Grain-scale Sr isotope heterogeneity in amphibolite (retrograded UHP eclogite, Dabie terrane): implications for the origin and flow behavior of retrograde fluids during slab exhumation

Shun Guo^{a, b*}, Yueheng Yang^a, Yi Chen^{a, b}, Bin Su^a, Yijie Gao^a, Lingmin Zhang^c, Jingbo Liu^a, Qian Mao^a

Abstract

To constrain the origin and flow behavior of amphibolite-facies retrograde fluids during slab exhumation, we investigate the textures, trace element contents, and *in situ* strontium (Sr) isotopic compositions (using LA-MC-ICP-MS) of multiple types of epidote and apatite in the UHP eclogite and amphibolites from the Hualiangting area (Dabie terrane, China). The UHP epidote porphyroblasts in the eclogite (Ep-E), which formed at ~ 28-30 kbar and 660-720 °C, contain high amounts of Sr, Pb, Th, Ba, and light rare earth elements (LREEs) and have a narrow range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70431 ± 0.00012 to 0.70454 ± 0.00010). Two types of amphibolite-facies epidote were recognized in the amphibolites. The first type of epidote (Ep-AI) developed in all the amphibolites and has slightly lower trace element contents than Ep-E. The Ep-AI has a same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio range as the Ep-E and represents the primary amphibolite-facies retrograde product that is associated with an internally buffered fluid at 8.0-10.3 kbar and 646-674 °C. The other type of epidote (Ep-AII) occurs as irregular fragments, veins/veinlets, or reaction rims on the Ep-AI in certain amphibolites. Elemental X-ray maps reveal the presence of Ep-AI relics in the Ep-AII domains (appearing as a patchy texture), which indicates that Ep-AII most likely formed by the partial replacement of the Ep-AI in the presence of an infiltrating fluid. The distinctly lower trace element contents of Ep-AII are ascribed to element scavenging by a mechanism of dissolution-transport-precipitation during replacement. The Ep-AII in an individual amphibolite exhibits large intra- and inter-grain variations in the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70493 ± 0.00030 to 0.70907 ± 0.00022), which are between those of the Ep-AI and granitic gneisses (wall rock of the amphibolites, 0.7097-0.7108). These results verify that the infiltrating fluid was externally derived from granitic gneisses. The matrix apatite in the amphibolites has the same initial

$^{87}\text{Sr}/^{86}\text{Sr}$ ratio range as the Ep-AI, indicating that the amphibolite-facies fluid involved in the apatite crystallization was also internally derived.

We propose that at least two separate stages of fluids were accounted for the amphibolite-facies retrogression of the Hualiangting eclogite. The fluid responsible for the growth of most of the amphibolite minerals was locally derived and behaved in a pervasive manner, whereas the influx of gneiss-derived fluid was transient, episodic, and highly channelized with a longer transport distance (> 60 m). The disparate origins and flow behavior of these fluids significantly influence the water budget and element transfer in exhumed HP-UHP slabs. This study also indicates that examining grain-scale Sr isotopic variations provides key information regarding the isotopic (dis)equilibrium, fluid origins, and fluid-flow regimes in metamorphic or metasomatic rocks that form in subduction-zone environments.

Key Words: *In-situ* Sr isotope; Retrograde fluid; Amphibolite; Eclogite; Dabie UHP terrane; Epidote

1. Introduction

High-pressure (HP) and ultra-high-pressure (UHP) metamorphic rocks, which represent fragments of ancient subducted crust, provide an ideal natural laboratory to investigate the origin, composition, scale, and flow mechanism of subduction-zone metamorphic fluids (e.g., [Angiboust et al., 2014](#); [Bebout, 2007](#); [Hermann et al., 2006, 2013](#); [Scambelluri and Philippot, 2001](#); [Spandler et al., 2011](#); [Zheng and Hermann, 2014](#)). Many previous studies have focused on prograde and peak fluids that are released from the HP-UHP rocks because these slab-derived fluids were expected to induce metasomatism and partial melting in the mantle wedge, the generation of intermediate-depth intra-slab earthquakes, and slab-mantle-arc material transfers in subduction zones (e.g., [Angiboust et al., 2014](#); [Bebout and Penniston-Dorland, 2016](#); [Hack et al., 2003](#); [Hermann et al., 2006](#); [John et al., 2012](#); [Scambelluri and Philippot, 2001](#); [Scambelluri et al., 2006](#); [Schmidt and Poli, 1998](#); [Spandler et al., 2011](#)). In contrast, the fluid actions that are associated with exhumation-related retrograde processes in HP-UHP rocks, such as the amphibolite- or blueschist-facies overprints of (UHP) eclogites have received relatively less attention (e.g., [Chen et al., 2007](#); [Heinrich, 1982](#); [Klemd et al., 1995](#); [Martin and Duchêne, 2015](#); [Vallis and Scambelluri, 1996](#); [van der Straaten et al., 2008](#)). Recent studies have indicated that the flow of retrogression-related fluids facilitates the development of shear zones and fault systems and decreases rock density, which would promote the buoyancy-driven uplift of HP-UHP metamorphic terranes (e.g., [Martin and Duchêne, 2015](#); [Miller et al., 2002](#); [Wain and Krabbendam, 1999](#)). More importantly, retrograde processes and associated mass transfers significantly influence the water budget and element redistribution in subduction channels (e.g., [Chen et al., 2007](#); [Heinrich, 1982](#); [Konrad-Schmolke et al., 2011](#); [Scambelluri and Philippot, 2001](#); [Uno et al., 2015](#)).

Therefore, it is also important to understand and characterize the nature and behavior of retrograde fluids during slab exhumation.

Investigations of the origin (e.g., internal vs. external) and flow manner (e.g., pervasive vs. channelized) of the fluids involved in amphibolite-facies overprints are of great significance for constraining the fluid behavior and fluid-rock interactions during slab exhumation (e.g., [Chen et al., 2007](#); [Konrad-Schmolke et al., 2011](#); [Scambelluri and Philippot, 2001](#); [Valley and O'Neil, 1984](#); [van der Straaten et al., 2008](#)). Generally, a pervasive fluid flows along grain boundaries or fine crack systems, by means of the pores in a rock (e.g., [Baumgartner and Valley, 2001](#); [Konrad-Schmolke et al., 2011](#)). Pervasive flow is independent of structural control and favors the homogenization of chemical potential and isotopes (e.g., [Valley and O'Neil, 1984](#)). In contrast, a channelized fluid flows along certain channel ways, such as shear zones, detachment faults, foliations, or other zones of structural weakness (e.g., [Ferry et al., 2013](#); [Miller et al., 2002](#); [Zack and John, 2007](#)). Channelized fluid flow tends to cause local chemical heterogeneities, enabling the infiltrated regions in the rock to be modified elementally and isotopically while others remain unaffected ([Baumgartner and Valley, 2001](#); [Putnis and Austrheim, 2010](#); [Zack and John, 2007](#)). Deformation has been regarded as a key mechanism that promotes the channelization and infiltration of fluid in rocks (e.g., [Miller et al., 2002](#); [Yardley et al., 2000](#)). Recent studies also highlighted that fluid flow could utilize a pre-existing foliation to gain access to rocks, taking advantage of mineral anisotropy (e.g., grain shape and size) rather than syn-deformation ([Kleine et al., 2015, 2016](#)). The distinctions in the fluid origin and flow manner are very useful to describe the genesis, flux, and transport scale of fluids.

Numerous studies have indicated that the fluids involved in amphibolite-facies

overprints are internally derived from their precursor HP-UHP rocks. Such fluids might be produced by the breakdown of HP-UHP hydrous minerals (e.g., [Li et al., 2004](#); [Zheng et al., 2007](#)), the release of residual water in hydrous minerals (e.g., [Martin and Duchêne, 2015](#)), the exsolution of structural hydroxyl and molecular H₂O from nominally anhydrous minerals (NAMs) (e.g., [Anderson and Moecher, 2007](#); [Chen et al., 2007](#)), and the decrepitation of fluid inclusions (e.g., [Miller et al., 2002](#); [Zheng, 2009](#)) during exhumation. In many cases, the flow of these locally derived fluids has been considered to be pervasive and to feature a relatively short transport distance (e.g., [Chen et al., 2007](#); [Zheng, 2009](#)). In contrast, other studies have suggested that the amphibolite-facies fluids are originated from external sources (e.g., wall rocks of amphibolites) based on field and geochemical evidence (e.g., [Heinrich, 1982](#); [Sorensen and Grossman, 1989](#); [Xiao et al., 2011](#); [Zhao et al., 2007](#)). In this scenario, the external fluids would transport over a long distance into the HP-UHP rocks along available fluid channels (e.g., [Kleine et al., 2015, 2016](#); [Miller et al., 2002](#); [Spandler et al., 2011](#)). In rare cases, both internal and external fluids can be detected in a single amphibolitic rock (e.g., [Miller et al., 2002](#); [Xie et al., 2004](#)). The complex fluid actions during amphibolite-facies overprints indicate that the origin and flow behavior of amphibolite-facies fluids are needed to be carefully clarified by appropriate petrologic or geochemical methods. In particular, whether more than one generation of amphibolite-facies fluids exists should be examined first.

Radiogenic strontium (Sr) isotope analysis can offer key constraints on the fluid origin and flow path during fluid-rock interactions due to the great sensitivity of Sr to metasomatism (e.g., [Glodny et al. 2002, 2003, 2008](#); [Guo et al., 2014](#); [John et al., 2012](#); [Xiao et al. 2011](#)). Recent studies have shown that the *in-situ* Sr isotopic analysis of minerals is especially useful to evaluate small-scale Sr isotopic variations, which in

turn help trace multiple fluid/melt sources and assess the influences of internal fluid buffers or external fluid influx into metamorphic or metasomatic rock systems (Campos-Alvarez et al., 2010; Guo et al., 2014, 2015a; Romer and Xiao, 2005). Epidote is a major rock-forming hydrous mineral in Ca-Al-rich HP-UHP metabasites (Enami et al., 2004; Mattinson et al., 2004; Poli and Schmidt, 2004) and is one of major host minerals of Sr, Pb, Th, U, light rare earth elements (LREEs), and middle REEs (MREEs) in these rocks (Frei et al., 2004; Feineman et al. 2007; Guo et al., 2013; Nagasaki and Enami, 1998; Zhang et al., 2008). This mineral can form under both UHP and amphibolite-facies conditions in metabasites (Guo et al., 2014; Poli and Schmidt, 2004). Apatite is another important Sr-rich hydrous mineral in metabasites. Both epidote and apatite have very low Rb contents and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (generally <0.01), which make them ideal minerals for Sr isotope studies because their initial Sr isotopic ratios are not sensitive to age correction. Thus, *in situ* Sr isotope analyses of epidote and apatite in amphibolites allow for examining isotope distribution down to the grain scale and identifying geochemical signatures of the amphibolite-facies fluids from which these minerals crystallized (Guo et al., 2014; Morrison, 2004; Yang et al., 2014).

In this study, we report the *in situ* Sr isotopic and trace element data of various types of epidote and apatite in amphibolites and their pre-existing equivalent (i.e., UHP eclogite) in the Dabie terrane, China, which are determined using laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). The results reveal substantial grain-scale (μm - to mm-scale) variations in the initial Sr isotopic ratios of different types of epidote within an individual amphibolite. These geochemical data, combined with the mineral textural characteristics and whole-rock Sr isotopic compositions, indicate that multiple fluids with distinct origins and flow

manners were directly involved in or influenced the amphibolite-facies metamorphic overprints during slab exhumation.

2. Geological background

The Dabie-Sulu UHP metamorphic terrane in east-central China formed from the northward subduction of the South China Block beneath the North China Block in the Triassic (Li et al., 1993; Zhang et al., 2009; Zheng et al., 2003). The presence of coesite, microdiamond, and exsolutions of clinopyroxene, rutile and apatite in garnet within the eclogites (Okay et al., 1989; Wang et al., 1989; Xu et al., 1992; Ye et al., 2000a), gneisses (Liu et al., 2001; Ye et al., 2000b), and marbles (Liu et al., 2006) in this metamorphic terrane demonstrates that the crustal rocks were subducted to mantle depths greater than 200 km to experience UHP metamorphism. The Dabie metamorphic terrane makes up the western segment of the Dabie-Sulu terrane, which is separated by approximately 500 km of left-lateral strike-slip displacement along the Tan-Lu fault (Fig. 1a). The Dabie terrane consists of a series of fault-bounded litho-tectonic units. Five main litho-tectonic zones exist from north to south (Okay, 1993): (1) the Beihuaiyang greenschist-facies metamorphic zone; (2) the North Dabie metamorphic core complex; (3) the coesite-eclogite-facies metamorphic zone; (4) the quartz-eclogite-facies metamorphic zone; and (5) the Susong blueschist- to greenschist-facies metamorphic zone (Fig. 1a).

The Dabie UHP metamorphic rocks consist of various types of gneisses with small quantities of lenses or layers of other types of rock, such as eclogite, garnet peridotite, pyroxenite, marble, and jadeite quartzite (Liou et al., 2000; Zhang et al., 2009). The protoliths of the UHP gneisses and eclogites have zircon U-Pb ages of 740-780 Ma (e.g., Li et al., 2004; Liu and Liou, 2011; Zheng et al., 2006) and have

183 been regarded as bimodal felsic-mafic igneous rocks that formed during the breakup
184 of the Rodinia supercontinent (e.g., [Zhang et al., 2009](#)). The UHP metamorphism in
185 the Dabie terrane occurred at approximately 245-225 Ma according to the U-Pb dating
186 of numerous coesite-bearing domains in metamorphic zircon from both the gneisses
187 and eclogites (e.g., [Liu et al., 2008](#); [Liu and Liou, 2011](#)). The HP eclogite-facies
188 recrystallization and amphibolite-facies retrogression of the Dabie UHP rocks
189 occurred at approximately 225-210 Ma (e.g., [Liu et al., 2008](#); [Wu et al., 2006](#)) and
190 215-205 Ma (e.g., [Ayers et al., 2002](#); [Liu et al., 2008](#)), respectively.

191 The study area is located east of the Hualiangting Reservoir (NW of the county
192 of Taihu) in the coesite-eclogite zone ([Carswell et al., 1997](#); [Okay et al., 1993](#)), where
193 UHP eclogites and their retrograde equivalents typically occur as large blocks or
194 boudins within muscovite-rich magnetite-bearing granitic gneisses ([Fig. 1b](#)). The
195 Hualiangting eclogites are characterized by large amounts of porphyroblastic hydrous
196 minerals (epidote and amphibole) ([Massonne, 2012](#); [Rolfo et al., 2000](#); [Shi and Wang,](#)
197 [2006](#)) and prismatic mineral assemblages (epidote+kyanite+quartz) after lawsonite
198 ([Guo et al., 2015a](#)). [Rolfo et al. \(2000\)](#) suggested a clockwise P-T path for the UHP
199 eclogite and estimated the metamorphic peak conditions to be $P \geq 26-27$ kbar and $T =$
200 710 ± 20 °C. [Shi and Wang \(2006\)](#) reported a large variation in the peak P-T
201 conditions of the eclogites in the Hualiangting area, ranging from 20 to 35 kbar and
202 from 640 to 840 °C. [Massonne \(2012\)](#) estimated that the peak-*P* and peak-*T*
203 conditions of the Hualiangting eclogites were greater than 35 kbar and 800 °C,
204 respectively, and suggested that a hydrous fluid infiltrated into the eclogite during
205 exhumation at ~24-27 kbar. [Guo et al. \(2015a\)](#) investigated the metamorphic
206 evolution and HP veining processes of the vein-hosting Hualiangting eclogites and
207 suggested that the eclogites followed a clockwise P-T path that was characterized by

significant fluid liberation from the breakdown of lawsonite during exhumation at ~28-30 kbar and 660-720 °C.

The studied outcrop is an approximately 400 m-long and 15 m-wide massive metamafic block of eclogites and amphibolites within amphibolite-facies gneisses (Fig. 1b). This outcrop was selected because the eclogites and amphibolites contain high amounts of epidote and apatite, making both lithologies ideal for an investigation of grain-scale Sr isotopic distributions. Amphibolites are distributed in both the margins and interiors of the metamafic block, implying that the amphibolitization cannot be simply ascribed to fluid infiltration along the eclogite-gneiss boundary. Small amounts of quartz- and plagioclase-rich segregations that are < 1.5 cm in width were found in the amphibolites. We focus on an eclogite-amphibolite transitional zone in the interior of the metamafic block (Fig. 2a), which is located approximately 60 m away from the nearest granitic gneiss. Samples of one eclogite (09HLT10) and three amphibolites (09HLT13, 09HLT14, and 09HLT16) near the transitional zone (Fig. 2a-c) were collected to examine the fluid origin, flow behavior, and transport scale during amphibolitization. The mineral assemblages and mineral abundances of the samples are summarized in Table 1. The mineral abbreviations are after Whitney and Evans (2010).

3. Analytical methods

3.1. Whole-rock major and trace element compositions

The whole-rock major element compositions were analyzed by X-ray fluorescence spectroscopy (XRF) with an AXIOS-Minerals spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The analytical uncertainties were generally within 3 % (RSD) according to the analyses of

two international rock reference materials (GSR-1 and GSR-3), and duplicate analyses of samples. The whole-rock trace element compositions were analyzed by ICP-MS using a Finnigan MAT Element spectrometer at the IGGCAS. The sample powders were digested in distilled HF+HNO₃ in high-pressure, screw-top Teflon bombs at 200 °C for 6 days, evaporated to near dryness and then diluted for analysis. The accuracy and precision of the data were better than 5 % for most trace elements according to the measurements of the GSR-1 and GSR-3 and replicate analyses of samples.

3.2. Major and trace element compositions of the minerals

Back-scattered electron (BSE) images and the major element compositions of the minerals were acquired using a JEOL JXA-8100 electron microprobe (EMP) at the IGGCAS. All the minerals were measured in wavelength dispersive (WDS) mode with an acceleration voltage of 15 kV, a beam current of 20 nA, and a spot size of 3 µm. The counting time for the SrO in epidote was 40 s, and the counting time for the other elements varied between 10 and 20 s. The ZAF procedure was used for matrix corrections, and the analytical uncertainties for most major oxides were < 1.5 %.

X-ray maps of Sr, Fe, Ca, and Al were acquired in WDS mode using the JEOL JXA-8100 EMP at the IGGCAS. The operating conditions were 15 kV accelerating voltage and 120 nA beam current. X-ray maps were produced at the resolutions of 1,024 × 1,024 pixels. The dwelling time per point was set to 65 ms, and the total scanning time for each X-ray map was approximately 22 h.

The trace element compositions of epidote and apatite were analyzed *in situ* on polished thin sections using an Agilent 7500a quadrupole inductively coupled plasma mass spectrometer (Q-ICP-MS) coupled to a 193-nm ArF laser ablation system at the

IGGCAS. The analytical protocol was similar to that described by Yang et al. (2014). A spot size of 32 μm was used for the epidote analyses, and a spot size of 90 μm was used for the apatite analyses. The output energy was 80 mJ and the energy density was 10 J/cm². The measurements were performed in time-resolved analysis mode by utilizing peak jumping with 1 point per mass peak. Each spot analysis consisted of approximately 20 s of background acquisition and 40 s of data acquisition for the sample. The NIST SRM 610 glass standard (Pearce et al., 1997), which was used for external calibration, was measured twice at the beginning and end of each analytical batch (9 analyses). The ⁴³Ca content determined by the EMP was used as the internal standard. Raw counts were processed offline, and the trace element concentrations were calculated using the Glitter laser ablation software (Griffin et al., 2008). The accuracy and reproducibility of the data were generally better than 6 % and 8 %, respectively, for most trace elements according to the analyses of the USGS rock standards.

3.3. Whole-rock Rb-Sr isotopes

The whole-rock Rb-Sr isotopes were analyzed using a Finnigan MAT262 thermal ionization mass spectrometer (TIMS) at the IGGCAS following the procedures described by Chu et al. (2009). Sample powders were dissolved in screw-top Teflon capsules after spiking with mixed ⁸⁷Rb-⁸⁴Sr tracers prior to HF+HNO₃+HClO₄ dissolution. The procedural blanks were 40 pg for Rb and <300 pg for Sr. The isotopic ratios were corrected for mass fractionation by normalizing to ⁸⁶Sr/⁸⁸Sr = 0.1194. The measured value of the standard NBS-987 was ⁸⁷Sr/⁸⁶Sr = 0.710246 ± 0.000014 (2 SD, n = 8). The USGS reference material BCR-2 was measured during the same period to monitor the accuracy of the analytical procedure; the result was in good agreement with the reported reference values (GeoREM, <http://georem.mpch-mainz.gwdg.de/>).

3.4. *In situ* Sr isotopic compositions

In situ Sr isotope analyses were performed on polished thin sections using a Neptune MC-ICP-MS equipped with a 193-nm ArF Excimer laser ablation system at the IGGCAS. The detailed instrument and analytical procedure have been described by Yang et al. (2009, 2014) and Guo et al. (2014, 2015a). Epidote and apatite were analyzed with spot sizes of 60 and 160 μm , respectively. The repetition rate was 6-8 Hz and the energy density was 10 J/cm². The data acquisition cycle consisted of a 40-s measurement of the Kr gas blank with the laser switched off and a 60-s measurement with laser ablation.

Several potential interferences were monitored during laser analysis. Isobaric interference corrections of ⁸⁴Kr and ⁸⁶Kr on ⁸⁴Sr and ⁸⁶Sr were conducted based on the natural Kr ratios of ⁸³Kr/⁸⁴Kr = 0.20175 and ⁸³Kr/⁸⁶Kr = 0.66474 (Christensen et al., 1995). The interferences of divalent REEs were corrected by monitoring the peaks of ¹⁶⁷Er²⁺, ¹⁷¹Yb²⁺, and ¹⁷³Yb²⁺ at masses of 83.5, 85.5 and 86.5, respectively. The potential interferences of ¹⁶⁸Er²⁺ and ¹⁶⁸Yb²⁺ to ⁸⁴Sr, ¹⁷⁰Er²⁺ and ¹⁷⁰Yb²⁺ to ⁸⁵Rb⁺, ¹⁷²Yb²⁺ to ⁸⁶Sr⁺, ¹⁷⁴Yb²⁺ to ⁸⁷Sr⁺ (⁸⁷Rb⁺), and ¹⁷⁶Yb²⁺ to ⁸⁸Sr⁺ were evaluated and corrected according to the isotopic abundances of Er and Yb (Chartier et al. 1999; Ramos et al., 2008; Vervoort et al. 2004). The natural ratio of ⁸⁵Rb/⁸⁷Rb (2.5926) was used to correct the isobaric Rb interference by an exponential law, assuming that Rb and Sr have the same discrimination behavior (Christensen et al., 1995; Ehrlich et al., 2001; Ramos et al., 2004).

Prior to the sample analyses, an in-house apatite standard (AP1, ~ 2500 ppm Sr) and a coral standard (> 1000 ppm Sr) were used to evaluate the reliabilities of the laser analyses, the calibration technique, and the matrix-matched effect (Guo et al., 2014; Yang et al., 2009, 2014). Forty-two analyses of AP1 and twenty-four analyses

of the coral yielded average values of 0.71137 ± 0.00008 (2 SD) and 0.70917 ± 0.00011 (2 SD), respectively. These results are identical to the values obtained from the solution-mode MC-ICP-MS analysis (0.711370 ± 0.000031 for AP1) and laser methods (0.71137 ± 0.00007 for AP1 and 0.70918 ± 0.00005 for coral) (Yang et al., 2009, 2014).

4. Results

4.1. Petrology of samples and the occurrence of epidote and apatite

The eclogite 09HLT10 predominantly consists of omphacite (30 vol.%), garnet (26 vol.%), and epidote (17 vol.%), with minor amounts of amphibole (9 vol.%), kyanite (6 vol.%), quartz (6 vol.%), and accessory (~5 vol.%) rutile and apatite (Table 1). All these minerals are randomly oriented in this eclogite (Fig. 2d). Epidote in the eclogite (Ep-E) typically occurs as euhedral to subhedral porphyroblasts (up to a centimeter in length) in a matrix of omphacite, garnet, and quartz (Fig. 3a, b). The Ep-E contains a multitude of fine-grained inclusions of omphacite, garnet, rutile, and radial “palisade” quartz aggregates (coesite pseudomorph) (Table 2; Fig. 3a, b). Matrix omphacite is rimmed by fine-grained symplectites of amphibole+plagioclase. Amphibole porphyroblasts with sizes of 0.3-3 mm contain inclusions of Ep-E, omphacite, and garnet. Fine-grained matrix apatite (< 100 μ m in diameter) is in textural equilibrium with Ep-E, omphacite, and garnet.

The amphibolites 09HLT13 and 09HLT14 share similar mineral assemblages and textural characteristics. Both samples consist of amphibole (35-40 vol.%), plagioclase (26-28 vol.%), epidote (18-20 vol.%), and quartz (9-14 vol.%), with minor amounts of rutile/Fe-Ti oxides, apatite, and garnet (Table 1). The grain size of the amphibole varies substantially, with coarse-grained amphibole ranging from 0.3 to

0.6 cm and fine-grained amphibole ranging from 0.1 to 0.5 mm (Fig. 2e and Fig. 3c, d). Coarse-grained amphibole occurs as porphyroblastic minerals that contain a multitude of fine-grained plagioclase and quartz inclusions (Fig. 3c). Epidote in the amphibolites (Ep-AI) occurs as colorless to pale-yellow, subhedral to anhedral, porphyroblasts (up to 3 mm in length, Fig. 3d) or matrix minerals (0.2-0.6 mm in length, Fig. 3c). Ep-AI contains inclusions of garnet, amphibole, plagioclase, quartz, rutile/Fe-Ti oxides, and apatite (Table 2; Fig. 3e-h), indicating that Ep-AI formed under amphibolite-facies conditions rather than as a relic mineral from eclogite-facies stage. The matrix minerals include fine-grained amphibole, plagioclase, Ep-AI, quartz, and apatite (Fig. 3c, d). Garnet occurs exclusively as fine-grained anhedral inclusions in the Ep-AI porphyroblasts (Fig. 3e-h).

Overall, the mineral assemblage and textural characteristics of the amphibolite 09HLT16 are similar to those of the amphibolites 09HLT13 and 09HLT14. However, two types of amphibolite-facies epidote can be found in the sample 09HLT16. The first type of epidote has identical textural characteristics to Ep-AI in the samples 09HLT13 and 09HLT14. For example, the first type of epidote (also named “Ep-AI”) in the sample 09HLT16 (~24 vol.%) likewise occurs as porphyroblasts that contain fine-grained garnet, amphibole, plagioclase, quartz, and Fe-Ti oxide inclusions (Fig. 4a). The other type of epidote, Ep-AII (< 3 vol.%), is characterized by a dark-yellow color in the microscopic images (Fig. 4b, c) and a bright color in the BSE images (Fig. 4d, e). The Ep-AII grains are unevenly distributed in the amphibolite and typically occur as irregular fragments that are distributed along “vein-like” channels (several hundred μm to several cm in length) (Table 2; Fig. 2f and Fig. 4b, c), which implies that Ep-AII formed along channelized cracks or fractures. Some veins or disseminated veinlets of the Ep-AII locally crosscut the amphibole and Ep-AI (Fig. 4d), and some

small Ep-AII grains were found as reaction-induced rims on earlier-crystallized Ep-AI (Fig. 4e). The BSE image (Fig. 5a) and elemental X-ray maps (Fig. 5c-f) show that the composition of Ep-AII is not homogeneous and that some irregular Ep-AI patches or bands occur in the interior of the Ep-AII. Ep-AII is in textural equilibrium with the amphibole, plagioclase, and quartz (Fig. 4 and Fig. 5) and no chlorite was found in the amphibolite 09HLT16.

Matrix apatite in the amphibolites 09HLT13 and 09HLT14 typically occurs as coarse (0.3-0.8 mm in diameter) anhedral grains that are in textural equilibrium with amphibole and plagioclase and contain inclusions of plagioclase and Ep-AI (Fig. 6a), suggesting the growth of apatite at amphibolite-facies stage. Matrix apatite in the amphibolite 09HLT16 likewise coexists with amphibole, plagioclase, and Ep-AI. Due to the rare occurrence of Ep-AII in this sample, most of the apatite grains are not in direct contact with Ep-AII. However, some apatite grains were found in locations that are close to (distances of $\sim 300\ \mu\text{m}$) the Ep-AII grains (Fig. 6b).

4.2. Whole-rock chemical compositions

The whole-rock compositions of one eclogite sample (09HLT10) and three amphibolite samples (09HLT13, 09HLT14, and 09HLT16) are listed in Table 3. The eclogite 09HLT10 has a mafic composition ($\text{SiO}_2 = 49.89\ \text{wt.}\%$), with high Al_2O_3 (16.99 wt.%) and CaO (8.94 wt.%) contents. The eclogite exhibits a steep LREE-rich chondrite-normalized pattern with a high $(\text{La}/\text{Yb})_{\text{N}}$ value of 5.5 (Fig. 7a). The Sr (459 ppm) and Ba (447 ppm) contents of the eclogite are relatively high, and the Cs (0.05 ppm) and Rb (2.1 ppm) contents are very low.

The amphibolites also have mafic compositions, with SiO_2 , Al_2O_3 , and CaO contents ranging from 45.48 to 51.22 wt.%, from 17.05 to 19.24 wt.%, and from 9.47 to 11.1 wt.%, respectively. All the amphibolites show a LREE-rich pattern, with

(La/Yb)_N values of 3.0-4.7 (Fig. 7a). The Sr (251-396 ppm) and Ba (103-117 ppm) contents of the amphibolites are lower than those of the eclogite, and the Cs and Rb contents in the amphibolites and eclogite are similar (Table 3). The amphibolite 09HLT16 has slightly lower Al₂O₃, Sr, and LREE contents and higher contents of Fe₂O₃, Cs, Rb, and heavy rare earth element (HREE) contents than the amphibolites 09HLT13 and 09HLT14.

4.3. Mineral compositions

4.3.1. Epidote

Three types of epidote (Ep-E, Ep-AI, and Ep-AII) in the Hualiangting eclogite and amphibolites were analyzed (Table 4). The UHP Ep-E in the eclogite has relatively low X_{Fe} [X_{Fe} = Fe/(Fe + Al), all iron was assumed to be ferric Fe] values (0.23-0.25) and high contents of Sr (3970-7200 ppm for Sr), Pb (40-126 ppm), Th (5-51 ppm), Ba (23-73 ppm), and LREEs (e.g., 110-325 ppm for La) (Fig. 8a-f). The Ep-E shows a steep LREE-rich chondrite-normalized pattern with high (La/Yb)_N values (20-100, Fig. 7b and Fig. 8c). No obvious Ce [$\delta\text{Ce} = 2\text{Ce}_\text{N}/(\text{La}_\text{N} + \text{Pr}_\text{N}) = 0.9-1.2$] or Eu [$\delta\text{Eu} = 2\text{Eu}_\text{N}/(\text{Sm}_\text{N} + \text{Gd}_\text{N}) = 1.0-1.3$] anomalies were observed for the Ep-E (Fig. 8g). The rim-core-rim profile analysis results indicate that the Ep-E rims have slightly lower X_{Fe} values and Sr, Pb, Th, Ba, and LREE contents than the cores (Table 4; Fig. 9a, c).

The Ep-AI in the three amphibolites (09HLT13, 09HLT14, and 09HLT16) has very similar compositions, with slightly higher X_{Fe} values (0.23-0.26) and lower Sr contents (2900-4600 ppm for Sr), Pb (30-67 ppm), Th (2-13 ppm), Ba (14-45 ppm), and LREEs (27-114 ppm for La) than the Ep-E (Fig. 8a-f). The Ep-AI exhibits similar LREE-rich patterns and (La/Yb)_N values (13-112) to those of the Ep-E (Fig. 7b, c and Fig. 8c). No obvious Ce ($\delta\text{Ce} = 0.8-1.2$) or Eu ($\delta\text{Eu} = 0.9-1.3$) anomalies were found for the Ep-AI (Fig. 7b, c and Fig. 8g). X-ray maps (Fig. 5c-f) and rim-core-rim profile

analysis results (Fig. 5b and Fig. 9b, d) indicate that the Ep-AI has a relatively homogenous composition.

The Ep-AII in the amphibolite 09HLT16 has much higher X_{Fe} values (0.30-0.42) and lower Sr (1640-2460 ppm for Sr), Pb (13-25 ppm), Th (<0.1 ppm), Ba (5-22 ppm), and LREE (0.2-1.8 ppm for La) contents than the other two types of epidote (Fig. 8a-f). In contrast with Ep-AI, Ep-AII shows a LREE-MREE-depleted pattern with very low $(\text{La/Yb})_{\text{N}}$ ratios (0.02-0.5) (Fig. 7b and Fig. 8c). In addition, Ep-AII has noticeably negative Ce ($\delta\text{Ce} = 0.2-0.8$) and positive Eu anomalies ($\delta\text{Eu} = 1.5-5.8$) (Fig. 7b and Fig. 8g). The profile analysis of a zone of coexisting Ep-AI and Ep-AII indicates that Ep-AII has a larger compositional range than Ep-AI (Fig. 5b and Fig. 10a-d). This characteristic corresponds to the results that were obtained from the X-ray maps (Fig. 5c-f), which indicate the presence of many irregular Ep-AI relics (low-Fe, high-Al/Sr patches) in the Ep-AII domains.

4.3.2. Garnet

The garnet inclusions in the Ep-E (Grt-E) and Ep-AI (Grt-A) were analyzed in this study. The Grt-E primarily consists of almandine (42-49 mol.%), pyrope (29-35 mol.%), and grossular (14-20 mol.%) components, with small amounts of andradite (3-8 mol.%) and spessartine (~1 mol.%) components (Appendix Table A1; Fig. 11a). The composition of the Grt-E is similar to that of the matrix garnet in the Hualiangting eclogites (Guo et al., 2015a). Compared with the Grt-E, the Grt-A is characterized by lower MgO (3-5 vs. 8-10 wt.%) and higher MnO (5-7 vs. <1 wt.%) contents (Fig. 11b), indicating that the Grt-A formed under lower P-T conditions than the Grt-E (Caddick and Kohn, 2013). The Grt-A has much lower pyrope components (13-19 mol.%) and higher almandine (47-54 mol.%), grossular (15-23 mol.%), and spessartine (11-15 mol.%) components than the Grt-E (Table A1; Fig. 11a). The

compositional distinctions between the Grt-E and Grt-A indicate that their host minerals (i.e., Ep-E and Ep-AI) formed during different metamorphic stages.

4.3.3. Amphibole, plagioclase, and apatite

The amphibole porphyroblasts in the eclogite were classified as winchite or barroisite according to [Leake et al. \(1997\)](#) (Appendix [Table A2](#); [Fig. 11c](#)). This type of amphibole is unzoned with high Si^{T} (7.47 to 7.76 pfu) and Na^{B} (0.62 to 1.36 pfu) and low Ca^{B} (0.40 to 1.12 pfu) contents. The amphibole porphyroblasts ([Fig. 3c](#)), the matrix amphibole ([Fig. 3c, d](#)), and the amphibole inclusions in the Ep-AI ([Fig. 3e-g](#) and [Fig. 4a](#)) in the amphibolites have similar chemical compositions and are mainly classified as pargasite, with low Si^{T} (6.38 to 6.48 pfu) and Na^{B} (<0.05 pfu) and high Ca^{B} (1.67 to 1.79 pfu) contents ([Fig. 11d](#)). The F and Cl contents in all types of amphibole are below the detection limits.

Plagioclase in the amphibolites occurs as either inclusions in the Ep-AI ([Fig. 3g, h](#)) or as a matrix mineral ([Fig. 3c-e](#) and [Fig. 4c](#)). Both types of plagioclase have similar compositional variation ranges, with albite components of 70-80 % (Appendix [Table A3](#); [Fig. 11e](#)).

The matrix apatite from different amphibolites has similar compositions, with high F (2.7-3.5 wt.%) and low Cl (< 0.1 wt.%) contents (Appendix [Table A4](#)). In addition, the apatite has a relatively high Sr content (550-870 ppm) and exhibits a LREE-depleted, MREE-HREE-flat pattern in the chondrite-normalized diagram ([Fig. 7b](#) and [Fig. 12](#)). The matrix apatite in the amphibolites has a similar composition with that in the eclogites ([Guo et al., 2015a](#)).

4.4. Whole-rock Rb-Sr isotopic compositions

The Rb-Sr isotopic compositions of the eclogite and amphibolites are listed in [Table 5](#). The initial Sr isotopic values were calculated at $t = 210$ Ma, which represents

the age of amphibolite-facies retrogression in the Dabie eclogites (e.g., [Chen et al., 2012](#); [Liu and Liou, 2011](#)). The eclogite 09HLT10 has a similar initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.704416 ± 0.000010) as the amphibolites 09HLT13 (0.704446 ± 0.000014) and 09HLT14 (0.704439 ± 0.000012) ([Fig. 13](#)). The amphibolite 09HLT16, in which both the Ep-AI and Ep-AII are present, has a slightly higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.704823 ± 0.000012) than the eclogite and the other two amphibolites (09HLT13 and 09HLT14) ([Fig. 13](#)). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the eclogite and amphibolites are noticeably lower than those of the Hualiangting gneisses (0.709710 ± 0.000013 to 0.710733 ± 0.000014 , [Fig. 13](#)), which are the wall rock of the studied metamafic block.

4.5. *In situ* Sr isotopic compositions of epidote and apatite

The *in situ* Sr isotopic data of Ep-E, Ep-AI, and Ep-AII are listed in [Table 6](#) and shown in [Fig. 9](#), [Fig. 10](#), [Fig. 12](#), and [Fig. 13](#). We also analyzed the rim-core-rim profiles of some porphyroblastic epidote grains to examine the intra-grain variations in the Sr isotopic compositions ([Fig. 9](#)). The *in situ* Sr isotopic data of matrix apatite from two amphibolites (09HLT13 and 09HLT16) are given in [Table 6](#) and shown in [Fig. 12](#) and [Fig. 13](#). The apatite in the eclogite was not analyzed due to the small grain sizes ($< 100\ \mu\text{m}$). The $^{87}\text{Rb}/^{86}\text{Sr}$ ratios of the epidote and apatite are less than 0.001 and 0.01, respectively, and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are not correlated with the $^{87}\text{Rb}/^{86}\text{Sr}$ ratios. Therefore, there is limited radiogenic ^{87}Sr in both minerals, and the observed variation in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is an inherent feature of the minerals rather than an analytical artifact ([Schmidberger et al., 2003](#); [Yang et al., 2009](#)). The initial Sr isotopic ratios of Ep-AI, Ep-AII, and apatite were calculated at $t = 210\ \text{Ma}$, and the initial ratios of Ep-E were calculated at $t = 230\ \text{Ma}$, which represents the age of UHP metamorphism in the Dabie eclogites ([Liu and Liou, 2011](#)).

Analyses of thirty-seven points on the Ep-E in the amphibolite 09HLT10 yielded

very homogeneous initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70431 ± 0.00012 to 0.70454 ± 0.00010 , Fig. 12 and Fig. 13). The analysis results of the rim-core-rim profile for a single Ep-E grain show no intra-grain Sr isotopic variation within analytical uncertainty (Fig. 9a, c). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Ep-E are essentially identical to those of the epidote inclusions and epidote porphyroblasts in the Hualiangting eclogites (i.e., the pale blue region in Fig. 13), which were previously reported by Guo et al. (2015a). The initial Sr isotopic compositions of the Ep-E are similar to the initial whole-rock Sr isotopic composition of the eclogite 09HLT10 (Fig. 13), implying that Sr isotopic equilibrium was achieved in the eclogite (Guo et al., 2015a).

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Ep-AI (0.70434 ± 0.00009 to 0.70457 ± 0.00011) in the amphibolites 09HLT13 and 09HLT14 are the same as those of Ep-E (Fig. 12 and Fig. 13). The rim-core-rim profile analysis results of an individual Ep-AI grain in the amphibolite 09HLT13 show no intra-grain Sr isotopic variation within analytical uncertainty (Fig. 9b, d). Analyses of four matrix apatite in the amphibolite 09HLT13 yielded identical initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as Ep-AI within analytical uncertainty (Table 6; Fig. 6a and Fig. 13). The initial *in situ* $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Ep-AI and apatite are close to the initial whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the amphibolites 09HLT13 and 09HLT14 but slightly lower than the initial whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the amphibolite 09HLT16 (Fig. 13).

In the amphibolite 09HLT16, both the Ep-AI and Ep-AII developed. To examine the difference in the initial Sr isotopic ratios between the Ep-AI and Ep-AII and the Sr isotopic variations in individual epidote grains in this amphibolite, we investigated four representative zones in a thin section (Zones A-D in Fig. 10a-d), where coexisting Ep-AI and Ep-AII were analyzed in detail. In Zones A and B, Ep-AII occurs as irregular fragments, which are isolated from (Fig. 10a) or in direct contact

with Ep-AI (Fig. 10b). In Zone C, Ep-AII occurs as veins or veinlets crosscutting the
 amphibolite-facies matrix and Ep-AI (Fig. 10c). In Zone D, Ep-AII occurs as reaction
 rims on Ep-AI (Fig. 10d). As shown in Fig. 10e-h, all the Ep-AI grains in the four
 zones have same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios within analytical uncertainty, and no
 intra-grain Sr isotopic variation was observed. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Ep-AI
 in the sample 09HLT16 (0.70437 ± 0.00008 to 0.70457 ± 0.00010) are identical to
 those of the Ep-AI in the samples 09HLT13 and 09HLT14 (Fig. 13). In contrast,
 different Ep-AII grains in the sample 09HLT16 exhibit significantly different ranges
 of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Fig. 10e-h). Intra-grain Sr isotopic variation is also obvious
 for each individual Ep-AII grain. Specifically, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of a single
 Ep-AII grain range from 0.70668 ± 0.00017 to 0.70907 ± 0.00022 in Zone A (Fig.
 10e), from 0.70643 ± 0.00017 to 0.70772 ± 0.00018 in Zone B (Fig. 10f), from
 0.70544 ± 0.00022 to 0.70788 ± 0.00015 in Zone C (Fig. 10g), and from $0.70555 \pm$
 0.00012 to 0.70598 ± 0.00018 in Zone D (Fig. 10h). Analyses of twenty-nine points
 on the Ep-AII in the sample 09HLT16 yielded a large range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios,
 ranging from 0.70493 ± 0.00030 to 0.70907 ± 0.00022 (mostly ranging between 0.705
 and 0.708, Table 6). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Ep-AII vary between those of Ep-AI
 and gneisses (Fig. 13). Six matrix apatite grains in the amphibolite 09HLT16 were
 analyzed. These apatite grains coexist with amphibole, plagioclase, and Ep-AI but are
 not in direct contact with Ep-AII (Fig. 6b). The apatite grains have a narrow range of
 initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, which are identical to those of Ep-AI within analytical
 uncertainty but different from those of Ep-AII (Fig. 13). For example, Fig. 6b shows
 that an apatite has an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70450 ± 0.00055 , which is much lower
 than that of its nearby Ep-AII (0.70692 ± 0.00015). The large intra- and inter-grain Sr
 isotopic variations of the Ep-AII and Sr isotopic difference between the Ep-AII and

Ep-AI/apatite indicate that small-scale Sr isotope heterogeneity exists in the sample 09HLT16.

5. Discussion

5. 1. Formation of multiple types of epidote in the eclogite-amphibolite system

Although epidote is a common mineral in both eclogite and amphibolite, the detailed types and growth stages of epidote in these rocks are rarely examined (Enami et al., 2004; Guo et al., 2014; Mattinson et al., 2004). Because epidote is a hydrous mineral (~2 wt.% H₂O), fluids play a key role in providing both H₂O and other components that are necessary for the formation of epidote (Klemm, 2004). Therefore, the multiple generations of epidote potentially provide insight into the evolution of the fluid system as the P-T conditions evolved from the peak UHP stage to retrograde amphibolite-facies stage during slab exhumation.

Three types of epidote (Ep-E, Ep-AI, and Ep-AII) have been distinguished in the Hualiangting eclogite-amphibolite system based on petrographic observations and geochemical analyses. These types of epidote have different textural features, inclusions, P-T conditions, and major and trace element compositions (Table 2), indicating that the physicochemical conditions for the metamorphic fluids involved in the formation of multiple epidote types were highly variable (Brunsmann et al., 2001; Enami et al. 2004; Feineman et al. 2007; Guo et al., 2014; Mattinson et al. 2004).

Ep-E generally occurs as porphyroblastic minerals in the eclogite matrix and is in textural equilibrium with typical eclogite-facies minerals, such as low-Mn/high-Mg garnet, omphacite, and rutile, or contains inclusions of these minerals (Fig. 3a, b). These observations indicate that Ep-E formed under eclogite-facies conditions. Guo et al. (2015a) reported the presence of coesite inclusions in this type of epidote, further

indicating that Ep-E is stable under UHP conditions. Based on the textural characteristics and phase equilibrium modeling, Ep-E was interpreted to be a pseudomorphic product after lawsonite during early-stage exhumation of the eclogite at ~28-30 kbar and 660-720 °C (Table 2, Guo et al., 2015a). Similar coesite-enclosing pseudomorphic epidote after lawsonite widely occurs in the Dabie eclogites, such as the Huangzhen (Castelli et al., 1998; Li et al., 2004), Xinxian (Wei et al., 2010), and Ganghe eclogites (Guo et al., 2012, 2013). The high Sr, Pb, Th, and LREE contents in Ep-E (Fig. 8b-g) were most likely inherited from pre-existing lawsonite, which contains large amounts of these trace elements in HP-UHP metabasites (Guo et al., 2013; Martin et al., 2011, 2014; Tsujimori et al., 2006; Vitale Brovarone et al., 2014).

Ep-AI is present in all the studied amphibolites and is a major mineral phase of these samples (Table 1). The occurrence of fine-grained high-Mn/low-Mg garnet, pargasite, plagioclase, and quartz inclusions (Fig. 3f-h and Fig. 4a) indicates that the Ep-AI grew during the garnet amphibolite-facies retrograde stage. The P-T conditions for the formation of Ep-AI were determined based on the mineral assemblages of inclusions by using the garnet-hornblende-plagioclase-quartz barometer (Dale et al., 2000) coupled with the hornblende-plagioclase thermometer (Holland and Blundy, 1994). The results show that the Ep-AI in all the amphibolites formed under similar P-T conditions of 8.0-10.3 kbar and 646-674 °C (Appendix Table A5), which indicate that these amphibolites have the same UHP peak mineral assemblage and share a common retrograde process. The experimental studies indicated that the compatibility of trace elements, especially REEs, in epidote decrease during cooling processes (Feineman et al. 2007; Martin et al. 2011). Therefore, the slightly lower Sr, Pb, Th, Ba, and LREE contents in Ep-AI than in Ep-E (Fig. 8b-f) could be attributed to decreasing epidote-fluid partition coefficients during amphibolite-facies retrogression of the

Hualiangting eclogite.

Ep-AII occurs in the amphibolite 09HLT16 but is absent in the amphibolites 09HLT13 and 09HLT14 (Table 2). The abundance of Ep-AII in the amphibolite 09HLT16 (<3 vol.%) is obviously lower than that of Ep-AI (~ 24 vol.%). Thus, the Ep-AII is expected to be distributed locally in the amphibolites. Texturally, the Ep-AII fragments are typically distributed along “vein-like” channels (Fig. 2f and Fig. 4c) or occur as μm - to mm-thick veins and disseminated veinlets (Fig. 4d), demonstrating that the formation of Ep-AII was related to a non-pervasive, episodic fluid event during retrogression. The Ep-AII veinlets locally crosscut the coarse-grained Ep-AI grains (Fig. 4d), and the Ep-AII grains occur as secondary reaction rims on earlier-crystallized Ep-AI (Fig. 4e), indicating that the growth of Ep-AII postdated the crystallization of Ep-AI. However, Ep-AII is also in textural equilibrium with pargasite and plagioclase (Fig. 4b, d and Fig. 5a), and no chlorite or tremolite were found in the amphibolite. These observations indicate that Ep-AII remained stable under amphibolite-facies conditions (Table 2). The presence of Ep-AI relics (patchy textures) in the Ep-AII domains (Fig. 5c-e) demonstrates that Ep-AII most likely formed by the partial or total replacement of primary Ep-AI in the presence of an infiltrating fluid (Jamtveit and Austrheim, 2010; Putnis and Austrheim, 2010; Putnis and John, 2010). In such a scenario, the fluid-assisted replacement and dissolution-precipitation process would allow rapid mass transfer along the fluid pathways (Herms et al., 2012; John et al., 2004; Kleine et al., 2015). The distinctly low Sr, Pb, Th, Ba, and LREE contents in the Ep-AII (Fig. 8b-f) indicate that these fluid-mobile elements were removed from the Ep-AI during the replacement process (Putnis, 2009; Putnis and Austrheim, 2010; Zack and John, 2007). A similar element transfer process was also observed during the interaction of epidote with a UHP

aqueous fluid (Guo et al., 2015b). The noticeably higher X_{Fe} values (0.30-0.42) of Ep-AII (Fig. 8a) are generally considered to be related to the high oxygen fugacity conditions of the infiltrating fluids during retrograde stages (e.g., Cao et al., 2011; Guo et al., 2014; Li et al., 2016; Mattinson et al. 2004; Nagasaki and Enami, 1998). This interpretation is also in accordance with the obviously negative Ce anomalies of Ep-AII ($\delta Ce = 0.2-0.8$) (Fig. 7b and Fig. 8g).

5. 2. Constraints on the fluid sources for amphibolite-facies metamorphism

Amphibolite-facies overprint is a common phenomenon during the retrogression of eclogites and is characterized by the formation of symplectitic intergrowths of Pl+Amph $\pm$ Qtz $\pm$ Cpx $\pm$ Ep after omphacite and garnet or the complete recrystallization of amphibolite-facies minerals. Fluids are regarded as an important factor in triggering retrogression because of their ability to accelerate reaction rates (acting as a catalyst) and provide H₂O and other essential chemical components (Jamveit and Austrheim, 2010; Martin and Duchêne, 2015; Miller et al., 2002). Our petrological results indicate that at least two stages of fluids were involved in the amphibolite-facies metamorphism (corresponding to the formation of Ep-AI and Ep-AII, respectively) in the Hualiangting amphibolites. In the following sections, we utilize new *in-situ* elemental and Sr isotopic data of the epidote and apatite that formed during different metamorphic stages to trace multiple amphibolite-facies fluid actions and constrain the sources of these fluids.

5.2.1. Internally derived amphibolite-facies fluid

As stated above, Ep-AI is the dominant epidote phase that formed during amphibolite-facies retrogression. The texture and mineral inclusions (Fig. 6) indicate that the matrix apatite in the amphibolites also formed at amphibolite-facies stage. The initial *in situ* $^{87}Sr/^{86}Sr$ ratios of the Ep-AI in all the amphibolites are identical

(0.70434 ± 0.00009 to 0.70457 ± 0.00011), and fall in the same range as those of the apatite in the amphibolites and the Ep-E in the eclogite (Fig. 13), indicating that the fluid involved in the amphibolite-facies recrystallization (~210 Ma) had the same Sr isotopic signature as the HP-UHP fluids attending the eclogite-facies metamorphism (~230 Ma). In contrast, the potential external source, i.e., the granitic gneiss that encloses the eclogite-amphibolite block, has much higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7097-0.7108, Guo et al., 2015a) at amphibolite-facies stage (Table 5; Fig. 13). These results indicate two possible scenarios for the origin of the amphibolite-facies fluid responsible for the formation of the Ep-AI and apatite. One is that the fluid was internally derived from the precursor eclogite. The other is that a Sr-poor fluid from the gneiss was introduced into the eclogite and then Sr-isotopically buffered by abundant released Sr from the eclogites during the retrogression. The fluids that are released by granitic gneisses generally contain high amounts of water-soluble elements (e.g., Cs and Rb) (Schmidt et al., 2004; Hermann et al., 2006). Therefore, infiltrations of the gneiss-derived fluids are expected to increase the contents of these water-soluble elements in the metasomatized rock compared to its unmetasomatized equivalent (e.g., Xiao et al., 2011). However, the water-soluble element contents of the amphibolites 09HLT13 and 09HLT14 are similar to those of the eclogite 09HLT10 (Table 3), implying that the amphibolitization (formation of Ep-AI and apatite) was not related to the infiltration of the gneiss-derived fluids. Therefore, the available data support the first scenario. The insignificant difference between the Sr isotopic ratios of Ep-E and Ep-AI should be ascribed to the low amount of radiogenic Sr internally generated in the rock during the limited time interval (~15-25 Ma, Liu et al., 2008) between the formation of the two types of epidote combined with the low $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (<0.025) of their host rocks (Table 5). The pargasite is in textural equilibrium

with Ep-AI or occurs as inclusions in the Ep-AI (Fig. 3c-h), implying that the same internal fluid source was responsible for both pargasite and Ep-AI growth. The internally derived fluid is expected to originate from the breakdown of Ep-E, barroisite, and winchite and the decompression exsolution of structural hydroxyl and molecular H₂O in NAMs in the precursor eclogite (Anderson and Moecher, 2007; Chen et al., 2007, 2012; Li et al., 2004; Martin and Duchêne, 2015; Zheng, 2009). A recent study conducted by Martin and Duchêne (2015) has indicated that slight differences in H₂O content in different eclogite domains within a single outcrop could lead to variable degrees of retrogression in these eclogites. Distinctions in porosity, permeability, mineral anisotropy, and deformation can also influence the retrograde degree of HP rocks (e.g., Kleine et al., 2015, 2016; Miller et al., 2002; Zack and John, 2007). These factors might enable the peak mineral assemblages of some eclogites (e.g., 09HLT10) in the Hualiangting outcrop to remain unaffected, while others (e.g., 09HLT13 and 09HLT14) develop into amphibolite-facies assemblages. Our present result, in accordance with many previous studies (e.g., Chen et al., 2007, 2012; Martin and Duchêne, 2015; Vallis and Scambelluri, 1996), supports the view that amphibolitization acted as an important sink for the cycling fluids that occurred in HP-UHP eclogites. The similar Sr, Pb, Th, U, and REE contents, element ratios, and REE patterns of the eclogite and amphibolites (Table 3; Fig. 7a) indicate that the majority of these trace elements in the epidote eclogites were redistributed into the epidote amphibolites during the internal fluid-induced retrograde process.

5. 2.2. External fluid infiltration during amphibolite-facies metamorphism

The distinct textural and geochemical characteristics of Ep-AII indicate that this type of epidote is closely related to the replacement of Ep-AI in the presence of an infiltrating fluid. This chemical modification during replacement, as revealed by the

patchy textures in the Ep-AII domains (Fig. 5c-f), would induce element transfer and isotopic exchange between Ep-AI and the infiltrating fluid. Therefore, the initial Sr isotopic compositions of Ep-AII provide important constraints on the origin of the infiltrating fluid. The twenty-nine *in situ* Sr isotope analyses show that the Ep-AII domains has noticeably different initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70493 ± 0.00030 to 0.70907 ± 0.00022) from those of Ep-AI, apatite, and the amphibolite 09HLT16 (0.704823 ± 0.000012) (Fig. 13). Both the Ep-AII and Ep-AI were stable under amphibolite-facies conditions. Therefore, although Ep-AII formed chronologically later than Ep-AI, the time interval between the growth of the two types of epidote should have been very short (<10-15 Ma, Liu and Liou, 2011). This result, along with the low $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (0.012-0.025) and the lack of mica minerals in both the eclogite and amphibolites, indicates that the observed Sr isotopic contrast between Ep-AII and Ep-AI cannot be simply generated by time-integrated radiogenic ingrowth in a closed system. The large compositional difference between Ep-AI and Ep-AII, especially the Ce and Eu anomalies (Fig. 7b and Fig. 8g), are also inconsistent with a purely internal fluid source for the formation of Ep-AII. We thus conclude that the external input of a high- $^{87}\text{Sr}/^{86}\text{Sr}$ fluid was required to form Ep-AII and increase the initial whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the amphibolite 09HLT16 (Fig. 13).

The direct wall rock of the eclogite-amphibolite block, granitic gneiss, has higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7097-0.7108, Table 5) at amphibolite-facies stage ($t = 210$ Ma) than the eclogite and amphibolites. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Ep-AII domains range between those of the eclogite/amphibolite (also the Ep-E/Ep-AI) and gneisses (Fig. 13), indicating that the external fluids should be derived from the granitic gneisses. The gneisses contain high amounts of hydrous minerals (mica and epidote). Other NAMs (e.g., feldspar, quartz, and magnetite) in the gneisses can also incorporate

considerable amounts of structural hydroxyl and molecular water (Chen et al., 2007). Therefore, the gneisses could release significant amounts of aqueous fluids or hydrous melts during slab exhumation (e.g., Heinrich, 1982; Schmidt et al., 2004; Hermann et al., 2006; El Korh et al., 2011). In particular, phengite-to-muscovite conversion in the gneisses during decompression could result in very high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the released fluids (e.g., Heinrich, 1982; Glodny et al., 2003, 2008). It is thus expected that the gneiss-derived high- $^{87}\text{Sr}/^{86}\text{Sr}$ fluid transported over long distances to infiltrate into the amphibolites, with a limited chemical equilibration between the infiltrating fluid and the metabasites (Glandy et al., 2003). Such fluid infiltration and metasomatism mainly occurred along the transport pathways of the fluid, which resulted in the random distribution of the metasomatized amphibolites (e.g., 09HLT16) in the amphibolite block (Fig. 2a) and higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the metasomatized amphibolites compared to their unmetasomatized equivalents (e.g., 09HLT13 and 09HLT14). The intra- and inter-grain variations in the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Ep-AII (Fig. 10a-d) should be controlled by various degrees of metasomatic interactions in different domains, depending on the extent and scale of the external fluid influx (Schmidberger et al., 2003). The highest Sr isotopic value would be recorded by the Ep-AII domains that experienced the largest degree of metasomatic interaction with the infiltrating fluid. In contrast, the compositional and Sr isotopic signatures of primary amphibolite-facies epidote (i.e., Ep-AI) remained essentially unchanged in the domains where the fluid infiltration is absent (Fig. 10). The studied apatite grains in the sample 09HLT16 has identical initial Sr isotopic ratios as Ep-AI (Fig. 12 and Fig. 13), indicating that these apatite grains are located in the domains that are devoid of external fluid metasomatism. This result is in accordance with the petrographic observations, which indicate that the studied apatite grains are not in direct contact

with the Ep-AII (i.e., the domains that were metasomatized by the external fluid) (Fig. 6b). In addition, the lack of high-diffusivity phases such as micas in this amphibolite might also prevent the Sr isotopic signature of the apatite from being affected by diffusion-controlled Sr isotopic exchange (Glodny et al., 2008). However, the pargasite in the metasomatized sample was crosscut by fine Ep-AII veins or veinlets (Fig. 4d), indicating that other rock-forming minerals in addition to the epidote might have also been infiltrated by the external fluid.

The preservation of small-scale Sr (or Nd and Pb) isotope heterogeneities in epidote-group minerals has been reported in many geological processes. Romer and Xiao (2005) observed a large initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio variation in a zoned allanite-epidote crystal from the Sulu UHP eclogite, ranging from 0.70601-0.70603 (allanite cores) to 0.70878-0.72021 (epidote rims). Campos-Alvarez et al. (2010) found that the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.70648-0.70736 in early-stage hydrothermal epidote to 0.70870-0.71078 in late-stage epidote in the Sudbury igneous complex. Guo et al. (2014) reported that low- $^{87}\text{Sr}/^{86}\text{Sr}$ UHP epidote porphyroblasts (0.70698-0.70721) were crosscut by later-stage high- $^{87}\text{Sr}/^{86}\text{Sr}$ epidote veinlets (0.70894-0.71172) in the Dabie UHP eclogite. These studies and the present results suggest that the micro-scale Sr isotope heterogeneity was closely related to the mixing of fluids from multiple sources or contributions from different precursor minerals, and thus is a key indicator of “open-system” behavior during metamorphic and hydrothermal processes. The existence of grain-scale Sr isotope heterogeneity in the Hualiangting amphibolite implies that intra-grain Sr diffusion was negligible even under the given metamorphic temperatures of $>640^{\circ}\text{C}$, although experimental or theoretical data of Sr isotope diffusion in epidote-group minerals are still lacking. According to the results of this and previous studies (Guo et al., 2014; Romer and Xiao, 2005), we speculate that

small-scale Sr isotope heterogeneities in epidote, if generated, can be maintained under most of the P-T conditions encountered by deeply subducted slabs (at fore-arc to sub-arc depths). These findings demonstrate that *in situ* Sr isotope analysis of epidote provides an effective, rapid method to examine the origin of multiple fluids and the open/closed behavior of the metamorphic systems in deep subduction zones.

5. 3. Implications for fluid flow during exhumation of a continental slab

Grain-scale elemental and Sr isotopic variations in the amphibolites from the Hualiangting area not only provide key constraints on the amphibolites-facies fluid origins but also are important indicators of the flow behavior of these fluids (Table 2). Our results demonstrate different flow manners and scales for the two stages of amphibolite-facies fluids in the retrograded eclogites during the exhumation of a subducted continental slab.

The high abundance and approximately even distribution of the Ep-AI grains in the amphibolites at the scales of hand specimens and thin sections (Fig. 2e) indicate that the flow of the early-stage amphibolite-facies fluid was predominantly pervasive (Table 2). The nature of an internal origin indicates that the flow of this fluid was limited to relatively small distances (meter scale or less), which is in consistent with the results of many previous studies (e.g., Chen et al., 2007; Vallis and Scambelluri, 1996; Zheng, 2009).

Ep-AII only developed in certain amphibolites and collectively formed only a minor proportion of epidote (Fig. 4b-e). The “vein-like” distribution, patchy internal texture, large compositional variation, and grain-scale Sr isotope heterogeneity of the Ep-AII strongly support a transient, channelized flow manner for the late-stage amphibolite-facies fluid (Konrad-Schmolke et al., 2011; Miller and Cartwright, 2000; Scambelluri and Philippot, 2001; Zack and John, 2007). In this regard, the distribution

of the Ep-AII fragments or veinlets (Fig. 4c, d) defines the morphology of the fluid flow channels. It is also worth noting that the accessory apatite in the metasomatized amphibolite 09HLT16 preserves the pristine Sr isotopic signatures from the external fluid infiltration even if the apatite is in close proximity (a distance of $\sim 300\ \mu\text{m}$) to the Ep-AII grains (Fig. 6b). This result provides further evidence that the external fluid transported along some highly channelized pathways with a very limited metasomatic scope. In the field, the nearest gneiss outcrops are approximately 60 m from the studied metabasite outcrop, which corresponds to a minimum estimation of the fluid flow distance. Deformation, hydraulic fracturing, and deep earthquakes are potential factors that can facilitate the episodic advection of channelized fluids during slab exhumation (e.g., Austrheim et al., 1996; Davies, 1999; Miller et al., 2002; Oliver and Bons, 2001). In such a scenario, the external fluids are expected to flow along certain zones of structural weakness or rheological contrast at different velocities, which could lead to various degrees of element transfers and isotopic exchange along the pathways (e.g., Baumgartner and Valley, 2001; Lewis et al., 1998; Spandler et al., 2011; Zack and John, 2007). The large compositional difference between Ep-AI and Ep-AII (Fig. 8) implies relatively high time-integrated fluid fluxes during the external fluid infiltration.

The different origins, flow behavior, and flow scales of the amphibolite-facies fluids in the retrograded eclogites indicate that the amphibolite-facies metamorphism cannot be simply assigned to a single fluid event as previously thought. The present data indicate that the movements of both pervasive internal fluids and channelized external fluids can be detected in an individual amphibolite sample, implying an episodic opening of the metamorphic system and external water influx during the retrogression of eclogites. In addition, our results indicate that pervasive internal fluid

flow led to the redistribution of Sr, Pb, Th, and REEs during eclogite-to-amphibolite conversion whereas significant amounts of these elements were removed out of the amphibolites during external fluid metasomatism along certain channels. Therefore, different origins and flow manners for the multiple fluids also influence the type and transfer degree of trace elements during the retrograde stages (also see [van der Straaten et al., 2008](#); [Zack and John, 2007](#)). In this regard, recognizing each type of retrograde fluid and characterizing their geochemical effects are crucial to understand the water budget, trace element transport capacity, and isotopic resetting in exhumed HP-UHP slabs.

6. Conclusions

The textural evidence, mineral geochemistry, and *in situ* Sr isotopic data from multiple types of epidote and apatite from the Hualiangting eclogite-amphibolite system indicate that the fluids responsible for the amphibolite-facies retrograde metamorphism were derived from multiple sources and exhibited different flow behavior. The retrograde fluid accounting for the growth of most of the amphibolite-facies minerals was internally derived. However, grain-scale chemical variations and Sr isotope heterogeneities in a few amphibolites indicate the episodic influx of an external fluid was derived from the wall rock granitic gneisses. The internally buffered retrograde fluid typically flowed in a pervasive manner and resulted in the substantial redistribution of trace elements (Sr, Pb, Th, Ba, and LREEs) during the transformation of epidote eclogites into epidote amphibolites. In contrast, the flow of the externally derived retrograde fluid was predominantly transient and channelized along certain pathways over a transport distance of more than 60 m, with limited Sr isotopic resetting. Significant amounts of Sr, Pb, Th, Ba, and LREEs

were removed out of the amphibolites during the episodic fluid infiltration. We suggest undertaking combined detailed petrographic studies and *in situ* Sr isotope analyses, from the hand specimen to mineral grain scales, can aid in evaluating the complex retrograde processes and multi-stage fluid actions during the exhumation of deeply subducted continental slabs.

Acknowledgments

This study was funded by The National Basic Research Program of China (973 Program 2015CB856103) and The National Science Foundation of China (Nos. 41372079, 41525012, 41672059, and 41490614). We thank Di Zhang and Yuguang Ma for the help during the EMP analyses, Yanbin Zhang for the help during the LA-(MC)-ICP-MS analyses, and Chaofeng Li for the help during the TIMS analyses. Careful and constructive comments from Dr. Johannes Glodny and an anonymous reviewer significantly improve the manuscript. We appreciate Dr. Macro Scambelluri for his editorial handing and thoughtful suggestions.

References

- Anderson, E.D., Moecher, D.P., 2007. Omphacite breakdown reactions and relation to eclogite exhumation rates. *Contributions to Mineralogy and Petrology* 154, 253-277.
- Angiboust, S., Pettke, T., De Hoog, J.C.M., Caron, B., Oncken, O., 2014. Channelized Fluid Flow and Eclogite-facies Metasomatism along the Subduction Shear Zone. *Journal of Petrology* 55, 883-916.
- Austrheim, H., Erambert, M., Boundy, T. M., 1996. Garnets recording deep crustal earthquakes. *Earth and Planetary Science Letters* 139, 223-238.
- Ayers, J.C., Dunkle, S., Gao, S., Miller, C.E., 2002. Constraints on timing of peak and retrograde metamorphism in the Dabie Shan ultrahigh-pressure metamorphic belt, east-central China, using U-Th-Pb dating of zircon and monazite. *Chemical Geology* 186, 315-331.
- Barker, A.K., Coogan, L.A., Gillis, K.M, Weis, D., 2008. Strontium isotope constraints on fluid flow in the sheeted dike complex of fast spreading crust: Pervasive fluid flow at Pito Deep. *Geochemistry, Geophysics, Geosystems* <http://dx.doi.org/10.1029/2007GC001901>.
- Baumgartner, L.P., Valley, J.W., 2001. Stable isotope transport and contact metamorphic fluid flow. *Reviews in Mineralogy and Geochemistry* 43, 415-467.
- Bebout, G.E., 2007. Metamorphic chemical geodynamics of subduction zones. *Earth and Planetary Science Letters* 260, 373-393.
- Bebout, G.E., Penniston-Dorland, S.C., 2016. Fluid and mass transfer at subduction interfaces-The field metamorphic record. *Lithos* 240, 228-258.
- Beinlich, A., Klemm, R., John, T., Gao, J., 2010. Trace-element mobilization during Cametasomatism along a major fluid conduit: eclogitization of a blueschist as a consequence of fluid-rock interaction. *Geochimica et Cosmochimica Acta* 74, 1892-922.
- Brovarone, A.V., Alard, O., Beyssac, O., Martin, L., Picatto, M., 2014. Lawsonite metasomatism and trace element recycling in subduction zones. *Journal of Metamorphic Geology* 32, 489-514.
- Brunsmann, A., Franz, G., Erzinger, J., 2001. REE mobilization during small-scale high-pressure fluid-rock interaction and zoisite/fluid partitioning of La to Eu. *Geochimica et Cosmochimica Acta* 65, 559-570.

- Caddick, M.J., Kohn, M.J., 2013. Garnet: Witness to the evolution of destructive plate boundaries. *Elements* 9, 427-432.
- Campos-Alvarez, N.O., Samsona, I.M., Fryer, B.J., Ames, D.E., 2010. Fluid sources and hydrothermal architecture of the Sudbury Structure: Constraints from femtosecond LA-MC-ICP-MS Sr isotopic analysis of hydrothermal epidote and calcite. *Chemical Geology* 278, 131-150.
- Cao, Y., Song, S.G., Niu, Y.L., Jung, H., Jin, Z.M., 2011. Variation of mineral composition, fabric and oxygen fugacity from massive to foliated eclogites during exhumation of subducted ocean crust in the North Qilian suture zone, NW China. *Journal of Metamorphic Geology* 29, 699-720.
- Carswell, D.A., O'Brien, P.J., Wilson, R.N., Zhai, M., 1997. Thermobarometry of phengite-bearing eclogites in the Dabie Mountains of central China. *Journal of Metamorphic Geology* 15, 239-252.
- Castelli, D., Rolfo, F., Compagnoni, R., Xu, S.T., 1998. Metamorphic veins with kyanite, zoisite and quartz in the Zhu-Jia-Chong eclogites, Dabie Shan, China. *Island Arc* 7, 159-173.
- Chartier, F., Aubert, M., Salmon, M., Tabarant, M., Tran, B.H., 1999. Determination of erbium in nuclear fuels by isotope dilution thermal ionization mass spectrometry and glow discharge mass spectrometry. *Journal of Analytical Atomic Spectrometry* 14, 1461-1465.
- Chen, R.X., Zheng, Y.F., Gong, B., Zhao, Z.F., Gao, T.S., Chen, B., Wu, Y.B., 2007. Origin of retrograde fluid in ultrahigh-pressure metamorphic rocks: constraints from mineral hydrogen isotope and water content changes in eclogite–gneiss transitions in the Sulu orogen. *Geochimica et Cosmochimica Acta* 71, 2299-2325.
- Chen, R.X., Zheng, Y.F., Hu, Z.C., 2012. Episodic fluid action during exhumation of deeply subducted continental crust: Geochemical constraints from zoisite-quartz vein and host metabasite in the Dabie orogen. *Lithos* 155, 146-166.
- Christensen, J.N., Halliday, A.N., Lee, D.C., Hall, C.M., 1995. In situ Sr isotopic analysis by laser ablation. *Earth and Planetary Science Letters* 136, 79-85.
- Chu, Z.Y., Wu, F.Y., Walker, R.J., Rudnick, R.L., Pitcher, L., Puchtel, I.S., Yang, Y.H., Wilde, S.A., 2009. Temporal evolution of the lithospheric mantle beneath the eastern North China Craton. *Journal of Petrology* 50, 1857-1898.
- Dale, J., Holland, T., Powell, R., 2000. Hornblende-garnet-plagioclase

thermobarometry: a natural assemblage calibration of the thermodynamics of
hornblende. *Contributions to Mineralogy and Petrology* 140, 353-362.

Davies, J.H., 1999. The role of hydraulic fractures and intermediate-depth
earthquakes in generating subduction-zone magmatism. *Nature* 398, 142-145.

Ehrlich, S., Gavrieli, I., Dor, L.B., Halicz, L., 2001. Direct high-precision
measurements of the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio in natural water, carbonates and related
materials by multiple collector inductively coupled plasma mass spectrometry
(MC-ICP-MS). *Journal of Analytical Atomic Spectrometry* 16, 1389-1392.

El Korh, A., Schmidt, S.T., Vennemann, T., Ulianov, A., 2011. Trace element and
O-isotope composition of polyphase metamorphic veins of the Ile de Groix
(Armorican Massif, France): implication for fluid flow during HP subduction and
exhumation processes. In: Dobrzhinetskaya LF, Faryad SW, Wallis S, Cuthbert S
(eds) *Ultrahigh-Pressure Metamorphism: 25 Years After the Discovery of Coesite
and Diamond*, Elsevier, pp. 243-291.

Enami, M., Liou, J.G., Mattinson, C.G., 2004. Epidote Minerals in High P/T
Metamorphic Terranes: Subduction Zone and High- to Ultrahigh-Pressure
Metamorphism. *Reviews in Mineralogy and Geochemistry* 56, 347-398.

Feineman, M.D., Ryerson, F.J., DePaolo, D.J., Plank, T., 2007. Zoisite-aqueous fluid
trace element partitioning with implications for subduction zone fluid composition.
Chemical Geology 239, 250-265.

Ferry, J.M., Winslow, N.W., Penniston-Dorland, S.C., 2013. Re-evaluation of
infiltration-driven regional metamorphism in northern New England: New
transport models with solid solution and cross-layer equilibration of fluid
composition. *Journal of Petrology* 54, 2455-2485.

Frei, D., Liebscher, A., Franz, G., Dulski, P., 2004. Trace element geochemistry of
epidote minerals. *Reviews in Mineralogy and Geochemistry* 56, 553-605.

Glodny, J., Austrheim, H., Molina, J.F., Rusin, A., Seward, D., 2003. Rb/Sr record of
fluid-rock interaction in eclogites: the Marun-Keu complex, Polar Urals, Russia.
Geochimica et Cosmochimica Acta 67, 4353-4371.

Glodny, J., Bingen, B., Austrheim, H., Molina, J. F., Rusin, A., 2002. Precise
eclogitization ages deduced from Rb/Sr mineral systematics: the Maksyutov
complex, Southern Urals, Russia. *Geochimica et Cosmochimica Acta* 66,
1221-1235.

- Glodny, J., Kühn, A., Austrheim, H., 2008. Geochronology of fluid-induced eclogite and amphibolite facies metamorphic reactions in a subduction-collision system, Bergen Arcs, Norway. *Contributions to Mineralogy and Petrology* 156, 27-48.
- Griffin, W.L., Powell, W.J., Pearson, N.J., O'Reilly, S.Y., 2008. GLITTER: data reduction software for laser ablation ICP-MS. In: Sylvester, P. (Ed.), *Laser ablation-ICP-MS in the Earth Sciences: current practices and outstanding issues*. Mineralogical Association Canada Short Course, 40, pp. 308-311.
- Guo, S., Chen, Y., Ye, K., Su, B., Yang, Y.H., Zhang, L.M., Liu, J.B., Mao, Q., 2015a. Formation of multiple high-pressure veins in ultrahigh-pressure eclogite (Hualiangting, Dabie terrane, China): Fluid source, element transfer, and closed-system metamorphic veining. *Chemical Geology* 417, 238-260.
- Guo, S., Ye, K., Chen, Y., Liu, J.B., Mao, Q., Ma, Y.G., 2012. Fluid-rock interaction and element mobilization in UHP metabasalt: constraints from an omphacite-epidote vein and host eclogites in the Dabie orogen. *Lithos* 136-139, 145-167.
- Guo, S., Ye, K., Cheng, N.F., Chen, Y., Su, B., Liu, J.B., 2015b. Metamorphic P-T trajectory and multi-stage fluid events of vein-bearing UHP eclogite from the Dabie terrane: insights from key mineral compositional zonations. *International Geology Review* 9-10, 1077-1102.
- Guo, S., Ye, K., Wu, T.F., Chen, Y., Zhang, L.M., Yang, Y.H., Liu, J.B., Mao, Q., Ma, Y.G., 2013. A potential method to confirm the previous existence of lawsonite in eclogite: the mass imbalance of Sr and LREEs in multi-stage epidote (Ganghe, Dabie UHP terrane). *Journal of Metamorphic Geology* 31, 415-435.
- Guo, S., Ye, K., Yang, Y.H., Chen, Y., Zhang, L.M., Liu, J.B., Mao, Q., Ma, Y.G., 2014. In situ Sr isotopic analyses of epidote: tracing the sources of multistage fluids in ultrahigh-pressure eclogite (Ganghe, Dabie terrane). *Contributions to Mineralogy and Petrology* DOI: 10.1007/s00410-014-0975-9.
- Hacker, B.R., Peacock, S.M., Abers, G.A., Holloway, S.D., 2003. Subduction factory-2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions? *Journal of Geophysical Research* 108, Doi: 10.1029/2001JB001129.
- Heinrich, C.A., 1982. Kyanite-eclogite to amphibolite facies evolution of hydrous mafic and pelitic rocks, Adula Nappe, Central Alps. *Contributions to Mineralogy and Petrology* 81, 30-38.

982 Hermann, J., 2002. Experimental constraints on phase relations in subducted
 983 continental crust. *Contributions to Mineralogy and Petrology* 143, 219-235.

984 Hermann, J., Spandler, C., Hack, A., Korsakov, A.V., 2006. Aqueous fluids and
 985 hydrous melts in high-pressure and ultra-high pressure rocks: implications for
 986 element transfer in subduction zones. *Lithos* 92, 399-417.

987 Hermann, J., Zheng, Y.F., Rubatto, D., 2013. Deep fluids in subducted continental
 988 crust. *Elements* 9, 281-287.

989 Herms, P., John, T., Bakker, R.J., Schenk, V., 2012. Evidence for channelized
 990 external fluid flow and element transfer in subducting slabs (Raspas Complex,
 991 Ecuador). *Chemical Geology* 310-311, 79-96.

992 Holland, T., Blundy, J., 1994. Non-ideal interactions in calcic amphiboles and their
 993 bearing on amphibole-plagioclase thermometry. *Contributions to mineralogy and
 994 petrology* 116, 433-447.

995 Jamtveit, B., Austrheim, H., 2010. Metamorphism: the role of fluids. *Elements* 6,
 996 153-158.

997 John, T., Gussone, N., Podladchikov, Y.Y., Bebout, G.E., Dohmen, R., Halama, R.,
 998 Klemm, R., Magna, T., Seitz, H.M., 2012. Volcanic arcs fed by rapid pulsed fluid
 999 flow through subducting slabs. *Nature Geosciences* 5, 489-492.

1000 John, T., Scherer, E., Haase, K., Schenk, V., 2004. Trace element fractionation during
 1001 fluid-induced eclogitization in a subducting slab: trace element and Lu-Hf/Sm-Nd
 1002 isotope systematics. *Earth and Planetary Science Letters* 227, 441-456.

1003 Kleine, B.I., Pitcairn, I.K., Skelton, A.D.L., 2015. The mechanism of infiltration of
 1004 metamorphic fluids recorded by hydration and carbonation of
 1005 epidote-amphibolite facies metabasaltic sills in the SW Scottish Highlands.
 1006 *American Mineralogist* 100, 2702-2717.

1007 Kleine, B.I., Pitcairn, I.K., Skelton, A.D.L., 2016. Mineralogical controls on
 1008 metamorphic fluid flow in metabasaltic sills from Islay, Scotland. *Lithos* 248,
 1009 22-39.

1010 Klemm, R., 2004. Fluid inclusions in epidote minerals and fluid development in
 1011 epidote-bearing rocks. *Reviews in mineralogy and geochemistry* 56, 197-234.

1012 Klemm, R., Broecker, M., Schramm, J., 1995. Characterisation of amphibolite-facies
 1013 fluids of Variscan eclogites from the Orlica-Snieznik dome (Sudetes, SW
 1014 Poland). *Chemical Geology* 119, 101-113.

1015 Konrad-Schmolke, M., O'Brien, P.J., Zack, T., 2011. Fluid migration above a

- subducted slab-constraints on amount, pathways and major element mobility from partially overprinted eclogite-facies rocks (Sesia Zone, Western Alps). *Journal of Petrology* 52, 457-486.
- Leake, B.E., 1997. Nomenclature of amphiboles: report of the subcommittee on amphiboles of the International Mineralogical Association Commission on new minerals and mineral names. *Mineralogical Magazine* 61, 295-321.
- Lewis, S., Holness, M., Graham, C., 1998. Ion microprobe study of marble from Naxos, Greece: grain-scale fluid pathways and stable isotope equilibration during metamorphism. *Geology* 26, 935-938.
- Li, S., Xiao, Y., Liu, D., Chen, Y., Ge, N., Zhang, Z., Sun, S.S., Cong, B., Zhang, R. Hart, S.R., Wang, S., 1993. Collision of the North China and Yangtze blocks and formation of coesite-bearing eclogites: timing and processes. *Chemical Geology* 109, 89-111.
- Li, X.P., Zheng, Y.F., Wu, Y.B., Chen, F.K., Gong, B., Li, Y.L., 2004. Low-T eclogite in the Dabie terrane of China: petrological and isotopic constraints on fluid activity and radiometric dating. *Contributions to Mineralogy and Petrology* 148, 443-470.
- Li, D.Y., Xiao, Y.L., Li, W.Y., Zhu, X., Williams, H.M., Li, Y.L. 2016. Iron isotopic systematics of UHP eclogites respond to oxidizing fluid during exhumation. *Journal of Metamorphic Geology*. doi:10.1111/jmg.12217.
- Liou, J.G., Zhang, R.Y., Jahn, B.M., 2000. Petrological and geochemical characteristics of ultrahigh-pressure metamorphic rocks from the Dabie-Sulu Terrane, East-Central China. *International Geology Review* 42, 328-352.
- Liu, F.L., Gerdes, A., Liou, J.G., Xue, H.M., Liang, F.H., 2006. SHRIMP U-Pb zircon dating from Sulu-Dabie dolomitic marble, eastern China: constraints on prograde, ultrahigh-pressure and retrograde metamorphic ages. *Journal of Metamorphic Geology* 24, 569-589.
- Liu, F.L., Gerdes, A., Zeng, L.S., Xue, H.M., 2008. SHRIMP U-Pb dating, trace element and Lu-Hf isotope system of coesite-bearing zircon from amphibolite in SW Sulu UHP terrane, eastern China. *Geochimica et Cosmochimica Acta* 72, 2973-3000.
- Liu, F.L., Liou, J.G., 2011. Zircon as the best mineral for P-T-time history of UHP metamorphism: A review on mineral inclusions and U-Pb SHRIMP ages of zircons from the Dabie-Sulu UHP rocks. *Journal of Asian Earth Sciences* 40,

1-39.

Liu, J.B., Ye, K., Maruyama, S., Cong, B.L., Fan, H.R., 2001. Mineral inclusions in zircon from gneisses in the ultra-high pressure zone of the Dabie Mountains, China. *Journal of Geology* 109, 523-535.

Martin, C., Duchêne, S., 2015. Residual water in hydrous minerals as a kinetic factor for omphacite destabilization into symplectite in the eclogites of Vårdalsneset (WGR, Norway). *Lithos* 232, 162-173.

Martin, L.A. J., Hermann, J., Gauthiez-Putallaz, L., Whitney, D.L., Vitale Brovarone, A., Fornash, K.F., Evans, N.J., 2014. Lawsonite geochemistry and stability-implication for trace element and water cycles in subduction zones. *Journal of Metamorphic Geology* 32, 455-478.

Martin, L., Wood, B.J., Turner, S., Rushmer, T., 2011. Experimental measurements of trace element partitioning between lawsonite, zoisite and fluid and their implication for the composition of arc magmas. *Journal of Petrology* 52, 1049-1075.

Massonne H.J., 2012. Formation of amphibole and clinozoisite-epidote in eclogite owing to fluid infiltration during exhumation in a subduction channel. *Journal of Petrology* 53, 1969-1998.

Mattinson, C.G., Zhang, R.Y., Tsujimori, T., Liou, J.G., 2004. Epidote-rich talc-kyanite-phengite eclogites, Sulu terrane, eastern China: P-T-f (O₂) estimates and the significance of the epidote-talc assemblage in eclogite. *American Mineralogist* 89, 1772-1783.

Miller, J.A., Buick, I.S., Cartwright, I., Barnicoat, A., 2002. Fluid processes during the exhumation of high-P metamorphic belts. *Mineral Magazine* 12, 827-840.

Miller, J.A., Cartwright, I., 2000. Evidence for large-scale fluid flow within the Corsican ophiolite. *Journal of Geochemical Exploration* 69-70, 297-301.

Morrison, J., 2004. Stable and radiogenic isotope systematics in epidote group minerals. *Reviews in Mineralogy and Geochemistry* 56, 607-628.

Nagasaki, A., Enami, M., 1998. Sr-bearing zoisite and epidote in ultra-high pressure (UHP) metamorphic rocks from the Su-Lu province, eastern China: An important Sr reservoir under UHP conditions. *American Mineralogist* 83, 240-247.

Okay, A.I., 1993. Petrology of a diamond and coesite-bearing metamorphic terrain, Dabie Shan, China. *European Journal of Mineralogy* 5, 659-675.

Okay, A.I., Xu, S., Sengor, A.M.C., 1989. Coesite from the Dabie Shan eclogites,

- central China. *European Journal of Mineralogy* 1, 595-598.
- Oliver, N.H., Bons, P.D., 2001. Mechanisms of fluid flow and fluid–rock interaction in fossil metamorphic hydrothermal systems inferred from vein–wallrock patterns, geometry and microstructure. *Geofluids* 1, 137-162.
- Pearce, N.J.G., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R. Chenery, S.P., 1997. A Compilation of New and Published Major and Trace Element Data for NIST SRM 610 and NIST SRM 612 Glass Reference Materials. *Geostandards Newsletters* 21, 115-144.
- Philippot, P., 1993. Fluid-melt-rock interaction in mafic eclogites and coesite-bearing metasediments: constraints on volatile recycling during subduction. *Chemical Geology* 108, 93-112.
- Poli, S., Schmidt, M.W., 2004. Experimental Subsolvus Studies on Epidote Minerals. *Reviews in Mineralogy and Geochemistry* 56, 171-195.
- Putnis, A., 2009. Mineral replacement reactions. *Reviews in mineralogy and geochemistry* 70, 87-124.
- Putnis, A., Austrheim, H., 2010. Fluid-induced processes: metasomatism and metamorphism. *Geofluids* 10, 254-269.
- Putnis, A., John, T., 2010. Replacement processes in the Earth's crust. *Elements* 6, 159-164.
- Ramos, F.C., Tepley, F.J., 2008. Inter- and intracrystalline isotopic disequilibria: techniques and applications. *Reviews in Mineralogy and Geochemistry* 69, 403-443.
- Ramos, F.C., Wolff, J.A., Tollstrup, D.L., 2004. Measuring $^{87}\text{Sr}/^{86}\text{Sr}$ variations in minerals and groundmass from basalts using LA-MC-ICPMS. *Chemical Geology* 211, 135-158.
- Rolfo, F., Compagnoni, R., Xu, S.T., Jiang, L.L., 2000. First report of felsic whiteschist in the ultrahigh-pressure metamorphic belt of Dabie Shan, China. *European Journal of Mineralogy* 12, 883-898.
- Romer, R.L., Xiao, Y.L., 2005. Initial Pb-Sr(-Nd) isotopic heterogeneity in a single allanite-epidote crystal: implications of reaction history for the dating of minerals with low parent-to-daughter. *Contributions to Mineralogy and Petrology* 148, 662-674.
- Scambelluri, M., Hermann, J., Morten, L., Rampone, E., 2006. Melt-versus fluid-induced metasomatism in spinel to garnet wedge peridotites (Ulten Zone,

- Eastern Italian Alps): clues from trace element and Li abundances. *Contributions to Mineralogy and Petrology* 151, 372-394.
- Scambelluri, M., Philippot, P., 2001. Deep fluids in subduction zones. *Lithos* 55, 213-227.
- Scambelluri, M., Philippot, P., Pennacchioni, G., 1998. Salt-rich aqueous fluids formed during eclogitization of metabasites in the Alpine continental crust (Austroalpine Mt. Emilius unit, Italian Western Alps). *Lithos* 43, 151-161.
- Schmidberger, S.S., Simonetti, A., Francis, D., 2003. Small-scale Sr isotope investigation of clinopyroxenes from peridotite xenoliths by laser ablation MC-ICP-MS—implications for mantle metasomatism. *Chemical Geology* 199, 317-329.
- Schmidt, M.W., Poli, S., 1998. Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Earth and Planetary Science Letters* 163, 361-379.
- Shi, Y.H., Wang, Q.C., 2006. Variation in peak P-T conditions across the upper contact of the UHP terrane, Dabieshan, China: gradational or abrupt? *Journal of Metamorphic Geology* 24, 803-822.
- Sorensen, S.S., Grossman, J.N., 1989. Enrichment of trace elements in garnet amphibolites from a paleo-subduction zone: Catalina Schist, southern California. *Geochimica et Cosmochimica Acta* 53, 3155-3177.
- Spandler, C., Pettke, T., Rubatto, D., 2011. Internal and external fluid sources for eclogite-facies veins in the Monviso meta-ophiolite, Western Alps: implications for fluid flow in subduction zones. *Journal of Petrology* 52, 1207-1236.
- Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), *Magmatism in the Ocean Basins*: Geological Society, London, Special Publication, pp. 313-345.
- Tsujimori, T., Sisson, V.B., Liou, J.G., Harlow, G.E., Sorensen, S.S., 2006. Very-low-temperature record of the subduction process: A review of worldwide lawsonite eclogites. *Lithos* 92, 609-624.
- Uno, M., Iwamori, H., Toriumi, M., 2015. Transition from dehydration to hydration during exhumation of the Sanbagawa metamorphic belt, Japan, revealed by the continuous P-T path recorded in garnet and amphibole zoning. *Contributions to Mineralogy and Petrology* 170, 1-22.

- Valley, J.W., O'Neil, J.R., 1984. Fluid heterogeneity during granulite facies metamorphism in the Adirondacks: stable isotope evidence. *Contributions to Mineralogy and Petrology* 85, 158-173.
- Vallis, F., Scambelluri, M., 1996. Redistribution of high-pressure fluids during retrograde metamorphism of eclogite-facies rocks (Voltri Massif, Italian Western Alps). *Lithos* 39, 81-92.
- van der Straaten, F., Schenk, V., John, T., Gao, J., 2008. Blueschist-facies rehydration of eclogites (Tian Shan, NW-China): Implications for fluid-rock interaction in the subduction channel. *Chemical Geology* 255, 195-219.
- Vervoort, J.D., Patchett, P.J., Soderlund, U., Baker, M., 2004. Isotopic composition of Yb and the determination of Lu concentrations and Lu/Hf ratios by isotopic dilution using MC-ICPMS. *Geochemistry, Geophysics, Geosystems* Q11002. doi:10.1029/2004GC000721.
- Wain, A., Krabbendam, M., 1999. Metamorphic reactivity and density changes in the formation and exhumation of ultrahigh-pressure rocks. *Meeting of the Metamorphic Studies Group: Exhumation of Metamorphic Terranes, Rennes, Abstract Volume*, p. 98, Mineralogical Society and Geological Society of London.
- Wang, X., Liou, J.G., Mao, H.K., 1989. Coesite-bearing eclogite from the Dabie Mountains in central China. *Geology* 17, 1085-1088.
- Wei, C.J., Li, Y.J., Yu, Y., Zhang, J.S., 2010. Phase equilibria and metamorphic evolution of glaucophane-bearing UHP eclogites from the Western Dabieshan Terrane, Central China. *Journal of Metamorphic Geology* 28, 647-666.
- Whitney, D.L. and Evans, B.W., 2010. Abbreviations for names of rock-forming minerals. *American Mineralogist* 95, 185-187.
- Wu, Y.B., Gao, S., Zhang, H.F., Yang, S.H., Liu X.C., Jiao, W.F., Liu, Y.S., Yuan, H.L., Gong, H.J., He, M.C., 2009. U-Pb age, trace-element, and Hf-isotope compositions of zircon in a quartz vein from eclogite in the western Dabie Mountains: Constraints on fluid flow during early exhumation of ultrahigh-pressure rocks. *American Mineralogist* 94, 303-312.
- Xiao, Y.L., Hoefs, J., Hou, Z.H., Simon, K., Zhang, Z.M., 2011. Fluid/rock interaction and mass transfer in continental subduction zones: constraints from trace elements and isotopes (Li, B, O, Sr, Nd, Pb) in UHP rocks from the Chinese Continental Scientific Drilling Program, Sulu, East China. *Contributions to Mineralogy and Petrology* 162, 797-819.

- Xie, Z., Zheng, Y.F., Jahn, B.M., Ballevre, M., Chen, J.F., Gautier, P., Gao, T.S., Gong, B., Zhou, J.B., 2004. Sm–Nd and Rb–Sr dating of pyroxene–garnetite from North Dabie in east-central China: problem of isotope disequilibrium due to retrograde metamorphism. *Chemical Geology* 206, 137-158.
- Xu, S.T., Su, W., Liu, Y.C., Jiang, L.L., Ji, S.Y., Okay, A.I., Sengör, A.M.C., 1992. Diamond from the Dabie-Shan Metamorphic Rocks and Its Implication for Tectonic Setting. *Science* 256, 80-82.
- Yardley, B., Gleeson, S., Bruce, S., Banks, D., 2000. Origin of retrograde fluids in metamorphic rocks. *Journal of Geochemical Exploration* 69, 281-285.
- Yang, Y.H., Wu, F.Y., Xie, L.W., Yang, J.H., Zhang, Y.B., 2009. In-situ Sr isotopic measurement of natural geological samples by LA-MC-ICP-MS. *Acta Petrologica Sinica* 25, 3431-3441 (In Chinese with English abstract).
- Yang, Y.H., Wu, F.Y., Yang, J.H., Chew, D.M., Xie, L.W., Chu, Z.Y., Zhang, Y.B., Huang, C., 2014. Sr and Nd isotopic compositions of apatite reference materials used in U-Th-Pb geochronology. *Chemical Geology* 385, 35-55.
- Ye, K., Cong, B.L., Ye, D.I., 2000a. The possible subduction of continental material to depths greater than 200 km. *Nature* 407, 734-736.
- Ye, K., Yao, Y.P., Katayama, I., Cong, B.L., Wang, Q.C., Maruyama, S., 2000b. Large areal extent of ultrahigh-pressure metamorphism in the Sulu ultrahigh-pressure terrane of East China: new implications from coesite and omphacite inclusions in zircon of granitic gneiss. *Lithos* 52, 157-164.
- Zack, T., John, T., 2007. An evaluation of reactive fluid flow and trace element mobility in subducting slabs. *Chemical Geology* 239, 199-216.
- Zhang, R.Y., Liou, J.G., Ernst, W.G., 2009. The Dabie-Sulu continental collision zone: A comprehensive review. *Gondwana Research* 16, 1-26.
- Zhang, Z.M., Shen, K., Sun, W.D., Liu, Y.S., Liou, J.G., Shi, C., Wang, J.L., 2008. Fluids in deeply subducted continental crust: Petrology, mineral chemistry and fluid inclusion of UHP metamorphic veins from the Sulu orogen, eastern China. *Geochimica et Cosmochimica Acta* 72, 3200-3228.
- Zhao, Z.F., Zheng, Y.F., Chen, R.X., Xia, Q.X., Wu, Y.B., 2007. Element mobility in mafic and felsic ultrahigh-pressure metamorphic rocks during continental collision. *Geochimica et Cosmochimica Acta* 71, 5244-5266.
- Zheng, Y.F., 2009. Fluid regime in continental subduction zones: petrological insights from ultrahigh-pressure metamorphic rocks. *Journal of the Geological Society*

1220 (London) 166, 763-782.

1221 Zheng, Y.F., Fu, B., Gong, B., Li, L., 2003. Stable isotope geochemistry of ultrahigh
 1222 pressure metamorphic rocks from the Dabie-Sulu orogen in China: implications
 1223 for geodynamics and fluid regime. *Earth-Science Reviews* 62, 105-161.

1224 Zheng, Y.F., Gao, T.S., Wu, Y.B., Gong, B., Liu, X.M., 2007. Fluid flow during
 1225 exhumation of deeply subducted continental crust: zircon U-Pb age and O-isotope
 1226 studies of a quartz vein within ultrahigh-pressure eclogite. *Journal of*
 1227 *Metamorphic Geology* 25, 267-283.

1228 Zheng, Y.F., Hermann, J., 2014. Geochemistry of continental subduction-zone fluids
 1229 *Earth, Planets and Space* 66, 342-374.

1230 Zheng, Y.F., Zhao, Z.F., Wu, Y.B., Zhang, S.B., Liu, X., Wu, F.Y., 2006. Zircon
 1231 U-Pb age, Hf and O isotope constraints on protolith origin of ultrahigh-pressure
 1232 eclogite and gneiss in the Dabie orogen. *Chemical Geology* 231, 135-158.

1233

Figure captions

Fig. 1. (a) Regional geological map showing the major litho-tectonic zones of the Dabie HP-UHP metamorphic terrane. Insert shows the location of the study area in China. (b) Simplified geological map (modified after [Guo et al., 2015a](#)) of the Hualiangting area showing the lithologic distribution and sample locality.

Fig. 2. (a) Field view illustrating the relationship between the UHP eclogite and amphibolites. The yellow dotted line showing the boundary of the eclogite and amphibolite. (b) Polished hand specimen of the UHP eclogite 09HLT10. (c) Polished hand specimen of the amphibolite 09HLT16, which includes a small amount of quartz-rich segregation. (d) Scanned thin section of the UHP eclogite showing the distribution of coarse-grained epidote porphyroblasts. (e) and (f) Scanned thin sections showing the characteristics of two amphibolites 09HLT13 and 09HLT16. Note that some epidote (Ep-AII) grains are distributed along “vein-like” channels in the sample 09HLT16. The detailed sampling locations of (b)-(f) are labeled in (a).

Fig. 3. Photomicrographs (a-d) and back-scattered electron (BSE) images (e-h) showing the textural characteristics of epidote in the eclogite (Ep-E) and amphibolites (Ep-AI). (a) and (b) Subhedral to anhedral Ep-E porphyroblasts contain omphacite, garnet, coesite pseudomorph (radial “palisade” quartz aggregates), and rutile inclusions in the eclogite 09HLT10: (a) under plane-polarized transmitted light and (b) under cross-polarized transmitted light. (c) Ep-AI in textural equilibrium with matrix amphibole, plagioclase, and quartz or occurring as inclusions in the amphibole porphyroblast in the amphibolite 09HLT13. (d) A coarse-grained Ep-AI porphyroblast in a matrix of fine-grained amphibole, plagioclase, quartz, rutile/Fe-Ti oxide, and apatite (09HLT13). (e)-(g) Inclusions of fine-grained garnet, amphibole, plagioclase, quartz, rutile/Fe-Ti oxide, and apatite in an Ep-AI porphyroblast (09HLT13). (h)

Inclusions of fine-grained garnet, plagioclase, quartz, rutile/Fe-Ti oxides, and apatite in an Ep-AI porphyroblast in the amphibolite 09HLT14.

Fig. 4. BSE images (a, d, e) and photomicrographs (b, c) showing the textural characteristics of the two types of epidote (Ep-AI and Ep-AII) in the amphibolite 09HLT16. Ep-AII is characterized by a dark-yellow color in the microscopic images and a bright color in the BSE image. (a) Inclusions of garnet, amphibole, quartz, plagioclase, Fe-Ti oxide, and apatite in an Ep-AI porphyroblast. (b) Coexisting zones of Ep-AI and Ep-AII. The anhedral Ep-AI grains occurring as irregular fragments that are in textural equilibrium with amphibole, plagioclase, quartz, Fe-Ti oxides, and apatite. (c) Several irregular Ep-AII fragments are distributed along a “vein-like” channel. The red dotted lines showing the distribution range of the Ep-AII grains. (d) Ep-AII occurring as metasomatic veins or disseminated veinlets that crosscut the earlier-stage Ep-AI and amphibole. (e) Fine-grained or coarse-grained Ep-AII reaction rims on earlier-stage Ep-AI.

Fig. 5. BSE image (a), compositional profile (b), and X-ray maps (c-d) of a zone of coexisting Ep-AI and Ep-AII showing the textural and compositional contrasts between the two types of epidote in the amphibolite 09HLT16. (a) A BSE image showing the textural relationship of Ep-AI and Ep-AII, referring to Fig. 4(c). (b) Variations in the X_{Fe} values and SrO contents of coexisting Ep-AI and Ep-AII along a transect. The detailed analytical locations are shown in (a). Notably, the Ep-AII shows obvious intra-grain compositional variation, whereas the Ep-AI has a homogenous composition. The SrO contents were measured by the EMP. (c) X-ray map of Fe. (d) X-ray map of Al. (e) X-ray map of Sr. (f) X-ray map of Ca. Notably, many small Ep-AI relics occur in the Ep-AII domains (appearing as patchy texture), indicating the replacement of Ep-AI by Ep-AII through fluid infiltration.

Fig. 6. Photomicrographs showing the textural characteristics and the initial Sr isotopic compositions of matrix apatite in the amphibolites. The red circles represent the locations of the *in situ* Sr isotopic analyses; the data are the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($t = 210$ Ma). (a) Coarse-grained apatite grains in textural equilibrium with amphibole and plagioclase in the amphibolite 09HLT13. Plagioclase inclusions in the apatite indicate the formation of apatite during amphibolite-facies stage. (b) Apatite grains in textural equilibrium with amphibole and plagioclase in the amphibolite 09HLT16. The red dotted lines showing the distribution range of the Ep-AII grains. Note that the apatite has an obviously different initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio with the nearby Ep-AII (a distance of ~ 300 μm).

Fig. 7. (a) Chondrite-normalized REE patterns of the eclogite and amphibolites. (b) Chondrite-normalized REE patterns of the Ep-E (09HLT10), Ep-AI (09HLT16), Ep-AII (09HLT16), and apatite (09HLT13 and 09HLT16). (c) Chondrite-normalized REE patterns of the Ep-AI (09HLT13 and 09HLT14). The normalization values are from [Sun and McDonough \(1989\)](#).

Fig. 8. Plots of X_{Fe} vs. SrO (a), Sr vs. La (b), $(\text{La}/\text{Yb})_{\text{N}}$ (c), Pb (d), Th (e), and Ba (f), and δEu vs. δCe (g) showing the compositional characteristics of multiple types of epidote in the eclogite and amphibolites. The SrO contents were measured by EMP and the Sr contents were acquired by LA-ICP-MS.

Fig. 9. Sketch maps of the Ep-E and Ep-AI (a, b) and mineral compositional and Sr isotopic variations (c, d) along the rim-core-rim profiles. (a) A representative Ep-E grain in the eclogite 09HLT10 (referring to [Fig. 3a](#)). (b) A representative Ep-AI grain in the amphibolite 09HLT13 (referring to [Fig. 3e](#)). (c) Variations in the X_{Fe} values, SrO/Sr contents, and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios along a rim-core-rim profile in Ep-E. (d) Variations in the X_{Fe} values, SrO/Sr contents, and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios along a

rim-core-rim profile in Ep-AI. The detailed locations of the profile analyses of the Ep-E and Ep-AII are shown in (a) and (b), respectively.

Fig. 10. (a-d) Sketch maps of four representative zones of coexisting Ep-AI and Ep-AII showing Sr isotopic variations at the grain scale in the amphibolite 09HLT16. Zone A refers to Fig. 4b; Zone B refers to Fig. 4c; Zone C refers to Fig. 4d; and Zone D refers to Fig. 4e. The locations of the LA-MC-ICP-MS analyses (red circles) and the corresponding initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are reported. The locations analyzed for Sr contents are positioned near the locations analyzed for the Sr isotopic ratios; thus, both analyses were conducted at approximately the same location. (e-h) Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the Ep-AI and Ep-AII in Zone A (shown in sketch map a), Zone B (shown in sketch map b), Zone C (shown in sketch map c), and Zone D (shown in sketch map d).

Fig. 11. Compositions of garnet (a, b), amphibole (c, d), and plagioclase (e). (a) Chemical ternary diagram showing the compositional differences between the Grt-E and Grt-A. (b) Plots of MgO vs. MnO showing the compositional differences between the Grt-E and Grt-A. (c) Compositions of the amphibole in the eclogite. (d) Compositions of the amphibole in the amphibolites. (e) Compositional ternary classification diagram of the plagioclase in the amphibolites.

Fig. 12. Plots of Sr vs. initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios showing the compositional and initial Sr isotopic compositions of various types of epidote and apatite ($t = 230$ Ma for Ep-E; $t = 210$ Ma for Ep-AI, Ep-AII, and apatite) in the Hualiangting eclogite and amphibolites. Ep-AI and apatite have the same initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as Ep-E, whereas Ep-AII has noticeably higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than Ep-E.

Fig. 13. Initial whole-rock Sr isotopic compositions of the Hualiangting eclogite, amphibolites, and gneisses ($t = 210$ Ma) and initial *in situ* Sr isotopic compositions of

1334 various types of epidote and apatite showing the disparate origins of the retrograde
1335 amphibolite-facies fluids (see the main text for details). The blue rectangular region
1336 defines the range of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the HP-UHP epidote in the
1337 Hualiangting eclogites, as previously reported by [Guo et al. \(2015a\)](#).

Figure

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Table 1 Mineral assemblages and mineral volume abundances of the investigated eclogite and amphibolites from the Hualiangting area

Sample	Rock types	Mineral assemblages and mineral volume contents (vol.%)
09HLT10	Eclogite	Omp 30, Grt 26, Ep-E 17, Amp 9, Qz 6, Ky 6, AM 5, Phn <1
09HLT13	Amphibolite	Amp 35, Pl 28, Ep-AI 18, Qz 14, AM 5, Grt <<1
09HLT14	Amphibolite	Amp 40, Pl 26, Ep-AI 20, Qz 9, AM 5, Grt <<1
09HLT16	Amphibolite	Amp 32, Pl 30, Ep-AI 24, Ep-AII <3, Qz 6, AM 5, Grt <<1

Table2

Table 2 Main characteristics of each type of epidote, defined by texture, coexisting mineral, inclusions, mineral chemistry, Sr isotopic composition, internal zoning, P-T conditions, and implications for retrograde fluid flow.

Epidote types	Ep-E	Ep-AI	Ep-AII
Host rock	Eclogite	Amphibolite	Amphibolite
Sample	09HLT10	09HLT13, 09HLT14, 09HLT16	09HLT16
Texture	Euhedral to subhedral, porphyroblasts	Anhedral, porphyroblasts or matrix minerals	Anhedral, fragments, or veins/veinlets, or secondary reaction rims on the Ep-AI
Coexisting mineral	Omp, Grt, Qz, Amp (Brs/Wnc), Rt, Ap	Amp (Prg), Pl, Qz, Rt/Ilm, Ap	Amp (Prg), Pl, Qz, Rt/Ilm, Ap
Inclusions	Omp, Grt-E (low-Mn/high-Mg), Qz (Coe), Rt, Ap	Grt-A (high-Mn/low-Mg), Amp (Prg), Pl, Qz, Rt/Ilm, Ap	None
X _{Fe}	Low (0.23-0.25)	Low (0.23-0.26)	High (0.34-0.42)
Trace element chemistry	Very high Sr (3970-7200 ppm), Pb (40-126 ppm), Th (5-51 ppm), Ba (23-73 ppm), and LREE (La, 110-325 ppm); LREE-rich pattern	High Sr (2900-4600 ppm), Pb (30-67ppm), Th (2-13), Ba (14-45), and LREE (La, 27-114 ppm); LREE-rich pattern	Low Sr (1640-2460 ppm), Pb (13-25 ppm), Th (<0.1 ppm), Ba (5-22 ppm), and LREE (La, 0.2-1.8 ppm); LREE-depleted pattern
⁸⁷ Sr/ ⁸⁶ Sr ratio	0.70431-0.70454	0.70434-0.70457	0.70493-0.70907
Internal texture and zoning of single grain	Slightly decrease of Sr in the rims; no Sr isotopic zonations	No compositional and Sr isotopic zonations	Patchy texture; highly heterogeneous composition and Sr isotope
Metamorphic stages	UHP eclogite-facies	Amphibolite-facies	Amphibolite-facies (chronologically later than the Ep-AI)
P-T conditions	28-30 kbar and 660-720 °C	8.0-10.3 kbar and 646-674 °C	Close to the Ep-AI
Insights into amphibolite-facies fluid flow	—	Internally-derived, pervasive flow manner, short transport distance (meter scale or less) for the early-stage amphibolite-facies fluid	Externally-derived (from gneiss), channelized flow manner, long transport distance (> 60 m) for the late-stage amphibolite-facies fluid

P-T conditions of the Ep-E (calculated by the phase equilibrium modeling) were form [Guo et al. \(2015a\)](#).

P-T conditions of the Ep-AI were calculated by the thermobarometers (for details, see appendix [Table A5](#)).

Table 3 Whole-rock compositions of the studied eclogite and amphibolites

Sample no.	09HLT10	09HLT13	09HLT14	09HLT16
Rock types	Eclogite	Amphibolite	Amphibolite	Amphibolite
Major elements (wt. %)				
SiO ₂	49.89	51.22	45.48	46.26
TiO ₂	1.56	1.36	1.41	2.08
Al ₂ O ₃	16.99	17.48	19.24	17.05
Fe ₂ O ₃	7.24	6.39	6.89	8.55
FeO	4.92	4.84	5.77	6.02
MnO	0.21	0.19	0.21	0.19
MgO	6.11	4.17	4.97	4.65
CaO	8.94	9.47	11.1	10.51
Na ₂ O	2.68	3.38	3.33	2.93
K ₂ O	0.15	0.19	0.27	0.27
P ₂ O ₅	0.41	0.28	0.34	0.53
LOI	0.62	0.88	0.84	0.97
Total	99.72	99.85	99.85	100.01
Trace elements (ppm)				
Li	8.02	7.00	6.77	8.82
Sc	28.2	31.5	29.9	48.3
V	211	204	203	335
Cr	321	48.3	46.2	24.4
Co	53.1	43.2	40.9	47.8
Ni	89.0	61.6	64.7	36.4
Cu	47.9	5.71	7.02	142
Ga	17.6	14.4	15.6	17.0
Rb	2.10	2.13	1.94	2.40
Sr	459	396	385	251
Cs	0.05	0.05	0.04	0.08
Ba	447	106	117	103
Pb	3.17	3.24	3.64	4.22
Th	1.52	1.29	1.25	1.85
U	0.23	0.19	0.17	0.20
Nb	3.80	4.22	4.84	3.66
Ta	0.25	0.19	0.21	0.22
Zr	152	140	139	129
Hf	3.96	3.34	3.56	3.92
La	21.1	18.6	19.7	14.0
Ce	44.3	43.1	38.9	31.7
Pr	6.37	5.26	5.53	4.82
Nd	28	22	24.4	22
Sm	7.41	5.18	5.53	5.57
Eu	2.70	1.72	1.64	2.06
Gd	7.17	4.71	4.89	5.37

Tb	1.05	0.75	0.78	0.91
Dy	5.67	4.68	4.57	5.52
Ho	1.1	1.0	0.97	1.2
Er	2.82	2.86	2.93	3.41
Tm	0.41	0.44	0.46	0.51
Yb	2.75	2.93	3.01	3.35
Lu	0.43	0.47	0.47	0.52
Y	24.7	23.7	23.3	26.9
(La/Yb) _N	5.50	4.55	4.69	3.00

Fe₂O₃ content was calculated by those of total iron and analyzed FeO.

N represents chondrite normalization.

Table4

Table 4 The representative compositions of epidote in the Hualiangting eclogite and amphibolites (oxide concentrations in wt.%, trace-element concentrations in ppm)

Mineral	Ep-E						Ep-AI										Ep-AII														
Sample	09HLT10						09HLT13					09HLT14					09HLT16					09HLT16									
Zoning	Core			Rim																											
SiO ₂	38.55	38.78	38.96	39.23	38.69	38.83	38.30	38.37	38.16	38.39	38.46	39.62	38.27	38.07	38.21	38.00	38.62	37.67	37.91	38.58	37.45	37.30	36.93	37.78	37.53	36.93	38.05	37.74	37.35	37.53	
TiO ₂	0.03	0.00	0.00	0.00	0.10	0.06	0.04	0.02	0.05	0.00	0.05	0.04	0.08	0.07	0.04	0.07	0.02	0.05	0.08	0.02	0.07	0.09	0.12	0.11	0.06	0.12	0.02	0.06	0.12	0.06	
Al ₂ O ₃	23.95	23.65	23.97	23.75	24.54	24.59	24.12	23.78	23.81	24.12	24.44	22.51	24.28	23.59	24.42	24.05	24.88	23.91	24.15	24.53	22.93	18.01	17.80	19.71	19.86	19.28	19.66	19.31	19.07	19.86	
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.01	0.02	0.00	0.00	0.01	0.01	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	
FeO	10.42	10.54	10.45	10.30	10.62	10.76	11.36	11.04	11.52	11.45	10.86	11.29	11.23	12.15	10.89	11.17	10.79	11.59	11.69	11.13	11.17	18.06	18.26	15.87	15.78	16.48	15.89	16.20	16.65	15.78	
MnO	0.25	0.29	0.25	0.26	0.08	0.08	0.02	0.00	0.03	0.05	0.03	0.02	0.04	0.11	0.08	0.06	0.04	0.04	0.04	0.03	0.05	0.00	0.00	0.01	0.05	0.05	0.02	0.04	0.02	0.05	
MgO	0.17	0.14	0.18	0.20	0.38	0.25	0.22	0.18	0.17	0.23	0.18	0.18	0.19	0.36	0.15	0.20	0.18	0.24	0.30	0.18	0.21	0.02	0.00	0.00	0.01	0.01	0.02	0.01	0.00	0.01	
CaO	22.11	22.22	22.32	21.76	21.96	22.25	22.46	22.66	22.39	22.21	22.54	22.12	22.44	21.50	22.40	22.56	22.76	22.19	21.79	22.30	22.38	23.05	22.87	23.09	22.85	22.99	23.10	22.79	22.76	22.85	
Na ₂ O	0.01	0.00	0.02	0.02	0.03	0.02	0.00	0.02	0.01	0.00	0.01	0.04	0.02	0.00	0.00	0.02	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	
SrO	0.96	0.97	0.88	0.87	0.72	0.73	0.76	0.74	0.72	0.76	0.77	0.72	0.75	0.74	0.77	0.81	0.82	0.82	0.86	0.79	0.73	0.31	0.33	0.38	0.46	0.34	0.41	0.45	0.36	0.46	
Total	96.45	96.58	97.02	96.43	97.16	97.63	97.29	96.80	96.85	97.20	97.34	96.53	97.29	96.62	96.98	96.95	98.13	96.52	96.83	97.58	95.00	96.85	96.32	96.95	96.61	96.21	97.17	96.62	96.32	96.61	
O	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	
Si ⁴⁺	3.075	3.078	3.078	3.073	3.028	3.027	3.031	3.051	3.034	3.038	3.037	2.953	3.027	3.033	3.030	3.022	3.027	3.011	3.015	3.038	3.041	3.028	3.019	3.042	3.035	3.007	3.056	3.053	3.034	3.035	
Ti ⁴⁺	0.002	0.000	0.000	0.000	0.006	0.004	0.002	0.001	0.003	0.000	0.003	0.003	0.005	0.004	0.003	0.004	0.001	0.003	0.005	0.001	0.004	0.005	0.007	0.007	0.004	0.008	0.001	0.003	0.007	0.004	
Al ³⁺	2.251	2.230	2.244	2.257	2.299	2.294	2.249	2.229	2.231	2.249	2.275	2.241	2.263	2.215	2.282	2.254	2.298	2.252	2.265	2.276	2.195	1.723	1.714	1.870	1.892	1.851	1.861	1.841	1.825	1.892	
Cr ³⁺	0.000	0.000	0.000	0.001	0.002	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.001	0.001	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.000	
Fe ³⁺	0.695	0.705	0.694	0.694	0.706	0.712	0.752	0.734	0.766	0.758	0.717	0.798	0.743	0.809	0.722	0.743	0.707	0.775	0.777	0.733	0.759	1.226	1.248	1.068	1.067	1.122	1.067	1.096	1.131	1.067	
Mn ²⁺	0.017	0.020	0.017	0.018	0.006	0.005	0.001	0.000	0.002	0.004	0.002	0.001	0.003	0.007	0.005	0.004	0.003	0.003	0.003	0.002	0.004	0.000	0.000	0.000	0.004	0.003	0.002	0.003	0.001	0.004	
Mg ²⁺	0.020	0.016	0.021	0.025	0.045	0.029	0.026	0.021	0.020	0.027	0.021	0.022	0.022	0.043	0.018	0.024	0.021	0.029	0.035	0.021	0.025	0.002	0.000	0.000	0.001	0.001	0.002	0.001	0.000	0.001	
Ca ²⁺	1.890	1.904	1.899	1.880	1.870	1.887	1.904	1.930	1.907	1.883	1.907	2.002	1.902	1.836	1.903	1.923	1.911	1.900	1.857	1.881	1.948	2.005	2.003	1.992	1.980	2.006	1.988	1.975	1.981	1.980	
Na ⁺	0.001	0.000	0.002	0.004	0.005	0.003	0.000	0.003	0.002	0.000	0.002	0.006	0.002	0.000	0.000	0.003	0.001	0.001	0.001	0.003	0.002	0.000	0.002	0.001	0.000	0.001	0.000	0.000	0.000	0.000	
Total	7.951	7.953	7.954	7.952	7.965	7.965	7.966	7.969	7.965	7.958	7.965	8.027	7.967	7.949	7.964	7.977	7.969	7.973	7.959	7.957	7.978	7.991	7.993	7.982	7.982	7.999	7.978	7.974	7.980	7.982	
X _{Fe}	0.236	0.240	0.236	0.235	0.235	0.237	0.251	0.248	0.256	0.252	0.240	0.263	0.247	0.268	0.240	0.248	0.235	0.256	0.255	0.244	0.257	0.416	0.421	0.364	0.361	0.377	0.364	0.373	0.383	0.361	
Ba	51.5	51.5	56.1	73.4	23.4	26.7	32.8	26.9	20.5	33.0	28.4	24.6	30.8	22.0	20.1	23.2	33.6	31.9	45.4	37.1	28.6	15.0	5.05	14.9	21.6	6.94	18.0	15.5	15.7	20.4	
Sr	6420	7220	5460	5460	3970	4250	4070	3370	3190	3810	4140	2980	3550	3530	3550	3650	4230	4300	4540	3740	3110	1680	1650	1720	2460	1670	1910	2300	1970	2210	
Pb	74.0	84.5	71.0	56.9	51.2	47.6	43.1	51.0	44.6	63.1	34.3	35.0	43.9	30.4	32.3	30.0	49.7	45.8	49.3	42.7	43.4	12.9	18.3	14.0	24.9	21.2	23.3	22.0	18.3	19.5	
Th	32.6	51.2	30.3	13.1	25.1	10.2	12.7	4.69	2.42	7.52	2.46	2.71	5.24	2.65	2.43	2.57	11.2	6.30	5.81	11.8	6.50	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02	
U	2.13	7.95	2.22	2.94	1.57	1.94	1.62	1.49	0.624	2.63	2.16	0.89	0.56	0.61	0.42	0.41	0.49	0.41	0.48	0.68	0.56	0.02	0.02	0.02	0.01	0.01	0.03	0.03	0.02	0.02	
Sc	27.3	25.8	25.5	33.5	30.3	33.6	33.9	34.3	23.1	40.5	17.0	24.9	38.4	17.4	19.1	14.6	26.4	25.8	31.3	33.1	42.8	12.3	2.25	10.7	32.3	21.0	5.77	10.9	34.0	2.94	

V	345	462	405	449	490	488	485	412	520	414	306	511	401	343	332	308	464	488	465	463	430	508	775	531	755	1090	1030	1100	996	1170
Cr	175	296	196	221	234	182	52.3	62.7	6.41	20.9	76.8	13.9	20.7	72.8	65.2	69.8	24.7	13.6	20.4	38.7	13.7	5.41	34.2	52.2	74.8	3.23	9.40	10.8	18.2	4.91
Co	4.91	5.29	4.62	3.35	3.27	2.82	2.60	0.82	1.86	1.54	3.97	2.16	2.99	3.79	4.44	4.08	2.67	2.61	2.28	2.95	2.72	12.2	0.59	10.1	4.10	1.41	0.41	0.47	7.54	0.728
La	260	321	325	113	173	133	75.6	63.2	27.6	76.9	103	31.2	49.9	72.1	38.8	78.1	114	53.3	54.2	93.1	73.9	0.45	0.24	0.29	1.84	0.21	0.44	0.34	0.81	0.71
Ce	593	872	750	268	392	305	191	154	60.2	181	165	71.2	128	115	78.3	138	285	128	140	219	170	0.45	0.17	0.30	2.41	0.46	0.30	0.31	1.00	0.47
Pr	78.8	99.9	94.0	33.1	50.6	37.5	26.3	21.1	8.34	24.8	23.3	10.0	16.9	14.7	10.7	16.3	37.6	17.4	18.3	27.6	23.4	0.15	0.12	0.18	0.39	0.09	0.09	0.09	0.16	0.11
Nd	375	442	436	159	228	172	127	94.0	43.2	118	92.8	48.3	82.5	68.9	45.4	80.8	181	79.7	88.6	143	117	0.70	bdl	0.94	1.91	0.49	0.61	bdl	0.68	0.65
Sm	75.6	83.4	95.7	37.2	46.0	38.7	33.4	25.3	14.6	31.8	20.6	13.2	20.9	16.1	12.3	17.7	38.9	20.5	21.7	29.5	30.4	0.33	0.26	1.04	1.32	0.62	0.39	0.53	0.82	bdl
Eu	27.4	30.8	26.8	13.3	15.5	14.3	13.2	10.8	6.46	13.1	8.11	5.26	8.07	7.05	4.43	8.22	13.7	7.40	8.40	10.5	10.5	0.48	0.42	1.03	1.44	0.89	0.86	1.18	0.75	1.11
Gd	61.8	56.1	61.3	33.4	37.5	32.5	27.5	26.4	19.5	36.2	23.7	13.2	23.2	16.3	12.2	19.6	27.9	17.4	20.2	27.0	27.9	1.82	0.83	2.02	2.23	0.84	0.94	0.72	0.66	0.58
Tb	7.76	7.21	7.17	4.85	4.86	4.41	4.32	4.67	3.68	6.5	3.91	2.33	3.83	2.74	1.76	2.86	3.19	2.40	2.86	3.66	4.21	0.33	0.27	0.59	0.45	0.46	0.32	0.25	0.26	0.10
Dy	32.6	28.2	27.7	21.7	18.2	18.7	16.9	22.6	20.4	35.9	23.4	9.02	23.0	15.3	10.2	18.4	12.5	10.5	15.4	17.4	23.0	2.73	1.92	5.12	4.05	3.17	2.20	2.41	2.54	0.82
Ho	4.01	3.51	3.54	3.20	2.42	2.69	2.54	3.56	3.26	5.27	4.10	1.31	3.86	2.34	1.66	2.66	1.93	1.67	2.40	2.20	3.83	0.78	0.40	1.34	0.87	0.92	0.58	0.77	0.69	0.30
Er	8.52	6.02	7.34	6.52	4.17	5.35	4.26	4.82	4.46	7.93	6.93	2.04	6.72	4.73	3.81	5.07	2.92	3.05	3.65	4.67	6.23	3.05	1.37	3.24	3.10	3.09	1.33	2.45	2.17	1.25
Tm	0.76	0.74	0.61	0.60	0.45	0.57	0.29	0.26	0.40	0.54	0.68	0.18	0.45	0.53	0.42	0.45	0.27	0.29	0.27	0.30	0.45	0.40	0.15	0.59	0.43	0.52	0.25	0.45	0.39	0.18
Yb	3.98	3.62	3.47	2.25	1.84	3.15	1.04	1.30	1.48	2.06	2.19	0.71	2.03	2.09	1.74	2.1	1.05	0.91	0.82	1.12	1.26	3.25	1.55	3.63	4.44	4.77	2.43	3.62	2.86	1.62
Lu	0.41	0.46	0.38	0.18	0.18	0.30	0.11	0.10	0.07	0.11	0.12	0.06	0.19	0.10	0.16	0.14	0.06	0.07	0.10	bdl	0.09	0.44	0.23	0.54	0.58	0.79	0.36	0.57	0.48	0.25
Y	107	85.4	90.7	83.9	56.3	63.0	62.6	80.6	73.3	126	97.7	32.1	94.5	75.6	51.2	79.8	49.6	44.1	59.1	65.3	92.7	29.0	11.4	33.7	30.4	20.8	14.9	19.2	19.0	10.3
(La/Yb) _N	46.9	63.6	67.2	36.0	67.4	30.3	52.1	34.9	13.4	26.8	33.7	32.0	17.6	24.7	16.0	26.7	77.9	42.0	47.4	59.6	42.1	0.10	0.11	0.06	0.30	0.03	0.13	0.07	0.20	0.31
δCe	1.01	1.18	1.04	1.06	1.01	1.04	1.05	1.03	0.96	1.01	0.79	0.98	1.08	0.82	0.93	0.90	1.06	1.03	1.09	1.05	1.00	0.42	0.24	0.31	0.66	0.83	0.36	0.44	0.64	0.37
δEu	1.19	1.30	1.00	1.13	1.10	1.20	1.29	1.26	1.17	1.18	1.12	1.21	1.12	1.32	1.09	1.34	1.21	1.17	1.21	1.12	1.08	1.49	2.51	2.14	2.55	3.77	4.16	5.84	3.02	-

$X_{\text{Fe}} = \text{Fe}^{3+} / (\text{Fe}^{3+} + \text{Al}^{3+})$; bdl= below detection limit; $\delta\text{Ce} = 2\text{Ce}_N / (\text{La}_N + \text{Pr}_N)$; $\delta\text{Eu} = 2\text{Eu}_N / (\text{Sm}_N + \text{Gd}_N)$.

Table 5 Whole-rock Rb-Sr isotopic compositions of the Hualiangting eclogite, amphibolites, and gneisses.

Sample no.	Rock types	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	2σ	⁸⁷ Sr/ ⁸⁶ Sr (<i>t</i> = 210 Ma)
09HLT10	Eclogite	2.03	488	0.0120	0.704452	0.000010	0.704416
09HLT13	Amphibolite	2.38	331	0.0208	0.704508	0.000014	0.704446
09HLT14	Amphibolite	2.44	407	0.0174	0.704491	0.000012	0.704439
09HLT16	Amphibolite	2.24	262	0.0248	0.704897	0.000012	0.704823
08HLT1	Gneiss	49.9	320	0.4515	0.711061	0.000013	0.709712
08HLT2	Gneiss	71.0	398	0.5166	0.712276	0.000014	0.710733
08HLT3	Gneiss	66.5	354	0.5440	0.711335	0.000013	0.709710
BCR-2	Standard	46.7	334	0.4052	0.704998	0.000012	

The Rb-Sr contents and isotopic compositions of the three gneisses are form [Guo et al. \(2015b\)](#).

Table 6 *In situ* Sr isotopic data of epidote and apatite in the Hualiangting eclogite and amphibolites.

Mineral	Sample no.	⁸⁴ Sr/ ⁸⁶ Sr	2σ	⁸⁴ Sr/ ⁸⁸ Sr	2σ	⁸⁷ Rb/ ⁸⁶ Sr	2σ	⁸⁷ Sr/ ⁸⁶ Sr	2σ	⁸⁷ Sr/ ⁸⁶ Sr(i)	2σ
Ep-E	Eclogite 09HLT10	0.0563	0.0007	0.00672	0.00008	0.0000	0.0001	0.70453	0.00013	0.70453	0.00013
		0.0568	0.0004	0.00678	0.00005	0.0001	0.0000	0.70439	0.00010	0.70439	0.00010
		0.0562	0.0004	0.00671	0.00004	0.0001	0.0000	0.70448	0.00008	0.70448	0.00008
		0.0562	0.0004	0.00671	0.00004	0.0000	0.0000	0.70445	0.00008	0.70445	0.00008
		0.0567	0.0004	0.00677	0.00004	0.0001	0.0000	0.70448	0.00008	0.70448	0.00008
		0.0564	0.0004	0.00673	0.00005	0.0000	0.0000	0.70446	0.00008	0.70446	0.00008
		0.0566	0.0002	0.00675	0.00003	0.0001	0.0000	0.70445	0.00006	0.70445	0.00006
		0.0566	0.0002	0.00676	0.00002	0.0001	0.0000	0.70449	0.00006	0.70449	0.00006
		0.0569	0.0004	0.00679	0.00005	0.0001	0.0000	0.70451	0.00009	0.70451	0.00009
		0.0567	0.0004	0.00677	0.00005	0.0000	0.0000	0.70449	0.00009	0.70449	0.00009
		0.0567	0.0003	0.00677	0.00004	0.0001	0.0000	0.70446	0.00008	0.70446	0.00008
		0.0567	0.0005	0.00678	0.00006	0.0001	0.0000	0.70454	0.00010	0.70454	0.00010
		0.0568	0.0006	0.00678	0.00007	0.0000	0.0000	0.70447	0.00013	0.70447	0.00013
		0.0553	0.0008	0.00660	0.00010	0.0004	0.0000	0.70446	0.00014	0.70446	0.00014
		0.0566	0.0003	0.00676	0.00003	0.0000	0.0000	0.70441	0.00007	0.70441	0.00007
		0.0564	0.0003	0.00673	0.00003	0.0000	0.0000	0.70440	0.00007	0.70440	0.00007
		0.0564	0.0003	0.00673	0.00004	0.0000	0.0000	0.70442	0.00008	0.70442	0.00008
		0.0563	0.0007	0.00672	0.00008	0.0000	0.0000	0.70445	0.00013	0.70445	0.00013
		0.0564	0.0004	0.00673	0.00005	0.0000	0.0000	0.70437	0.00009	0.70437	0.00009
		0.0568	0.0003	0.00678	0.00003	0.0000	0.0000	0.70447	0.00007	0.70447	0.00007
		0.0568	0.0006	0.00679	0.00007	0.0000	0.0000	0.70446	0.00010	0.70446	0.00010
		0.0565	0.0003	0.00674	0.00004	0.0000	0.0000	0.70439	0.00008	0.70439	0.00008
		0.0560	0.0004	0.00669	0.00004	0.0000	0.0000	0.70438	0.00010	0.70438	0.00010
		0.0565	0.0003	0.00674	0.00003	0.0000	0.0000	0.70442	0.00007	0.70442	0.00007
		0.0574	0.0011	0.00685	0.00013	0.0003	0.0001	0.70453	0.00012	0.70453	0.00012
		0.0565	0.0007	0.00675	0.00008	0.0000	0.0000	0.70438	0.00012	0.70438	0.00012

		0.0564	0.0003	0.00673	0.00004	0.0001	0.0000	0.70439	0.00008	0.70439	0.00008
		0.0557	0.0007	0.00665	0.00008	0.0003	0.0001	0.70434	0.00013	0.70434	0.00013
		0.0567	0.0007	0.00677	0.00008	0.0000	0.0000	0.70431	0.00014	0.70431	0.00012
		0.0570	0.0006	0.00680	0.00007	0.0001	0.0000	0.70441	0.00011	0.70441	0.00011
		0.0571	0.0006	0.00681	0.00008	0.0000	0.0000	0.70444	0.00012	0.70444	0.00012
		0.0562	0.0006	0.00671	0.00007	0.0000	0.0000	0.70438	0.00012	0.70438	0.00012
		0.0571	0.0007	0.00682	0.00009	0.0001	0.0000	0.70448	0.00010	0.70448	0.00010
		0.0557	0.0009	0.00666	0.00011	0.0000	0.0000	0.70434	0.00011	0.70434	0.00011
		0.0573	0.0010	0.00684	0.00011	0.0000	0.0000	0.70442	0.00010	0.70442	0.00010
		0.0562	0.0011	0.00671	0.00013	0.0000	0.0001	0.70443	0.00014	0.70443	0.00014
		0.0565	0.0012	0.00675	0.00014	0.0002	0.0000	0.70449	0.00014	0.70449	0.00014
Ep-AI	Amphibolite 09HLT13	0.0563	0.0003	0.00672	0.00004	0.0000	0.0000	0.70443	0.00012	0.70443	0.00012
		0.0569	0.0008	0.00679	0.00010	0.0000	0.0000	0.70447	0.00017	0.70447	0.00017
		0.0568	0.0007	0.00678	0.00008	0.0000	0.0000	0.70447	0.00014	0.70447	0.00014
		0.0558	0.0005	0.00667	0.00006	0.0000	0.0000	0.70455	0.00010	0.70455	0.00010
		0.0562	0.0004	0.00671	0.00005	0.0000	0.0000	0.70447	0.00010	0.70447	0.00010
		0.0565	0.0005	0.00675	0.00006	0.0000	0.0000	0.70454	0.00012	0.70454	0.00012
		0.0552	0.0006	0.00660	0.00007	0.0000	0.0000	0.70443	0.00015	0.70443	0.00015
		0.0567	0.0005	0.00677	0.00006	0.0001	0.0000	0.70445	0.00010	0.70445	0.00010
		0.0565	0.0006	0.00675	0.00007	0.0001	0.0000	0.70454	0.00011	0.70454	0.00011
		0.0566	0.0005	0.00676	0.00006	0.0001	0.0000	0.70445	0.00010	0.70445	0.00010
		0.0562	0.0005	0.00670	0.00006	0.0000	0.0000	0.70449	0.00011	0.70449	0.00011
		0.0563	0.0002	0.00673	0.00003	0.0000	0.0000	0.70439	0.00006	0.70439	0.00006
		0.0562	0.0005	0.00671	0.00006	0.0000	0.0000	0.70447	0.00010	0.70447	0.00010
		0.0564	0.0005	0.00673	0.00006	0.0001	0.0000	0.70451	0.00012	0.70451	0.00012
		0.0563	0.0007	0.00672	0.00009	0.0000	0.0000	0.70441	0.00015	0.70441	0.00015
	Amphibolite 09HLT14	0.0567	0.0007	0.00677	0.00008	0.0000	0.0000	0.70445	0.00012	0.70445	0.00012
		0.0568	0.0004	0.00678	0.00005	0.0000	0.0000	0.70450	0.00009	0.70450	0.00009
		0.0567	0.0006	0.00677	0.00007	0.0000	0.0000	0.70457	0.00011	0.70457	0.00011

		0.0565	0.0007	0.00675	0.00008	0.0001	0.0001	0.70444	0.00012	0.70444	0.00012
		0.0566	0.0005	0.00676	0.00006	0.0000	0.0000	0.70441	0.00013	0.70441	0.00013
		0.0552	0.0006	0.00660	0.00007	0.0000	0.0000	0.70443	0.00015	0.70443	0.00015
		0.0561	0.0006	0.00670	0.00007	0.0002	0.0004	0.70443	0.00012	0.70443	0.00012
		0.0562	0.0005	0.00671	0.00006	0.0000	0.0000	0.70440	0.00010	0.70440	0.00010
		0.0561	0.0005	0.00670	0.00005	0.0000	0.0000	0.70434	0.00009	0.70434	0.00009
		0.0568	0.0005	0.00679	0.00006	0.0000	0.0000	0.70453	0.00010	0.70453	0.00010
		0.0561	0.0006	0.00669	0.00008	0.0000	0.0000	0.70452	0.00012	0.70452	0.00012
		0.0564	0.0005	0.00673	0.00006	0.0000	0.0000	0.70439	0.00010	0.70439	0.00010
		0.0571	0.0008	0.00682	0.00009	0.0000	0.0000	0.70438	0.00017	0.70438	0.00017
		0.0562	0.0005	0.00671	0.00006	0.0000	0.0000	0.70454	0.00013	0.70454	0.00013
		0.0565	0.0006	0.00675	0.00007	0.0001	0.0000	0.70452	0.00014	0.70452	0.00014
	Amphibolite 09HLT16	0.0565	0.0005	0.00675	0.00005	0.0000	0.0000	0.70450	0.00011	0.70450	0.00011
		0.0561	0.0005	0.00670	0.00005	0.0004	0.0000	0.70452	0.00010	0.70452	0.00010
		0.0563	0.0006	0.00672	0.00007	0.0000	0.0000	0.70455	0.00013	0.70455	0.00013
		0.0564	0.0004	0.00673	0.00005	0.0000	0.0000	0.70450	0.00009	0.70450	0.00009
		0.0563	0.0005	0.00673	0.00007	0.0001	0.0000	0.70455	0.00011	0.70455	0.00011
		0.0565	0.0006	0.00675	0.00007	0.0001	0.0000	0.70452	0.00014	0.70452	0.00014
		0.0567	0.0005	0.00677	0.00006	0.0000	0.0000	0.70457	0.00010	0.70457	0.00010
		0.0564	0.0005	0.00674	0.00006	0.0000	0.0000	0.70451	0.00010	0.70451	0.00010
		0.0562	0.0005	0.00671	0.00006	0.0000	0.0000	0.70454	0.00010	0.70454	0.00010
		0.0563	0.0003	0.00672	0.00004	0.0000	0.0000	0.70440	0.00012	0.70440	0.00012
		0.0567	0.0004	0.00677	0.00004	0.0000	0.0000	0.70445	0.00011	0.70445	0.00011
		0.0563	0.0005	0.00672	0.00005	0.0000	0.0000	0.70454	0.00009	0.70454	0.00009
		0.0572	0.0005	0.00683	0.00006	0.0001	0.0000	0.70453	0.00010	0.70453	0.00010
		0.0574	0.0007	0.00685	0.00008	0.0002	0.0000	0.70452	0.00015	0.70452	0.00015
		0.0563	0.0004	0.00672	0.00005	0.0000	0.0000	0.70454	0.00010	0.70454	0.00010
		0.0564	0.0004	0.00673	0.00004	0.0001	0.0000	0.70440	0.00009	0.70440	0.00009
		0.0570	0.0005	0.00680	0.00006	0.0000	0.0000	0.70440	0.00009	0.70440	0.00009

		0.0569	0.0006	0.00679	0.00007	0.0000	0.0000	0.70447	0.00011	0.70447	0.00011
		0.0566	0.0005	0.00676	0.00005	0.0000	0.0000	0.70439	0.00010	0.70439	0.00010
		0.0566	0.0008	0.00675	0.00010	0.0000	0.0000	0.70451	0.00015	0.70451	0.00015
		0.0560	0.0007	0.00669	0.00009	0.0000	0.0000	0.70447	0.00014	0.70447	0.00014
		0.0562	0.0006	0.00671	0.00007	0.0000	0.0000	0.70443	0.00012	0.70443	0.00012
		0.0563	0.0003	0.00672	0.00004	0.0000	0.0000	0.70437	0.00008	0.70437	0.00008
		0.0567	0.0003	0.00678	0.00003	0.0000	0.0000	0.70450	0.00007	0.70450	0.00007
		0.0566	0.0008	0.00676	0.00010	0.0000	0.0000	0.70449	0.00017	0.70449	0.00017
		0.0568	0.0007	0.00678	0.00009	0.0000	0.0000	0.70440	0.00010	0.70440	0.00010
Ep-AII	Amphibolite 09HLT16	0.0560	0.0006	0.00669	0.00007	0.0002	0.0000	0.70643	0.00017	0.70643	0.00017
		0.0562	0.0004	0.00671	0.00005	0.0000	0.0000	0.70742	0.00014	0.70742	0.00014
		0.0561	0.0004	0.00670	0.00004	0.0000	0.0000	0.70665	0.00034	0.70665	0.00034
		0.0565	0.0005	0.00675	0.00006	0.0010	0.0002	0.70580	0.00018	0.70580	0.00018
		0.0565	0.0003	0.00674	0.00004	0.0000	0.0000	0.70758	0.00030	0.70758	0.00030
		0.0568	0.0002	0.00678	0.00003	0.0000	0.0000	0.70756	0.00013	0.70756	0.00013
		0.0563	0.0007	0.00673	0.00008	0.0002	0.0000	0.70772	0.00018	0.70772	0.00018
		0.0564	0.0003	0.00673	0.00004	0.0000	0.0000	0.70668	0.00017	0.70668	0.00017
		0.0565	0.0006	0.00675	0.00007	0.0001	0.0000	0.70789	0.00014	0.70789	0.00014
		0.0568	0.0006	0.00679	0.00007	0.0001	0.0000	0.70907	0.00022	0.70907	0.00022
		0.0563	0.0011	0.00673	0.00013	0.0004	0.0001	0.70683	0.00022	0.70683	0.00022
		0.0567	0.0015	0.00677	0.00018	0.0008	0.0010	0.70548	0.00032	0.70548	0.00032
		0.0561	0.0007	0.00670	0.00008	0.0000	0.0000	0.70544	0.00022	0.70544	0.00022
		0.0572	0.0004	0.00683	0.00005	0.0000	0.0000	0.70771	0.00017	0.70771	0.00017
		0.0565	0.0004	0.00674	0.00005	0.0000	0.0000	0.70638	0.00020	0.70638	0.00020
		0.0563	0.0004	0.00672	0.00005	0.0000	0.0000	0.70788	0.00015	0.70788	0.00015
		0.0569	0.0008	0.00679	0.00009	0.0000	0.0000	0.70688	0.00018	0.70688	0.00018
		0.0563	0.0003	0.00672	0.00004	0.0001	0.0000	0.70555	0.00012	0.70555	0.00012
		0.0567	0.0003	0.00677	0.00003	0.0000	0.0000	0.70598	0.00018	0.70598	0.00018
		0.0552	0.0020	0.00660	0.00024	0.0001	0.0001	0.70514	0.00020	0.70514	0.00020

		0.0547	0.0017	0.00653	0.00020	0.0001	0.0001	0.70493	0.00030	0.70493	0.00030
		0.0565	0.0009	0.00675	0.00011	0.0004	0.0001	0.70539	0.00019	0.70539	0.00019
		0.0559	0.0006	0.00668	0.00007	0.0000	0.0000	0.70540	0.00012	0.70540	0.00012
		0.0562	0.0006	0.00671	0.00007	0.0000	0.0000	0.70692	0.00015	0.70692	0.00015
		0.0574	0.0008	0.00686	0.00009	0.0001	0.0000	0.70763	0.00016	0.70763	0.00016
		0.0569	0.0007	0.00680	0.00008	0.0001	0.0000	0.70703	0.00013	0.70703	0.00013
		0.0570	0.0006	0.00681	0.00008	0.0000	0.0000	0.70744	0.00014	0.70744	0.00014
		0.0565	0.0007	0.00674	0.00008	0.0000	0.0000	0.70731	0.00015	0.70731	0.00015
		0.0567	0.0007	0.00677	0.00008	0.0000	0.0000	0.70751	0.00012	0.70751	0.00012
Apatite	Amphibolite 09HLT13	0.0564	0.0004	0.00675	0.00010	0.0011	0.0003	0.70440	0.00034	0.70440	0.00034
		0.0562	0.0011	0.00671	0.00014	0.0031	0.0006	0.70440	0.00035	0.70439	0.00035
		0.0567	0.0008	0.00677	0.00010	0.0002	0.0005	0.70446	0.00034	0.70446	0.00034
		0.0566	0.0004	0.00675	0.00005	0.0007	0.0002	0.70445	0.00047	0.70445	0.00047
	Amphibolite 09HLT16	0.0566	0.0006	0.00675	0.00007	0.0032	0.0005	0.70450	0.00028	0.70449	0.00028
		0.0548	0.0022	0.00655	0.00027	0.0103	0.0020	0.70440	0.00025	0.70437	0.00025
		0.0562	0.0074	0.00671	0.00089	0.0007	0.0001	0.70450	0.00055	0.70450	0.00055
		0.0583	0.0017	0.00696	0.00021	0.0013	0.0001	0.70460	0.00034	0.70460	0.00034
		0.0567	0.0012	0.00681	0.00009	0.0009	0.0004	0.70451	0.00026	0.70451	0.00026
		0.0562	0.0010	0.00688	0.00006	0.0023	0.0008	0.70441	0.00028	0.70440	0.00028

For initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio calculation of the Ep-E, $t = 230$ Ma; for initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio calculation of the Ep-AI, Ep-AII, and apatite, $t = 210$ Ma.