., 2011; Zheng et al., 2011). This involves high geothermal gradients and thus is called as the "hot" exhumation in comparison to the continental "cold" subduction. Partial melting can take place during the "hot" exhumation of deeply subducted continental crust from peak UHP depths if sufficient water becomes available from decomposition of hydrous minerals (Hermann, 2002a; Patiño Douce, 2005; Auzanneau et al., 2006). As soon as the melting occurs in UHP rocks, it transforms water bound in hydrous minerals and nominally anhydrous minerals to aqueous fluids and hydrous melts, which may be also an efficient catalyst for the tectonic exhumation of UHP slices from mantle depths.