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

**Key words:** *UHP metamorphism; eclogite; P-T path; pseudosection modeling; thermobarometry; zircon U-Pb; zircon oxygen isotope; exhumation pattern; Chinese Southwestern 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 paths 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 meters) 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 ~  $2.95 \pm 0.2$  GPa,  $510 \pm 20$  °C around  $318.0 \pm 2.3$  Ma to HP peak metamorphism ~  $2.45 \pm 0.2$  GPa,  $540 \pm 20$  °C at  $316.8 \pm 0.8$  Ma, then, with eclogite-facies deformation ~  $2.0 \pm 0.15$  GPa,  $525 \pm 25$  °C at  $312 \pm 2.5$  Ma, exhumed to near surface within ca. 303 to ca. 280 Ma. Our P-T-time-isotopic results combined to 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.  $315 \pm 5$  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), the 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 tightly enough link recrystallization observations with P-T data. In 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 (~5m) 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 metamorphic 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 (SCTS; 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 et al., 1995; Gao and Klemd, 2000, 2003). 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 boudins 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., 2016; 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; Gao et al., 1999; Klemd et al., 2002; Li et al., 2015; Li et al., 2016; Li et al., 2012; Lü et al., 2009; Lü et al., 2012; Tian and Wei, 2013; Wei et al., 2003) may a priori arise from contrasting assumptions for thermodynamic modeling (and/or difficulties in determining  $\text{Fe}^{3+}$  content and assessing  $\text{H}_2\text{O}$  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 (figures 2a and 2b), 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  $319 \pm 3$  Ma and  $321 \pm 2$  Ma (Liu et al., 2014a; Su et al., 2010) and similar to a U-Pb age of  $318 \pm 7$  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  $309 \pm 4.6$  Ma,  $306 \pm 15$  Ma and  $305 \pm 11$  Ma for eclogites from the Habutengsu river (Fig. 1b). An age of  $317 \pm 5$  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  $318.4 \pm 3.9$  Ma and  $326.9 \pm 2.9$  Ma on blueschists (Soldner et al., 2016) 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 > than ~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.

### 3. Sample selection and whole-rock composition

Samples were collected from the second eastern tributary up the Atantayi valley (Fig. 1b) in a ~six meter thick, layered eclogitic mafic slice. In order to detailedly reconstruct its tectono-metamorphic evolution (pro- and retrograde), three fresh eclogite samples were chosen from the core of the thick-layered eclogite outcrop (Fig. 3; oriented samples: GJ01-6, 11AT06-2; for geochemistry: 11AT06-1) and one garnet-clinopyroxene-quartz bearing micaschist from the meta-volcanosedimentary host-rock (GJ01-1). Considering the relative low Zr content (only ca. 50 ug/g) of the metabasalts (Table. 2), about 100 kilograms of eclogite were sampled for the zircon study and approximately 500 zircon grains were collected and mounted (detailed processing is given in the Analytical methods in the Appendix).

Bulk- and trace-element geochemical data are shown in table. 2 and figure.

4. Loss on ignite on ranges between 1.8 and 3.3 wt. %, in agreement with modal abundances of hydrous mineral such as amphibole (5 to 8 vol%).

Chondrite- and primitive mantle-normalized (Sun and McDonough, 1989) rare earth element (REE) and trace-element patterns of the eclogites are

similar to N-MORB (Figs. 4a, b), as further supported by a Th/Yb vs. Nb/Yb plot (Fig. 4c) and by the  $\epsilon\text{Nd}(t)$  value of +8.5 ( $t = \text{ca. } 312 \text{ Ma}$ , Table. 7). They show a positive slope in LREEs to MREEs and flat in HREEs, with  $(\text{La/Yb})_N = 0.542 - 1.097$ ,  $(\text{La/Sm})_N = 0.524 - 0.666$ ,  $(\text{Gd/Yb})_N = 0.999 - 1.536$  and a  $\Sigma\text{REE}$  concentration of 49.9 to 58.2 ppm (Table. 2). Primitive mantle-normalized trace-element variations show moderate Rb, Ba, U and Pb enrichments (Fig. 4b) for these three eclogite samples. As expected for MORB type samples, there is no Nb-Ta depletion recorded.

The meta-volcanosedimentary rock is characterized by relatively high  $\text{SiO}_2$  (~ 54.3 wt.%) and  $\text{Al}_2\text{O}_3$  (~ 14.7 wt.%) contents. LREEs are enriched with La contents ~100 times higher than for chondrite, while HREE patterns are flat. REE and trace-element patterns for this meta-volcanosedimentary sample are close to that of the average upper continental crust (Fig. 4b, Rudnick and Gao, 2003) except for Rb.

#### 4. Petrology

Mineral occurrences and modal abundances are given in Table. 1. Mafic samples are true eclogites with > 70 vol. % of garnet and omphacite (Carswell, 1990). Mineral constituents of eclogite samples are garnet, omphacite, epidote-group minerals, paragonite, blue amphibole (rimmed in places by

blue-green amphibole), quartz, as well as rutile/titanite, calcite and phengite (Figs. 5a-f) in subordinate amounts. The fraction of hydrous minerals (especially amphibole) increases in the vicinity of the host-rock.

Garnet in sample 11AT06 occurs as idioblastic porphyroblasts (~0.4 to 2.5 mm in diameter; Figs. 5d, 5e) in a medium-grained omphacite matrix. The inclusion-rich cores (Fig. 5e) host omphacite, epidote, chlorite, paragonite, quartz and glaucophane/barroisite (Fig. S2). Box-shaped inclusions of aggregates of paragonite and epidote could represent pseudomorphs after lawsonite (Fig. S2). Coesite inclusions (Figs. 7b,c) were found in the garnet mantle (Fig. 7d), where inclusions are much less than in the core.

Omphacite occurs as small subhedral-anhedral grains (~0.05 to 0.1 mm across), either as the main matrix phase or as inclusions in garnet, epidote and paragonite (Figs. 5b, 5d, 5f, 5i). Epidote is subhedral and contains inclusions of omphacite, quartz and rutile (Fig. 5d). Blue amphibole is found as inclusions in some garnets (Fig. 5h) and in the core of late-stage blue-green amphibole (Fig. 5g). Rutile is present both in garnet porphyroblasts (Fig. 5e), paragonite and amphibole grains as armored relicts, and in the matrix (Fig. 5g), where it is replaced by helicitic rims of titanite (Fig. S1). Retrograde albite is rare and xenoblastic. Chlorite replaces or cuts across garnet (Fig. 5e).

In oriented eclogite samples (11AT06-2 and GJ01-6), omphacite defines a weak to moderate foliation, and contain aggregates of epidote group minerals

and paragonite aligned along the matrix foliation (Figs. 5f, 6a, 6b). In the XZ plane of deformation,  $\sigma$ -type garnet porphyroclasts with recrystallized aggregate tails made of epidote, omphacite and paragonite/phengite indicate top to NE shear senses.

The meta-volcanosedimentary sample GJ01-1 is strongly deformed and the foliation defined by lepidoblastic phengite/paragonite, albite and amphibole wraps around garnet porphyroclasts (Fig. 6c). Garnet occurs as idioblastic to subidioblastic ~ 3.0 mm sized porphyroblasts in a fine- to medium-grained matrix, and contains inclusions of phengite/paragonite, epidote group minerals, quartz and chlorite. Matrix feldspar porphyroblasts contain numerous inclusions. Shear sense indicators, again top to the NE, correspond to retrograde greenschist/blueschist facies recrystallization.

## 5. Mineral chemistry

A selection of representative EPMA analyses is provided in Table. 3. Mineral abbreviations are after Whitney and Evans (2010).

### 5.1. Garnet

Garnet porphyroblasts in eclogite sample 11AT06-1 exhibit systematic compositional zoning (e.g., Fig. 7e) with a core-mantle increase in pyrope ( $X_{\text{prp}}$ )

and a slight decrease in spessartine and grossular content ( $X_{\text{sps}}$  and  $X_{\text{grs}}$ ). The almandine ( $X_{\text{alm}}$ ) profile is fairly constant from core to mantle then decreases steadily towards the outermost part of the rim (Fig. 7e). Second-order fluctuations in  $X_{\text{grs}}$  and  $X_{\text{sps}}$  but also in  $X_{\text{alm}}$  can be observed (Fig. 7e). Garnet profiles may show a rim-outer rim coeval increase in  $X_{\text{alm}}$  and decrease in  $X_{\text{prp}}$ , which is generally attributed to retrograde reequilibration by diffusion (Wei et al., 2009).

Garnet zoning in eclogite is highlighted by seven spots along the EMPA profile (Fig. 7e), which are used in pseudosection modeling (section 8.2). Overall, garnet composition changes from core to mantle and rim from  $\text{Alm}_{67}\text{Py}_{10}\text{Grs}_{20}\text{Sps}_4$  to  $\text{Alm}_{70}\text{Py}_{12}\text{Grs}_{18}\text{Sps}_1$  to  $\text{Alm}_{57}\text{Py}_{21}\text{Grs}_{22}\text{Sps}_{0.3}$  (Table. 3). These average values correspond to the Grt-C, Grt-M1 to M2 and Grt-M5 to R zones defined in Fig. 7d, and to the approximate location of the LA-ICPMS trace element analyses of the garnet core, mantle and rim.

## 5.2. Omphacite

Clinopyroxene is always omphacitic, but inclusions in garnet and matrix clinopyroxene show distinct compositional variations (Fig. 7f). Inclusions have a lower jadeite content (31-45 mol.%, average 38 mol.%) and a higher total FeO content (4.3-12.9 wt.%, average 7.7 wt.%) than matrix omphacite (40-51 mol.% Jd and 2.5-6.5 wt.% FeO, respectively). Both have similar values of

$\text{Na}_\text{N}/(\text{Na}_\text{N}+\text{Ca}_\text{N})$  ( $\sim 0.48$ ; Table. 3). Omphacite inclusions in paragonite lie on the upper bound for jadeite content and  $\text{Na}_\text{N}/(\text{Na}_\text{N}+\text{Ca}_\text{N})$  but on the lower bound for the total FeO content.

### 5.3. Amphibole

Amphibole in the layered eclogite is either glaucophane or barroisite (Fig. 7g). Glaucophane occurs as euhedral porphyroblasts ( $\sim 0.5$  mm across) with barroisite rims (Fig. 5g). Both glaucophane and barroisite appear as inclusions in garnet, with a wide range of compositions for the latter, across the magnesio-katophorite field (Leake, 1978) and a systematic decrease in  $(\text{Na})_{\text{M4}}$  (Fig. 5h). Glaucophane inclusions have higher  $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$  and  $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al})$  ratios. Some amphibole grains have a clear zonation, with glaucophane in the core and barroisite in the rim, similar to the Tianshan garnet-omphacite blueschist samples described by Klemd et al. (2002).

### 5.4. White mica

Paragonite and minor phengite appear as matrix mineral and as inclusions in garnet. Paragonite flakes occur as subhedral fine grains ( $\sim 0.05$  mm across) or occasionally as porphyroblasts in the matrix ( $\sim 0.5$  to 2 mm across, Figs. 5f, 5g, 5i). They are parallel or subparallel to the foliation (Figs. 5f, 5g), contain omphacite and rutile inclusions (Figs. 5g, 5i), and are interpreted to result from post-peak retrograde metamorphism. Phengite mainly occurs as subhedral fine



grains in the matrix (~0.02 mm across) or as inclusions in garnet porphyroblasts (Fig. S2). Both of them exhibit a similar Si content (~3.43 p.f.u.).

### 5.5. Epidote-group minerals

Epidote-group minerals occur as 0.5-0.7 mm large porphyroblasts or as subhedral grains close to garnet porphyroblasts (Figs. 5c, 5d, 5e). Porphyroblasts are randomly oriented in the matrix with mineral inclusions of omphacite and rutile (Fig. 5c). The pistacite ( $=\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al})$ ) contents of epidote range from 0.09 to 0.17 (Table. 3).

### 5.6. Chlorite

Chlorite appears as matrix minerals filled into the fractures of garnet porphyroblasts or as inclusions in garnet (Table. 3).

### 5.7. Rutile/Titanite

Rutile appears as acicular or irregular crystals inclusions in paragonite (Fig. 5g), glaucophane/barroisite (Fig. 5g), garnet (Fig. S2) and matrix minerals (Fig. S1). A titanite-armor around rutile is observed in both matrix omphacite (Figs. S1a, S1b) and quartz (Figs. S1c, S1d). The  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  contents of titanite are respectively about 37.9 wt % and 2.11 wt % (Table. 3).

## 6. Trace-element pattern of zircon and garnet

Zircon in layered eclogite occurs as 30 to 50  $\mu\text{m}$  grains in the matrix (Fig. 7a) or in garnet (Figs. 7a, S2). Cathodoluminescence images of zircon grains are used below as a proxy for variations in zircon chemistry (whereas trace-element patterns are discussed in next section). Zircon grains from eclogitic samples show two to four growth zones preserved (Figs. 8, S2a-l). A dull-luminescent core domain is found in all zircon grains (Figs. 8, S2a-l), with typical sector zoning. A large overgrowth is generally present and herein referred to as the 'mantle'. Complex zoning patterns (chaotic and wavy zoning) were also observed (Figs. 8a, 8e and S2). A light-luminescent outer rim can also be distinguished in many grains (e.g., Fig. 8 and Fig. S3). A metamorphic origin may be attribute to these zircon domains when considering the  $< 0.01$  Th/U ratios and the presence of diagnostic HP minerals, such as omphacite and rtile, detected via Raman spectroscopy (with peaks at  $682\text{ cm}^{-1}$  and  $609\text{ cm}^{-1}$ , respectively; Figs. S3m, S3n). Quartz was observed but never coesite.

### 6.1. Trace-element pattern and oxygen isotopes of zircon

Based on differences in cathodoluminescence (CL) images and chondrite-normalized REE patterns (and U-Pb chronology, which will be discussed in section 7.1), four zircon domains (or growth stages) have been defined from core to rim: respectively (1) the zircon core, (2) a zone enriched in

HREE (with the same CL characteristics as the core, but more rarely preserved), (3) a mantle zone and (4) the zircon rim.

Chondrite-normalized REE patterns of zircon cores (Fig. 9a) show a typically positive slope from LREE to MREE, a relative enrichment in HREE ( $(\text{Lu}/\text{Sm})_{\text{N}} \sim 22.94$ ) and flat HREE patterns ( $(\text{Lu}/\text{Tb})_{\text{N}} \sim 1.53$ ). This core is also characterized by low Th/U ratios ( $< 0.01$ ), medium U ( $\sim 980$  ppm), low Th ( $\sim 4$  ppm) and moderate Y, Ti, P and Nb contents (with average values of 89, 2670, 27 and 6 ppm, respectively; Table. 4).

Some of the zircon cores show HREE contents 2-3 times higher ( $(\text{Lu}/\text{Sm})_{\text{N}} \sim 51.72$ ;  $(\text{Lu}/\text{Tb})_{\text{N}} \sim 2.71$ ; Y  $\sim 230$  ppm; Figs. 9a, S3i-l; Table. 4). They are also distinct in terms of U-Pb isotopic composition (Fig. 10), but have similar Th/U ratios ( $< 0.01$ ), U and Th contents.

The zircon mantle domain (Fig. 9b) shows a more gentle positive slope from LREE to MREE and a flat HREE distribution with lower HREE and Y absolute contents ( $(\text{Lu}/\text{Eu})_{\text{N}} \sim 3.17$ ;  $(\text{Lu}/\text{Tb})_{\text{N}} \sim 0.94$ ; Y content  $\sim 45$  ppm; Table. 4).

The REE pattern of zircon rims differ largely from that of the former three zones discussed above by a steeper MREE to HREE distribution (with  $(\text{Lu}/\text{Gd})_{\text{N}} \sim 10$  and  $(\text{Lu}/\text{Tb})_{\text{N}} \sim 34$ , Table. 4) and the absence of a HREE plateau. Its Y, P, Th and U contents are also much lower (i.e., respectively,  $\sim 48$ , 21, 0.17 and 30 ppm). The Th and U contents are about 30 times less than in the other

three zircon domains.

## 6.2. Trace-element pattern of garnet

Laser spots for the analysis of garnet core, mantle and rim corresponding to EPMA analyses of the C, M1 to M2 and M5 to R areas (shown in Fig. 7d).

Chondrite-normalized REE patterns of garnet core, mantle and rim (Fig. 9b) are broadly similar (and comparable to the REE distributions within zircon), with relatively high and flat HREE content and relative depletion in MREE and LREE. Garnet cores show the highest HREE enrichment with  $(\text{Lu/Sm})_N \sim 12$ , compared to the mantle domain  $((\text{Lu/Sm})_N \sim 2)$ . Garnet mantle shows the highest LREE and a slightly negative slope for HREE. Garnet rims show the strongest depletion in MREE and a slightly lower HREE content compared to that of mantle.

## 7. Geochronology and oxygen isotope

### 7.1. U-Pb dating and isotopes of zircon

Fifty spots of twenty-seven zircon grains from eclogite sample 11AT06 have been analyzed to unravel the oxygen isotope composition and data the four growth domains (Table. 5; Th/U ratios vary between 0.001 to 0.005). Core domains give apparent  $^{206}\text{Pb}/^{238}\text{U}$  ages from 310.0 to 324.3 Ma, a mean

Concordia age of  $316.8 \pm 0.83$  Ma (MSWD = 1.01,  $n = 31$ ) and a weighted mean age of  $316.3 \pm 1.6$  Ma (MSWD = 0.71,  $n = 31$ ) (Fig. 10e). Similar results are found for the HREE enriched cores, with apparent  $^{206}\text{Pb}/^{238}\text{U}$  ages varying from 315.3 to 320.4 Ma, a mean Concordia age of  $318.0 \pm 2.3$  Ma (MSWD = 2.7,  $n = 4$ ) and a weighted mean age of  $317.4 \pm 4.6$  Ma (MSWD = 0.25,  $n = 4$ ) (Fig. 10d).

The mantle domain gives younger apparent  $^{206}\text{Pb}/^{238}\text{U}$  ages, from 297.2 to 307.1 Ma, a mean Concordia age of  $303.1 \pm 1.7$  Ma (MSWD = 0.49,  $n = 7$ ) and a weighted mean age of  $303.1 \pm 3.3$  Ma (MSWD = 0.58,  $n = 7$ ) (Fig. 10f).

Owing to the low U contents of the outer rims (5 of 8 analyzed spots have U contents mostly ranging from 1 to 49 ppm; Table. 5), U-Pb results for this domain are presented on the Tera-Wasserburg plot and of poorer quality than the other domains. Common lead contents of the 8 analyzed spots are highly variable, with values of  $f_{206}$  between 0.09 % and 34.21 % (Table. 5). The linear regression of the data points (MSWD = 0.81,  $n = 8$ ) gives a lower intercept age of  $280.8 \pm 4.9$  Ma and the upper intercept with  $^{207}\text{Pb}/^{206}\text{Pb} = 0.381$  for the common Pb composition (Fig. 10g). The weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of this rim domain is  $280.5 \pm 4.3$  Ma (MSWD = 0.64,  $n = 8$ ) using the  $^{207}\text{Pb}$ -based common-lead correction (Williams, 1998) with the terrestrial Pb isotope composition from Stacey and Kramers (1975), which is consistent with the lower intercept age within errors.

By contrast, oxygen isotope  $\delta^{18}\text{O}$  compositions measured in the four zircon domains are very similar (Fig. 10b; Table. 6), with most values ranging between 8.9 ‰ and 9.5 ‰ (Fig. 10b; mean value =  $9.13 \pm 0.09$  ‰, MSWD = 5.6,  $n = 56$ ; Table. 6).

## 7.2. Sm-Nd isotopic chronology

Whole rock, omphacite and garnet (including core and rim) Sm-Nd isotopic data of the oriented eclogite sample 11AT06-2 are given in Table. 7. Sm and Nd concentrations of whole rock powder separates (1.68 and 4.26 ppm respectively) are in good agreement with results obtained from whole-rock trace-elements analyses by ICP-MS (Table. 3). Whole rock and omphacite separates have  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of 0.2841, 0.2452 and 0.2510 respectively. Garnet separates have a Sm/Nd ratio of about 2.13 and  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of 1.2828 and 1.2843, which are close to values reported for other SW Tianshan eclogites (Gao and Klemd, 2003). The WR-Omp-Grt isochron yields a Sm-Nd age of  $312.1 \pm 2.4$  Ma (MSWD = 0.78, Fig. 11), close to the Omp-Grt isochrone isochron ( $311.9 \pm 2.6$  Ma), with  $\epsilon\text{Nd}(t)$  of + 8.5 ( $t = \text{ca. } 312$  Ma, Table. 7).

## 8. Pressure-Temperature estimates

### 8.1. Multi-equilibrium thermobarometry

P-T estimates for prograde equilibrium stages (using mineral inclusion pairs within garnet porphyroblast cores of sample 11AT06-1; Fig. 7d), peak eclogitic-facies and retrograde blueschist- to greenschist-facies recrystallizations (e.g., recrystallized tails of  $\sigma$ -type porphyroclasts in oriented samples 11AT06-2, GJ01-6 and GJ01-1; Fig. 6a, 6b, 6c), are constrained using THERMOCALC average PT multi-equilibrium thermobarometry (Holland and Powell, 1998, 2011; version 3.33 with updated database tc-ds55). Average PT results and used representative mineral compositions are given in Table. S1.

P-T estimates of  $495 \pm 20$  °C and  $2.75 \pm 0.05$  GPa were derived assuming equilibrium between garnet cores and inclusions of omphacite and amphibole (i.e., red square #1 in Fig. 7d). Equilibrating omphacite inclusions and the garnet mantle (red square #2 in Fig. 7d), in the vicinity of coesite inclusion, yield higher P-T estimates of  $520 \pm 15$  °C and  $3.0 \pm 0.75$  GPa but with considerable pressure uncertainties. Lower P but higher T values, around  $570 \pm 35$  °C and  $2.4 \pm 0.3$  GPa, are obtained for garnet rims, considering an omp-grt-ph-amp equilibrium assemblage (i.e., red square #3; Fig. 7d; Table. S1). Quartz (or coesite) was assumed to be present in all calculations and water activity was set to 1.0. Lowering the water activity (e.g.  $a_{\text{H}_2\text{O}} = 0.8$ ) only

results in a minor decrease in temperature ( $\leq 15$  °C) and pressure ( $\leq 0.05$  GPa).

P-T estimates obtained for the garnet rim, omphacite-amphibole-epidote $\pm$  phengite assemblage marking the foliation of both sheared eclogitic samples (Figs. 6a, 6b; GJ01-6 and 11AT06-2) are  $525 \pm 25$  °C &  $2.0 \pm 0.15$  GPa.

P-T conditions for the retrograde, blueschist- to (or) greenschist-facies equilibration stages associated with top-to-NNE shear senses (Fig. 6c, GJ01-1) were estimated from the mineral assemblage amphibole + paragonite + epidote + chlorite + feldspar (albite) at  $380 \pm 50$  °C and  $1.0 \pm 0.2$  GPa, and  $420 \pm 25$  °C &  $0.9 \pm 0.1$  GPa.

## 8.2. Phase equilibrium modeling

Pseudosection modeling for sample 11AT06-1 was performed in the system MnNCKFMASHTO (Tables. 1, 2, 3), with excess SiO<sub>2</sub> (i.e., quartz or coesite). TiO<sub>2</sub> must be considered due to the presence of rutile and/or titanite in the matrix or as inclusions in porphyroblasts. The fluid phase is assumed to be pure H<sub>2</sub>O and was set in excess. CO<sub>2</sub> was neglected as only small amounts of carbonate occur as thin secondary veins. Fe<sub>2</sub>O<sub>3</sub> was set at 22.5 mol% of total FeO according to XRF data (Table. 2).

In order to take into account the sequestration of elements induced by the growth zoning of garnet porphyroblast, effective bulk compositions were



adjusted from XRF compositions by removing part of the garnet modal abundance, following the method of Carson et al. (1999). For the modelling of prograde and peak conditions (EBC-1), half of the modal abundance of zoned garnet (Warren and Waters, 2006; Wei et al., 2009) was removed from the XRF composition. For the retrograde path (EBC-2), garnet porphyroblasts were subtracted from the bulk-rock composition (see Table. 2 for XRF, EBC-1 and EBC-2 compositions).

The P-T pseudosections were calculated using the software Perple\_X 6.68 (Connolly, 1990, 2005) and an internally consistent thermodynamic dataset (hp02ver.dat, Connolly and Kerrick, 2002; Holland and Powell, 2003) based on the effective recalculated bulk rock composition (EBC-1 and EBC-2; Table. 2). Mineral solid-solution models are Gt(HP) for garnet (Holland and Powell, 1998), Omph(GHP) for omphacite (Green et al., 2007), Amph (DP) for amphibole (Diener et al., 2007), Mica(CHA) for white mica (Coggon and Holland, 2002), Chl(HP) for chlorite (Holland and Powell, 1998), Ep(HP) for epidote/clinozoisite (Holland and Powell, 1998), and H<sub>2</sub>O-CO<sub>2</sub> fluid solution model is from Connolly and Trommsdorff (1991).

The pseudosection for sample 11AT06-1 is shown in Fig. 12b. It is dominated by tri- and quadrivariant fields with a few di- and quini- variant fields. P-T conditions were further constrained by comparing predicted garnet isopleths with measured garnet compositions (boxes on Fig. 12b incorporate

typical uncertainties on EMPA analyses, ca. 3% to 5%, Lifshin and Gauvin, 2001; Williams and Jercinovic, 2006).

Stage I, as defined by core-mantle zoning (i.e., garnet zoning from Grt-C to Grt-M3 in Fig. 7e; see compositions in Table. 3), is marked by an increase in both T and P, from 2.55~2.70 GPa and 495~505°C to 2.95~3.30 GPa and 500~520°C. Peak pressure ( $P_{\max}$ ) is constrained by using the garnet mantle compositions (corresponding to Grt-M2 to Grt-M4) which have the lowest  $X_{\text{grs}}$  content, and coincide with the location of coesite inclusions (Figs. 7a-d).

Stage II is constrained by the mantle-rim zoning (corresponding to Grt-M4, Grt-M5 and Grt-R in Fig. 7d, Table. 3) and the mineral assemblage omp-amp<sub>1</sub>(gln)-mica<sub>1</sub>(ph)-lws-grt-rt. It is marked by a slight increase in T at 550~560°C and a pressure decrease at 2.35~2.60 GPa, further constrained by the Si content of phengite included in garnet (3.43 p.f.u.; Table. 3). Later retrograde re-equilibration, based on the EBC-2 whole-rock composition, is estimated from measured  $(\text{Na})_{\text{M4}}$  contents in amphibole and  $(\text{Na})_{\text{M4}}$  isopleths modeled from pseudosection (Fig. 12c) at ca. 1.20 GPa and 548°C.

## 9. Discussion

### 9.1. Nature of the protolith and P-T-(fluid) constraints

The studied mafic eclogites show LREE-depleted and HREE-flat N-MORB

patterns (Sun and McDonough, 1989), with enrichments in Rb, Ba, U, Pb, and Sr.  $\delta^{18}\text{O}$  values for multistage zircons ( $\sim 9.13 \pm 0.09$  ‰; Fig. 10b) with modelled bulk-rock  $\delta^{18}\text{O}_{\text{P peak}}$  of ca. 8.47 ‰ (Table. 6, oxygen fractionation factors from Zheng, 1991, 1993) are similar to those of typical altered ocean crust (AOC,  $\sim 7.9$  to  $9.5$  ‰ from Cocker et al., 1982; Miller and Cartwright, 2000), suggesting that the metamorphic zircons may have inherited the composition of the bulk (e.g., Rubatto and Angiboust, 2015). Some characteristic element patterns (e.g., in Rb vs K, Nb/U vs U, K/Th vs Ba/Th and Ba/Nb vs U/Nb diagrams, Bebout, 2007, 2013) suggest that the N-MORB protolith was later slightly enriched in LILE during metamorphism. By contrast, the meta-volcanosedimentary host rock yields an Upper Continental Crust-like trace-element and REE-distribution pattern, with notable Nb and Ta anomalies (Fig. 4).

The  $\delta^{18}\text{O}$  values of the various zircon domains are remarkably constant despite considerable multistage growth from ca.  $\sim 318$  to  $280$  Ma. This suggests that the rock system remained essentially closed over  $\sim$ ca. 40 Ma, during metamorphic re-equilibration, with respect to potential external fluid infiltration, at both the cm- and m-scale (zircon grains were collected from rock fragments from different parts of the outcrop), and/or that fluids were derived from (or equilibrated with) a similar source. External fluids derived from subduction-related lithologies would indeed have likely shifted the  $\delta^{18}\text{O}$

signature (unaltered slab mantle and oceanic crust  $\sim 5.7\text{‰}$ , serpentinized slab mantle  $\sim 1\text{--}8\text{‰}$ , metasediment  $\sim 12\text{--}29\text{‰}$  from van der Straaten et al., 2012). We therefore hypothesize that external fluid infiltration was limited and/or  $\delta^{18}\text{O}$  was internally buffered (Martin et al., 2006; Martin et al., 2008).

The P-T evolution followed by mafic eclogites (Fig. 12) is characterized by burial along a typical subduction gradient ( $\sim 7^\circ\text{C}/\text{km}$ ) with a moderate heating (up to  $50\text{--}80^\circ\text{C}$ ) during decompression. This is consistent with recent results of thermodynamic modeling (Li et al., 2015; Li et al., 2016; Lü et al., 2009; Tian and Wei, 2013; Wei et al., 2003), though in contrast to some early claims of counterclockwise (Lin and Enami, 2006) or hairpin-shaped P-T trajectories (Gao et al., 1999).

Thermodynamic modelling of successive re-equilibration stages yield P-T estimates within  $\sim 0.2\text{ GPa}$  and  $20^\circ\text{C}$  ( $1\sigma$ -error, see also discussion by Li et al., 2016), considering uncertainties on solid solution models and thermodynamic properties (Dachs et al., 2012; Worley and Powell, 2000), effective bulk composition (Carson et al., 1999; Evans, 2004) and microprobe analyses (Lifshin and Gauvin, 2001; Williams and Jercinovic, 2006). Conventional thermobarometry give consistent and robust P-T results (Fig. 13a) but with larger uncertainties for the pressure peak (Fig. 12a, Table S1). When considering these uncertainties, most previous published P-T paths in fact will overlap (Fig. 13b, except for Li et al., 2015; Li et al., 2016; van der Straaten et

al., 2008; Wei et al., 2003). Most studies concord on  $T_{\max}$  conditions for peak burial in the range 510-570 °C (Fig. 13b). Our results ( $520 \pm 30^{\circ}\text{C}$  for UHP peak burial and  $550 \pm 30^{\circ}\text{C}$  for the temperature peak) are consistent with the recent independent results obtained by Raman spectroscopy of carbonaceous matter (ca.  $540 \pm 30^{\circ}\text{C}$ , Meyer et al., 2016).

Future studies should help clarify their contrasts in  $P_{\max}$  estimates, which cluster in three distinct groups (dashed boxes; Fig. 13b): 1) a UHP group ranging from ca. 2.7 to 3.3 GPa (e.g., Tian and Wei, 2013; Wei et al., 2009; Xin et al., 2013) (and this study), 2) a HP group in the range of ca. 1.8-2.5 GPa (e.g., Beinlich et al., 2010; Du et al., 2014; Li et al., 2015; Li et al., 2016 ; Li et al., 2014; Meyer et al., 2016; Soldner et al., 2016) and 3) a blueschist-facies group ranging from ca. 1.3 to 1.9 GPa (e.g., Gao et al., 1999; Klemd et al., 2002; van der Straaten et al., 2008; Wei et al., 2003).

## 9.2. Linking garnet with zircon growth

This section attempts to link the potential of garnet as thermobarometer (e.g., Konrad-Schmolke et al., 2008) with that of zircon as geochronometer (e.g., Rubatto, 2002) to closely tie U-Pb ages to metamorphic conditions and finally derive a precise P-T-time path.

Figure 9b shows that REE patterns for successive garnet and zircon metamorphic growth are almost parallel, except for the zircon rim. Partitioning data for REE between zircon and garnet (Rubatto, 2002; Rubatto and Hermann, 2003) suggest that zircon preferentially sequesters Y and HREE over garnet, with D-values of ~2-4 (Fig. 14a). Data show that only the zircon high HREE core and/or core domains (and not the zircon mantle and rim) have higher HREE contents than garnet (Fig. 14b, Table. 4) and may therefore have equilibrated with it.

Zircon high-HREE cores may have co-crystallized either with the garnet core or mantle domains (Fig. 14b), but the  $D^{Y+HREEs}_{zrn/grt}$  pattern of the second option is more similar to the one reported in eclogite vein by Rubatto and Hermann (2003). For the zircon core domain, the most likely candidate would be the garnet rim. We thus tentatively propose (Figs. 14c, 15) that zircon high-HREE core grew in equilibrium with the garnet mantle at ~ ca. 318 Ma at UHP conditions (~ ca. 2.6-3.1 GPa; Grt-M1 to M2 stages with coesite inclusions; Fig. 7), while zircon core grew in equilibrium with the garnet rim at ~ ca. 316 Ma (~ ca. 2.3-2.7 GPa; Grt-M5 to R stage).

The zircon mantle domain (~ ca. 303 Ma, Fig. 10f), with similar but lower HREE patterns (Fig. 9a), could have inherited its HREE content from the partial resorption of garnet (and/or zircon cores, i.e., Degeling et al., 2001), while garnet abundance was still buffering the HREE budget. By contrast, the

different REE pattern of the last zircon rim overgrowth (~ ca. 280 Ma, Fig. 10g), hints to the breakdown of another Zr-bearing mineral during greenschist/blueschist-facies exhumation, possibly rutile (Kohn et al., 2015; Lucassen et al., 2010). Similar multi-stage zircon growth from the Dabie mountain (but with zircon from separate eclogite and quartz vein, Liu et al., 2014b; Zheng et al., 2007) was interpreted as a witness of channelized fluid flow during exhumation.

### 9.3. Age constraints and regional-scale tectonic implication

Based on garnet-zircon equilibrium, ages of ~ ca. 318 and ca. 316 Ma can be ascribed to the peak burial (UHP) and peak temperature (HP) metamorphic stages, respectively (Figs. 14c and 15). Whole rock-grt-omp and grt-omp Sm-Nd isochrons give additional, consistent age constraints at  $\sim 312 \pm 2.5$  (Fig. 11; Table. 7). Although experimentally determined closure temperatures for Nd diffusion differ in garnet (~500-850°C, Li et al., 2000) and omphacite (~1050°C, Sneeringer et al., 1984), questioning Nd equilibrium between these phases at a peak temperature of  $530 \pm 30^\circ\text{C}$ , consistent mineral pair and whole rock Sm-Nd isochron were reported for similar fine-grained eclogites from distinct localities in the Dabie mountains (Li et al., 2000).

This WR-garnet-omphacite Sm-Nd age of ca. 312 Ma (Fig. 11, Table. 7) can therefore be treated as constraining the post-peak eclogite-facies

deformation event coeval with omphacite growth in the matrix (Fig. 6a, 6b), slightly after or coeval with the growth of zircon cores in equilibrium with garnet rims (i.e., ~ ca. 316 Ma). These age constraints are broadly consistent with a recent Sm-Nd WR-grt-omp age of  $\sim 307 \pm 11$  Ma interpreted as dating the timing of HP metamorphism (Du et al., 2014) and a Sm-Nd WR-grt-gln age of  $318.4 \pm 3.9$  Ma for a blueschist equilibrated close to HP peak metamorphism (Soldner et al., 2016). Ages between 318 and 312 Ma are also consistent with the  $320.4 \pm 3.7$  Ma zircon-rim U-Pb age obtained on coesite-bearing meta-volcanosedimentary rocks (Xin et al., 2013) and with the  $315.2 \pm 1.6$  Ma garnet-multi-point Lu-Hf age obtained for eclogites (Klemd et al., 2011).

Overall, the present study allows to conclude that  $315 \pm 5$  Ma can be taken as a reliable value for the attainment of HP to UHP conditions in the Chinese Southwestern Tianshan UHP-HP/LT metamorphic complex. The dispersion of Ar/Ar ages (Fig. 16b, Gao and Zhang, 2000; Klemd et al., 2005; Wang et al., 2010; Xia et al., 2015) may therefore be due to a problem of excess argon, at least in some eclogite/blueschist samples. Indeed the same outcrop yielded very distinct Ar-Ar plateau ages (e.g.,  $401 \pm 1$  and  $364 \pm 1$  Ma by Gao and Zhang, 2000 versus ca. 320 Ma by Klemd et al. 2005), and similar ages were obtained for Rb/Sr and Ar/Ar ages by Klemd et al. (2005), for which white mica closure temperatures (if strictly under fluid-assisted recrystallization-free assuming) differ by 100 °C or more (Li et al., 1994; Ruffet et al., 1997; Villa,



1998; Villa and Puxeddu, 1994).

The 303 Ma age derived from zircon mantle recrystallization (Fig. 10f) is here taken as a minimum age for the garnet-free or garnet resorption greenschist-facies metamorphism. This conclusion is strengthened by a greenschist-facies Ar-Ar plateau age of  $\sim 293.1 \pm 1.7$  Ma reported by Xia et al. (2015). Later recrystallization of zircon rims at  $\sim 280$  Ma, though of poor quality (Fig. 10g) could correspond to the late exhumation movements, as similar ages were reported for the extensive ductile strike-slip deformation of the Southwestern Central Tianshan Suture zone (i.e., de Jong et al., 2009; Laurent - Charvet et al., 2003). Note that late, post-exhumation rodingitization was constrained at  $291 \pm 15.0$  Ma (Li et al., 2010c) and that crosscutting, undeformed leucogranites were dated at  $\sim 284.9 \pm 2.0$  Ma (Gao et al., 2011).

These age constraints point to decreasing exhumation velocities, from ca.  $12.0 \pm 6.5$  mm/yr for early UHP to HP exhumation (if  $< 2$  Ma) to  $3.6 \pm 2.0$  mm/yr for blueschist-facies exhumation (within ca. 13 Ma) and  $0.8 \pm 0.4$  mm/yr for greenschist-facies exhumation (within ca. 22 Ma). The average exhumation rate, ca. 2.6 mm/yr, falls within the range of 1-5 mm/yr for exhumed oceanic rocks worldwide (Agard et al., 2009). Importantly, the timing of HP-UHP metamorphism appears very restricted (at  $315 \pm 5$  Ma; i.e.,  $< 10$  Ma) compared to the likely duration of active subduction ( $> 50$ -100 My, since an oceanic

domain existed in the region from at least  $\sim 422 \pm 10$  Ma to ca. 280-300 Ma, Li et al., 2010c).

Although this study focuses on a single key exposure, a simple geodynamic reconstruction is provided (Figs. 17a, 17b) to set back our results in a tentative evolution of the Chinese Southwestern Tianshan metamorphic complex. HP-UHP/LT rocks were detached or exhumed after their peak burial only at about  $315 \pm 5$  Ma (Figs. 16a, 16b) and brought back to the surface to greenschist-facies conditions between ca. 310 and 300 Ma (Fig. 17b). Pervasive north-trending shear senses deduced from eclogite-, blueschist- and greenschist-facies recrystallizations (this study, Fig. 6, see also in Lin et al., 2008; Wang et al., 2010) are interpreted to result from southwest-trending extrusion of the AMC (Figs. 17a, 17b).

At present, thorough large-scale structural studies and/or extensive P-T(-t) mapping across the whole HP/UHP complex are still missing to assess whether the punctuated exhumation at  $315 \pm 5$  Ma is associated with chaotic block-in-matrix mixing, with heterogeneous P-T and/or fluid conditions (e.g., extremely complex zoning of both garnet and amphibole, Li et al., 2016) or to accretion of tectonic slices of volcanosedimentary material hosting stripped pieces from the seafloor (i.e., mafic meta-volcanics).

## 10. Conclusions

This study provides P-T-radiometric-isotopic constraints on several eclogitic samples from a key coesite-bearing location in the Chinese Southwestern Tianshan UHP-HP/LT metamorphic complex. Together with an exhaustive review of available P-T (-time) constraints for the area, the following conclusions can be drawn from these new data:

- (1) Mafic eclogites have slightly LILE-enriched N-MORB like features with  $\delta^{18}\text{O}_{\text{zircon}}$  values of  $\sim$  ca. 9.0 ‰ typical of an AOC protolith. The constant  $\delta^{18}\text{O}$  values for the successive zircon growths suggest a metamorphic system closed (or very limited) to external fluid infiltration.
- (2) Thermodynamic modeling permits a complete recovery of their P-T trajectory from pre-peak burial to UHP conditions ( $\sim$  2.95 GPa  $\pm$  0.2 and 510°C  $\pm$  20) and later exhumation. REE partitioning between multistage zircon and garnet growth domains allows for a critical assessment of the P-T-time path: the ca. 318 Ma and 316 Ma zircon ages are tied to UHP and HP metamorphism, respectively, along with a consistent ca. 312 Ma Sm-Nd age for HP eclogite-facies deformation. Thus, peak burial can be constrained at about 315  $\pm$  5 Ma. These P-T-t constraints point to decreasing exhumation velocities, from ca. 12.0  $\pm$  6.5 mm/yr for early UHP to HP exhumation to 3.6  $\pm$  2.0 mm/yr for blueschist facies exhumation and 0.8  $\pm$  0.4 mm/yr for greenschist facies exhumation.

(3) The comparison of P-T (-time) estimates between this study and the compilation of previous works outlines the existence of a short-lived detachment of subducted eclogites ( $< 10$  Ma) with respect to the “long-term” subduction duration ( $> 50$ - $100$  Ma).

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## APPENDIX

### Analytical methods

#### Bulk-rock analyses

Four bulk-rock chemical analyses were performed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) on three samples from one eclogite outcrop (see location in Fig. 4; 11AT06-1, 11AT06-2 and GJ01-6), and one sample from the wall-rock mica schist ~3 meters away (GJ01-1). Major oxides were determined by a PHILLIPS PW1480 X-ray fluorescence spectrometer (XRF) on fused glass discs. Loss on ignition (LOI) was measured after heating to 1,000 °C. Uncertainties for most major oxides are ca. 2%, for MnO and P<sub>2</sub>O<sub>5</sub> ca. 5%, and totals are within 100 ± 1 wt.%. Whole rock Fe<sub>2</sub>O<sub>3</sub> content is constrained by potassium permanganate titration. Trace element concentrations were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) using a Finnigan MAT ELEMENT spectrometer at the IGGCAS. The detailed analytical procedure is identical to that used by Qian et al. (2006). Relative standard deviations (RSD) are within ±10% for most trace elements but reach ± 20% for V, Cr, Co, Ni, Th and U according to analyses of rock standards. Detail major and trace elements analyses are

presented in Table. 2.

### **Mineral major elements**

In situ major element compositions of garnet and inclusion minerals were obtained from polished thin sections by electron microprobe analyses at the IGGCAS with the use of JEOL JXA 8100. Quantitative analyses were performed using wavelength dispersive spectrometers with an acceleration voltage of 15 kV, a beam current of 15 nA, a 3  $\mu\text{m}$  beam size and 30 s counting time. Natural minerals and synthetic oxides were used as standards, and a program based on the ZAF procedure was used for data correction. Representative microprobe analyses for pseudosection modeling and for Thermocalc averagePT calculations are presented in Table. 3 and Table. 8, respectively.

### **Mineral trace elements**

In situ trace element analyses of zoned garnet and zircon were performed by LA-ICP-MS at the IGGCAS with a single collector quadrupole Agilent 7500a ICM-MS, equipped with an UP193Fx argon fluoride New Wave Research Excimer laser ablation system. The glass reference material NIST SRM 610 and NIST SRM 612 were used as standards for external calibration. LA-ICP-MS measurements were conducted using a spot size diameter of 40 to 60  $\mu\text{m}$ , a laser frequency of 15 Hz and 0.63 GW/cm<sup>2</sup> and a fluence of 3.32

J/cm<sup>2</sup>. Acquisition time was 20 s for the background and 120 s for the mineral analyses. The Ca-content of garnet determined by EMP analyses and the Si-content of zircon constrained by standard zircon 91500 were used as internal standards. Reproducibility and accuracy, which were determined for NIST SRM 610 and NIST SRM 612, are usually < 8 % and < 6 %. Trace element concentrations were then calculated using GLITTER Version 3 (Van Achterbergh et al., 1999). Representative average trace element data of the relevant garnet and zircon domains are given in Table. 4.

### **Raman analyses**

In order to identify coesite inclusions in garnet or small high-pressure mineral inclusions in zircon (e.g. omphacite or rutile), Raman spectroscopy was performed at IGGCAS using a Renishaw Raman MKI-1000 system equipped with a CCD detector and an Ar ion laser. The laser beam with a wavelength of 514.5 nm was focused on the coesite inclusion through 50× and 100× objectives of a light microscope. The laser spot size was focused to 1 μm. The reproduction of spectra for the same spot is better than 0.2 cm<sup>-1</sup>.

### **Sm-Nd isotope chronology analyses**

Sm-Nd isotopic analyses were obtained at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. 100 mg of samples were first mixed with <sup>149</sup>Sm-<sup>150</sup>Nd diluent, dissolved afterwards in a purified

HF-HClO<sub>4</sub>-HNO<sub>3</sub>-mixture, and finally heated on an electric hot plate for a week.

Separation and purification of bulk REE were conducted by a silica-column with an AG50W-X12 exchange resin (200–400 mesh, 2ml), those of Sm and Nd by a silica-column with Teflon powder (1 ml) as exchange medium. Isotopic ratios of Sm and Nd were measured using a Finnigan MAT-262 thermal ionization mass spectrometer. Nd isotopic data of unknowns were normalized to <sup>146</sup>Nd/<sup>144</sup>Nd of 0.7219, and corrected using Ames (<sup>143</sup>Nd/<sup>144</sup>Nd = 0.512138) as external standard. Errors in element concentrations and 147Sm/144Nd-ratios are less than 0.5% (2σ). Sm-Nd data for the studied sample is shown in Table.

7.

#### **U-Pb isotope chronology and Oxygen isotope of zircon**

For the preparation of zircon study, and considering the relative low Zr content (only ca. 50 ug/g) of this N-MORB type meta-basalt (Table. 2), about 100 kilograms eclogite were sampled from outcrop (detailed sampling locations are shown in Figs. 3a, 3c. 11AT06-1, ca. 40 kg, sampled in 2011; 11AT06-2, ca. 60 kg, sampled in 2013), and approximately 500 zircon grains were collected and mounted in three different epoxy mounts. Fifty point analyses on different zircon domains from grains selected via CL images were chosen for investigating the U-Pb isotopic chronology and Oxygen isotopic composition of the potential multistage growth of zircon.



Zircon grains of sample 11AT06 were prepared by conventional crushing techniques and were hand-picked, mounted onto epoxy resin disks and polished with 0.25  $\mu\text{m}$  diamond paste. The zircon grains and zircon standards (Plesovice, Peng Lai and Qing Hu zircon were used here as standards) were mounted in epoxy mounts and then polished to section the crystals in half. Assessment of zircon grains and the choice of analytical sites were based on the transmitted and reflected light microscopy and cathodoluminescence (CL) images. CL imaging was processed on the LEO145VP scanning electron microscope with a Mini detector at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing (IGGCAS). The mount was vacuum-coated with high-purity gold prior to secondary ion mass spectrometry (SIMS) analyses. Measurements of U, Th and Pb were conducted using the Cameca IMS-1280 SIMS. U-Th-Pb ratios and absolute abundances were determined relative to the standard zircon 91500 (Wiedenbeck et al., 1995), analyses of which were interspersed with those of unknown grains, using operating and data processing procedures similar to those described by Li et al. (2009). A long-term uncertainty of 1.5% (1 RSD) for  $^{206}\text{Pb}/^{238}\text{U}$  measurements of the standard zircons was propagated to the unknowns (Li et al., 2010a) despite that the measured  $^{206}\text{Pb}/^{238}\text{U}$  error in a specific session is generally around 1% (1 RSD) or less. Measured compositions were corrected for common Pb using non-radiogenic  $^{204}\text{Pb}$ . Further details on instrument

parameters, analytical method, calibration and correction procedures can be found in (Li et al., 2010b). Results of U-Pb isotopic chronology of zircon for sample 11AT06 are listed in Table. 5.

Oxygen isotope analyses at the exact locations of U-Pb isotope zircon were also processed with the use of the Cameca IMS-1280 SIMS at IGGCAS. After U-Pb dating, the mount was carefully repolished for the O isotope analyses. The Gaussian focused Cs<sup>+</sup> ions are used as a primary beam to sputter zircon for O-isotope analyses. The primary beam size is ~10  $\mu\text{m}$  in diameter, and 2.5-3 nA in intensity. The <sup>16</sup>O and <sup>18</sup>O ions are detected simultaneously by two Faraday cups, and the currents are amplified by 10<sup>10</sup> ohms and 10<sup>11</sup> ohms resistors, respectively. Each spot analysis consists of pre-sputtering, beam centering in apertures, and a signal collecting process. A single spot analysis lasts 3 mins, including 2 mins for pre-sputtering and centering the secondary beam, and 1 min to collect 16 cycles of <sup>16</sup>O and <sup>18</sup>O signals. Oxygen isotopes were measured using the multi-collection mode. The instrumental mass fractionation (IMF) was corrected using an in-house zircon standard Penglai with  $\delta^{18}\text{OVSMOW} = 5.31 \pm 0.10\text{‰}$  (Li et al., 2010d). The measured <sup>18</sup>O/<sup>16</sup>O ratios were normalized to the VSMOW composition, then corrected for IMF as described in (Li et al., 2010b):  $\text{IMF} = \delta^{18}\text{O}_M - \delta^{18}\text{O}_{\text{Standard}}$ , and  $\delta^{18}\text{O}_{\text{Sample}} = \delta^{18}\text{O}_M + \text{IMF}$ , where  $\delta^{18}\text{O}_M = [({}^{18}\text{O}/{}^{16}\text{O})_M / 0.0020052 - 1] \times 1000 (\text{‰})$  and  $\delta^{18}\text{O}_{\text{Standard}}$  is the recommended  $\delta^{18}\text{O}$  value for the zircon

standard on the VSMOW scale. Corrected  $\delta^{18}\text{O}$  values are reported in the standard per mil notation with  $2\sigma$  errors. Analytical conditions, instrumentation and operation conditions are similar to Li et al. (2010d); Tang et al. (2015), and the results of oxygen isotope for zircon in sample 11AT06 are listed in Table. 6.

## FIGURE AND TABLE CAPTIONS

**Fig. 1:** Simplified geological map of (a) the Chinese Western Tianshan and (b) close-up map for the area (modified after Gao et al. (1999) with tagged locality distribution of previous radio-chronological data. Red stars mark the location of UHP reports (the finding of coesite). Green overlays indicate the inferred distribution of eclogites based on literature data. The dashed blue box marks the sample location (Fig. 3) of this study. Letters on the lower-left corner of the age boxes refer to lithology: “M” for mafic (typical eclogite), “m” for matrix (mainly meta-volcanic sediment with abundant amphibole) and “m” for micaschist (mainly felsic). Numbers on the upper-right corner of the boxes correspond to publications listed in Table. S2. #1: blueschist (used to be eclogite), Grt-Gln-WR Lu-Hf & Grt-Gln-WR Sm-Nd isochron ages, Soldner et al. (2016); #2: granitoids, zircon SHRIMP age, (LePu et al., 2011); #3: calc-Alkaline granite and granodiorite, Zircon LA-ICP-MS and SHRIMP age, Gao et al. (2009); #4: eclogite, rutile SIMS U-Pb age, Li et al. (2011); #5:

eclogite, Grt-Omp-WR Sm-Nd isochron age, (Du et al., 2014); #6: eclogite, Grt-Omp-WR Lu-Hf isochron age, Klemd et al. (2011); #7: eclogite, zircon SHRIMP U-Pb age, Zhang et al. (2007); #8: blueschist, crosstie & phengite Ar-Ar plateau age, Gao and Klemd (2003); #9: eclogite, zircon SHRIMP U-Pb age, Zhang et al. (2007); #10: eclogite & micaschist, white-mica Ar-Ar plateau & Rb-Sr isochron age, Klemd et al. (2005); #11: eclogite, zircon SHRIMP U-Pb age, Zhang et al. (2007); #12: eclogite, glaucophane & white-mica Ar-Ar plateau age, Gao and Zhang (2000); #13: blueschist, white-mica Ar-Ar plateau age, Gao and Zhang (2000); #14: blueschist, glaucophane Ar-Ar plateau age, Gao and Zhang (2000); #15: Blueschist, white-mica & glaucophane Ar-Ar plateau age, (Gao et al., 2006); #16: eclogite, Grt-Gln Sm-Nd isochron age, Gao and Klemd (2003); #17: eclogite, zircon SHRIMP U-Pb age, Zhang et al. (2007); #18: micaschist, zircon SHRIMP U-Pb age, Xin et al. (2013); #19 : eclogite, zircon SHRIMP U-Pb age, Su et al. (2010); #20: eclogite (Terrigenous detrital material), zircon SIMS U-Pb age, Liu et al. (2014a);

**Fig. 2:** Compilation of age data (a) as a function of estimated  $P_{\max}$  and (b) shown as a histogram (detail see Table. S2). Sources listed in the captions of Fig. 1 and Table. S2. “1”:  $P_{\max}$  range for previous “blueschist” ages lacking precise P-T constraint; “2”: same for eclogites; “3”: range of zircon U-Pb data from SP leucogranite dikes (Gao et al., 2011); “4”: range of zircon (inherited core) U-Pb data from regional rodingite (Li et al., 2010c).

**Fig. 3:** (a) Schematic outline of the studied outcrop; (b) field view of the sampling and (c) location of the samples in the layered eclogite.

**Fig. 4:** Whole-rock discrimination diagrams for the samples: (a) chondrite-normalized REE patterns, (b) primitive mantle-normalized spider diagram and (c) Th/Yb *versus* Nb/Yb diagram (Pearce, 2008). Reference curves for average N-MORB and OIB from Sun and McDonough (1989), and from Rudnick and Gao (2003) for upper continental crust.

**Fig. 5:** Mineral assemblages and microstructures of the studied eclogites. (a,b) Typical eclogitic facies mineral assemblages in sample 11AT06: subhedral-anhedral omphacite matrix grains (partially replaced by euhedral-subhedral amphibole porphyroblasts and subhedral paragonite grains), idioblastic garnet porphyroblasts and minor rutile grains in the omphacite matrix (cross-polar view). (c,d) Idioblastic garnet porphyroblasts partially replaced by subhedral epidote group minerals. (e) typical texture of studied garnet porphyroblast (same as in Figs. 7a, 7d), with abundant mineral inclusions (showed both in cross polar and plane polar view) within the core-mantle domain and slightly replaced by chlorite. (f) Moderately foliated omphacite matrix in the oriented sample of the studied layered eclogite (cross polars). (g) Occurrence of rutile inclusions in paragonite porphyroblast. Note the amphibole with a glaucophane core (pale blue) and a more barroisitic greenish rim. (h) Glaucophane inclusions in the core of a garnet porphyroblast.

(i) Omphacite inclusions in a paragonite porphyroblast. Mineral abbreviations: grt, garnet; omp, omphacite; brs, barrosite; gln, glaucophane; ph, phengite; pg, paragonite; ep, epidote; zo, zoisite; qz, quartz; rt, rutile; pyr, pyrite; chl, chlorite.

**Fig. 6:** Thin-section scale shear senses in eclogite and greenschist facies for the UHP eclogite and its meta-volcano-sedimentary host-rock, respectively. (a, b) Foliated omphacite matrix and  $\sigma$ -type garnet porphyroclasts with epidote, omphacite and phengite recrystallized tails. (c) Foliated albite and amphibole matrix, and  $\sigma$ -type fractured porphyroclasts of garnet with quartz, albite, paragonite and amphibole recrystallized tails. Gray solid-circles show the location of EMPA analyses for Thermocalc averagePT calculations (see Table S1). Mineral abbreviations as for figure 5.

**Fig. 7:** Garnet porphyroblast and mineral inclusions: (a) BSE imaging and location of mineral inclusions in the garnet core-mantle domain (dashed blue boxes shown in Fig. S2); (b) Raman spectrum of the analysed coesite inclusion; (c) Close-up view of the coesite inclusion in the garnet mantle domain; (d) Sketch of mineral inclusion distribution and location of analyses. Black dashed circles: laser-ICP-MS spots (see Fig. 9b); thick dashed line: EMPA profile (see Fig. 7e; Table. 3); red dashed rectangles: region with coexisting mineral inclusions chosen for thermocalc averagePT calculations; (e) Composition profile across the center of the studied garnet porphyroblast (Fig. 7a, 7d); (f) composition of sodic clinopyroxene (Morimoto, 1988) outlining the distinct

omphacite generations; (g) Chemical composition of amphiboles in studied eclogite after Hawthorne and Oberti (2006). Mineral abbreviations as for figure 5.

**Fig. 8:** Cathodoluminescence imaging and sketches of analyzed zircon grains, showing multistage growth features. The location of U-Pb, REEs,  $\delta^{18}\text{O}$  analyses is shown by red solid-ellipse ( $10 \times 15 \text{ um}^2$  beam-size via SIMS), orange dash-circle (with  $40 \times 40 \text{ um}^2$  beam-size via Laser-ICP-MS) and blue solid-circle (with  $20 \times 20 \text{ um}^2$  beam-size via SIMS) respectively (see Table. 5). Other zircon grains are shown in Fig. S3.

**Fig. 9:** Chondrite-normalized (Sun and McDonough, 1989) REE abundances of the various zircon (a) and garnet domains (b) (Table. 4). Overlays outline the compositional range of the various generations observed (taking into account the  $1\text{-}\sigma$  uncertainty). For a better comparison of REEs patterns, average patterns of core, core with high HREEs, mantle and rim domains of zircon are labelled 1, 2, 3, 4. Circled numbers 1, 2, 3 in Fig. 9b correspond to REE patterns of the core, mantle and rim of garnet (e.g. marked as grt-c, R, 02), identified as potentially coexisting with metamorphic zircon domain (rim), in the eclogite-facies micaschist of Rubatto (2002).

**Fig. 10:** Results of SIMS U-Pb isotopic dating and  $\delta^{18}\text{O}$  compositions for various zircon domains: (a, b) All SIMS analyses of the four zircon domains. (c) concentrations of  $\delta^{18}\text{O}$  (‰) versus U-Pb ages of multistage zircon domains.

The results of SIMS U-Pb age and  $\delta^{18}\text{O}$  composition of ,respectively, (d, number “1” with square in Fig. 10b) zircon core domain with high HREEs content (corresponding to green contour in Fig. 9a), (e, number “2” with square in Fig. 10b) zircon core domain (corresponding to red contour in Fig. 9a), (f, number “3” with square in Fig. 10b) zircon mantle domain (corresponding to blue contour in Fig. 9a) and (g, number “4” with square in Fig. 10b) zircon rim domain (corresponding to yellow contour in Fig. 9a) are listed in Tables. 5 and 6.

**Fig. 11:** WR-garnet-omphacite Sm-Nd isochron age for the oriented sample (11AT06-2; Table. 7).

**Fig. 12:** P-T estimates for the studied UHP eclogites, inferred from Perple\_X pseudosection modeling and Thermocalc averagePT calculation: (a) compilation of Thermocalc averagePT results (Table. S1); the pink arrow features the estimated trajectory, taking into account the uncertainties from avPT calculations. (b) P-T pseudosection in the system NMnCKFMASHTO for the studied UHP eclogite (effective bulk composition in Table. 2). Seven spots across the core-rim EMPA profile (Fig. 7e; Table. 3) were used to estimate PT conditions based on calculated isopleths. Blue boxes also consider ca. 5 %-calculated uncertainties. White arrow: estimated P-T trajectory from pseudosection modelling; dashed box: estimation of retrograde P-T conditions from the  $(\text{Na})_{\text{M4}}$  content of matrix amphibole. Mineral abbreviations as in figure



5.

**Fig. 13:** P-T trajectory estimates from this study (a) and previous works (b). See text for details. Brown boxes mark: estimates of peak metamorphism for UHP mica schist (Wei et al. (2009) Xin et al. (2013). Light-green box: peak metamorphic UHP conditions for metabasite from Tian and Wei (2013). Ages shown in figure 13a are discussed in section 9.3.

**Fig. 14:** (a-b) Patterns of trace element distribution coefficients between various possibly coexisting zircon and garnet domains. (c) sketch summarizing the various growth zones observed in zircon and garnet.

**Fig. 15:** Sketch depicting the petrologic evolution of mineral growth within metabasalts and inferred mobility of elements (mainly REEs) within the garnet-zircon-matrix metamorphic system during subduction and exhumation.

**Fig. 16:** Previous radiometric data (see Table. S2) and results from this study place constraints on the main tectonic stages for the area (i.e., detachment, exhumation, etc), as well as on exhumation rates.

**Fig. 17:** Simplified geodynamic cartoon setting back the studied samples and the overall time constraints inferred from this study within the evolution of the Chinese Southwestern Tianshan HP-UHP/LT metamorphic belt.

**Table 1:** Mineral modes in the studied samples (vol.%).

**Table 2:** Bulk rock major- and trace-element compositions of layered eclogite

samples and their meta-volcano-sedimentary host rock. Estimated effective bulk rock compositions for pseudosection modelling are indicated (EBC1 and EBC2).

**Table 3:** Representative microprobe analyses.

**Table 4:** Average Laser-ICP-MS trace-element compositions of various garnet and zircon domains.

**Table 5:** SIMS zircon U-Pb isotopic data.

**Table 6:** SIMS zircon oxygen isotopic data and modeled mineral & bulk-rock oxygen isotopic data at peak pressure conditions.

**Table 7:** TIMS Sm-Nd isotopic data.

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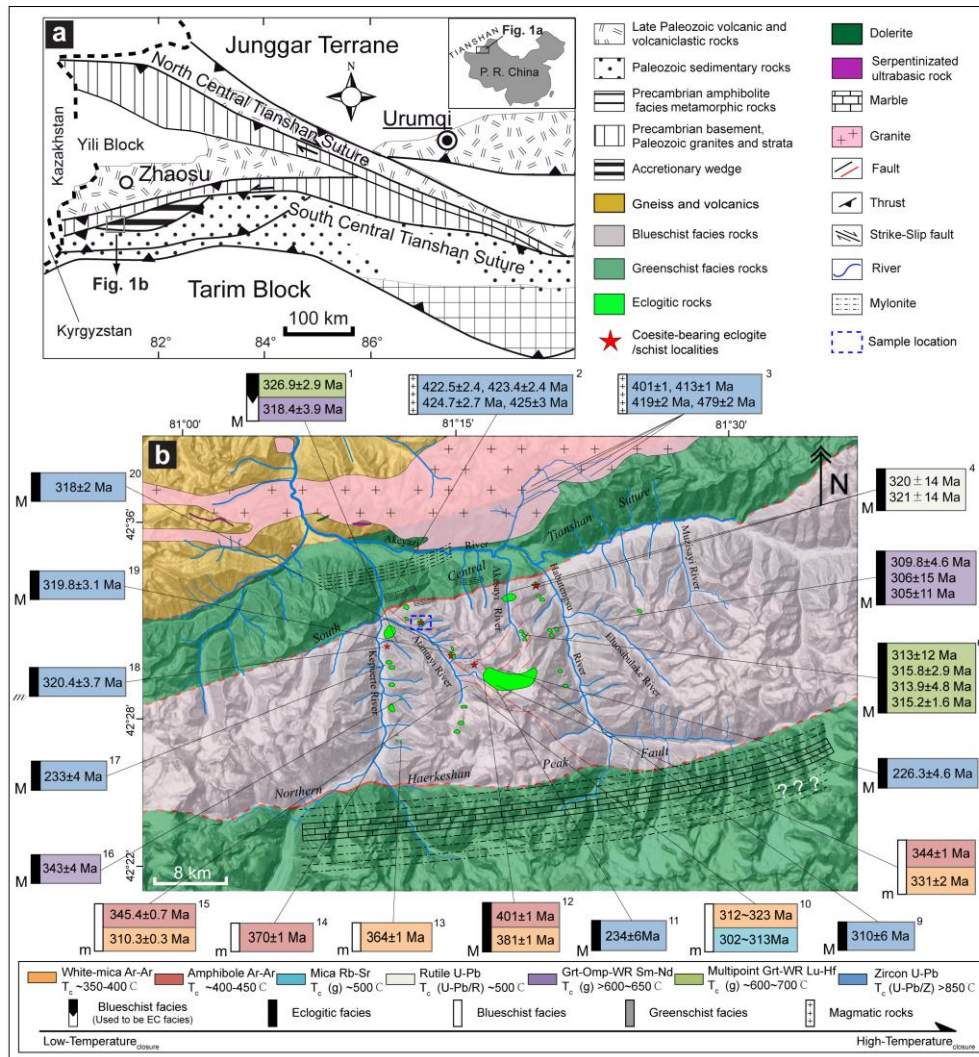


Figure 1



Figure 2

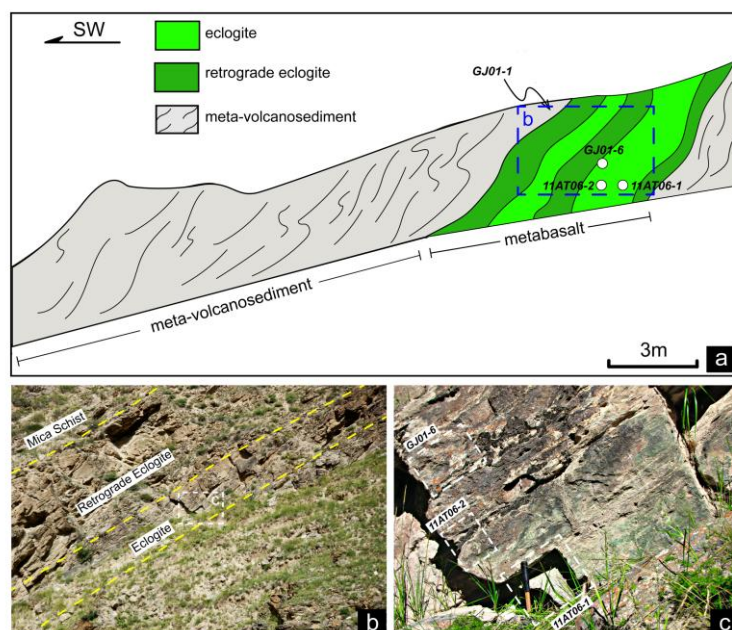


Figure 3



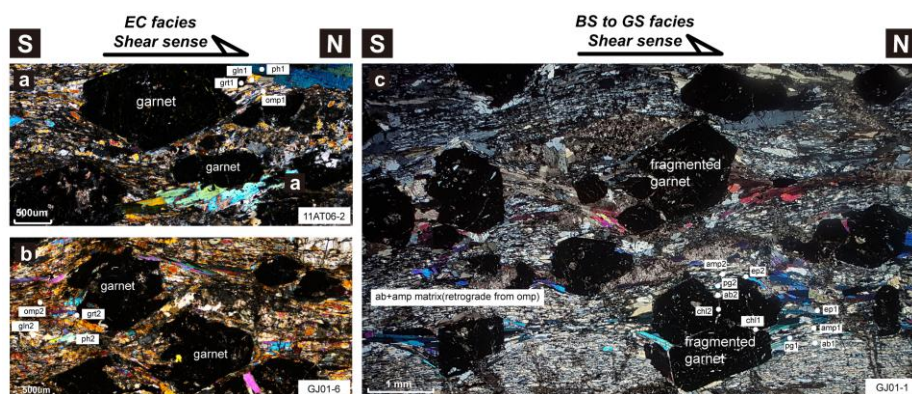


Figure 4

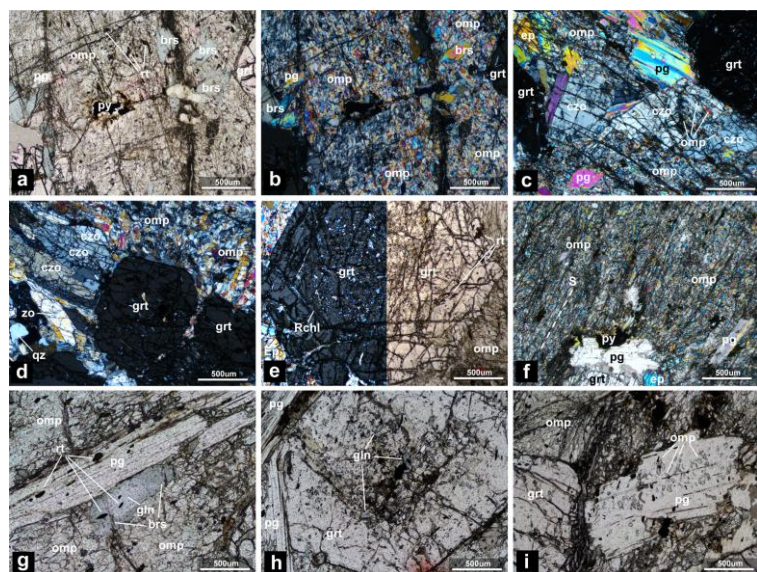


Figure 5

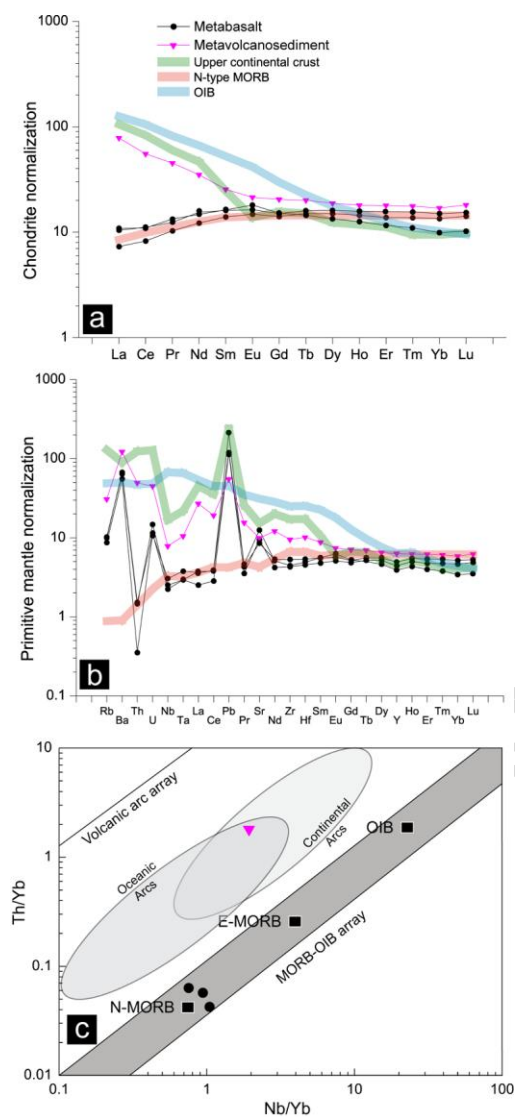


Figure 6

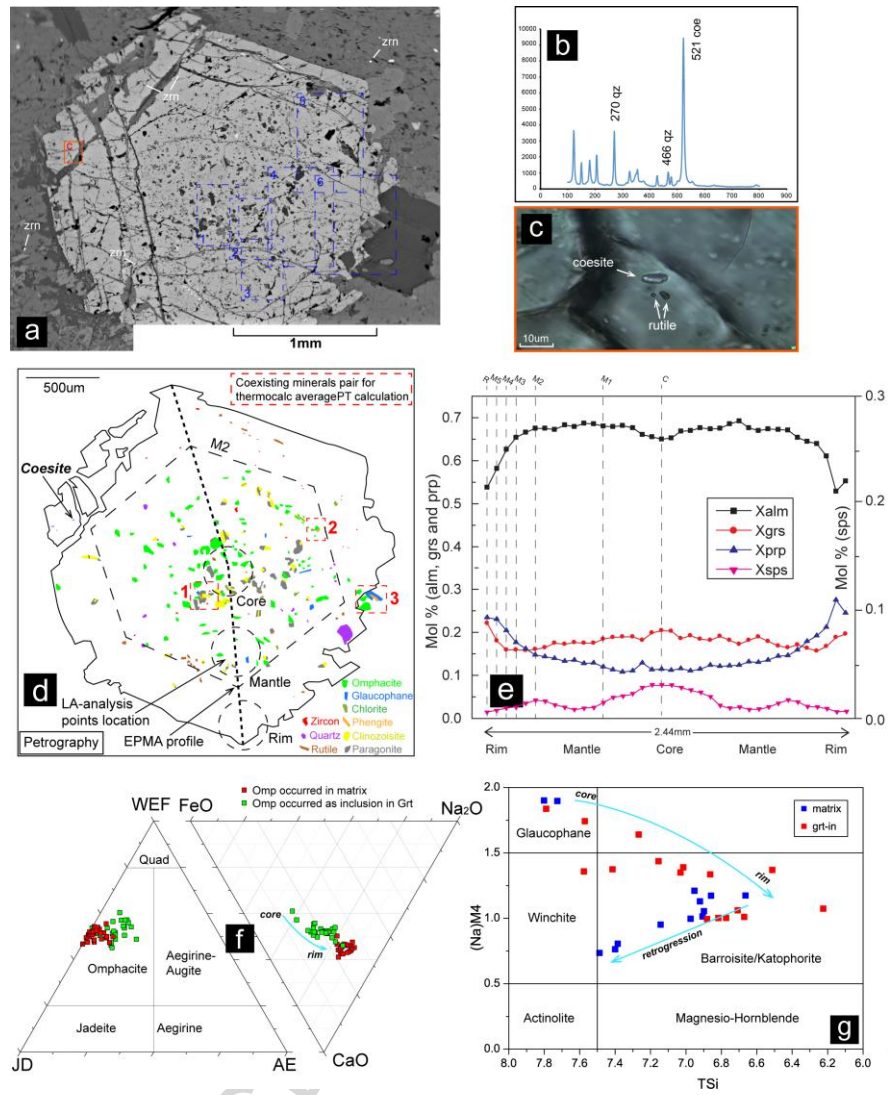


Figure 7

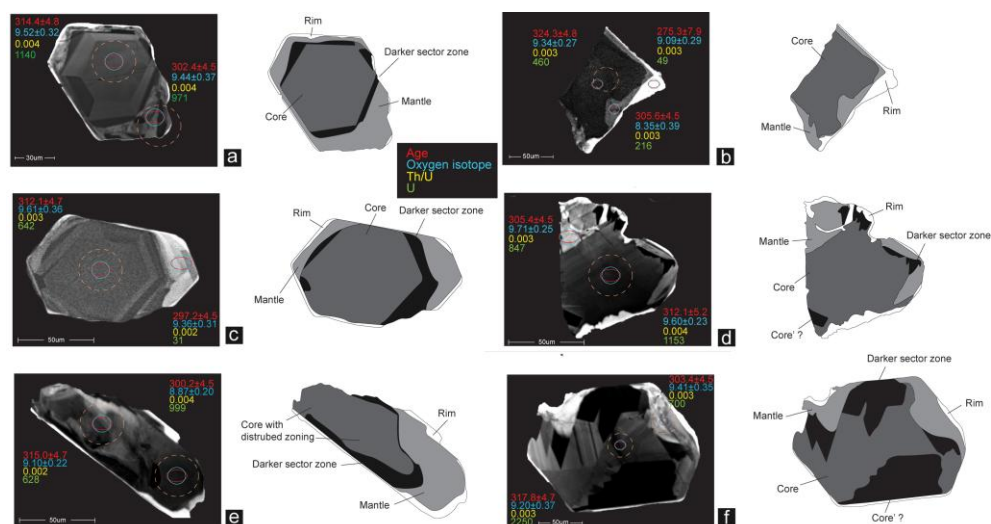
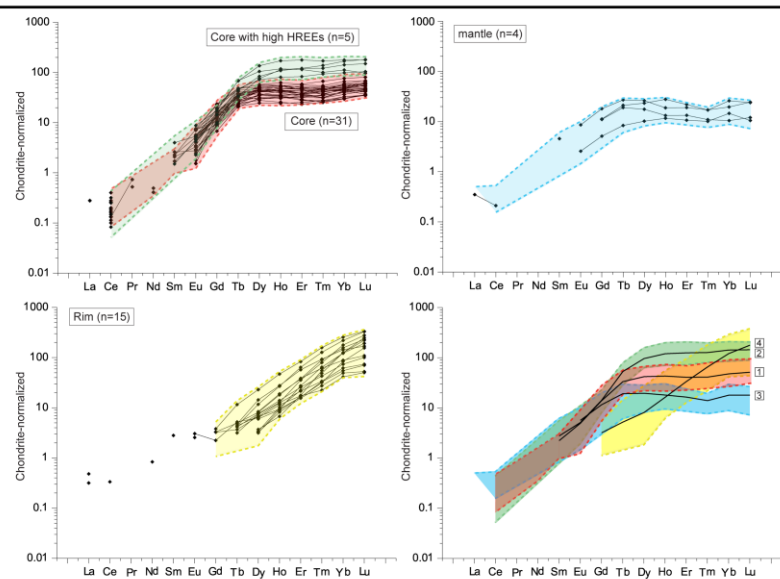


Figure 8

**a zircon domains**



**b garnet domains**

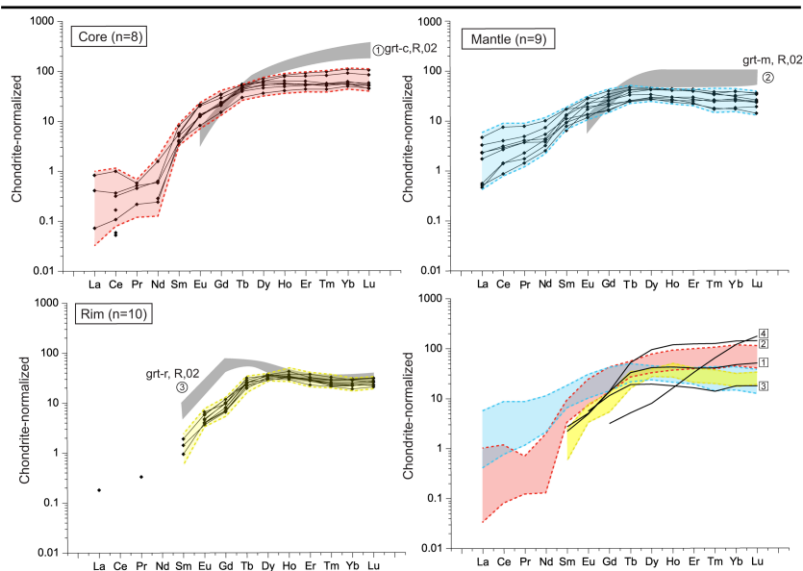


Figure 9



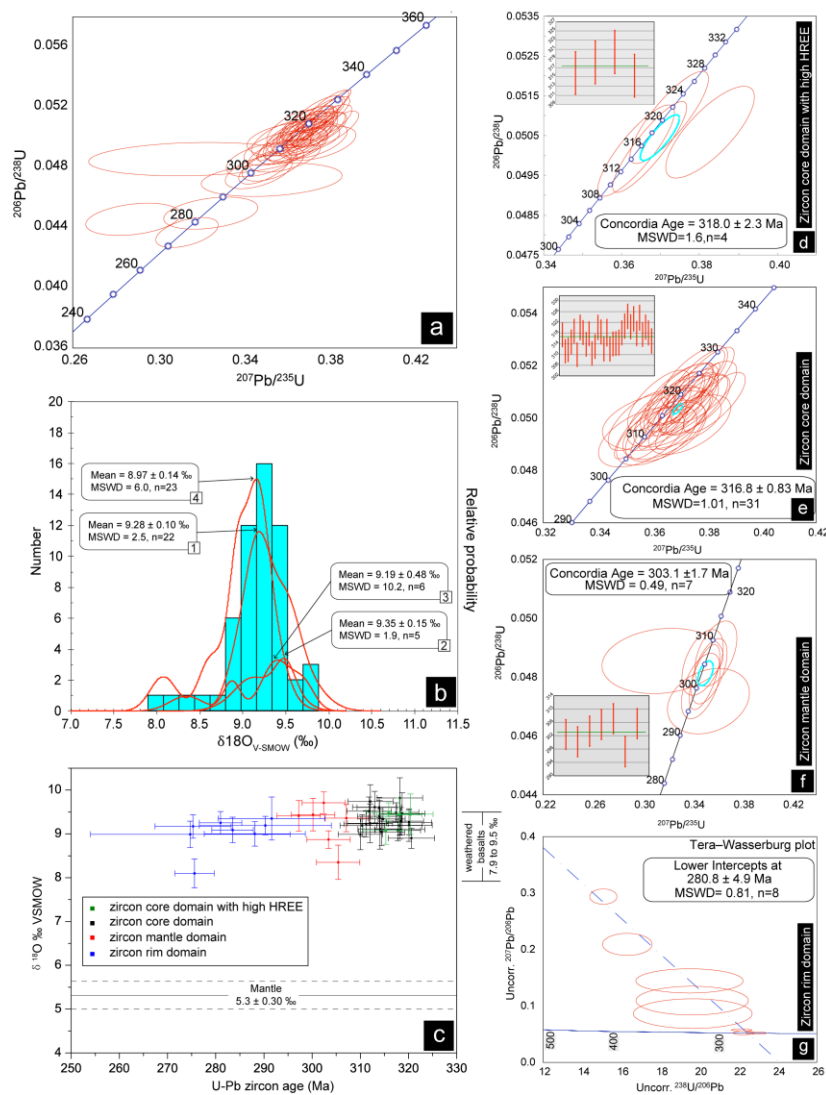


Figure 10

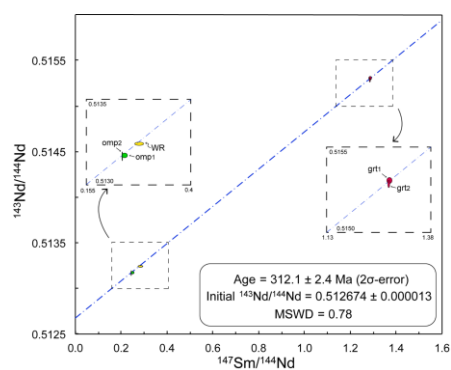


Figure 11



Figure 12

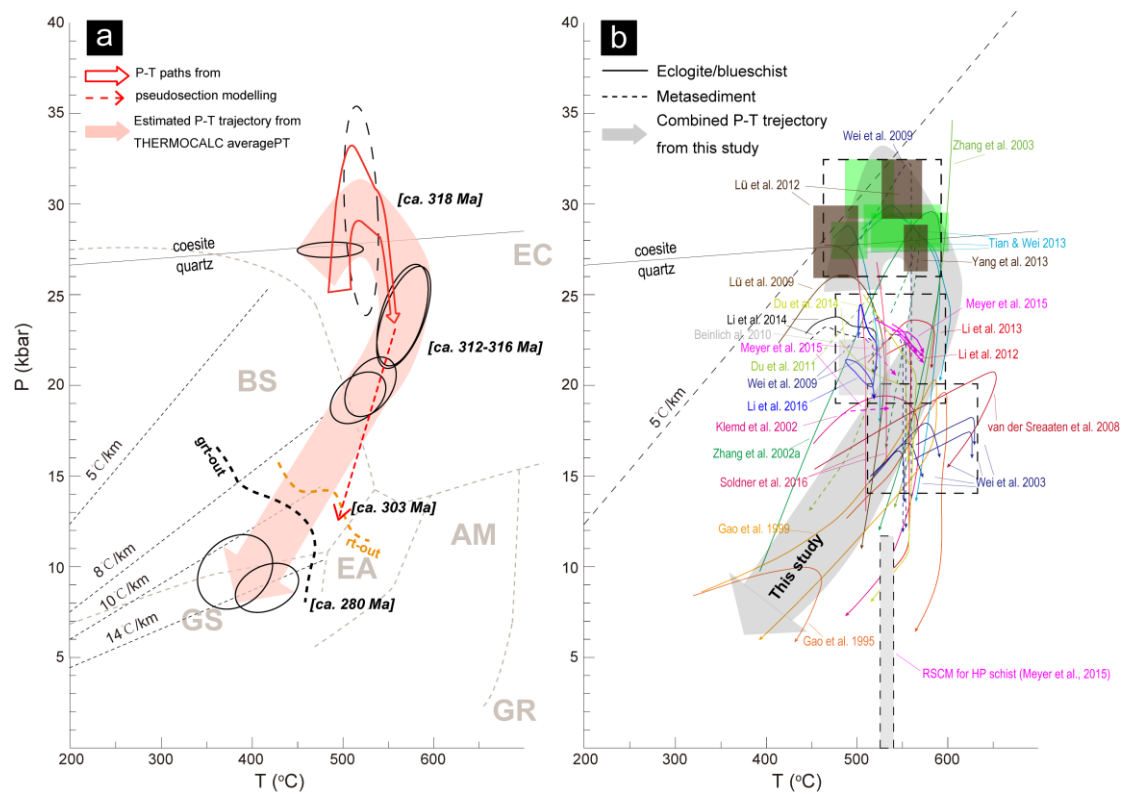


Figure 13

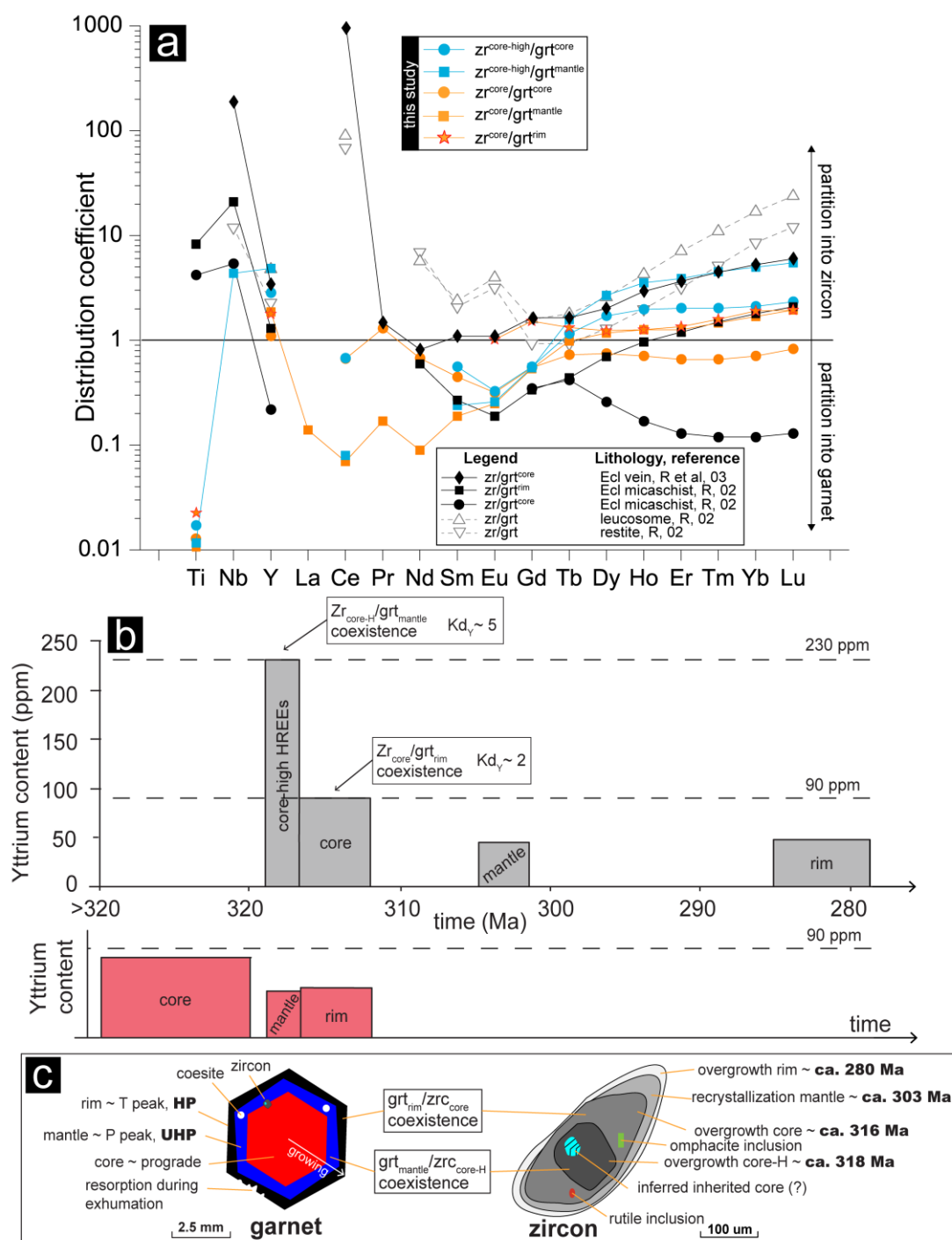


Figure 14

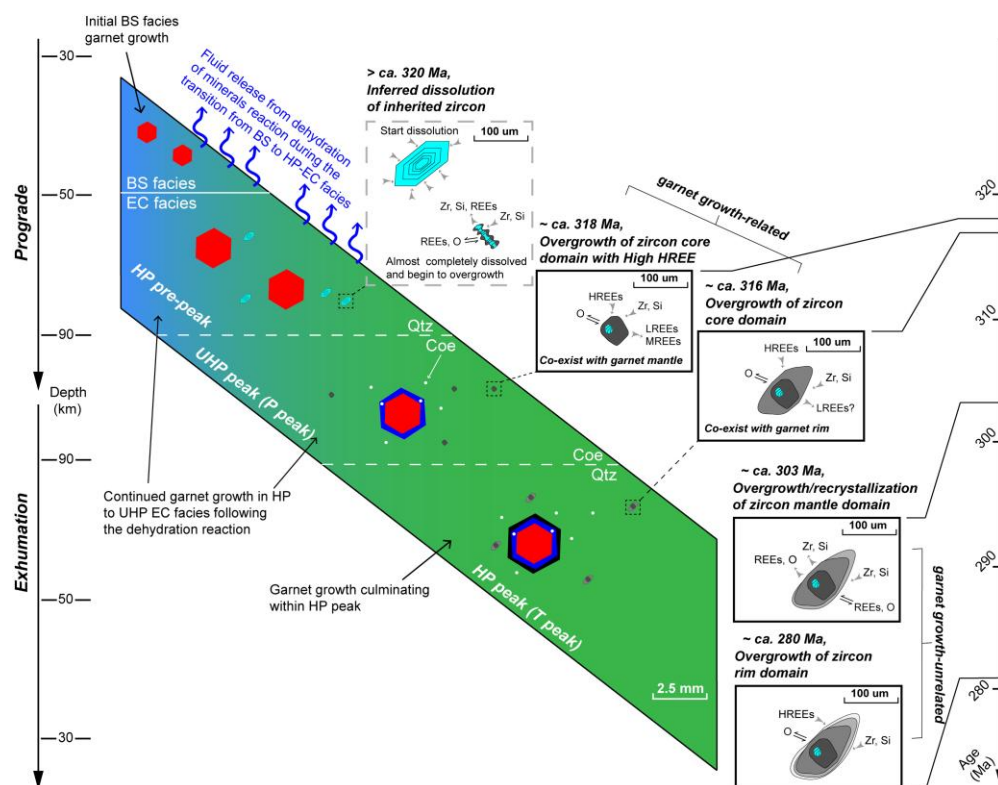


Figure 15

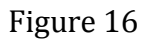


Figure 16

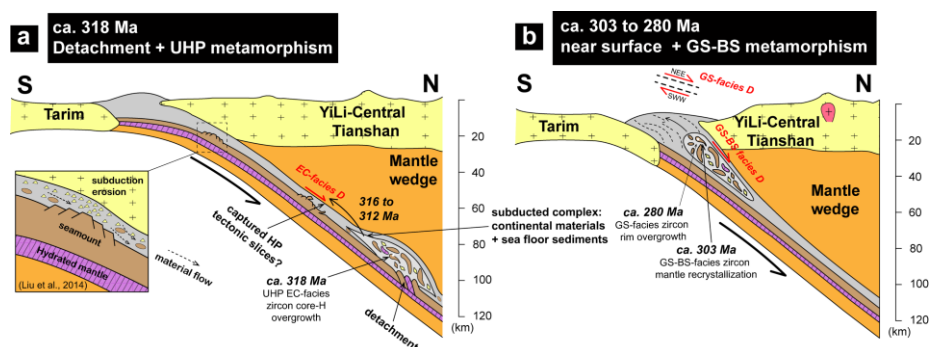


Figure 17

Table 1

Modal abundances of mineral assemblage in vol.%

Samples	Grt	Omp	Amp	Ph	Pg	Ep/Zo	Qz	Ap	Rt	Ttn	Lws	Fe-Ti oxide
eclogite												
11AT06-1	18	58	5	0.5	5.5	8	1	1	1.5	0.5	-	1
11AT06-2	19	55	7	1	4	6	3	2	1	1	-	1
GJ01-6	22	56	6	0.5	3.5	7	2	1	1	0.5	-	0.5
Modeled abundances for Peak T condition (ca. 550°C+2.5GPa)	18.4	71	-	0.8	-	-	1	-	0.9	-	7.4	-
Wall-rock mica schist												
GJ01-1	20	29	2	5	15	1	22	5	0.5	0.5	-	0.1

NOTES: Mineral modes were determined from the thin section by point counting on the basis of petrographic observations. The uncertainty of modal abundances of minerals was estimated to be less than 10% by repeating the same operations. Modeled abundances of mineral assemblage for peak T condition are calculated by pseudosection modeling with EBC-1.

Table 2

		XRF data			EBC-1	EBC-2
Lithology		eclogite		Mica schist	eclogite	eclogite
Sample	11AT06-1	11AT06-2	GJ01-6	GJ01-1	11AT06-1	11AT06-1
Major elements (wt %)						
SiO <sub>2</sub>	47.97	47.62	46.92	54.33	50.63	52.47
TiO <sub>2</sub>	0.86	0.87	1.01	0.65	1.15	1.27
Al <sub>2</sub> O <sub>3</sub>	14.87	14.55	15.23	14.65	14.62	14.06
MnO	0.23	0.14	0.14	0.14	0.10	0.05
MgO	7.22	6.38	6.75	4.03	6.28	6.65
CaO	10.05	11.75	10.69	7.18	11.53	12.15
Na <sub>2</sub> O	4.15	4.60	5.10	3.96	5.31	5.92
K <sub>2</sub> O	0.18	0.30	0.12	0.84	0.08	0.09
P <sub>2</sub> O <sub>5</sub>	0.42	0.08	0.20	0.14	-	-
Fetot <sub>a</sub>	11.88	10.23	10.68	9.09	-	-
FeO	8.72	7.28	7.80	-	8.23	5.87
Fe <sub>2</sub> O <sub>3</sub>	2.19	2.14	2.01	-	2.06	1.47
LOI	1.86	3.34	2.68	4.86	-	-
Sum	99.69	99.86	99.52	99.87	100.00	100.00
Trace elements (ug/g)						
Li	33.2	34.8	34.5	21.7		
Be	0.537	0.370	0.480	0.680		



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Sc	43.9	42.7	44.4	32.7
V	263	263	273	179
Cr	290	299	320	104
Co	43.8	39.7	34.4	25.0
Ni	137	128	103	86.6
Cu	86.7	103	62.1	105
Zn	172	144	156	94
Ga	14.8	14.9	16.6	19.1
Rb	6.28	5.51	6.50	19.6
Sr	180	200	263	209
Y	22.5	20.1	17.8	28.6
Zr	59.3	48.1	50.0	106
Nb	2.17	1.60	1.79	5.57
Cs	1.03	0.610	0.580	1.53
Ba	10.0	386	454	853
La	2.47	1.73	2.57	18.6
Ce	6.81	5.05	6.69	33.9
Pr	1.18	0.980	1.27	4.29
Nd	7.20	5.69	6.90	16.4
Sm	2.46	2.13	2.49	3.89
Eu	0.949	0.860	1.05	1.24
Gd	3.08	2.89	3.12	4.20
Tb	0.599	0.560	0.540	0.750
Dy	4.08	3.81	3.40	4.78

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Ho	0.894	0.820	0.710	1.02
Er	2.59	2.28	1.92	2.96
Tm	0.396	0.350	0.280	0.450
Yb	2.55	2.29	1.68	2.88
Lu	0.391	0.360	0.260	0.460
Hf	1.66	1.40	1.51	3.13
Ta	0.156	0.120	0.120	0.430
Tl	0.141	0.070	0.070	0.130
Pb	14.9	8.44	8.79	3.90
Bi	0.142	0.030	0.050	0.090
Th	0.129	0.030	0.120	4.210
U	0.232	0.240	0.310	0.940
ΣREE	58.2	49.9	50.7	124.4
(La/Yb) <sub>N</sub>	0.695	0.542	1.10	4.62
(La/Sm) <sub>N</sub>	0.648	0.524	0.666	3.08
(Gd/Yb) <sub>N</sub>	1.00	1.04	1.54	1.21
Nb/Ta	13.9	13.3	14.9	13.0
Zr/Hf	35.7	34.3	33.1	34.0
Th/Ta	0.827	0.250	1.00	9.79
Ta/Hf	0.094	0.086	0.079	0.137

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NOTES: "-" means do not detect or calculate; EBC means calculated effective bulk

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composition for pseudosection modeling; "Fetot<sub>a</sub>" means the total amount of iron oxide analysed from XRF; The Fe<sub>2</sub>O<sub>3</sub> content of bulk-rock is constrained from potassium permanganate titration method; The Fe<sub>2</sub>O<sub>3</sub> and FeO contents of EBCs were calculated based on the constant ratio of Fe<sup>3+</sup>/Fe<sup>2+</sup> from XRF data for evaluated composition;

Table 3

Mine	Grt-C	Grt-M1	Grt-M2	Grt-M3	Grt-M4	Grt-M5	Grt-R	Gln-i n-grt	Gln-c- matrix	Brs-i n-grt	Brs-r- matrix	Omp-i n-grt-c	Omp-in -grt-m	Omp- in-pg	Omp- matrix	Ph-i n-grt	Ph-m atrix	Pg-i n-grt	Pg-m artix	Cz o	Chl-Ep matri x	Rt	Ttn	
SiO <sub>2</sub>	37.52	38.24	37.33	37.86	38.10	38.02	38.09	57.17	57.83	46.62	49.90	55.00	58.48	56.80	56.58	51.44	51.92	46.39	48.87	39.51	38.30	25.63	0.03	29.82
TiO <sub>2</sub>	0.15	0.16	0.06	0.02	0.01	0.06	0.00	0.180	0.030	0.230	0.410	0.070	0.040	0.120	0.040	0.330	0.270	0.020	0.060	0.106	0.103	0.02	99.32	37.86
Al <sub>2</sub> O <sub>3</sub>	21.15	20.94	21.47	21.39	21.65	21.76	21.93	10.27	12.21	13.96	11.85	8.12	10.19	12.47	10.38	27.64	27.71	38.62	39.44	30.65	26.87	19.26	0.02	2.11
Cr <sub>2</sub> O <sub>3</sub>	0.03	0.21	0.04	0.06	0.03	0.09	0.01	0.020	0.050	0.080	0.040	0.020	0.080	0.020	0.000	0.050	0.040	0.090	0.070	0.000	0.000	0.060	0.19	0.03
Fe <sub>2</sub> O <sub>3</sub>	0.73	0.00	1.31	0.83	0.39	1.02	0.92	1.78	0.54	2.00	0.55	4.48	0.00	1.62	2.09	0.00	0.00	0.00	0.00	4.48	8.89	0.00	0.00	0.00
FeO	30.20	31.89	30.91	30.89	29.93	27.66	25.92	11.52	7.53	14.22	11.14	4.78	4.34	1.50	1.97	3.58	1.83	1.12	0.24	0.000	0.000	25.31	0.46	1.07
MnO	1.48	0.70	0.81	0.52	0.48	0.39	0.21	0.100	0.040	0.150	0.020	0.080	0.050	0.040	0.030	0.030	0.010	0.040	0.000	0.000	0.210	0.00	0.02	
MgO	2.46	2.56	3.20	3.86	4.47	5.15	5.28	9.75	11.33	8.78	11.77	7.50	8.20	8.28	9.29	2.38	3.37	0.12	0.11	0.000	0.000	14.75	0.01	0.01
CaO	6.88	6.09	5.41	5.42	5.44	6.25	7.76	1.51	1.14	7.15	7.95	13.32	11.62	12.51	13.58	0.10	0.01	0.29	0.29	23.03	23.00	0.13	0.08	29.11
Na <sub>2</sub> O	0.02	0.11	0.07	0.01	0.04	0.06	0.03	6.96	7.27	5.06	4.20	6.57	6.28	7.69	6.83	0.42	0.80	7.10	7.37	0.000	0.000	0.15	0.01	0.05



	03	17	11	02	06	09	04	3		5					4	2	2	4	01	00		00	03	
K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00		0.01					0.69	0.77	0.03	0.02	0.00	0.0		0.0	0.0	
	00	02	00	00	01	00	01	3	0.005	1	0.049	0.001	0.005	0.000	0.000	6	1	8	7	00	00	0.022	00	01
X(ph	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.39		0.47					0.23	0.33	0.01	0.00						
ase)	98	02	29	52	76	03	07	9	0.272	6	0.347	0.340	0.420	0.480	0.420	6	2	2	0	-	-	0.464	-	-
Y(ph	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.10		1.42										0.00	0.1			
ase)	96	74	56	53	54	77	19	0	0.027	5	1.159	0.471	0.495	0.527	0.476	-	-	-	-	86	74	-	-	-

NOTES: Microprobe data presented here are calculated from RAW data via AX\_2 program (Holland; <http://www.esc.cam.ac.uk/research/research-groups/holland/ax>); X (grt) = Xpy =  $Mg / (Fe^{2+} + Mn + Mg + Ca)$ , X (omp) = Xjd, X (Brs, gln, chl) =  $Fe^{2+} / (Fe^{2+} + Mg)$ , X (Ph, pa) =  $Mg^{2+}$ ; Y (grt) = Xgr =  $Ca / (Fe^{2+} + Mn + Mg + Ca)$ , Y (omp) = j(o) =  $Na / (Na + Ca)$ , Y (gln, ep, czo) =  $Fe^{3+} / (Fe^{3+} + AlVI)$ , Y (Brs) = (Na)M4; c, core; m, mantle; r, rim; -in-phase: inclusion mineral in phase, -matrix: mineral in the matrix; "-" means did not calculate.

Table 4

			Garnet						Zircon					
	Core		Mantle		Rim		Core		Core high HREEs		Mantle		Rim	
Element	Average	Std(N=8)	Average	Std(N=9)	Average	Std(N=10)	Average	Std(N=30)	Average	Std(N=5)	Average	Std(N=4)	Average	Std(N=15)
P	53.5	31.9	117	155	13.9	2.84	27.2	9.92	34.6	10.4	-	-	21.2	6.27
Ti	681	152	1661	979	106	17.5	2.89	1.04	10.6	3.77	1.55	0.140	1.93	0.930
Nb	bd	bd	1.43	1.74	bd	bd	5.75	1.22	6.27	1.20	5.27	0.979	5.62	1.04
Y	81.2	17.6	47.4	11.5	49.8	5.42	89.1	17.2	231	57.7	44.6	8.57	47.6	19.3
La	bd	bd	0.471	0.356	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd
Ce	0.181	0.204	1.63	1.35	bd	bd	0.121	0.060	0.123	0.064	bd	bd	bd	bd
Pr	0.042	0.015	0.314	0.214	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd
Nd	0.308	0.249	2.38	1.16	bd	bd	bd	bd	bd	bd	bd	bd	bd	bd
Sm	0.746	0.245	1.77	0.590	bd	bd	0.336	0.051	0.420	0.269	bd	bd	bd	bd
Eu	0.882	0.281	1.13	0.360	0.278	0.060	0.284	0.115	0.294	0.137	0.325	0.248	bd	bd
Gd	5.14	1.38	5.18	1.63	1.83	0.401	2.81	0.905	2.87	0.873	2.34	1.09	0.648	0.135
Tb	1.69	0.301	1.24	0.328	0.926	0.125	1.23	0.299	1.96	0.578	0.705	0.291	0.192	0.093
Dy	13.9	2.74	8.91	1.95	8.46	0.772	10.5	2.14	24.0	6.72	4.91	1.80	2.03	1.32
Ho	3.38	0.788	1.89	0.458	1.89	0.208	2.40	0.539	6.70	1.86	1.01	0.411	0.913	0.603
Er	10.0	2.64	5.23	1.37	4.87	0.614	6.63	1.62	20.37	5.64	2.69	0.853	5.48	3.38
Tm	1.56	0.455	0.703	0.193	0.646	0.096	1.03	0.271	3.18	0.791	0.351	0.096	1.65	0.994
Yb	11.2	3.58	4.72	1.29	4.19	0.660	8.00	2.00	23.72	5.80	3.00	1.13	20.2	10.9
Lu	1.54	0.535	0.654	0.187	0.654	0.098	1.28	0.331	3.61	1.01	0.450	0.190	4.42	2.47

Ta	bd	bd	bd	bd	bd	bd	0.071	0.044	0.077	0.026	0.095	0.042	0.099	0.054
Hf	bd	bd	bd	bd	bd	bd	10127	366	10306	359	10553	317	10341	671
Th	bd	bd	bd	bd	bd	bd	3.59	3.00	5.39	5.27	2.86	1.57	0.174	0.107
U	bd	bd	bd	bd	bd	bd	982	660	982	657	740	255	30.6	34.9
Pb	bd	bd	bd	bd	bd	bd	232	158	229	141	170	60.6	16.3	12.8
(Lu/S m) <sub>N</sub>	12.4		2.23		-		22.9		51.7		-		-	
(Lu/Eu ) <sub>N</sub>	3.99		1.33		5.37		10.3		28.0		3.17		-	
(Lu/Tb ) <sub>N</sub>	1.35		0.779		1.04		1.53		2.71		0.940		33.9	

NOTES: "bd" means below detected; "-" do not calculated; Here the Std-dev is 1 sigma;



Table 5

Zircon core (n=31)	U (ug/g)	Th (ug/g)	Th/U	$f_{206}$ (%)	$^{207}\text{Pb}$ $^{235}\text{U}$	$\pm 1s$ %	$^{206}\text{Pb}$ $^{238}\text{U}$	$\pm 1s$ %	$\rho$	$^{207}\text{Pb}$ $^{235}\text{U}$	$\pm 1s$	$^{206}\text{Pb}$ $^{238}\text{U}$	$\pm 1s$
11AT06-1a @10	631	1.690	0.003	0.330	36991	2.56	0.0505	1.50	0.5882	319.6	7.0	317.4	4.7
11AT06-1a @14	659	2.440	0.004	0.130	36494	2.68	0.0495	1.50	0.5614	315.9	7.3	311.2	4.6
11AT06-1a @15	750	2.940	0.004	0.230	36427	2.73	0.0496	1.50	0.5500	315.4	7.4	311.8	4.6
11AT06-1a @18	612	1.290	0.002	0.430	36714	2.53	0.0500	1.50	0.5956	317.5	6.9	314.7	4.6
11AT06-1a @2	746	1.940	0.003	0.030	36225	2.07	0.0507	1.50	0.7258	313.9	5.6	318.7	4.7
11AT06-1a @20	795	2.690	0.003	0.230	35596	2.91	0.0493	1.51	0.5199	309.2	7.8	310.0	4.6
11AT06-1a @28	653	1.570	0.002	0.090	37086	2.39	0.0509	1.54	0.6442	320.3	6.6	320.1	4.8
11AT06-1a @29	1114	4.020	0.004	0.110	37306	1.96	0.0506	1.50	0.7682	321.9	5.4	318.2	4.7
11AT06-1a @32	671	1.160	0.002	0.290	35594	2.25	0.0499	1.50	0.6686	309.2	6.0	313.9	4.6
11AT06-1a @36	870	4.550	0.005	0.220	37544	2.29	0.0505	1.50	0.6566	323.7	6.4	317.8	4.7
11AT06-1a @38	1034	3.460	0.003	0.210	36159	2.69	0.0493	1.51	0.5630	313.4	7.3	310.4	4.6
11AT06-1a @39	624	2.030	0.003	0.110	37371	2.64	0.0497	1.51	0.5699	322.4	7.3	313.0	4.6
11AT06-1a @6	731	3.470	0.005	0.190	37025	2.14	0.0509	1.51	0.7046	319.8	5.9	320.1	4.7
11AT06-1b @6	992	3.080	0.003	0.090	36843	1.82	0.0506	1.50	0.8259	318.5	5.0	318.4	4.7
11AT06-1c @2	642	2.000	0.003	0.000	35589	1.82	0.0496	1.55	0.8485	309.1	4.9	312.1	4.7
11AT06-1c @6	1021	3.930	0.004	0.480	37138	2.05	0.0506	1.67	0.8115	320.7	5.7	318.2	5.2
11AT06-1d @1	582	1.770	0.003	0.000	36228	1.86	0.0496	1.53	0.8221	313.9	5.0	312.0	4.7
11AT06-1d @33	180	0.450	0.003	0.820	36347	3.96	0.0499	1.51	0.3817	314.8	10.8	314.0	4.6
11AT06-1d @22	571	1.290	0.002	0.040	37170	1.86	0.0499	1.50	0.8071	320.9	5.1	314.1	4.6
11AT06-1d @6	1140	4.000	0.004	0.000	36469	1.72	0.0500	1.56	0.9084	315.7	4.7	314.4	4.8
11AT06-1d @19	439	0.650	0.001	0.060	36804	2.00	0.0506	1.50	0.7510	318.2	5.5	318.1	4.7

11AT06-1d @30	751	3.540.005	0.020.37868	2.13	0.0510	1.52	0.7131	326.1	6.0	320.6	4.8
11AT06-1d @7	460	1.190.003	0.200.37550	2.12	0.0516	1.50	0.7079	323.7	5.9	324.3	4.8
11AT06-1a @23	1347	3.370.002	0.030.37595	1.85	0.0514	1.50	0.8098	324.1	5.2	323.4	4.7
11AT06-1d @10	2250	6.570.003	0.010.37210	1.60	0.0505	1.52	0.9451	321.2	4.4	317.8	4.7
11AT06-1a @35	1051	4.760.005	0.040.37629	2.00	0.0505	1.50	0.7528	324.3	5.6	317.5	4.7
11AT06-1b @34	3354	25.690.008	0.150.37570	1.59	0.0509	1.51	0.9441	323.9	4.4	320.2	4.7
11AT06-1d @13	2740	11.910.004	0.240.37897	1.92	0.0515	1.53	0.8000	326.3	5.4	323.8	4.8
11AT06-1a @33	628	1.390.002	0.100.36444	2.48	0.0501	1.53	0.6188	315.5	6.7	315.0	4.7
11AT06-1d @14	573	1.720.003	0.000.37136	1.97	0.0503	1.51	0.7661	320.7	5.4	316.4	4.7
11AT06-1e @2	1153	4.640.004	1.600.37476	3.16	0.0496	1.51	0.4790	323.2	8.8	312.1	4.6
<u>Zircon core with high HREEs (n=4)</u>											
11AT06-1b @1	991	2.230.002	0.060.36720	1.71	0.0502	1.50	0.8780	317.6	4.7	315.9	4.6
11AT06-1d @29	476	1.010.002	0.020.38270	1.96	0.0506	1.50	0.7666	329.0	5.5	318.1	4.7
11AT06-1a @42	3392	14.140.004	0.030.37221	1.79	0.0510	1.50	0.8395	321.3	4.9	320.4	4.7
11AT06-1b @5	605	1.620.003	0.180.36372	1.79	0.0501	1.51	0.8451	315.0	4.9	315.3	4.7
<u>Zircon mantle (n=7)</u>											
11AT06-1a @1	971	4.000.004{0.28}	0.35010	2.32	0.0480	1.52	0.6532	304.8	6.1	302.4	4.5
11AT06-1a @11	999	4.000.004{0.30}	0.34716	2.98	0.0477	1.54	0.5181	302.6	7.8	300.2	4.5
11AT06-1a @21	700	2.000.003{0.13}	0.35383	2.70	0.0482	1.52	0.5613	307.6	7.2	303.4	4.5
11AT06-1a @9	847	3.000.003{0.19}	0.34857	3.15	0.0485	1.52	0.4813	303.6	8.3	305.4	4.5
11AT06-1a @37	661	3.000.004{0.50}	0.35923	3.12	0.0488	1.50	0.4823	311.6	8.4	307.1	4.5
11AT06-1c @1	31	0.060.002{0.00}	0.35326	6.18	0.0472	1.56	0.2519	307.2	16.5	297.2	4.5
11AT06-1d @8	216	0.580.003{1.43}	0.31633	10.20	0.0486	1.51	0.1480	279.1	25.2	305.6	4.5

continued

Zircon rim (n=8)	U (ug/g)	Th (ug/g)	Th/U	$f_{206}$ (%)	$\frac{^{238}\text{U}}{^{206}\text{Pb}}$ *	$\pm 1s$ %	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ *	$\pm 1s$ %	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\pm 1s$
11AT06-1a @13	665	1.64	0.002	{1.32}	22.149	1.58	0.05735	1.90	281.0	4.4
11AT06-1a @31	287	1.66	0.006	{0.09}	22.896	1.51	0.05207	2.69	275.6	4.1
11AT06-1a @7	187	0.66	0.004	{0.00}	22.241	1.57	0.05238	4.20	283.5	4.3
11AT06-1d @31	8	0.03	0.004	{9.84}	19.487	9.29	0.14442	9.81	291.6	11.1
11AT06-1e @3	5	0.02	0.004	{10.30}	19.625	9.667	0.10951	15.34	288.1	10.5
11AT06-1e @4	1	0.01	0.009	{14.43}	19.656	10.210	0.08647	20.06	274.7	20.7
11AT06-1d @9	49	0.15	0.003	{34.21}	15.081	3.06	0.29376	3.04	275.3	7.9
11AT06-1d @34	6	0.05	0.009	{24.88}	16.306	5.14	0.20910	6.17	290.3	13.7

NOTES:  $f_{206}$  (%) is the percentage of common  $^{206}\text{Pb}$  in total  $^{206}\text{Pb}$ , calculated by  $^{207}\text{Pb}$ -based;  $t_{206/238}$  is  $^{206}\text{Pb}$ - $^{238}\text{U}$  age calculated by  $^{207}\text{Pb}$ -based common-lead correction; "\*" means that the ratios are common Pb uncorrected;

Table 6

Sample	$\delta^{18}\text{O}(\text{‰})_a$	$2\sigma(\text{‰})$	Sample	$\delta^{18}\text{O}(\text{‰})_a$	$2\sigma(\text{‰})$
zircon core			zircon rim		
11AT06-1a @10	9.49	0.22	11AT06-1a @13	9.25	0.26
11AT06-1a @14	9.23	0.30	11AT06-1a @31	8.10	0.33
11AT06-1a @15	9.52	0.32	11AT06-1a @7	9.09	0.29
11AT06-1a @18	9.34	0.27	11AT06-1d @31	9.35	0.49
11AT06-1a @2	9.46	0.48	11AT06-1e @3	9.00	0.28
11AT06-1a @20	8.99	0.35	11AT06-1e @4	8.99	0.30
11AT06-1a @28	9.20	0.37	11AT06-1d @9	9.17	0.27
11AT06-1a @29	9.82	0.46	11AT06-1d @34	9.19	0.21
11AT06-1a @32	9.60	0.23	11AT06-1e @6	9.19	0.20
11AT06-1a @36	9.08	0.24	11AT06-1e @7	8.06	0.29
11AT06-1a @38	9.19	0.25	11AT06-1e @8	8.93	0.15
11AT06-1a @39	9.61	0.36	11AT06-1e @9	9.02	0.33
11AT06-1a @6	9.26	0.28	11AT06-1e @10	9.43	0.28
11AT06-1b @6	9.29	0.31	11AT06-1e @11	8.88	0.28
11AT06-1c @2	9.74	0.38	11AT06-1e @12	9.16	0.40
11AT06-1c @6	9.10	0.22	11AT06-1e @13	9.22	0.28
11AT06-1d @1	9.24	0.44	11AT06-1e @14	9.10	0.35
11AT06-1d @33	9.40	0.36	11AT06-1e @15	8.94	0.24
11AT06-1d @22	9.11	0.46	11AT06-1e @16	9.27	0.29
11AT06-1d @6	9.04	0.31	11AT06-1e @17	9.22	0.36
11AT06-1d @19	9.19	0.22	11AT06-1e @18	8.55	0.22

11AT06-1d @30	8.90	0.23	11AT06-1e @19	8.91	0.44
			11AT06-1e @20	8.66	0.22
zircon mantle					
11AT06-1a @1	9.71	0.25	zircon high HREEs		
11AT06-1a @11	9.44	0.37	11AT06-1b @1	9.49	0.22
11AT06-1a @21	8.87	0.20	11AT06-1a @42	9.45	0.46
11AT06-1a @9	8.35	0.39	11AT06-1b @7	8.98	0.47
11AT06-1a @37	9.36	0.31	11AT06-1d @29	9.44	0.38
11AT06-1c @1	9.41	0.35	11AT06-1e @5	9.08	0.32
Modeled results	$\delta^{18}\text{O}(\text{‰})$	Assumed mode in P peak (vol %)	assumed end-member		
zircon	9.0000	1.00	zircon100%		
garnet	9.0995	20.00	alm60%,grs20%,prp20%		
omphacite	9.1144	70.00	Di50%,Jd50%		
coesite	9.1534	2.00	Stishovite100%		
bulk-rcok	8.47	-	-		

NOTES: <sup>a</sup> The  $\delta^{18}\text{O}$  values have been corrected by the instrumental mass fractionation; Modeled results were calculated based on methods and relevant factors from Zheng (1991, 1993); P peak is setted on 530°C.

Table 7

Sample	Mineral	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ error	grt-omp-WR age (Ma)	grt-omp age (Ma)	$\epsilon_{\text{Nd}}(t)$
11AT06-2	WR	1.680	4.260	0.2841	0.513251	0.000008	$312.1 \pm 2.4$	$311.9 \pm 2.6$	8.5
	grt1	0.621	0.292	1.2843	0.515307	0.000014			
	grt2	0.624	0.294	1.2828	0.515286	0.000018			
	omp1	0.287	0.692	0.2510	0.513186	0.000011			
	omp2	0.290	0.714	0.2452	0.513180	0.000022			

NOTES: WR means the whole rock, the absolute errors of  $^{143}\text{Nd}/^{144}\text{Nd}$  and isochron ages are given in  $2\sigma$ ;  $\lambda = 6.54 \times 10^{-12} \text{ year}^{-1}$ ;  $^{147}\text{Sm}/^{144}\text{Nd}_{\text{CHUR}} = 0.1967$ ,  $^{147}\text{Sm}/^{144}\text{Nd}_{\text{DM}} = 0.2137$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}}(0) = 0.512638$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{DM}}(0) = 0.513151$  are used for the calculation.

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### Highlights

- Constant  $\delta^{18}\text{O}$  of multistage zircon domains suggest a nearly closed metamorphic system.
- Multistage zircon ages are tied to metamorphism by test REE partitioning with garnet.
- Detailed P-T-t-isotopic history of SW-Tianshan coesite-bearing eclogite is obtained.
- Zircon chronology and Sm-Nd isochron constrain peak burial at ca.  $315 \pm 5$  Ma.
- Exhaustively compiled regional data outline a short-lived detachment and exhumation.