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Revision 1

Inherited Eocene magmatic tourmaline captured by the Miocene Himalayan leucogranites

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Abstract

The Miocene Cuonadong leucogranites, in the easternmost section of the Tethyan Himalaya, Southern Tibet are characterized by two types of tourmaline. Tourmaline occurs as needle-like crystals in the two-mica ± tourmaline granites (Tur G) and large patches in the pegmatites (Tur P). Both the granite and the pegmatites yield Miocene ages (ca. 20 Ma) based on monazite U(-Th)-Pb dating, whereas $^{40}Ar/^{39}Ar$ geochronology of the coarse-grained tourmalines (Tur P) crosscut by pegmatite veins yielded an Eocene mini-plateau age of 43 ± 6 Ma. Major element concentrations of tourmaline indicate that both Tur P and Tur G belong to the schorl group with a magmatic origin, but trace elements such as V indicate that they are not cogenetic. Boron isotopes suggest that Tur P (average -9.76‰) was derived from typical crustal sources whereas Tur G (average -7.65‰) contains relatively more mafic input. The capture of Eocene tourmaline by the Miocene leucogranites at Cuonadong suggests that the crustally-derived Eocene magmatism may have occurred in the southern Tethyan Himalaya. Identification of the inherited magmatic tourmaline (Tur P), although not common, challenges the current application of tourmaline chemistry to the investigation of magmatic-hydrothermal systems.

Keywords: Inherited tourmaline, Himalayan leucogranite, $^{40}Ar/^{39}Ar$ and U(-Th)-Pb geochronology, B isotope

Introduction

The Himalayan continent-continent collisional belt resulted from the convergence and collision of India and Asia along the Indus-Tsangpo Suture zone that began in the Cenozoic (Yin and Harrison, 2000). Crustal anatexis related to this large-scale continental collision resulted in the formation of a series of leucogranites (Yin et al., 2006), which generally consist of cogenetic two-mica-, tourmaline- and garnet-bearing rocks, with widespread dikes and stocks of pegmatite (Wu et al., 2020). Two sub-parallel E-trending leucogranite belts, the Higher Himalayan and Tethyan

Himalayan (Supplementary Figs. 1a, b), have been recognized, with the former exposed along the South Tibetan Detachment System (STDS) in the Higher Himalayan Sequence (HHS) and the latter mainly occurring in the core of the North Himalayan Gneiss Domes (NHGDS) (Supplementary Fig. 1b; Wu et al., 2020). The majority of the leucogranites have yielded Miocene ages (26–7 Ma), with a small number of samples with Eocene ages (46–30 Ma) being found in the eastern most region of the Tethyan Himalayan (Wu et al., 2020). The Miocene and Eocene leucogranites were proposed to have formed from distinct episodes of crustal anatexis with clearly separated distribution in Southern Tibet (Supplementary Fig. 1; Patiño Douce and Harris, 1998; Hou et al., 2012). Tourmaline, which is very common in the Himalayan leucogranites and typically the dominant reservoir of B in the rocks, is stable in various P-T-X conditions and could record the physical and chemical conditions under which it formed (Marschall and Jiang, 2011; Slack and Trumbull, 2011). Due to its robustness, tourmaline chemistry has recently been used to investigate the genesis of Himalayan leucogranites (Yang et al., 2015; Hu et al., 2018). However, these studies relied on the assumption that the tourmalines formed cogenetically with their magmatic host rocks as is widely interpreted in most of the global tourmaline occurrences (van Hinsberg et al., 2011). Following the approach illustrated by Thern et al. (2020), we applied the $^{40}Ar/^{39}Ar$ dating method to coarse-grained tourmalines from the Miocene Cuonadong leucogranite, which yielded Eocene ages. The identification of inherited tourmalines not only contributes new insights into the Himalayan collisional orogeny, but also provides constraints on application of tourmaline chemistry to petrological studies.

Cuonadong tourmaline petrography

The Cuonadong leucogranite is located in the easternmost section of the Tethyan Himalaya (Supplementary Fig. 1a) and consists mainly of two-mica ± tourmaline granite and granitic pegmatite. The pegmatites commonly occur as veins or pockets in the leucogranites, without clear boundaries between them (Supplementary Fig. 2). The wall rocks consist mainly of sandstone, mudstone, slate and schist intercalated with carbonates (Li et al., 2017; Zhou et al., 2019). Two types of tourmalines have been identified in the Cuonadong leucogranites, large tourmaline crystals in the pegmatites (Tur P; Figs. 1a-d) and needle-like tourmaline crystals in the two-mica ± tourmaline granite (Tur G; Fig. 1e). The Tur P are pervasively distributed in the pegmatites, and are cut by abundant quartz/pegmatite/quartz-muscovite veins along fractures (Figs. 1a-d; Supplementary Fig. 3a). Abundant micro-fractures and some zircon inclusions were observed in the Tur P in backscattered electron (BSE) images (Supplementary Fig. 3b). The Tur G occur as disseminated needle-like crystals, coexisting with muscovite, quartz and feldspar in the granites and show clear core-rim zoning in thin section but not in BSE images (Fig. 1e, Supplementary Figs. 2c-d). Both Tur P and Tur G are commonly homogeneous in BSE images.

Methods

Tourmaline $^{40}Ar/^{39}Ar$ analyses were performed on one pegmatite sample using an ARGUS VI at the Western Australian Argon Isotope Facility, Curtin University. Monazite LA ICP-MS U(-Th)-Pb geochronology of both granite and pegmatite were

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performed utilizing a system consisting of ASI RESOlution S-155 193nm ArF Excimer laser coupled to Thermo Scientific iCAP Qc quadrupole ICP-MS at the State Key Laboratory for Mineral Deposits Research, Nanjing University, China. The detailed analytical procedures and conditions of all the above and other methods are listed in Supplementary Appendix A.

Results

The Tur P in the pegmatites yielded a $^{40}Ar/^{39}Ar$ mini-plateau age of 43 ± 6 Ma (MSWD = 0.8; P = 0.57; Supplementary Table 1; Fig. 2a), which includes 66.3% of the total amount of ^{39}Ar that was released. Commonly for low potassium minerals containing excess argon, a saddle-shaped ^{39}Ar release spectrum during stepped heating will be displayed (Kelley, 2002), which is not shown in our Tur P data indicating the absence of excess ^{40}Ar in the lattice during crystallization (Qiu et al., 2007), suggesting that the calculated Ar plateau age represents the true age of tourmaline, rather than the result of excess argon. The high apparent step ages (older than 70 Ma) displayed within the first few percent of gas released are likely attributed to excess ^{40}Ar in fluid inclusions or the margins of the crystals. We calculated a mini-inverse isochron age of 58 ± 15 Ma (MSWD = 0.8; P = 0.63), associated with a trap $^{40}Ar/^{36}Ar$ ratio of 251 ± 52. This ratio, although imprecise, does overlap with atmospheric compositions (~ 298.6; Lee et al., 2006) which would indicate the mini-plateau age (which assumes a $^{40}Ar/^{36}Ar$ ratio of 298.6) is correct. Note that a sub-atmospheric ratio and the absence of saddle-shaped ^{39}Ar release spectrum suggest that no excess ^{40}Ar is present in this part of the age spectrum. In addition, some monazite grains in the granite yielded similar ages to the mini-plateau age (Fig. 2b). In general, the mini-plateau and mini-inverse isochron ages of 43 ± 6 Ma and 58 ± 15 Ma (Fig. 2a), respectively, overlap with each other and are both clearly older than the U-Th-Pb age of ca. 20 Ma for the monazite (Figs. 2b and 2c).

Monazite often has excess ^{206}Pb, resulting in high $^{206}Pb/^{238}U$ age and reverse discordance on U-Pb diagrams (Schärer, 1984). Thus, the $^{207}Pb/^{235}U$ may provide the best estimate of the age. However, the Himalaya leucogranites are too young to yield reliable $^{207}Pb/^{235}U$ (Wu et al., 2015). As a result, the Th-Pb ages are often used for monazite geochronology of the Himalaya leucogranites (Harrison et al., 1995). Monazite grains from the two-mica ± tourmaline granite sample yielded a $^{208}Pb/^{232}Th$ age of 20.3 ± 0.2 Ma, with two grains having older ages of 45.2 ± 1.6 Ma and 43.9 ± 1.4 Ma (Supplementary Table 2; Fig. 2b). The older ages are consistent with the plateau $^{40}Ar/^{39}Ar$ age of the Tur P and represent inherited monazite crystals. The pegmatite sample yielded a monazite $^{208}Pb/^{232}Th$ age of 20.5 ± 0.1 Ma (Supplementary Table 2; Fig. 2c), nearly identical to the two-mica granite ages and distinct from the plateau $^{40}Ar/^{39}Ar$ age of Tur P.

Major and trace element compositions of the tourmaline are provided in Supplementary Table 3. Both Tur P and Tur G are dominantly schorl end-member tourmalines, with Fe/(Fe+Mg) ratios of 0.67–0.85 for Tur P, 0.75–0.87 for the Tur G cores and 0.74–0.87 the Tur G rims. Tourmaline grains have wide ranges of Ti (0.04–0.15 apfu for the Tur P, 0.01–0.09 apfu for the Tur G core, 0.02–0.11 apfu for the Tur G rim) and Al concentrations (6.23–6.55 apfu for the Tur P, 6.04–6.50 apfu for the Tur G core and 6.00–6.70 apfu for the Tur G rim). On the Al-Fe-Mg diagram, both the Tur P and the Tur G plot in the field of Li-poor granitoids and associated pegmatites and aplites, suggesting a magmatic origin (Supplementary Fig. 4). The trace element compositions in tourmaline are commonly low, from tens of ppm for the LILE (Large Ion Lithophile Elements) to ppb for the HFSE (High Field Strength Elements). The concentrations of Cr, Co, Ni, Sr, V and Sc in Tur P are commonly higher than those of the Tur G. The Tur P have a wider range and lower average δ^{11}B values than the Tur G, with the former ranging from -14.14‰ to -7.06‰ (average -9.76‰) and the latter from -8.82‰ to -6.79‰ (average -7.69‰, Tur G core) and -10.25‰ to -5.83‰ (average -7.61‰, Tur G rim; Fig. 2d), respectively. The δ^{11}B values for Tur P and Tur G are well within the range reported for other granites in the world (Supplementary Table 4; ca. -15% and ca. -5%, Marschall and Jiang, 2011).

Discussion and implications

Tourmaline is common in highly evolved granites and pegmatites and has been widely studied to investigate their petrogenesis (e.g., Yang et al., 2015) and to decipher the process of fluid flow during the magmatic-hydrothermal transition (Launay et al., 2018). All of these studies depend on the assumption that the formation of the tourmaline was coeval with, and has a genetic connection to, the host rocks. Our work at Cuonadong shows that some tourmalines in the granite/pegmatite may be inherited and thus unrelated to the host granite. Two lines of evidence support the inherited origin of Tur P: 1) Monazite grains in the pegmatites and two-mica ±

tourmaline granites yielded ages of ca. 20 Ma (Fig. 2b), whereas the Tur P $^{40}Ar/^{39}Ar$ dating yielded an Eocene age of ca. 40 Ma, coincided with the presence of two Eocene monazite grains in the granite (Figs. 2a, b), and significantly older than the crystallization age of the host pegmatites; 2) The common occurrence of fractures in these tourmalines and the presence of the pegmatite mineral assemblages in the fractures suggests that they predate the pegmatites (Figs. 1a-d).

Several lines of evidence suggest that the two-mica granite and pegmatite evolved in a cogenetic system, with the pegmatite magmas representing the late evolved phase: 1) They yield comparable ages; 2) Both the granite and pegmatite have similar mineral assemblages consisting of plagioclase, k-feldspar, muscovite ± tourmaline; 3) The occurrences of the pegmatites as veins or pockets in the granites, without clear boundaries between them (Supplementary Fig. 2); 4) Xie et al. (2020) studied zircon grains in the granite and pegmatite at Cuonadong and proposed magmatic evolution from the granites to pegmatites based on the Zr/Hf ratios of zircon.

However, Tur P should be xenocrysts in the host granitoids. In a cogenetic system, tourmaline crystallized in early-stage granite should have higher V contents compared to those formed in a late pegmatite because V is preferentially fractionated into early-crystallized ilmenite, biotite and tourmaline during magma crystallization (van Hinsberg, 2011). Therefore, if Tur P is a primary phase in the host pegmatite, it should have lower V contents than Tur G which represents the early crystallization stage (two-mica granite). However, the obviously higher V concentrations in Tur P

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suggest that it was not a product of the same Miocene magmatism as the host pegmatite (Supplementary Table 3).

What was the source of the Eocene Tur P and how was it incorporated in the Miocene leucogranite? Based on $^{40}Ar/^{39}Ar$ geochronology, the Tur P formed at ca. 40 Ma. These ages are coeval with the emplacement ages of the Yardoi granitoids (Zeng et al., 2011; Hou et al., 2012), which is ca. 100 km north of Cuonadong and one of the few occurrences of Eocene intrusions in the northern Tethyan Himalaya (Supplementary Fig. 1). The Yardoi granitoids were interpreted to have formed from the partial melting of the lower crust of the India plate during Eocene crustal thickening and the subsequent Neo-Tethyan slab break-off in the early stage of the India-Asian collision (Fig. 3a; Zeng et al., 2011; Hou et al., 2012). Tourmalines are not common in the Yardoi granitoids but recent boron isotope analyses showed that the $\delta^{11}B$ values of the Yardoi granitoids range from -8.9‰ to -6.6‰ (Fig. 2c; Hu et al., 2018), partially overlapping with those of Tur P having ranges of -14.14‰ to -7.06‰ (average -9.76‰). However, $\delta^{11}B$ values for Tur P are relatively lighter, approximating the average boron isotopes of continental crust (-10 ± 3‰, Marschall and Jiang, 2011), whereas the Yardoi and the Miocene tourmalines at Cuonadong (Tur G) have higher $\delta^{11}B$ values. The differences may suggest more involvement of lower crust (mafic magma) during crustal anatexis for the latter (Fig. 2d), supported by regional tectonic evolution models for the Eocene Yardoi granitoids and Miocene Cuonadong leucogranite (Hou et al., 2012; Wu et al., 2020). We propose that partial melting of upper crustal materials may have occurred in the Cuonadong area during

Eocene crustal thickening, when shear heating elevated the surface heat flow (Hartz and Podladchikov, 2008), causing the temperature to reach the solidus, generating the felsic magmatism and forming Tur P (Figs. 3a). During later geologic events, the Tur P was preserved due to their robustness (Marschall and Jiang, 2011; Slack and Trumbull, 2011). The widespread Miocene leucogranite magmatism (including the early-stage two-mica granite and late evolved pegmatite phase), formed either by decompressional melting of the crust (Wu et al., 2020) or extensive long-living shear heating (Whittington et al., 2009; Hou et al., 2012) linked to Indian plate rollback and breakoff (DeCelles et al., 2011). The magma ascended to the upper crust (Fig. 3a) where the late pegmatite phase in the upper part of the two-mica granite incorporated the early-stage Eocene granitoids and Tur P at shallow levels in the crust (Figs. 3b, c). Although no Eocene tourmaline has been found in the two-mica granite, the presence of Eocene-age monazite xenocrysts (Fig. 2b) are consistent with assimilation of Eocene granites by the Miocene granite at Cuonadong.

Our studies document the spatial coexistence of Miocene and Eocene magmatism in the Tethyan Himalaya and suggest petrogenesis through upper crust anatexis during shear heating for the Eocene magmas in Southern Tibet. The presence of inherited tourmaline means that the K/Ar clock in the tourmaline was not reset by thermal diffusion during the emplacement of the granitic pegmatite, perhaps due to the high closure temperature and low diffusion rates for major and trace elements within the tourmaline lattice (Dutrow and Henry, 2011). Thus, caution must be used when applying tourmaline geochemistry to the investigation of the petrogenesis of the host magmatic rocks.

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Figure captions

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Fig. 1 (a) Hand specimen of the Cuonadong pegmatites, showing abundant fractures in the tourmaline grains. A part of a thin section was scanned as insert, showing the common occurrences of fractures in Tur P; (b) Another sample of the Cuonadong pegmatites showing fractured tourmaline; (c) Photomicrograph showing Tur P crosscut by a quartz vein in pegmatite; (d) Photomicrograph showing Tur P crosscut by a quartz-muscovite vein in pegmatite; (e) The crystal habit of tourmaline (Tur G) in the two-mica ± tourmaline granite.

Fig. 2 (a) Plateau $^{40}Ar/^{39}Ar$ dating results, and $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ normal and inverse isochron plots of the Tur P; (b) and (c) Monazite geochronological results of the Cuonadong leucogranites; (d) Boron isotope compositions of the Tur P and Tur G and comparison with various boron reservoirs in nature (after Marschall and Jiang, 2011; Hu et al., 2018).

Fig. 3 (a) Schematic regional section showing the Eocene Yardoi granitoids and granitoids at Cuonadong (100 km south to Yardoi) during crustal thickening. The large-scale Miocene Himalayan leucogranites due to intense activity of the STD and HHS extrusion emplaced at Cuonadong area. STD: South Tibetan Detachment; MCT = Main Central Thrust; MBT: Main Boundary Thrust; HHS = High Himalayan Sequence; THS = Tethyan Himalayan Sequence; IYS = Indus-Yarlung suture; GTS = Gangdese thrust system; (b) A simplified cartoon for emplacement of the Miocene Cuonadong leucogranites, represented by the two-mica granite and the late cogenetic pegmatite phase, and xenoliths of the Eocene granitic units containing Tur P; (c) Schematic diagram showing the capture of the Eocene Tur P by the Miocene pegmatites at Cuonadong. Pl = plagioclase; Qz = quartz; Kfs = K-feldspar; Mnz = monazite; Ms = muscovite.

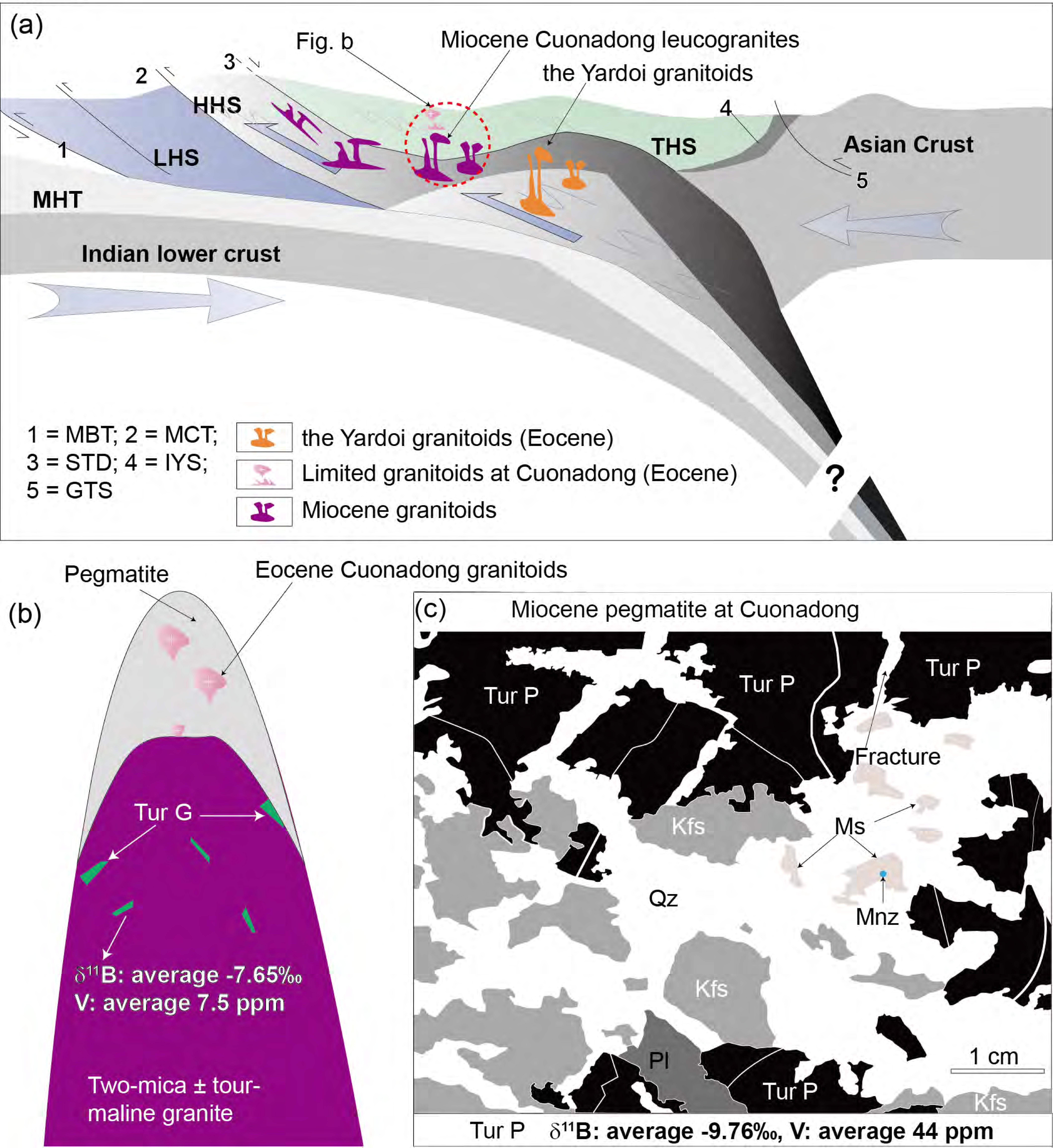
Figure 1

(a)
1 cm
Fractures
Tur P
Pegmatite
Kfs
Qz
Pl
Fractures
Tur P
(b)
Tur P
Fractures
(c)
Qz
Qz
Tur P
Tur P
Fracture
400 µm
(d)
Qz
Tur P
Ms
Tur P
Tur P
Qz
Fracture
300 µm
(e)
Tur G
Two mica ± tourmaline granite
2 cm

Figure 2

Inverse Isochron 58 ± 15 Ma
MSWD = 0.8, P = 0.57
40Ar/36Ar: 251 ± 52
36Ar/40Ar
39Ar/40Ar
Plateau age = 43 ± 6 Ma
MSWD = 0.8, P = 0.57
(a)
Age (Ma)
Cumulative 39Ar Released (%)
(b) Two mica ± tourmaline granite
45.2 ± 1.6 Ma
43.9 ± 1.4 Ma
Weighted mean age = 20.3 ± 0.2 Ma
MSWD = 4, n = 16
208Pb/232Th age
(c) Pegmatite
Weighted mean age = 20.5 ± 0.1 Ma
MSWD = 1.5, n = 25
208Pb/232Th age
(d)
Tur P
Tur G
Rim
Core
Frequency count
δ11B(‰)
Yardoi leucogranite
Non-marine evaporites
-30‰
10‰
Continentinental crust
-1‰
MORB+mantle
Degassing, melt-fluid fractionation

Figure 3



(a)
Fig. b
Miocene Cuonadong leucogranites
the Yardoi granitoids
1
2
3
4
5
HHS
LHS
THS
MHT
Asian Crust
Indian lower crust
?
1 = MBT; 2 = MCT;
3 = STD; 4 = IYS;
5 = GTS
the Yardoi granitoids (Eocene)
Limited granitoids at Cuonadong (Eocene)
Miocene granitoids
(b)
Pegmatite
Eocene Cuonadong granitoids
Tur G
δ11B: average -7.65‰
V: average 7.5 ppm
Two-mica ± tourmaline granite
(c)
Miocene pegmatite at Cuonadong
Tur P
Fracture
Kfs
Ms
Qz
Mnz
Pl
1 cm
Tur P δ11B: average -9.76‰, V: average 44 ppm