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RAPID COMMUNICATION

Zircon SIMS U–Pb geochronology of the Lushan terrane: dating metamorphism of the southwestern terminal of the Palaeoproterozoic Trans-North China Orogen

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Abstract

High-resolution SIMS U–Pb dating of metamorphic zircons of the TTG gneisses, gneissic granitoid and amphibolites of the Lushan terrane, Taihua metamorphic complex, suggests that the metamorphism had taken place at least as early as ∼1.96–1.86 Ga. These new dates, along with reference data, demonstrate that the southern and middle terranes of the Trans-North China Orogen had been involved in the continent–continent collision between the Western Block and the Eastern Block of the North China Craton. This orogenic process started as early as 1.96 Ga and lasted as late as 1.80 Ga.

Keywords: SIMS U–Pb dating, zircon, Lushan terrane, Taihua metamorphic complex, the Trans-North China Orogen.

1. Introduction

The continent–continent collision process is the subsequent process after subduction, which is generally characterized by clockwise *P–T* paths, including an early prograde process and later isothermal decompression (ITD) process following peak metamorphism, recorded in metamorphic rocks, especially the Precambrian metamorphic terranes. Thus, clockwise *P–T* paths characterized by ITD segments are considered to be one of the important indicators in recognizing plate tectonics, especially in the Earth's early history (e.g. Zhao, 2007). After reviewing metamorphic *P–T* paths preserved in the different metamorphic terranes and combining lithological, structural, geochemical and geochronological data, Zhao *et al.* (1998, 2000*a*, 2001, 2005, 2012) recognized three orogenic belts in the North China Craton (NCC), i.e. the Trans-North China Orogen (TNCO), the Jiao-Liao-Ji Belt and the Khondalite Belt (Fig. 1a), quite similar to present-day subduction zones.

In the last two decades, metamorphic investigations of the metamorphic terranes (e.g. Huai'an, Hengshan, Wutai, Fuping, Lüliang and Zanhuang terranes) within the northern and middle sections of the TNCO have confirmed that these terranes all record clockwise *P–T* paths including retrograde ITD segments (Zhao, Cawood & Lu, 1999; Zhao *et al.* 2000*b*, 2001, 2010; Guo, O'Brien & Zhai, 2002; Xiao *et al.* 2011*a*,*b*). Geochronological studies suggest that the metamorphism of all these terranes occurred at ∼1.85 Ga (Zhao *et al.* 2002, 2008*a*,*b*; Guo *et al.* 2005; Liu *et al.* 2006; Xiao *et al.* 2013). In recent years, geologists have been aware of the importance of the metamorphic terranes in the southern section of the TNCO, especially the Taihua metamorphic complex (Wan *et al.* 2006; Diwu *et al.* 2007, 2010; Liu *et al.* 2009; Xu *et al.* 2009; Huang *et al.* 2010, 2012; Jiang *et al.* 2011; Shi *et al.* 2011; Wang *et al.* 2012, 2013; Huang, Wilde & Zhong, 2013; Yu *et al.* 2013; Lu *et al.* 2013). Our previous work (Lu *et al.* 2013) suggested that the Taihua metamorphic complex had been involved in the subduction and collision between the Western and Eastern blocks of the NCC and experienced later uplift processes during late Palaeoproterozoic time. However, our previous work focused solely on the gneissic amphibolites. In this contribution, we report detailed secondary ion mass spectroscopy (SIMS) dating of metamorphic zircons separated from the tonalite–trondhjemite–granodiorite (TTG) gneisses, gneissic granitoids and amphibolite boudins with weak or no gneissosity enclosed in the TTG gneisses, to further constrain the Palaeoproterozoic tectonometamorphic evolution of the Taihua metamorphic complex.

2. Regional setting

The Taihua metamorphic complex is located on the southwestern margin of the TNCO, which is comprised of five discrete terranes (Huashan, Xiaoshan, Luoning, Lushan and Wugang) scattered across the Shanxi and Henan provinces, north China (Fig. 1b). The Taihua metamorphic complex consists mainly of TTG gneisses, amphibolites, metapelitic gneisses, marbles and quartzites; experienced upper-amphibolite-facies metamorphism and intense deformation; and records clockwise *P–T* paths including ITD segments (Lu *et al.* 2013).

In Lushan County, Henan Province, the southwestern Taihua metamorphic complex is uncomformably covered by unmetamorphosed volcanic strata of the Xiong'er Group dated at ∼1.78 Ga (He *et al.* 2009), and the northeastern Taihua metamorphic complex is in fault contact with the Mesoproterozoic Ruyang Group and other Neoproterozoic

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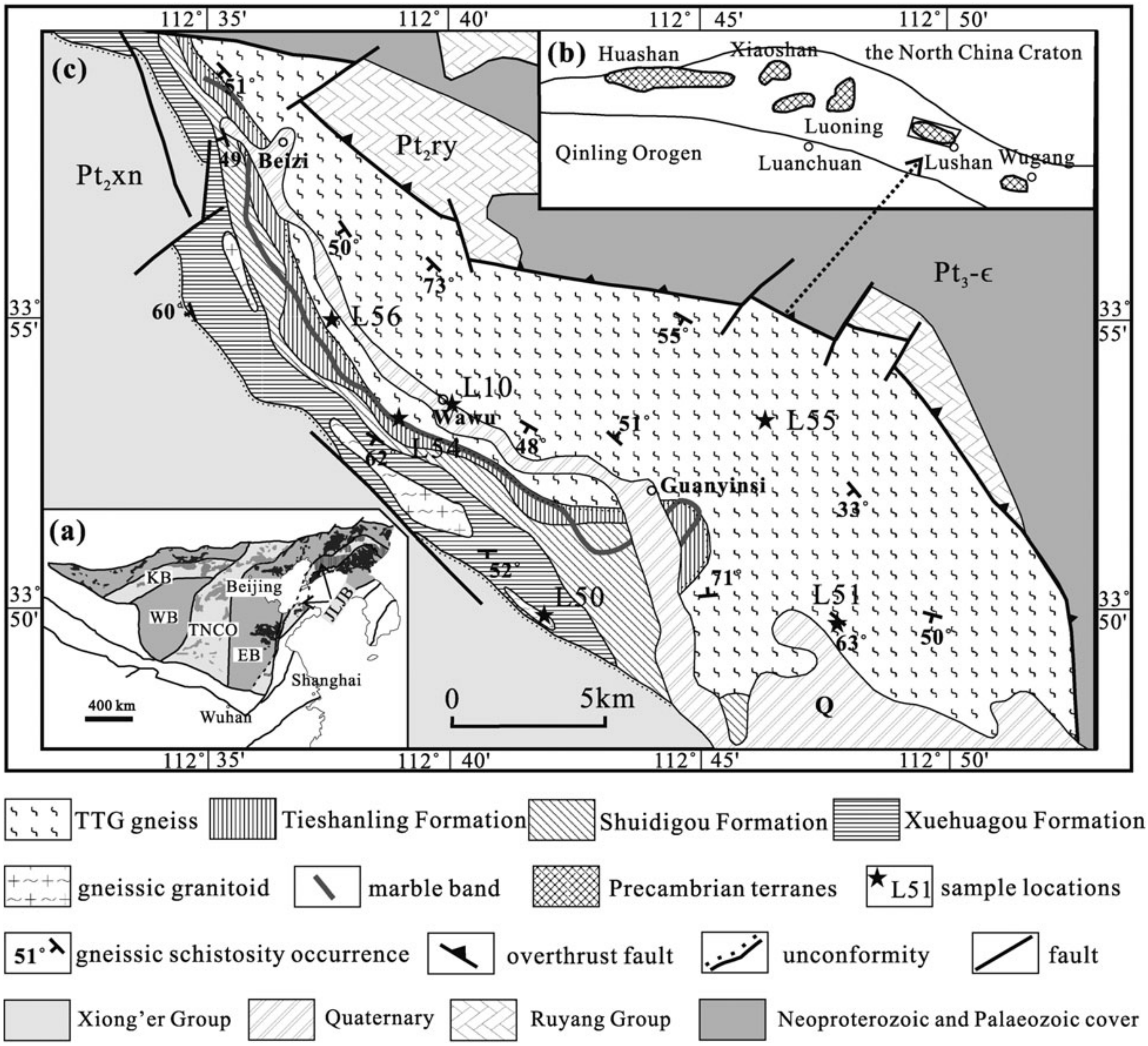

Figure 1. (a) Geological sketch map of the North China Craton (after Zhao *et al*. 2005); (b) the Lushan terrane in the Taihua metamorphic complex within the Trans-North China Orogen (modified after Xu *et al*. 2009); and (c) simplified geological map of the Lushan terrane (modified after Xu *et al*. 2009). Sample locations are shown. Pt_2ry – Ruyang Group; Pt_2xn – Xiong'er Group; Pt_3 – Late Proterozoic; ϵ – Cambrian; Q – Quaternary; KB – Khondalite Belt; WB – Western Block; TNCO – Trans-North China Orogen; EB – Eastern Block; JLJB – Jiao-Liao-Ji Belt.

and Palaeozoic covers. The Taihua metamorphic complex exposed in the Lushan terrane was subdivided into the Lower and Upper Taihua subgroups separated by the interstitial characteristic marble stratum exposed approximately along the Dangze River. On the northeastern side of the Dangze River is the Lower Taihua Subgroup, which is mainly composed of TTG gneisses and patchy amphibolites within the TTG gneisses. The TTG gneisses formed at 2.75–2.84 Ga (Kröner *et al*. 1988; Diwu *et al*. 2007; Liu *et al*. 2009) and the protolith of the amphibolites formed at ~2.73 Ga and underwent a peak metamorphic event at ~1.95 Ga (Lu *et al.* 2013). On the southeastern side of the Dangze River is the Upper Taihua Subgroup, which mainly consists of metapelitic gneisses, gneissic granites and marbles. SHRIMP U–Pb dating of zircons (Wan *et al.* 2006) determined that the Upper Taihua Subgroup was formed during Palaeoproterozoic time (between 2.26 and 2.14 Ga) and experienced metamorphism at ~1.85 Ga.

3. Sample selection and analytical methods

In this work, six representative metamorphic rock samples were selected for SIMS U–Pb dating of zircons (Fig. 1c).

Samples L10 and L56 are fine-grained garnet-bearing amphibolites showing weak or no gneissosity, occurring as short dykes within the TTG gneisses. Residual ophitic textures and intrusive relationships with the country TTG rocks are locally preserved. The amphibolites mainly consist of hornblende (35–40 %) + plagioclase (20–15 %) + quartz (20 %) + garnet (15 %) and clinopyroxene (5 %) (Fig. 2a, b).

Samples L51, L54 and L55 are grey coarse-grained TTG gneisses, and are mainly composed of plagioclase (35–53 %) + quartz (20–35 %) + hornblende (15–20 %) and biotite (2–15 %) (Fig. 2c–e). Garnets are locally observed in sample L55.

Sample L50 is a gneissic granitoid collected from Limeigou Village and is mainly composed of quartz

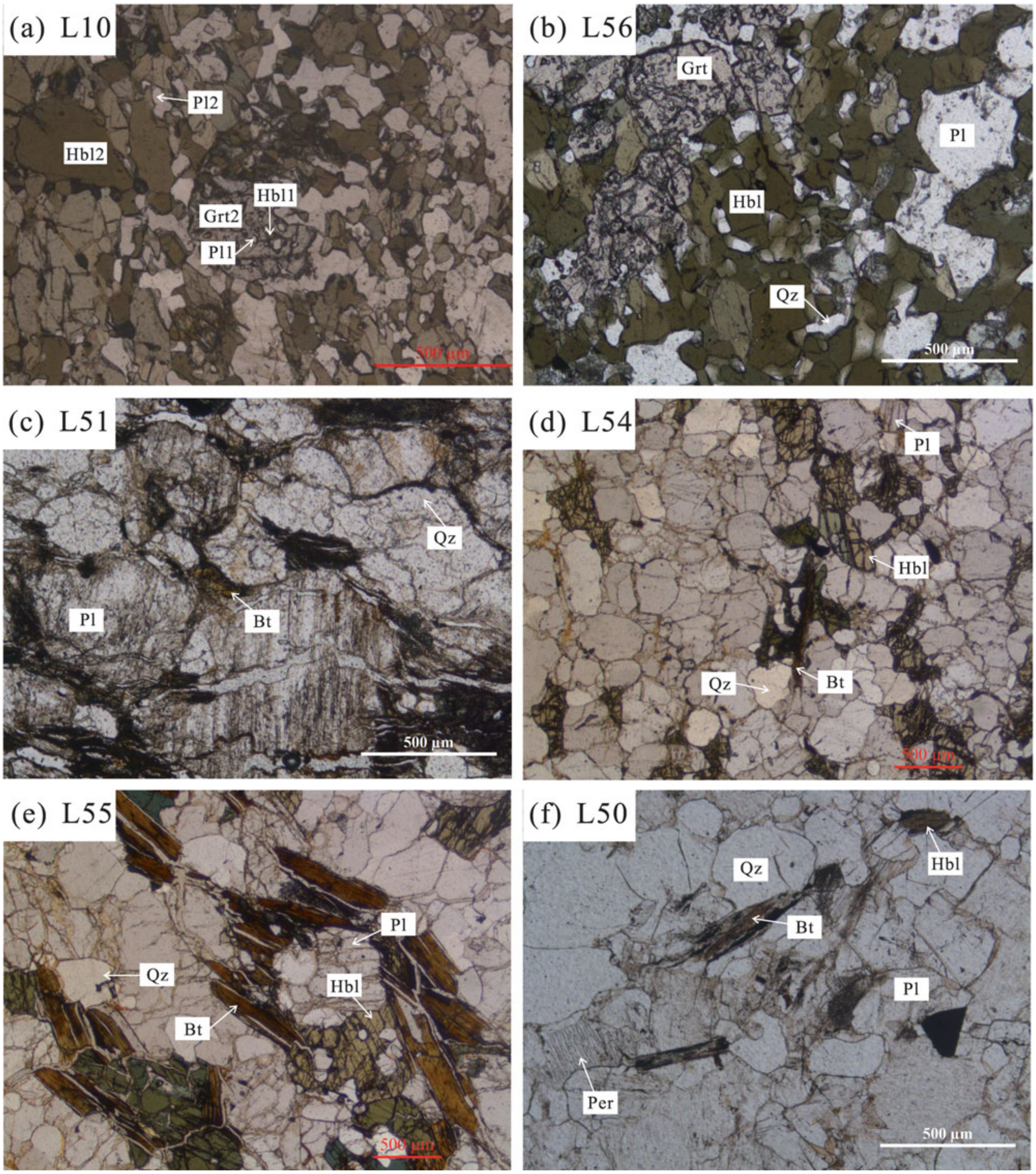

Figure 2. (Colour online) Photomicrographs of amphibolites (a, b), TTG gneisses (c, d, e) and gneissic granitoid (f). Symbols for minerals are after Whitney & Evans (2010).

(50 %) + perthite (35 %) + plagioclase (8 %) + K-feldspar (5 %) and biotite (2 %) (Fig. 2f).

Zircons for SIMS U–Pb geochronological studies were collected by conventional magnetic and density separation techniques. Zircon grains, together with the zircon standards Plešovice and Qinghu, were mounted in epoxy mounts which were then polished to section the crystals in half for analysis. Prior to the SIMS analysis, micrographs of all zircons were taken using transmitted and reflected light as well as cathodoluminescence (CL) to reveal their internal structures. Measurements of U, Th and Pb isotopes were conducted using a Cameca IMS 1280 large-radius SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing. The analytical beam was about 20 × 30 μm in size. Analytical procedures, conditions and data processing procedures are the same as those described by Li *et al.* (2009). Data reduction was carried out using the Isoplot/Ex v. 3.75 program (Ludwig, 2012). The SIMS zircon U–Pb dating results are listed in Table S1 in the online Supplementary Material available at http://journals.cambridge.org/geo. The uncertainties in Table S1 and on the cathodoluminescence (CL) diagrams for individual analyses are quoted at the

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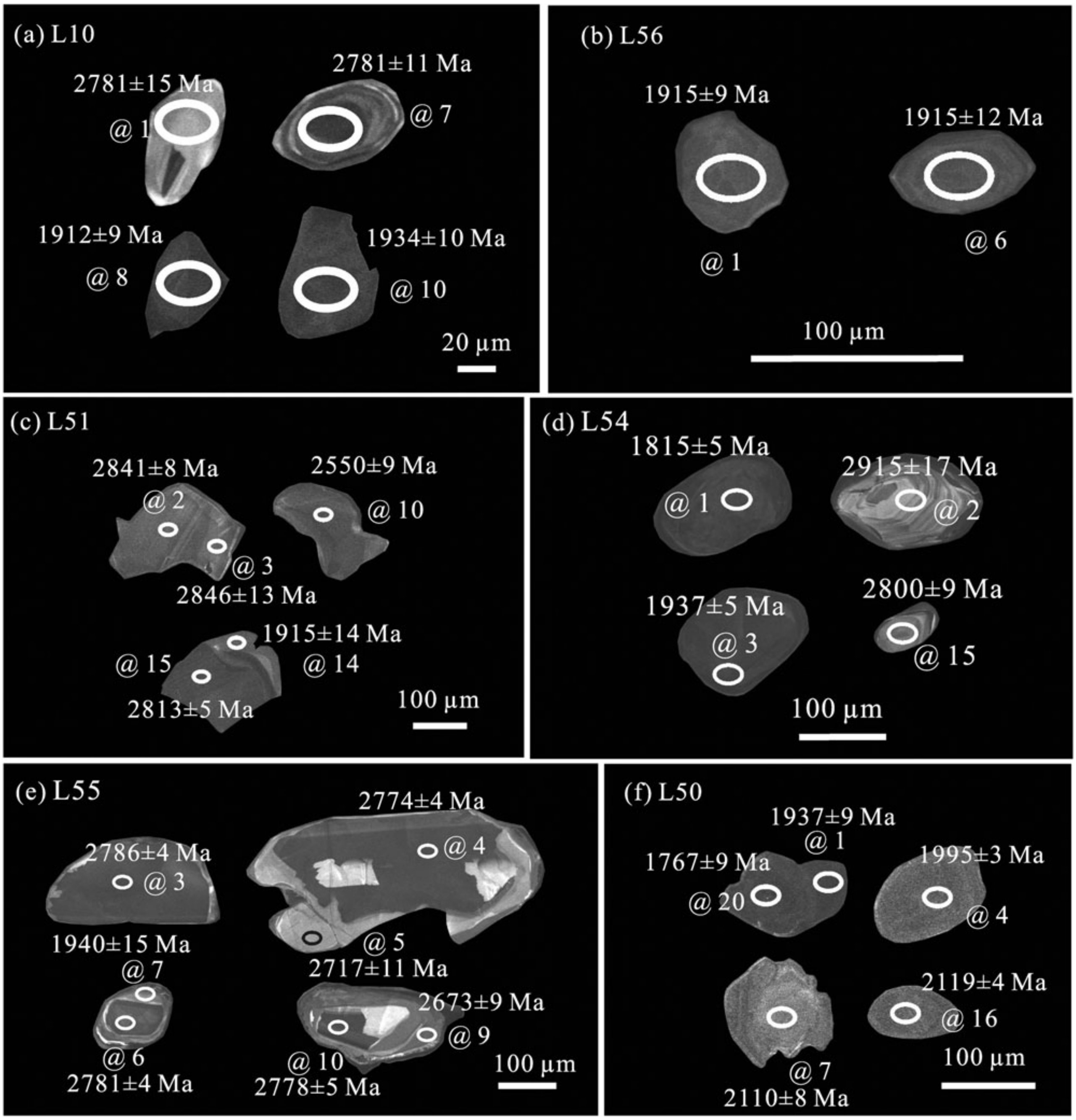

Figure 3. Representative cathodoluminescence (CL) images of zircons separated from amphibolites (a, b), TTG gneisses (c, d, e) and gneissic granitoid (f), Lushan terrane. The numbers refer to the analytical spots and the corresponding data are list in Table S1 in the online Supplementary Material available at http://journal.cambridge.org/geo.

1σ level, whereas the errors on weighted mean ages given in Figure 4 and in the text are quoted at the 95 % confidence level.

In order to monitor the external uncertainties of the SIMS U–Pb measurements calibrated against the Plešovice standard, the Qinghu zircon standard was additionally analysed as an unknown together with the unknown zircons that were mounted in mounts A2206, A2420 and A2421 during the course of this study. A total of 27 measurements were conducted on the Qinghu zircon (Table S1 in the online Supplementary Material available at http://journals.cambridge.org/geo), and the Concordia ages (Ludwig, 2012) of 159.5 ± 2.5 Ma, 160.8 ± 0.8 Ma and 159.0 ± 0.75 Ma were obtained for the Qinghu zircon in mounts A2206, A2420 and A2421, respectively. These three measured ages define a mean of 159.77 ± 0.91 Ma, which is identical to the recommended value of 159.5 ± 0.7 Ma (Li *et al.* 2009), within error.

4. Geochronological results and interpretations

4.a. Amphibolites

Zircons separated from the amphibolites (samples L10 and L56) bear close resemblance to one another and are anhedral and round in shape, varying from 40 to 90 µm in length. They are internally homogeneous with weak to medium luminescence in the CL images (Fig. 3a, b), except for a few grains in Sample L10 with weak zoning.

In Sample L10, three age groups have been recognized. The first group is represented by spots 1, 7 and 16. Spots

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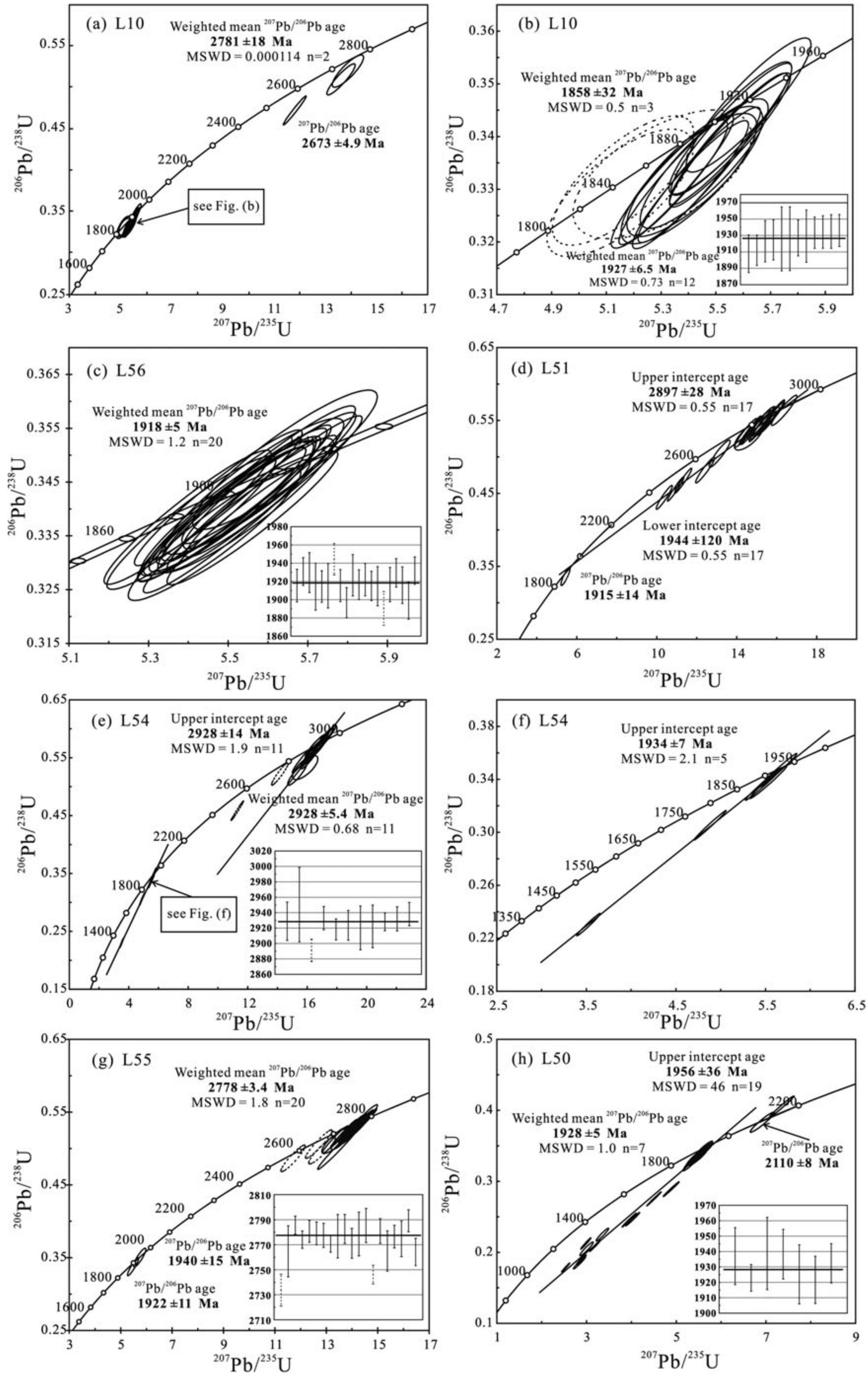

Figure 4. The U–Pb Concordia diagrams for SIMS U–Pb dating of zircons from the amphibolites (a–c), TTG gneisses (d–g), as well as from the gneissic granitoid (h).

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1 and 7 are distributed near the Concordia line (Fig. 4a) and give a weighted mean ^{207}Pb–^{206}Pb age of 2781 ± 18 Ma (MSWD = 0.000114), possibly indicating the protolith age or possible xenocrystic grains from host TTG rocks. The second group consists of 12 spots (spots 3–6, 8–11, 13, 14, 17 and 18), and their U, Th and Pb contents and Th/U ratios are in the range of 189–295 ppm, 36–99 ppm, 77–122 ppm and 0.19–0.40, respectively. They plot around the Concordia curve (Fig. 4a, b), defining a weighted mean ^{207}Pb–^{206}Pb age of 1927 ± 6.5 Ma (MSWD = 0.73) (Fig. 4b), which is interpreted as possibly the peak metamorphic age. The third group contains three spots (spots 2, 12 and 15), and their U, Th and Pb contents and Th/U ratios are in the range of 207–255 ppm, 56–100 ppm, 105–817 ppm and 0.27–0.39, respectively. They all plot near the Concordia curve, giving a weighted mean ^{207}Pb–^{206}Pb age of 1858 ± 32 Ma (MSWD = 0.5) (Fig. 4b), possibly defining a post-peak metamorphic event.

In Sample L56, 20 spots were analysed on 20 grains. Their U, Th and Pb contents and Th/U ratios are in the range of 210–314 ppm, 36–175 ppm, 86–130 ppm and 0.13–0.58, respectively. These spots are distributed on the Concordia line and define a weighted mean ^{207}Pb–^{206}Pb age of 1918 ± 5 Ma (MSWD = 1.2) (Fig. 4c), which is interpreted as possibly recording peak metamorphism.

4.b. TTG gneisses

Zircons extracted from the TTG gneisses (samples L51, L54 and L55) show diverse features. Zircons from samples L51 and L55 are transparent, anhedral and prismatic or stubby in shape varying from 90 to 570 μm in length. Zircons from Sample L54 vary from 80 to 160 μm in length and are obviously smaller than those from samples L51 and L55. They are classified into two different types: the first type are stubby or round in shape and are internally homogeneous with weak luminescence in CL images (Fig. 3d), indicating a possible metamorphic origin. The second type are stubby in shape and show obvious oscillatory zoning in CL images (Fig. 3d), indicating a possible magmatic origin.

Eighteen spot analyses were conducted on 16 zircon grains from Sample L51. The analytical location of spot 14 is on the rim of the zircon (Fig. 3c), plots near the Concordia curve and gives a ^{207}Pb–^{206}Pb age of 1915 ± 14 Ma (Fig. 4d), which is interpreted as possibly representing the metamorphic peak. The other spots show variable Pb loss and yield an upper intercept age of 2897 ± 28 Ma (MSWD = 0.55) (Fig. 4d), which is interpreted to be the possible protolith age of the TTG gneiss. It is noteworthy that, although the lower intercept age 1944 ± 120 Ma (MSWD = 0.55) (Fig. 4d) has a larger error, it is also consistent with the metamorphic age of spot 14.

In Sample L54, 19 spot analyses were performed on 19 zircon grains. The first group of zircons contains five spots (spot 1, 3, 9, 13 and 16), and their U, Th and Pb contents and Th/U ratios are in the range of 530–1905 ppm, 10–150 ppm, 201–492 ppm and 0.02–0.12, respectively (Table S1 in the online Supplementary Material available at http://journals.cambridge.org/geo), defining an upper intercept age of 1934 ± 7 Ma (MSWD = 2.1) (Fig. 4e, f), which is ascribed to the possible peak metamorphic age. In the second type of zircons, their U, Th and Pb contents and Th/U ratios are in the range of 34–1163 ppm, 20–239 ppm, 26–631 ppm and 0.21–0.87, respectively (Table S1 in the online Supplementary Material available at http://journals.cambridge.org/geo), and yield ^{207}Pb–^{206}Pb ages ranging from 2641 to 2950 Ma. Except for spots 7 and 15, the other spots define an upper intercept age of 2928 ± 14 Ma (MSWD = 1.9) (Fig. 4e), which is coeval with the weighted mean ^{207}Pb–^{206}Pb age of 2928 ± 5.4 Ma (MSWD = 0.68) (Fig. 4e), confining the protolith age of the TTG gneiss.

Twenty-six spots of 19 zircon grains from Sample L55 were analysed. Two rim spots (spots 7 and 16) are plotted near the Concordia curve and their ^{207}Pb–^{206}Pb ages are 1940 ± 15 Ma and 1922 ± 11 Ma, respectively, possibly representing the metamorphic age recorded in the TTG gneiss. The rest of the spots yield ^{207}Pb–^{206}Pb ages ranging from 2602 to 2789 Ma with their U, Th and Pb contents and Th/U ratios in the range of 42–319 ppm, 7–239 ppm, 28–232 ppm and 0.13–0.82, respectively (Table S1 in the online Supplementary Material available at http://journals.cambridge.org/geo). Without spots 5, 9 and 14, the rest of the data define a weighted mean ^{207}Pb–^{206}Pb age of 2778 ± 3.4 Ma (MSWD = 1.8) (Fig. 4g), restricting the protolith age of the TTG gneiss.

4.c. Gneissic granitoid

Zircons separated from the gneissic granitoid (Sample L50) are transparent, prismatic or stubby in shape, with weak zoning in CL images and vary from 70 to 180 μm in length (Fig. 3f). A total of 20 spots on 18 grains were analysed and two age groups have been recognized. The first group is represented by spots 7 and 16. Spot 7 is plotted on the Concordia curve with a ^{207}Pb–^{206}Pb age of 2110 ± 8 Ma, which is interpreted as the protolith age and is consistent with the result of Wan *et al.* (2006). Spot 16 is located above the Concordia curve, which may possibly be influenced by the tiny inclusion minerals within it. The second group of zircons show varying degrees of Pb loss and yield an upper intersect age of 1956 ± 36 Ma (MSWD = 46) (Fig. 4h) in the conventional Concordia diagram, and the modest/weakest Pb loss zircons define a weighted mean ^{207}Pb–^{206}Pb age of 1928 ± 5 Ma (MSWD = 1.0) (Fig. 4h), which is older than those obtained by Wan *et al.* (2006) and is deciphered to represent the peak metamorphic age.

It is suggested that from this new high-resolution SIMS U–Pb dating of the zircons, two periods of protolith ages of the TTG gneisses can be recognized: the first one is ~2.93–2.90 Ga recorded in samples L51 and L54, which is older than previous studies (Kröner *et al.* 1988; Diwu *et al.* 2007; Liu *et al.* 2009); the second one is 2.78 Ga recorded in Sample L55, which is in accordance with the results obtained by Diwu *et al.* (2010).

5. Discussion

Zhao *et al.* (2012) summarized the metamorphic chronological data obtained from the different metamorphic terranes within the TNCO, and the dataset suggests that the metamorphism occurred during ~1.89–1.80 Ga based on Sm–Nd isochron dating of metamorphic minerals, electron microprobe analyser (EMPA) chemical dating of metamorphic monazites, ^{40}Ar–^{39}Ar dating of metamorphic hornblendes and a great quantity of single grain evaporation, sensitive high-resolution ion microprobe (SHRIMP) and inductively coupled plasma mass spectrometry (ICP-MS) U–Pb dating of metamorphic zircons. Furthermore, it is noted that the Wutai metamorphic terrane, in the middle segment of the TNCO, experienced metamorphism dated at about 1.91 Ga based on Sm–Nd isochron dating of metamorphic minerals from the garnet-bearing amphibolites, and at about 1.92 Ga via EMPA chemical dating of metamorphic monazites from the metapelites (Liu *et al.* 2004). For the Lüliang metamorphic terrane, in the middle segment of the TNCO, the

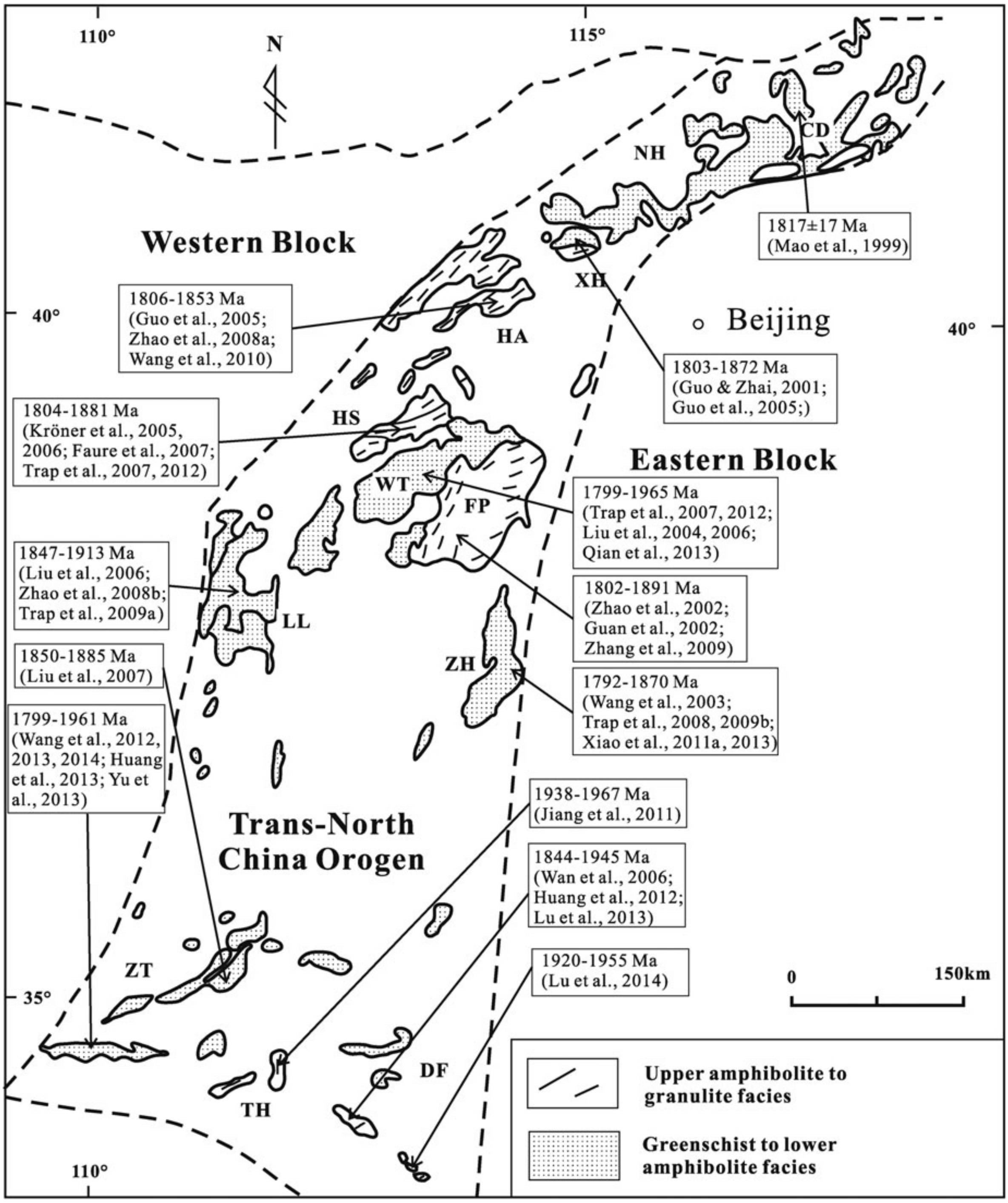

Figure 5. Sketch metamorphic ages of the metamorphic terranes within the Trans-North China Orogen (TNCO) (after Zhao & Zhai, 2013). Abbreviations for the metamorphic complexes: CD – Chengde; DF – Dengfeng; FP – Fuping; HA – Huai'an; HS – Hengshan; LL – Lüliang; NH – Northern Hebei; TH – Taihua; WT – Wutai; XH – Xuanhua; ZH – Zanhuang; ZT – Zhongtiao.

metamorphism was dated to have occurred at about ~1.90–1.86 Ga via EMPA chemical dating of metamorphic monazites from the metapelites and granitic gneisses (Liu *et al.* 2007); the Zhongtiao metamorphic terrane, in the southern segment of the TNCO, was dated to have been metamorphosed at about 1.88~1.85 Ga through EMPA chemical dating of metamorphic monazites from the monzogranitic gneisses (Liu *et al.* 2007).

In recent years, metamorphic geochronological data from the Taihua metamorphic complex have also been reported (Fig. 5), including 1.84 and 1.87 Ga ages from the Upper Taihua Subgroup, Lushan terrane by Wan *et al.* (2006), 1.94 Ga to 1.97 Ga ages from metamorphic zircons through LA-ICP-MS dating in the Luoning terrane (Jiang *et al.* 2011), 1.96 Ga to 1.82 Ga ages through LA-ICP-MS and CAMECA SIMS U–Pb dating of metamorphic zircons and a ~1.80 Ga age obtained by ^{40}Ar–^{39}Ar dating of metamorphic hornblendes in the Huashan terrane (Wang *et al.* 2012, 2013), 1.94 Ga to 1.86 Ga ages through SHRIMP dating in the Huashan terrane (Huang, Wilde & Zhong, 2013) and 1.88 Ga to 1.87 Ga ages through LA-ICP-MS dating of metamorphic zircons in the Huashan terrane (Yu *et al.* 2013). These data further suggest that the tectonometamorphic event of the TNCO started at least as early as ~1.96 Ga, much earlier

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than the previously deciphered ~1.85 Ga (Zhao *et al.* 1998, 2005, 2012).

Different types of rocks collected from the Upper Taihua Subgroup and the Lower Taihua Subgroup in the Lushan terrane all record an identical metamorphic event varying from 1.96 Ga to 1.86 Ga, which is in accordance with our previous study (Lu *et al.* 2013). Therefore, it may be confidently concluded that the Taihua metamorphic complex obviously records an older metamorphic process than the northern metamorphic terranes of the TNCO.

Therefore, the orogenic process of the southernmost terminal of the TNCO including subduction, collision and tectonic denudation not only occurred earlier than, but lasted longer than the metamorphic terranes of the northern sections of the TNCO. Meanwhile, it is noticed that the tectono-metamorphic event of the Taihua metamorphic complex was almost coeval with the collision of the Jiao-Liao-Ji Belt at ~1.95 Ga (Luo *et al.* 2004, 2008; Lu *et al.* 2006; Tam *et al.* 2011) and at about ~1.96 Ga of the Khondalite Belt (Yin *et al.* 2009, 2011; Zhou & Geng, 2009).

The ubiquitously distributed undeformed, unmetamorphosed Palaeoproterozoic sedimentary rocks (Liu *et al*. 2012) and mafic dykes (~1.77 Ga) (Wang *et al*. 2004, 2008; Peng *et al*. 2005, 2008, 2012; Peng, Zhai & Guo, 2006) throughout the TNCO post-date the collision events of the orogenic belt.

6. Brief conclusion

(1) Combining available data, it is concluded that the different metamorphic rocks that crop out within the Lushan terrane, including the amphibolites, TTG gneisses and gneissic granitoid, all experienced the Palaeoproterozoic metamorphic event at about 1.96–1.86 Ga.

(2) The possible subduction and collision of the southernmost terminal of the TNCO started obviously earlier than that of the northern terranes of the TNCO.

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Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0016756814000430.

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