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Focus paper

On ultrahigh temperature crustal metamorphism: Phase equilibria, trace element thermometry, bulk composition, heat sources, timescales and tectonic settings

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Ultrahigh temperature (UHT) metamorphism is the most thermally extreme form of regional crustal metamorphism, with temperatures exceeding 900 °C. UHT crustal metamorphism is recognised in more than 50 localities globally in the metamorphic rock record and is accepted as 'normal' in the spectrum of regional crustal processes. UHT metamorphism is typically identified on the basis of diagnostic mineral assemblages such as sapphirine + quartz, orthopyroxene + sillimanite ± quartz and osumilite in Mg–Al-rich rock compositions, now usually coupled with pseudosection-based thermobarometry using internally-consistent thermodynamic data sets and/or Al-in-Orthopyroxene and ternary feldspar thermobarometry. Significant progress in the understanding of regional UHT metamorphism in recent years includes: (1) development of a ferric iron activity–composition thermodynamic model for sapphirine, allowing phase diagram calculations for oxidised rock compositions; (2) quantification of UHT conditions via trace element thermometry, with Zr-in-rutile more commonly recording higher temperatures than Ti-in-zircon. Rutile is likely to be stable at peak UHT conditions whereas zircon may only grow as UHT rocks are cooling. In addition, the extent to which Zr diffuses out of rutile is controlled by chemical communication with zircon; (3) more fully recognising and utilising temperature-dependent thermal properties of the crust, and the possible range of heat sources causing metamorphism in geodynamic modelling studies; (4) recognising that crust partially melted either in a previous event or earlier in a long-duration event has greater capacity than fertile, unmelted crust to achieve UHT conditions due to the heat energy consumed by partial melting reactions; (5) more strongly linking U–Pb geochronological data from zircon and monazite to *P*–*T* points or path segments through using Y + REE partitioning between accessory and major phases, as well as phase diagrams incorporating Zr and REE; and (6) improved insight into the settings and factors responsible for UHT metamorphism via geodynamic forward models. These models suggest that regional UHT metamorphism is, principally, geodynamically related to subduction, coupled with elevated crustal radiogenic heat generation rates.

1. Introduction

Ultrahigh temperature (UHT) metamorphism is the most thermally extreme type of regional crustal metamorphism, defined by Harley (1998b) as non-igneous crustal temperatures above 900 °C. UHT metamorphism of continental crust is now widely accepted as a relatively common—rather than anomalous—characteristic of deep crustal processes, greatly assisted by the large (and growing) number of localities worldwide that contain mineral assemblages whose stability has been constrained experimentally (Schreyer and Seifert, 1969a,b; Hensen and Green, 1970; Hensen, 1971, 1972a,b, 1977; Hensen and Essene, 1971; Hensen and Green, 1971, 1972, 1973; Chatterjee and Schreyer, 1972; Newton 1972; Doroshev and Malinovskiy, 1974; Newton et al., 1974; Seifert, 1974; Ackermand et al., 1975; Kiseleva, 1976; Arima and Onuma, 1977; Annersten and Seifert,

Mineral and phase abbreviations: bi, biotite; cd, cordierite; crn, corundum; cpx, clinopyroxene; g, garnet; ilm, ilmenite; ksp, K-feldspar; ky, kyanite; liq, silicate melt; mt, magnetite; opx, orthopyroxene; osm, osumilite; pl, plagioclase; q, quartz; ru, rutile; sa, sapphirine; sill, sillimanite; sp, spinel.

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1981; Bertrand et al., 1991; Motoyoshi et al., 1993; Audibert et al., 1995; Carrington, 1995; Carrington and Harley, 1995a,b, 1996; Das et al., 2001, 2003; Hollis and Harley, 2003; Brigida et al., 2007; Fockenberg, 2008; Podlesskii et al., 2008; Podlesskii, 2010) and reinforced by calculated phase equilibria (Kelsey et al., 2004; Kelsey et al., 2005; Podlesskii et al., 2008; Podlesskii, 2010; Taylor-Jones and Powell, 2010; Holland and Powell, 2011; Korhonen et al., 2012b; Wheller and Powell, 2014). UHT metamorphism has been documented at relatively local scales (e.g. Sandiford et al., 1987; Harley and Fitzsimons, 1991; Gnos and Kurz, 1994), including adjacent to anorthositic/mafic intrusions (e.g. Berg and Wheeler, 1976; Berg, 1977; Caporuscio and Morse, 1978; Kars et al., 1980; Arima and Gower, 1991; Dasgupta et al., 1997; Westphal et al., 2003; Peng et al., 2010; Kooijman et al., 2011; Guo et al., 2012; Mitchell et al., 2014), as well as on a regional scale (e.g. Ellis et al., 1980; Grew, 1980; Sheraton et al., 1980; Grew, 1982b; Lal et al., 1987; Harley and Hensen, 1990; Dasgupta et al., 1994; Brown and Raith, 1996; Ouzegane and Boumaza, 1996; Raith et al., 1997; Sengupta et al., 1999; Hollis and Harley, 2002; Sarkar et al., 2003a; Schmitz and Bowring, 2003; Sajeev et al., 2004; Santosh and Sajeev, 2006; Bose and Das, 2007; Braun et al., 2007; Harley and Kelly, 2007a; Brandt et al., 2011; Das et al., 2011; Smithies et al., 2011; Adjerid et al., 2013; Korhonen et al., 2013a; Collins et al., 2014; Sarkar and Schenk, 2014; Walsh et al., 2014). Extensive exposures of UHT granulites are an exciting phenomenon as they imply that Earth's crust is mechanically capable of attaining and tolerating extreme thermal conditions on a regional scale (Harley, 2004), perhaps during 'normal' tectonic events (e.g. Vielzeuf et al., 1990; Harley, 2008; Kelsey, 2008). The reality that crustal rocks can be regionally subjected to such extreme temperatures has implications for lithospheric rheology and crust–mantle interactions and coupling (e.g. crustal growth and differentiation) (e.g. Vielzeuf et al., 1990; Collins, 2002; Harley, 2004; Kemp et al., 2007) and the geodynamic setting in which UHT metamorphism can be attained (e.g. Vielzeuf et al., 1990; Harley, 1998b; Harley, 2000; Clark et al., 2011; Sizova et al., 2014). An essential aspect of attempting to constrain the tectonic and/or geodynamic settings in which UHT granulites develop is to accurately constrain the pressure–temperature–time (P–T–t) evolution of UHT granulite terranes, and significant progress has been made in this regard in recent years.

The recent progress has led to numerous advances that have improved our understanding of thermally extreme deep crustal processes. The advances include: (1) expanded thermodynamic models for UHT minerals such as sapphirine; (2) new microanalytical tools for the chemical analysis of trace elements in minerals, which has proven particularly useful where the concentration of these elements may be calibrated as a thermometer, such as in the slightly pressure-dependent Ti-in-zircon and Zr-in-rutile thermometers; (3) a more realistic consideration of the thermal properties of the crust in geodynamic modelling, and the role these play in the calculated thermal structure/profile of the crust; (4) geodynamic modelling that has specifically targeted the question of how the crust attains temperatures >900 °C and what tectonic settings are most probable for generating UHT conditions; and (5) voluminous geochronological data sets that have provided much-needed information about timescales of UHT (and granulite) metamorphism, particularly where geochronological data has been linked to the growth and/or breakdown of rock-forming minerals (usually garnet), and thus to P–T points or segments, via constraints from trace element partitioning. In addition, there is an increased global interest in UHT metamorphism, as shown by the greater-than-threefold (>300%) increase in the number of scientific papers published on or around the topic of UHT metamorphism since 2007 compared with the interval 2000–2006. In view of these considerations, it is useful to provide an update of the advances and progress from the past five years or so.

First we will provide an overview of what is currently known about UHT metamorphism (see Kelsey (2008) and Harley (2008) for additional details), including UHT localities identified since 2007. The second part of this review will discuss new advances outlined above that have improved our understanding of UHT metamorphism. This contribution is provided primarily as a comprehensive update of Kelsey (2008) and Harley (2008). Nevertheless, much of the information provided in Kelsey (2008) and Harley (2008) remains relevant.

2. What is UHT crustal metamorphism?

Ultrahigh temperature crustal metamorphism was defined by Harley (1998b) as a subdivision of granulite facies metamorphism, with temperatures in excess of 900 °C at pressures of 7–13 kbar (Fig. 1; *metamorphic petrologists subdivision* in Stüwe, 2007). The UHT subdivision was proposed partly in response to the (then) new concept of ultrahigh pressure metamorphism, reasoning that accepting that the crust can sustain thermally extreme conditions provides a new challenge to understand the tectonic and geodynamic drivers. The low-temperature bound of 900 °C for UHT metamorphism was defined on the basis of the experimentally-constrained location of the spinel-absent invariant point, which marks the low P–T stability limit of the comparatively rare orthopyroxene + sillimanite + quartz + silicate melt assemblage (see later) in the K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O, or KFMASH, model (experimental) chemical system (Carrington and Harley, 1995a; Harley, 1998b). As anticipated by Harley's (1998b) original definition of UHT, Pattison et al. (2003) demonstrated that there is no thermal gap between UHT and high-temperature (HT; ~750–900 °C) granulite facies metamorphism. Rather, there is a continuum in the distribution of temperature conditions retrieved from granulite facies rocks, from approximately 750 °C up to approximately 1100 °C (see also Brown, 2014).

Brown (2006, 2007a,b) and Stüwe (2007) also defined UHT metamorphic conditions in terms of the apparent thermal gradient of the crust (Fig. 1; *tectonicists subdivision* in Stüwe, 2007). UHT (and granulite) conditions are defined as those where the thermal gradient exceeds 75 °C $kbar^{-1}$, or approximately 20 °C km^{-1} (Brown, 2007a; Stüwe, 2007; Brown, 2010b, 2014). The logic behind characterising the crust in terms of thermal gradient (dT/dz, or dT/dP, where z is depth), or thermal structure, is that different tectonic settings are characterised by different thermal regimes. Characterising Earth's crust in terms of apparent thermal gradients is useful for appreciating that UHT metamorphism is probably occurring at depth in numerous parts of the modern/contemporary world (e.g. Sandiford and Powell, 1986a; Harley, 1989; Hayob et al., 1989; Hayob and Essene, 1990; Hacker et al., 2000; Blackburn et al., 2011; Ortega-Gutiérrez et al., 2012), and that many regional lower grade, high-geothermal gradient terranes are likely to be underlain by UHT rocks. Therefore, our view of UHT metamorphism should not be restricted only to exhumed terranes. Indeed, the notion of recognising, via xenoliths for example, or hypothesising (probable) UHT metamorphism at depth in the crust on the basis of contemporary heat flow is powerful as it allows for tectonic/geodynamic settings of the modern Earth to be interrogated as potential sites of modern as well as ancient UHT metamorphism (Sandiford and Powell, 1986a; Hyndman et al., 2005; Currie and Hyndman, 2006; Brown, 2007a,b; Hyndman and Currie, 2011).