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U–Pb zircon geochronology of Tianshan eclogites in NW China: implication for the collision between the Yili and Tarim blocks of the southwestern Altaids

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Abstract: Zircon grains separated from an eclogite boudin intercalated within blueschists in Tianshan (NW China) were investigated by Raman spectroscopy, cathodoluminescence imaging and secondary ion mass spectrometry (SIMS). These grains have a thin homogeneous rim and an oscillatory inner zone domain with or without a relict inherited core. Omphacite, phengite and rutile inclusions were identified within the rim domain of zircon grains only, indicating that the rim had formed during peak eclogite-facies metamorphism. U–Pb zircon data record three distinct age populations: 2450 ± 31 to 1956 ± 26 Ma (for the inherited core), 486 ± 8 to 428 ± 6 Ma (oscillatory inner zone) as well as 319.5 ± 2.9 Ma and 318.7 ± 3.3 Ma (for the metamorphic rim). These new ages suggest that the metamorphism associated with the collision of the Yili and the Tarim blocks along the southwestern margin of the Altaids must have occurred during the Late Carboniferous (*ca.*, 320 Ma).

Key-words: eclogite, U–Pb zircon age, collision time, high-pressure metamorphism, Tianshan.

1. Introduction

The poor constraint on the timing of the regional high-pressure low-temperature (H*P*–L*T*) metamorphism has led to discussions about the exact timing of the final closure of the South Tianshan Ocean and the collision between the Yili and Tarim blocks, which is of primary importance in understanding the amalgamation of Eurasia and the Phanerozoic continental growth of the Altaids (Fig. S1A in Supplementary Material, freely available online on the GSW website of the journal, http://eurjmin.geoscienceworld.org/; *e.g.*, Charvet *et al.*, 2007; Zhang *et al.*, 2007; Gao *et al.*, 2009; Xiao *et al.*, 2009). This collision is considered to have occurred at Late Palaeozoic time, which has been supported by recent age data from H*P*–L*T* rocks in the western Tianshan comprising a Sm–Nd isochron age of 343 ± 44 Ma (omphacite–garnet–-glaucophane–whole rock), a ^{40}Ar/^{39}Ar crossite age of 344 ± 3 Ma, Rb–Sr isochron ages of 313–302 Ma (mica–whole rocks), ^{40}Ar/^{39}Ar phengite ages of 331–310 Ma (Gao & Klemd, 2003; Klemd *et al.*, 2005), ^{40}Ar/^{39}Ar phengite ages of 331–316 Ma (Wang *et al.*, 2010) and ^{40}Ar/^{39}Ar phengite and glaucophane ages of 327–324 Ma (Simonov *et al.*, 2008). The age of *ca.* 345 Ma was suggested to be the best approximation for the timing of the eclogite-facies metamorphism, while the younger ^{40}Ar/^{39}Ar and Rb–Sr ages were interpreted as resetting during exhumation of the high-pressure rocks (Klemd *et al.*, 2005; Wang *et al.*, 2010). However, on the basis of SHRIMP U–Pb ages of 233−226 Ma obtained for zircon rims separated from eclogites it has also been proposed that the collision occurred in the Triassic (Zhang *et al.*, 2007). Therefore, knowledge of the exact timing of peak eclogite-facies metamorphism in the Tianshan eclogites is imperative for constraining the final amalgamation time between the Tarim and Yili blocks and for understanding the tectonic evolution of the Altaids.

Here we report new U-Pb zircon ages measured with a Cameca 1280 ion microprobe in context with geological field evidence for the Tianshan eclogites and demonstrate that the collision between the Tarim and Yili blocks along the southwestern Altaids must have transpired in the Late Carboniferous (*ca.*, 320 Ma).

2. Geological background and sample descriptions

The western Tianshan (also referred to as the South Tianshan or Southwestern Tianshan in the literature) H*P*–L*T* metamorphic belt in NW China occurs along a suture between the Yili (–Central Tianshan) and the Tarim blocks (Gao *et al.*, 1999; Fig. S1A). It is mainly

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composed of blueschist-, eclogite- and greenschist-facies meta-sedimentary rocks and some mafic metavolcanic rocks with N-MORB, E-MORB, OIB and arc basalt affinities (Gao & Klemd, 2003; John *et al.*, 2008). Blueschists occur within greenschist-facies metasediments as small discrete bodies, lenses, bands and thick layers. Eclogites are interlayered with the blueschist layers as pods, boudins, thin layers or as massive blocks interpreted to represent a tectonic mélange (Gao *et al.*, 1999; van der Straaten *et al.* 2008). Most eclogites have experienced peak metamorphism estimated to range between 480 and 580 °C at 1.4–2.1 GPa at a regional scale (*e.g.*, Klemd *et al.*, 2002; Wei *et al.*, 2003). Ultrahigh-pressure (UH*P*) peak metamorphic conditions for some eclogites were reported and controversially discussed (*e.g.*, Klemd, 2003; Zhang *et al.*, 2002, 2003). UH*P* conditions (confirmed by the presence of coesite) of 2.7–3.3 GPa at 570–630 °C have been reported for eclogitic mica schists and ecologies from one locality (Habutengsu valley; Lü *et al.*, 2008, 2009).

To the north of the H*P*–L*T* belt, the southern margin of the Yili (–Central Tianshan) block (Fig. S1) is mainly composed of amphibolite- and granulite-facies rocks, Late Silurian and Early Carboniferous island-arc-type volcanics and volcaniclastic rocks as well as Caledonian-Variscan granitoids superimposed on a Precambrian basement (Allen *et al.*, 1992). The U–Pb zircon ages of the granitoids vary from 470 to 276 Ma (*e.g.*, Han *et al.*, 2004; Gao *et al.*, 2009).

To the south, the H*P*–L*T* belt is overlain by a succession of Palaeozoic sedimentary strata, which are considered to represent the passive continental margin of the Tarim block (Allen *et al.*, 1992; Carroll *et al.*, 1995). A few ophiolitic blocks or slices are thrust over the sedimentary sequences as klippen and are possibly crustal remnants of a Silurian-Early Carboniferous ocean between the Tarim and Yili blocks (Gao *et al.*, 1998). Permian syenites, nepheline syenites, aegirine syenites, two-mica peraluminous granites and A-type rapakivi granites extensively intruded into Palaeozoic sedimentary strata (Konopelko *et al.*, 2007; Solomovich, 2007; Long *et al.*, 2008).

Two representative eclogite samples (071-6a, 071-8a) from the Atantayi River area (N 42°30′29.6″, E 81°14′51.4″) in the western Tianshan H*P*–L*T* belt (Fig. S1B) were selected for U–Pb zircon dating. The eclogite is exposed as a boudin (*ca.*, 0.69 × 0.93 m^2 in plane view, Fig. S1C), which is intercalated with blueschists and surrounded by blueschist-facies mica schists. It is composed of garnet (5 %), omphacite (68–70 %), amphibole (9–10 %), paragonite/phengite (5–7 %), quartz (1–2 %), rutile (1 %) and minor titanite, albite and zircon. The idioblastic garnet typically contains inclusions, such as omphacite, amphibole, paragonite, quartz, rutile and minor zircon. The omphacite is idioblastic to xenoblastic and occurs as a matrix mineral together with amphibole and mica, the latter of which comprises lepidoblastic phengite and paragonite. Sub- to idioblastic amphibole porphyroblasts (about 2.5 mm in length) occasionally contain omphacite inclusions. Texturally primary Ca–Na–amphibole (barroisite) was replaced by Ca–amphibole (Mg–hornblende) along the rims. Zircon grains predominantly occur as inclusions in garnet or omphacite. The chemical composition of the representative minerals is presented as a supplementary material (Table S1). The average *P*–*T* estimates using the computer software THERMOCALC (tc321) (Powell & Holland, 1994) of 545 ± 50 °C at 1.7 to 2.0 GPa for peak metamorphic conditions are in agreement with former geothermobarometric investigations of eclogite-facies rocks in this area (*e.g.*, Klemd *et al.*, 2002; Wei *et al.*, 2003). The foliation of the blueschist is represented by N60-30N, parallel to that of the mica schist and belongs to the main ENE regional trend. The blueschist is mainly composed of garnet (10 %), glaucophane (53 %), phengite/paragonite (18 %), quartz (2 %), rutile (2 %), titanite (2 %) and retrograde albite (3 %). Relict omphacite inclusions were detected in the glaucophane, indicating that blueschist and eclogite underwent an identical metamorphic evolution (Klemd *et al.*, 2002). The mineral assemblage of the country blueschist-facies mica schist is similar to that of the blueschist with relatively higher quartz contents (>20 %).

Detailed analytical procedures of microprobe, Raman spectroscopy, cathodoluminescence imaging and Cameca 1280 ion microprobe are presented in the supplementary materials.

3. Results

3.1. Mineral inclusion in zircon

Most zircon crystals are pale yellow to pale brown, contain dusty cores and colourless homogeneous overgrowths. They are 50−250 μm in length, subhedral to euhedral or short prismatic, and most of them are rounded (with ratios of 1:1–1:2; Fig. 1a, c). Cathodoluminescence images reveal that the majority of zircon grains are composed of an irregular low-luminescent nucleus (inherited zone; *ca.* 100–150 μm), an oscillatory bright-luminescent inner zone (inner zone; *ca.* 100–150 μm) and a thin bright-luminescent rim (rim; *ca.* 10–50 μm; Fig. 1b, d). A clear straight boundary was detectable between the inner zone and the rim of the zircon grains.

Index high-pressure metamorphic mineral inclusions such as omphacite, phengite and rutile were found within the rim domains of zircon. The omphacite is prismatic (1 × 6 μm–3 × 18 μm in size) and identified by the characteristic Raman peak at 678 cm^{-1} (Fig. 1e). Rutile and phengite inclusions, coexisting with omphacite, have characteristic Raman peaks at 611 cm^{-1} and 445 cm^{-1} (Fig. 1f), 704 cm^{-1} and 268 cm^{-1}, respectively. Additionally, quartz, calcite and apatite inclusions were found within the inner zone/core of zircon grains.

3.2. Ion microprobe U–Pb dating

Zircon U–Pb data are presented as a supplementary table (Table S2). Twenty-three spots were analysed on zircon grains from sample 071-6a; the results are shown on a Concordia plot (Fig. 2a). Concordant data points yield apparent ^{206}Pb/^{238}U ages ranging from 2450 Ma to

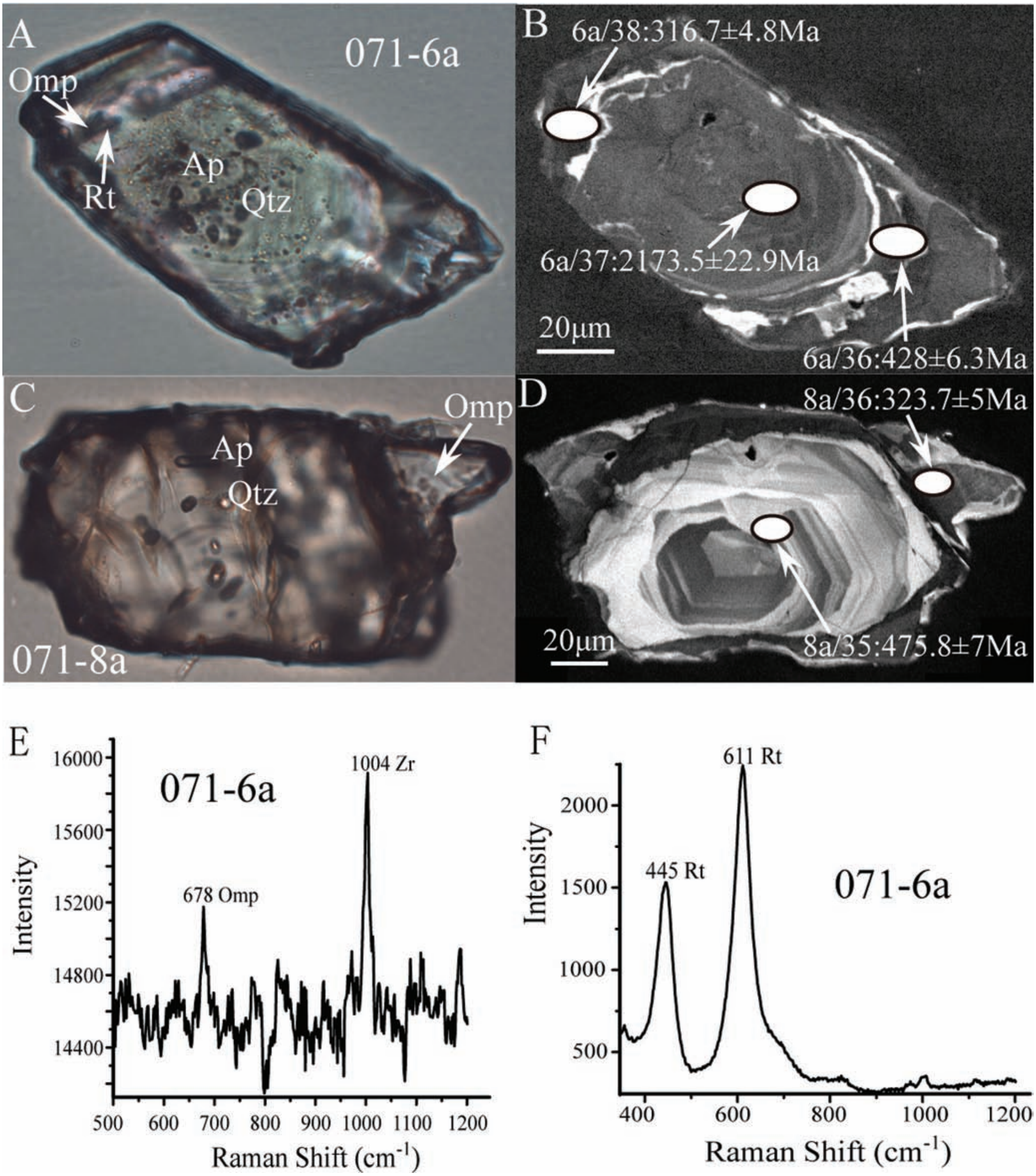

Fig. 1. Micro-photographs (A and C) and CL images (B and D) for zircon grains and representative Raman spectra (E and F) of omphacite and rutile inclusions in zircon from the eclogites. SIMS U–Pb analyzed spots have also been marked in the CL image. Omp, omphacite; Rt, rutile; Ap, apatite; Qtz, quartz; Zr, zircon.

314 Ma (Table S2). The inherited core, which contains mineral inclusions such as quartz and apatite, gives an apparent $^{206}Pb/^{238}U$ age of 2450–2085 Ma. The inner zone yields apparent $^{206}Pb/^{238}U$ ages ranging from 485.8 ± 8 Ma to 428 ± 6.3 Ma with the Th/U ratio varying from 0.42 to 0.92. Eleven analyses of the rim domains record $^{206}Pb/^{238}U$ concordant ages ranging from 327 ± 4.8 Ma to 314 ± 4.7 Ma, with a mean Concordia age of 319.9 ± 2.7

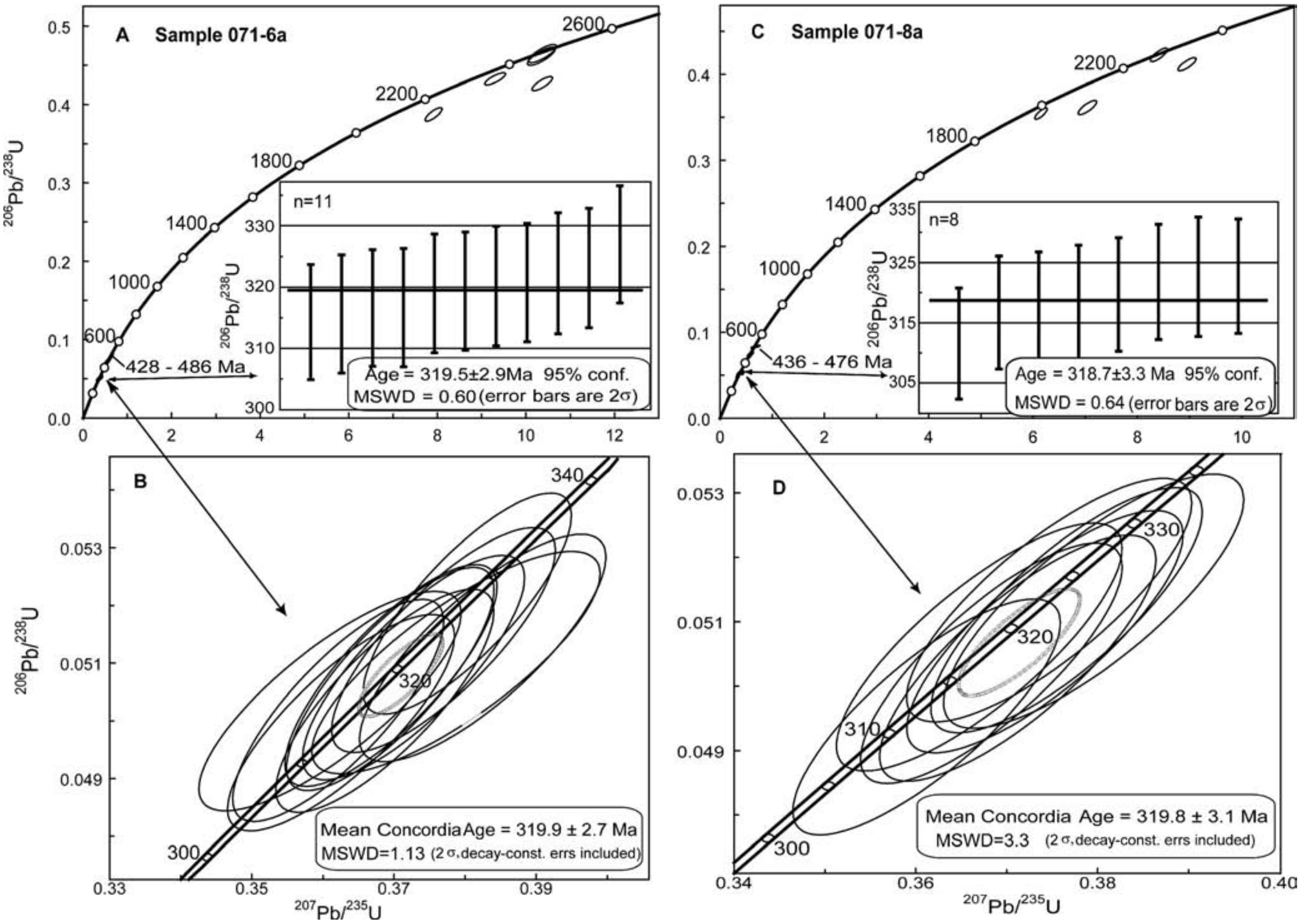

Fig. 2. U–Pb Concordia diagram and weighted average diagram for eclogite samples 071-6a (a and b) and 071-8a (c and d).

Ma as 2 sigma percent and MSWD (of concordance) = 1.13, and a weighted mean $^{206}Pb/^{238}U$ age of 319.5 ± 2.9 Ma (MSWD = 0.6) (Fig. 2a, b). The Th/U ratio of the measured spots varies from 0.002 to 0.004.

Twenty-two analyses were performed on zircon grains from sample 071-8a. Concordant data points yield ages ranging from 2272.4 ± 28.9 Ma to 311.6 ± 4.6 Ma (Fig. 2c). The inherited core gives an apparent $^{206}Pb/^{238}U$ age of 2272–1956 Ma. Eight analytical points of the oscillatory inner zone yield apparent $^{206}Pb/^{238}U$ ages ranging from 475.8 ± 7.0 Ma to 436.4 ± 6.5 Ma, whereby their Th/U ratio varies from 0.37 to 2.14. Eight spots analyzed on the rim domains of zircons record $^{206}Pb/^{238}U$ concordant ages ranging from 323.7 ± 5.0 Ma to 311.6 ± 4.6 Ma with a mean Concordia age of 319.8 ± 3.1 Ma as 2 sigma percent and MSWD (of concordance) = 3.3, giving a weighted mean $^{206}Pb/^{238}U$ age of 318.7 ± 3.3 Ma with MSWD = 0.64 (Fig. 2c, d). Their Th/U ratio varies from 0.002 to 0.016 (Table 1).

4. Discussion and conclusion

Zircon grain rims from sample 071-6a give a weighted mean $^{206}Pb/^{238}U$ age of 319.5 ± 2.9 Ma and that of sample 071-8a an age of 318.7 ± 3.3 Ma. These rims contain omphacite, phengite and rutile inclusions, which also constitute the peak metamorphic minerals of the host eclogite. Hence the rims of the zircon grains are interpreted to have formed during or close to peak eclogite-facies metamorphism at *ca.* 320 Ma. Additionally, the Th/U ratio of the measured spots is less than 0.016, similar to that reported for zircon grains that formed during eclogite-facies metamorphism (*e.g.*, Rubatto & Hermann, 2003).

A *ca.* 320 Ma age is in agreement with $^{40}Ar/^{39}Ar$ plateau ages of 327–324 Ma for phengite and glaucophane of eclogites in Kyrgyz southern Tianshan (Simonov *et al.*, 2008), while it is somewhat older than the $^{40}Ar/^{39}Ar$ ages of 316 Ma and 311 Ma reported for phengite of blueschists and the Rb–Sr isochron ages of 313–302 Ma in the Chinese Tianshan (Klemd *et al.*, 2005; Wang *et al.*, 2010). This age overlaps within error with the Sm–Nd age of 343 ± 44 Ma for eclogites, however, it is younger than the $^{40}Ar/^{39}Ar$ age of 344 Ma for crossite and the $^{40}Ar/^{39}Ar$ age of 331 Ma for phengite (Gao & Klemd, 2003). The occurrence of excess argon reported for phengite and sodic-amphibole from other high-/ultrahigh-pressure metamorphic rocks (*e.g.*, Li *et al.*, 1994) could be a reason for an ‘‘older’’ (344–331 Ma) $^{40}Ar/^{39}Ar$ plateau age for crossite and phengite. However, the *ca.* 320 Ma age is much older than the zircon rim SHRIMP U-Pb age of 233–226 Ma reported for eclogites from the same area (Zhang *et al.*, 2007). A possible explanation for this age discrepancy implies that the eclogite-facies rocks with an age of *ca.* 320 Ma and those with an age of 233–226 Ma are the result of the tectonic introduction of eclogite-facies bodies and sheets into the southern Tianshan orogen. This would mean that there is a tectonic relationship in a mélange-type environment (*e.g.*, Gao *et al.*, 1999; van der Straaten *et al.*, 2008) between eclogite-facies rocks that were originally metamorphosed at different times. However, the eclogite with the zircon rim age of 233–226 Ma (Zhang *et al.*, 2007) and the eclogite with zircon rim U–Pb ages of *ca.* 320 Ma (this study) stem from the same tectonic unit (Fig. S1B; Zhang *et al.*, 2007; Lü *et al.*, 2008). Furthermore this is in contrast with the fact that no granitoids and volcanics, which probably would have accompanied a second Triassic subduction event, with an age younger than 240 Ma have been reported up to now in the South Tianshan Orogen (*e.g.*, Gao *et al.*, 2009). The younger U–Pb zircon age of 233–226 Ma has been further interpreted to be due to the fluid-mediated alteration or recrystallization of existing zircon grains (Jong *et al.*, 2009), which is supported by the absence of eclogite-facies minerals such as omphacite and phengite in the rim domain of these zircon grains *(cf.*, Zhang *et al.*, 2007). An alteration-based origin of the Triassic zircon rims is further supported by their trace element REE patterns which are all strongly depleted against chondrite (Figure 5a, b in Zhang *et al.*, 2007). Such patterns were also reported for hydrothermal zircon from Guatemala jadeitite (Yui *et al.*, 2010). Furthermore, the Th/U ratio of zircon is often considered as useful parameter to distinguish magmatic from metamorphic zircon (*e.g.*, Rubatto & Hermann, 2003). Yet several studies have shown that Th/U in zircon is often influenced by the protolith characteristics and/or local chemical environment of formation (*e.g.*, Schulz *et al.*, 2006). This would fit well with the alteration history of the zircon grains and thus may explain the large variation in Th/U from 0.01 to 1.12 in the Triassic zircon rims (Table 1, samples 1067 and 106 in Zhang *et al.*, 2007). Altered and/or recrystallized zircon grains have been shown to display very low Th/U (*cf.*, Geisler *et al.*, 2007). Consequently no evidence exists that unambiguously proves that the zircon rims with an age of 233–226 Ma were formed during eclogite-facies metamorphism. Hence the possibility that different tectonic slices of eclogite-facies rocks with different ages (from about 345 to 225 Ma) related to different subduction events occur in a tectonic mélange is less likely. In summary, the new zircon U–Pb age results indicate that the eclogite-facies metamorphism of the Tianshan eclogites occurred in the Late Carboniferous (*ca.*, 320 Ma).

Furthermore, the closure of the ''South Tianshan Ocean'', which separated the Tarim block to the south and the Yili (−Central Tianshan) block to the north (Gao & Klemd, 2003; Zhang *et al.*, 2007), must have been almost terminated at the beginning of the Late Carboniferous (Fig. S2). The arc-volcanic rocks originally derived from the southern margin of the Yili block may have been involved in the subduction process and subsequently transformed to eclogite with the zircon- inherited core (concordant) ages of 2450–1956 Ma and of 485–428 Ma obtained in this study. Furthermore, the eclogites may have been exhumed to upper greenschist-facies levels during the collision of the Tarim and Yili blocks at *ca.* 300 Ma (Fig. S2). Combined with widespread post-collisional granites in the South Tianshan, the collision of the Tarim and Yili blocks must have occurred during the Late Carboniferous (from 320 Ma to *ca.*, 300 Ma). However, subsequent to amalgamation intra-continental polyphase strike-slip shearing took place along the major sutures during Permian to Triassic (Charvet *et al.*, 2007; Wang *et al.*, 2007).

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