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P–T–time-isotopic evolution of coesite-bearing eclogites: Implications for exhumation processes in SW Tianshan

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ABSTRACT

The Chinese Southwestern Tianshan high- to ultra-high pressure low temperature (HP–UHP/LT) metamorphic belt exhibits well-preserved mafic layers, tectonic blocks/slices and boudins of different sizes and lithology embedded within dominant meta-volcanosedimentary rocks. Despite a wealth of previous studies on UHP relicts, P–T path estimates and age constraints for metamorphism, controversies still exist on P–T–t assessments and regional exhumation patterns (i.e., tectonic mélange versus internally coherent “sub-belt” model). This study focuses on a group of coesite-bearing eclogite samples from a thick (~5 m) layered metabasalt outcrop in order to unravel its detailed tectono-metamorphic evolution through space and time (both prograde, peak and exhumation). Using SIMS zircon U–Pb and oxygen isotope analyses, TIMS Sm–Nd multi-point isochron dating, in situ laser-ICP-MS trace-element analyses, classical thermobarometry and thermodynamic modeling, we link the multistage zircon growth to garnet growth and reconstruct a detailed P–T–time-isotopic evolution history for this UHP tectonic slice: from UHP peak burial ~2.95 ± 0.2 GPa, 510 ± 20 °C around 318.0 ± 2.3 Ma to HP peak metamorphism ~2.45 ± 0.2 GPa, 540 ± 20 °C at 316.8 ± 0.8 Ma, then, with eclogite-facies deformation ~2.0 ± 0.15 GPa, 525 ± 25 °C at 312 ± 2.5 Ma, exhumed to near surface within ca. 303 to ca. 280 Ma. Our P–T-time-isotopic results combined with the compilation of regional radiometric data and P–T estimates notably point to the existence of a short-lived period of rock detachment and exhumation (<10 Ma, i.e. at ca. 315 ± 5 Ma) with respect to subduction duration.

1. Introduction

Mechanisms and processes responsible for the occasional recovery of negatively buoyant, ocean-derived high- to ultra-high pressure low temperature (HP–UHP/LT) eclogites equilibrated along the subduction plate interface and for their juxtaposition as tectonic slices or blocks during exhumation remain a matter of debate (Agard et al., 2009; Burov et al., 2014; Chen et al., 2013; Federico et al., 2005; Gerya et al., 2002; Guillot et al., 2009; Klemd et al., 2011; Lü et al., 2012; Warren, 2013; Warren et al., 2008). The Southwestern Tianshan Akeyazi HP–UHP/LT metamorphic belt potentially provides an interesting test example, with well-preserved mafic horizons or tectonic blocks/slices/boudins of different sizes (from the cm- to km-scale) embedded in volumetrically dominant meta-volcanosedimentary rocks (Gao and Klemd, 2003; Gao et al., 1999; Meyer et al., 2016).

However, despite numerous previous works (on UHP relicts, detailed petrology, P–T estimates on isolated blocks/slices and time constraints on the timing of metamorphism; Section 2), this area is still a matter of controversy as to (i) the exact P–T evolution and age of metamorphism, (ii) whether the metamorphic belt may be composed of two distinct HP and UHP slices and (iii) whether mafic bodies represent a tectonic mélange (Du et al., 2014; Gao et al., 1999; Klemd et al., 2011; Li et al., 2015; Meyer et al., 2016) or an assembly of km-scale tectonic slices (Lü et al., 2012).

Uncertainties partly arise from the fact that conclusions were drawn on spectacular but isolated samples (sometimes from loose scree and river beds) rather than on an extensive coverage of the area, and do not sufficiently link recrystallization observations with P–T data. In

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order to contribute to clarifying these issues, we herein review and reappraise available P–T–t constraints for the area (Figs. 1b, 2) and perform a combined P–T-radiometric-isotopic study on several eclogitic samples from a key location. Samples come from a thick (~5 m) layered eclogite outcrop close to where UHP was previously reported (Lü and Zhang, 2012, Fig. 1b) and were chosen to provide detailed constraints on their tectono-metamorphic and geochronological evolution (prograde, peak and exhumation stages) using SIMS high precision U–Pb isochron dating of zircon grains and whole-rock the TIMS Sm–Nd technique. Implications for recrystallization and exhumation processes are discussed and set back within the frame of the regional geodynamic evolution.

2. Geological setting

2.1. The Chinese Southwestern Tianshan HP–UHP/LT metamprphic complex

The Chinese Southwestern Tianshan high- to ultrahigh-pressure low-temperature metamorphic complex extends for about 200 km along the Southwestern Central Tianshan Suture Zone (SCTSZ; Fig. 1). It is correlated with the Atbashi metamorphic complex in the Southwestern Tianshan Accretionary Complex (Hegner et al., 2010) and the Fan–Karategin metamorphic belt (Volkova and Budanov, 1999). Gao et al. (1998) proposed that this HP–UHP/LT complex formed from the northward subduction of the South Tianshan Ocean and subsequent collision between the already amalgamated Kazakhstan–Yili-Central Tianshan terrane, in the north, and the Tarim–Karakum plates in the south. Subduction polarity is still debated, however, with alternative suggestions of southward subduction (e.g. Lin et al., 2008).

The Southwestern Central Tianshan Suture Zone bounds to the north the Chinese section of the HP–UHP/LT metamorphic complex, known as the Akeyazi metamorphic complex. This contact, now a ~0.5 km wide sinistral strike-slip shear zone, was active from the late Permian to early Triassic (Gao and Klemd, 2000, 2003; Gao et al., 1995). To the north lies a LP–HT Palaeozoic active continental margin (Allen et al., 1993; Gao et al., 1998; Klemd et al., 2014), mainly made of amphibolite- and granulite-facies rocks, along with Late Silurian and Early Carboniferous continental arc-type volcanic and volcaniclastic rocks and granitoids (Gao and Klemd, 2003; Gao et al., 2009; Xia et al., 2014). The Akeyazi metamorphic complex (AMC) is overlain to the southwest by unmetamorphosed Palaeozoic sedimentary strata representing the northern, passive continental margin on margin of the Tarim plate (Allen et al., 1993; Carroll et al., 1995).

The Akeyazi metamorphic complex is predominantly composed of strongly schistosed meta-volcanosedimentary rocks hosting mafic metavolcanics, marbles and rare ultramafic rocks. Mafic metavolcanics are eclogites and/or blueschists showing gradual transitions or interlayering (Li et al., 2012). They are distributed as pods, boudins, thin layers or massive blocks in the host rocks (Gao and Klemd, 2003). The AMC was interpreted by some as a tectonic mélange and thought to have formed in a subduction accretionary wedge during subduction of the Southwestern Tianshan ocean (Gao and Klemd, 2003; Gao et al., 1999). Both the metavolcanics and the matrix meta-volcanosedimentary were variably retrogressed under blueschist and/or greenschist facies conditions.

Whole-rock geochemical data for the mafic metavolcanics suggest ocean basalt or arc-related affinities (Gao and Klemd, 2003; John et al., 2008; Klemd et al., 2005). A recent study indicated that some eclogite boundins also have a continental arc affinity protolith, possibly originating from the basement of a Palaeozoic continental arc setting (Liu et al., 2014a).

2.2. Previous age constraints on the P–T evolution of tectonic slices/blocks

Most peak metamorphic estimates for eclogites and prograde blueschists (differences are largely controlled by lithology) yield eclogite-facies HP–LT conditions within the range 480–580 °C and 1.5–3.0 GPa (Beinlich et al., 2010; Gao et al., 1999; John et al., 2008; Klemd et al., 2002; Li et al., 2016; Meyer et al., 2016; Soldner et al., in press; Wei et al., 2003). A range of P–T conditions of 570–630 °C at 2.7–3.3 GPa was obtained for eclogite-facies micaschists (Wei et al., 2009; Xin et al., 2013), and 470–510 °C at 2.4–2.7 GPa for eclogites (e.g. Meyer et al., 2016, see Table S2 for references). Evidence for UHP metamorphism comes from both relict coesite inclusions in garnet in several localities (stars in Fig. 1b) and thermodynamic pseudosection modeling (Lü et al., 2008, 2009; Lü et al., 2012; Tian and Wei, 2013; Wei et al., 2009). The spread of P–T estimates (Du et al., 2011; Gao et al., 1995, 1999; Klemd et al., 2002; Li et al., 2012, 2015, 2016; Lü et al., 2009, 2012; Tian and Wei, 2013; Wei et al., 2003) may a priori arise from contrasting assumptions for thermodynamic modeling (and/or difficulties in determining Fe^{3+} content and assessing H_2O activity) or from the complexity of metamorphic evolutions in individual HP–UHP tectonic slices.

The exhaustive compilation of age data (location on Fig. 1b), and the comparison of previous age data versus their assessed P_{max} estimates (Fig. 2a and b), evidence a considerable spread in ages too, with an overlap between eclogite and blueschist ages, whatever the protolith (Fig. 2a). The timing of peak metamorphic conditions falls in the range 325–305 Ma. Garnet growth by multi-point Lu–Hf isochron was dated at ca. 315 Ma (Klemd et al., 2011), for both eclogites and blueschists from a variety of valleys within AMC. U–Pb SIMS ages from metamorphic zircon rims in eclogites are indistinguishable within error, at 319 ± 3 Ma and 321 ± 2 Ma (Liu et al., 2014a; Su et al., 2010) and similar to a U–Pb age of 318 ± 7 Ma obtained for eclogite-facies rutile (Li et al., 2011). Du et al. (2014) also reported a suite of relative consistent Sm–Nd isochron ages of 309 ± 4.6 M, 306 ± 15 Ma and 305 ± 11 Ma for eclogites from the Habutengsu river (Fig. 1b). An age of 317 ± 5 Ma was obtained on high-pressure veins crosscutting a blueschist wall-rock, interpreted as the prograde dehydration-related transformation of blueschist to eclogite (Rb–Sr multi-point isochron, John et al., 2012). Recent Sm–Nd and Lu–Hf isochron ages of 318.4 ± 3.9 Ma and 326.9 ± 2.9 Ma on blueschists (Soldner et al., in press) were interpreted as peak eclogite-facies and prograde metamorphism, respectively. Post-peak cooling was constrained by white mica K–Ar, Ar–Ar and Rb–Sr ages at around 310 Ma (Klemd et al., 2005). Ages <280 Ma or >~325 Ma were considered by most authors as resulting from limitations of isotopic dating (e.g. excess Ar in Ar–Ar system; Nd disequilibrium in Sm–Nd system; difficulties to relate zircon U–Pb ages to metamorphic stages) or taken as evidence for distinct HP–UHP episodes.

2.3. Controversy on regional exhumation

The Akeyazi metamorphic complex is either interpreted as a tectonic mélange or as made of two main units. In the first interpretation, mafic slices/blocks derived from different depths (UHP and HP conditions) were juxtaposed and mixed during exhumation in a meta-volcano-sedimentary subduction channel-like setting (Klemd et al., 2011; Li et al., 2016; Meyer et al., 2016). Despite, indications that rocks may have partly re-equilibrate with fluids in equilibrium with serpentinites (van der Straaten et al., 2008, 2012), serpentinites, which can act as buoyant material during exhumation processes (Guillot et al., 2015), are extremely rare (Shen et al., 2015). Meta-volcanosedimentary rocks could also act as buoyant material and promote the exhumation of denser, negative-buoyant oceanic HP–UHP/LT rocks in a subduction channel (Gerya et al., 2002).

In contrast, the coherent sub-belt model (Lü et al., 2012), based on several individual UHP occurrences in the northern part of the AMC and the prevalence of blueschist facies rocks without UHP "signal" in the south, considers that the AMC consists of two internally coherent metamorphic "sub-belts": a UHP in the north and a HP belt in the south, separated by a major fault contact (only inferred at present) and later juxtaposed during exhumation.