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Detrital zircon age model of Ordovician Wenquan quartzite south of Lungmuco-Shuanghu Suture in the Qiangtang area, Tibet: Constraint on tectonic affinity and source regions

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Early to Middle Ordovician strata, including Wenquan quartzite, occur widely in the Himalaya, Lhasa, and south Qiangtang blocks. The Wenquan quartzite occurs on the south side of the Lungmuco-Shuanghu Suture in the Qiangtang area, Tibet. A total of 145 analyses on detrital zircons from the quartzite show five age ranges of 520–700, ca. 800, 900–1100, 1800–1900, and 2400–2500 Ma, with particularly distinct age peaks of 625 and 950 Ma. The reliable youngest detrital zircon age is 525 Ma, and the oldest, 3180 Ma. Detrital zircons show large variations in Hf isotope composition, with depleted mantle model ages t_{DM}(Hf) ranging from 750 to 3786 Ma. Based on data obtained in this study and by others, the main conclusions are as follows: 1) Low-grade metamorphic sedimentary rocks are distributed extensively in the south of the Lungmuco-Shuanghu Suture and are Phanerozoic in age; 2) Pan-African and Grenville-Jinning tectono-thermal events were well developed in the source region of the Wenquan quartzite; 3) the source region shows crustal addition and recycling of different periods; 4) Wenquan quartzite was derived from the Gondwana metamorphic basement, suggesting that the Qiangtang block is a Gondwanan fragment.

Gondwana, Tibetan Plateau, detrital zircon, SHRIMP dating, Hf isotope, Pan-African movement, Grenville-Jinning movement

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Arising from the wide application of *in situ* U-Pb dating techniques such as by the SHRIMP ion microprobe, age distribution model studies of detrital zircons from (meta-) sedimentary rocks play more and more important roles in tracing the source region of detrital materials, understanding the evolution of ancient basement, determining the formation age of sedimentary rocks, and revealing the tectonic affinity of different blocks. The low-grade metamorphic Wenquan quartzite of the Early to Middle Ordovician age is the oldest geological body recently identified in the south side of the Lungmuco-Shuanghu Suture, central Tibetan Plateau. This paper reports U-Pb ages and Hf isotope compositions of detrital zircons of the quartzite in order to better understand the source characteristics and tectonic affinity of the Southern Qiangtang block.

1 Geological background

The Lungmuco-Shuanghu Suture is an important break in the Tibetan Plateau and is considered a boundary between Gondwanan crustal blocks in the south and Eurasia in the

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north. Based on the geological and fossil records and geochronology of eclogites, blueschists, and ophiolites, the final collision of both the continents happened during the Triassic [1–7].

Low-grade metamorphic strata are widely distributed in the south side of the Lungmuco-Shuanghu Suture. The upper portion of these contains abundant fossils, such as cephalopods, crinoids, graptolites and tentaculites, indicating deposition in the Middle Ordovician [2, 8, 9] (Figure 1). In the southern Himalaya area, Middle Ordovician conglomerate rests uncomfortably on metamorphic basement [10]. In the western Nepal, Ordovician conglomerate is identified and many detrital zircons of 530–480 Ma were found in Ordovician-Devonian strata [11]. In the northern Himalaya area, Early Ordovician conglomerate has also been identified [12–14]. Ordovician-Permian strata in southern Qiangtang, Gangdise, and northern Himalaya have the same sedimentary formation and biostratigraphic sequence. They are the oldest covers on metamorphic basement on the Tibetan plateau and are considered of Gondwanan affinity [14, 15].

Quartzite sample (XZ0701) was taken from the Wenquan area, Nima County, south of the Lungmuco-Shuanghu Suture (N32°57′20″, E86°33′50″, Figure 1). The quartzite occurs in the lower stratigraphic portion of low-grade metasedimentary rocks, in which no fossils have been found. However, it is covered comformably by Middle Ordovician-Devonian strata with abundant fossils. The quartzite is provisionally named the Wenquan quartzite, and no similar stratigraphic unit has been discovered in Qiangtang and adjacent areas [2, 8, 9]. The quartzite is more than 300 m thick, and shows medium to thick layering and large-scale cross-bedding, with dipping trend and angle being 30°–40° and 20°–30°, respectively. The quartzite is grey in color and contains mostly quartz, with some plagioclase and microcline (totally <3%). Quartz grains show wavy extinction and along their margins show recrystallisation into subdomains. These features are due to deformation and metamorphism. The quartzite may have undergone low greenschist facies metamorphism in terms of the existence of metamorphic sericite.

2 Analytical techniques

Zircons were dated on the SHRIMP II ion microprobe at the

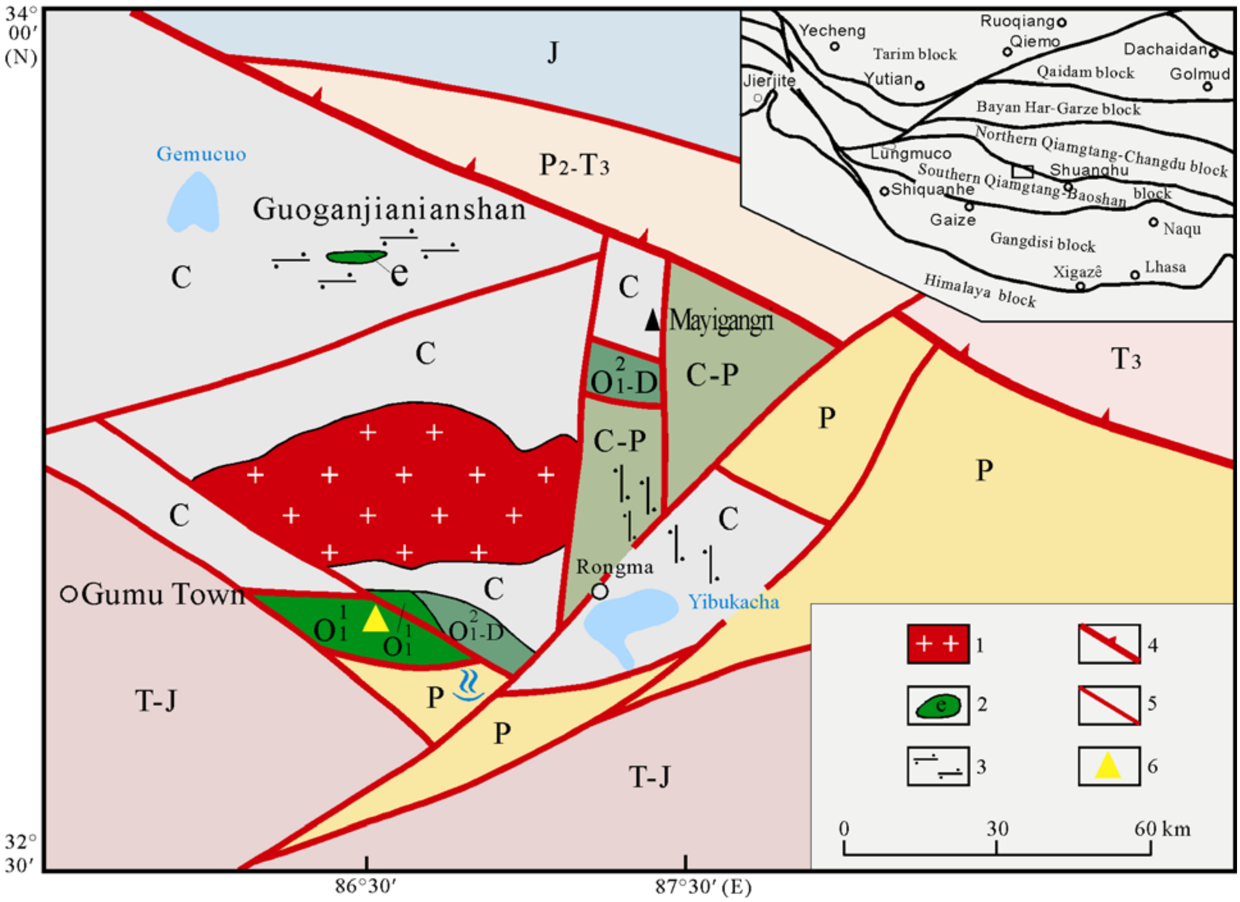

Figure 1 Geological map of central Qiangtong, Tibetan Plateau. O_1^2-D, upper Lower Ordovician-Devonian; O_1^1, Wenquan Quartzite of lower Lower Ordovician. 1, Indosinian granitoid; 2, eclogite; 3, kyanite-schist; 4, main verge of Lungmuco-Shuanghu Suture; 5, fault; 6, sample location. The study area is shown by a rectangle in the top-right map.

Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences. Reflected and transmitted light and cathodoluminescence (CL) images were taken before dating in order to understand zircon origin and determine spot locations. The analytical procedures were similar to those described by Williams [16] and Wan et al. [17]. Three to four scans through the mass stations were made for each age determination of unknown, but five for zircon standards. The intensity of the primary ion beam was 4–5 nA. Primary beam size was 25–30 μm, and each site was rastered for 120–200 s prior to analysis. Standards SL13 (U = 238 ppm, Williams [16]) and TEMORA ($^{206}Pb/^{238}U$ age=417 Ma; Black et al. [18]) were used for calibration of U abundance and $^{206}Pb/^{238}U$ ratio. The TEMORA: sample ratio is about 1:5. Data processing was carried out using the Squid and Isoplot programs [19]. Measured ^{204}Pb was applied for the common lead correction. The uncertainties for individual analyses in Table A1 are quoted at the 1 confidence level. The $^{206}Pb/^{238}U$ age is used when zircons are <1.2 Ga. This is because the relatively small amount of ^{207}Pb accumulated during that time does not permit precise $^{207}Pb/^{206}Pb$ dating [20]. For analyses >1.2 Ga, the $^{207}Pb/^{206}Pb$ age is used. If zircons show lead loss, $^{207}Pb/^{206}Pb$ age is still used, although the $^{206}Pb/^{238}U$ age is <1.2 Ga.

In situ Lu-Hf isotope and REE analysis of zircon was measured at the State Key Laboratory of Continental Dynamics at Northwest University in Xi'an, using a GeoLas200M laser ablation system. The analysis procedure has been described in detail by Yuan et al. [21]. The carrier gas for the ablated aerosol was helium. Spot size, repetition rate, and laser power are ca. 45 μm, 10 Hz, and 90 mJ/pulse, respectively. The $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ values of zircon were corrected by using $^{176}Lu/^{175}Lu = 0.02669$ [22] and $^{176}Yb/^{172}Yb=0.5886$ [23]. Reference zircon 91500 and GJ-1 were analyzed during the unknowns and yielded average $^{176}Hf/^{177}Hf(c)$ values of 0.282295 ± 0.000029 (n = 17, 2σ) and 0.282049±0.000023 (n=10, 2σ), similar to the recommendation values of 0.2823075 ± 0.000058 (2σ) [24] and 0.282015±0.000019 (2σ) [25], respectively. Some parameters for $\varepsilon_{Hf}(t)$ and t_{DM}(Hf) calculations are as follows: the ^{176}Lu decay constant is 1.865×10^{-11} year^{-1} [26], the present-day chondritic values of $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ are 0.282772 and 0.0332 [27], and the present-day depleted-mantle values of $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ are 0.28325 and 0.0384 [28].

3 Zircon features and SHRIMP U-Pb dating

Most zircons are ellipsoid or equant with only a few that are elongate, commonly 100–150 μm in size. Zircons show oscillatory zoning in CL images (Figure 2, suggesting that they are derived mainly from a granitoid source. However, some zircons have overgrowth rims of metamorphic origin (Figure 2(a), (d) and (e)). The metamorphic zircons are not formed after deposition of the quartzite, but are derived from their source region. The discordant relationships between the outer shape and inner texture of zircons clearly indicate their detrital origin, including the metamorphic shells, consistent with their surface features such as irregular or trianglar abrasion pits. One hundred and fourty-five analyses were made on 140 zircons. Their U and Th contents and Th/U ratios are 78–1731, 20–1535 and 0.03–1.81 (Table A1, available at http://earth.scichina.com and http://www.springerlink.com; Figure 3(a)), respectively, with most >0.1 in Th/U (Figure 3(b)). The zircons with Th/U being <0.1 are metamorphic or anatectic in origins in terms of CL images (Figure 2(e)) and have ages of 1.1–0.5 Ga. Only a few metamorphic zircons have been dated, but zircons with metamorphic overgrowth rims are quite common, as indicated by zircon CL images. This suggests that the source region experienced both igneous and high grade metamorphic events, during the Grenville-Jinning period. Most analyses are distributed along or near concordia, but late Neoarchean zircons commonly show strong lead loss, with upper and low intercept ages being ca. 2.5 Ga and ca. 550 Ma (Figure 4(a)). There are five age ranges apparent in the histogram diagram, namely 520–700 Ma, ~800 Ma, 900–1100 Ma, 1800–1900 Ma, and 2400–2500 Ma, with strong age peaks of 625 Ma and 950 Ma (Figure 4(b)). The youngest detrital zircons have ages of 499±10 Ma (7.1) and 506±9 Ma (74.1), but both show strong lead loss (with discordant of 28% and 20%). The youngest detrital zircon close to concordia gives an age of 525±10 Ma (14.1, discordance=6%); this zircon shows clear oscillatory zoning. The oldest detrital zircon gives an age of 3180±16 Ma (109.1).

4 Zircon Hf isotopic signatures and REE compositions

A total of 89 analyses were made on eighty-nine zircon grains (Table A2 available at the same sites as Table A1). Among them, 46 analyses are on the zircons of the Pan-African and Grenville-Jinning ages. They have $\varepsilon_{Hf}(t)$ values ranging from −15.09 to 16.20, t_{DM1}(Hf) and t_{DM2}(Hf) model ages from 750 to 1852 Ma and from 739 to 2114 Ma, respectively, apart from analyses 89 and 28 which have low $\varepsilon_{Hf}(t)$ values (−37.89 and −28.19) and old t_{DM1}(Hf)/t_{DM2}(Hf) ages (2746 Ma/2605 Ma and 3325 Ma/3092 Ma) (Figure 5, Table A2). These suggest that in their source region there are rocks derived from mantle and continental crust, with the latter being mainly late Palaeoproterozoic in age. Fifty-three analyses were made on zircons older than 1200 Ma and have $\varepsilon_{Hf}(t)$, t_{DM1}(Hf) and t_{DM2}(Hf) ranging from −17.71 to 8.90, 1610 to 3786 Ma and 1156 to 4067 Ma (Figure 5). Some analyses have positive $\varepsilon_{Hf}(t)$ values, even

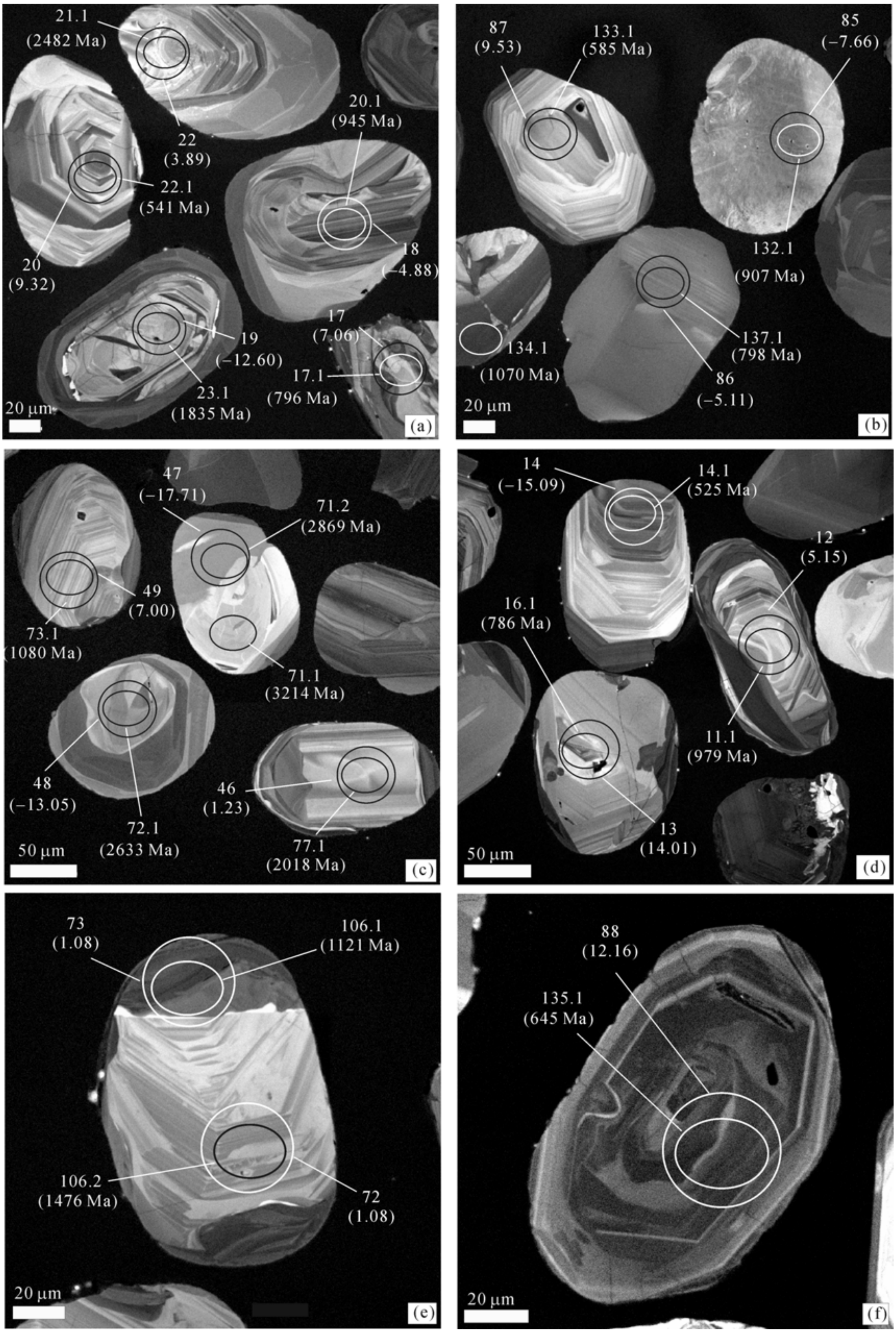

Figure 2 Cathodoluminescence images of detrital zircons from Wenquan quartzite (XZ0701). Zircons commonly show oscillatory zoning ((a)–(f)), with some having metamorphic overgrowth rims ((a)–(e)). Some zircons show discordant relationships between outer shape and inner zoning, indicative of a detrital origin. Ellipses (ca. 30 μm) show positions of SHRIMP analytical sites with their identification numbers and ages as in Table A1. Circles (ca. 45 μm) show positions of Hf isotope analytical sites with their identification numbers and $\varepsilon_{\mathrm{Hf}}(t)$ values as in Table A2.

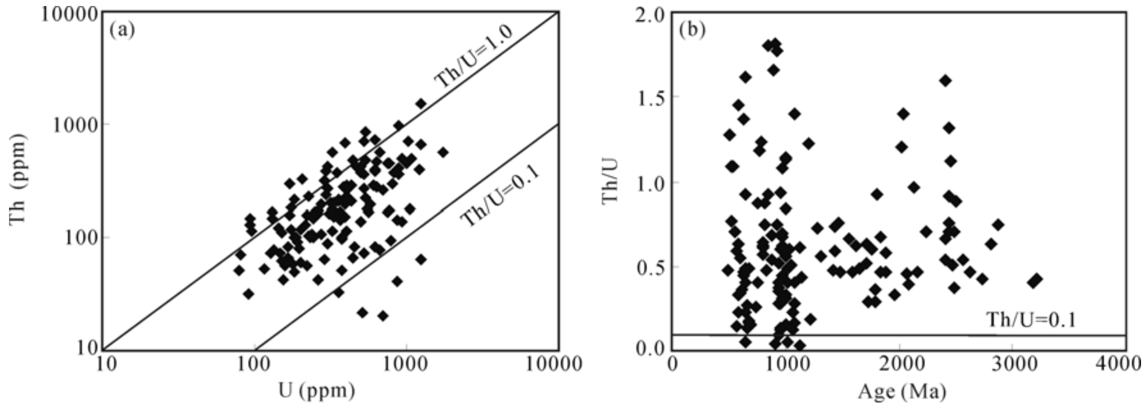

Figure 3 U-Th diagram (a) and age-Th/U diagram (b) of detrital zircons in Wenquan quartzite (XZ0701).

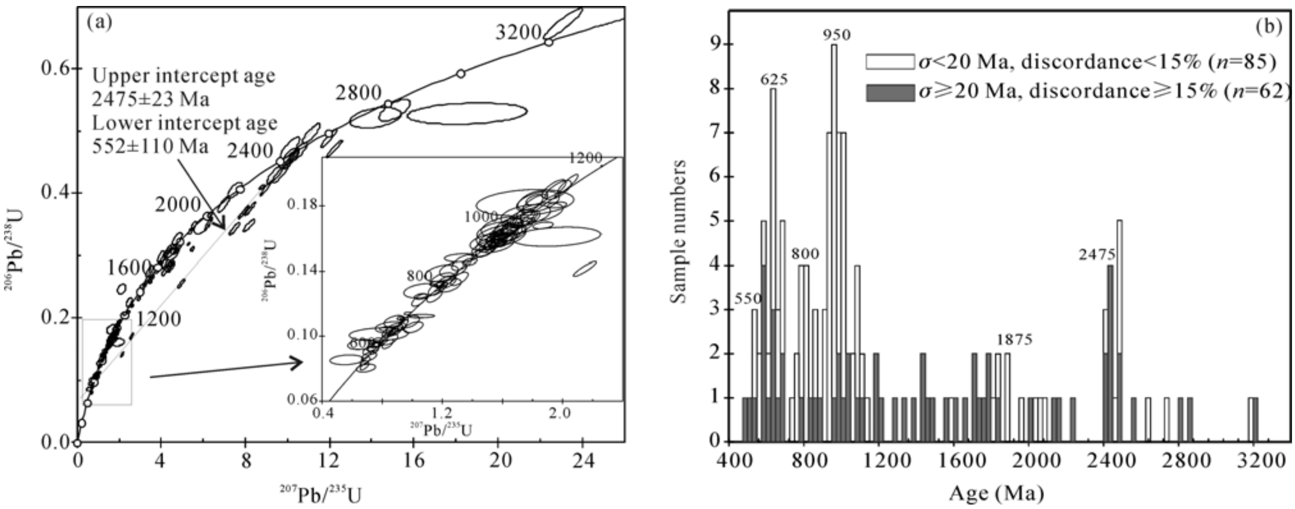

Figure 4 Concordia diagram (a) and age histogram diagram (b) of SHRIMP data for detrital zircons from Wenquan quartzite (XZ0701). The $^{206}Pb/^{238}U$ age is used when zircons are <1.2 Ga; for analyses >1.2 Ga, the $^{207}Pb/^{206}Pb$ age is used. See text for more explanation.

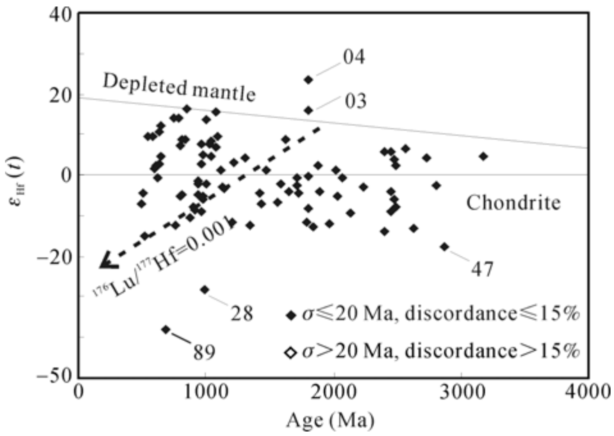

Figure 5 Age-$\varepsilon_{\rm Hf}(t)$ diagram for detrital zircons from Wenquan quartzite (XZ0701). The locations of Hf isotope analysis are same as the ones of SHRIMP dating. The $^{206}Pb/^{238}U$ age is used when zircons are <1.2 Ga; for analyses >1.2 Ga, the $^{207}Pb/^{206}Pb$ age is used. For some analyses, the ages here should be younger than their "ture" ages because of lead loss.

beyond the depleted mantle evolution line (analyses 04 and 03), but most analyses show negative $\varepsilon_{\rm Hf}(t)$ values. The oldest $t_{\rm DM1}$(Hf) and $t_{\rm DM2}$(Hf) model ages are 3786 Ma and 4067 Ma. Therefore, rocks in their source region are mainly products of recycling of old continental materials, with some being very old.

5 REE zircon compositions

Among all the 89 analyses, the ones made on zircons of <700, 700–1200, and >1200 Ma are 13, 33, and 53, respectively. Analysis 07 is high in light REE and has very high total REE contents (12611 ppm), probably because of the laser beam overlapping an REE-enriched mineral inclusion. The remaining also shows a large variation in total REE contents, ranging from 31 to 3585 ppm (Table A3, available at the same sites as Table A1). They show similar REE patterns with the heavy REEs strongly enriched and the light REEs depleted, with positive Ce and negative Eu anomalies. The Ce and Eu anomalies become weaker with total REE contents increasing (Figure 6). This may be related to variations in magma composition and temperature-pressure condition or result from hydrothermal events [29]; another possibility is that detrital zircons are from different sources. Most zircons show the composition features of magmatic zircons from granitoids [30, 31]. Zircons of analyses 48 and 83 have flat heavy REE patterns (Figure 6), similar to metamorphic zircons from garnet- bearing rocks [32, 33]. However, they could not come from eclogite facies rocks because of strong negative Eu anomalies [34].

6 Discussions

The most robust youngest age is 525 Ma for the detrital zircons from the Wenquan quartzite. Combined with the presence of Middle Ordovician fossils in the strata over the quartzite, it supports the notion that the widely-distributed,

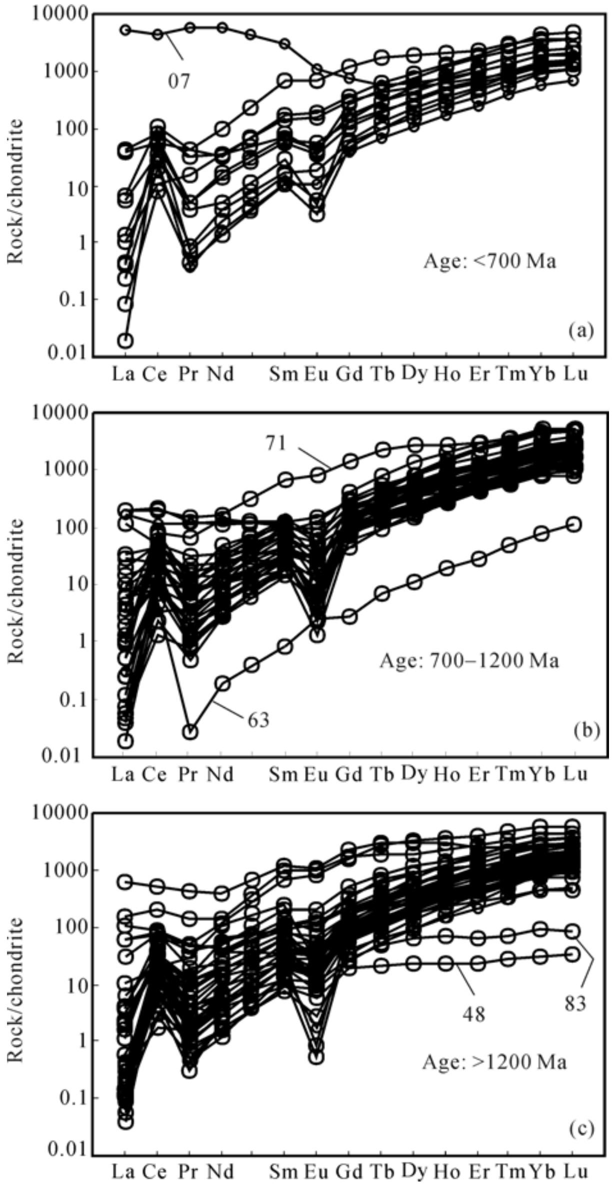

Figure 6 REE patterns for detrital zircons from Wenquan quartzite (XZ0701).

low-grade metamorphic sedimentary rocks in the south side of the Lungmuco-Shuanghu Suture are not Precambrian in formation age [8]. The detrital zircons of the Wenquan quartzite show a large age variation, mainly concentrated in 520–700, ca. 800, 900–1100, 1800–1900, and 2400–2500 Ma. Hf isotope composition of the detrital zircons indicates that both crustal recycling and addition play important roles in the formation of the rocks of different ages in the source region, with juvenile magmatism being more important during Pan-African and Grenville-Jinning periods. Similar age distribution patterns for detrital zircons have also been obtained for metamorphic sediments in the Qiangtang area [35, 36] and Ordovician and younger (meta-)sediments in Gomori, south Qiangtang and Himalaya (Zhu DC, personal communication) [37]. These suggest that a huge source region provides abundant detritus for the covers. It is convenient to divide the ages of the detrital zircons into three segments, namely 520–700, 800–1100, and >1200 Ma, for discussing their geological significance.

6.1 Pan-African tectono-magmatic event (520–700 Ma)

There was a strong Pan-African tectono-magmatic event in India [38, 39]. Similar to the India Craton, the Himalaya-Lhasa blocks have Pan-African basement affinities [13, 15, 37, 40–47]. The Pan-African event is also widely identified in the Nierong and Kaqiong micro-continents along the Bangong-Nujiang Suture. The micro-continents are composed mainly of high-grade paragneiss, similar to the rocks in India and the Himalaya areas [15]. An earlier study considered that the low-grade metamorphic sedimentary rocks constitute the Proterozoic basement in the south side of the Lungmuco-Shuanghu Suture and the lower and upper parts of the basement are the crystalline “hard basement” and metasedimentary “soft basement” [48–50]. However, the discovery of abundant fossils in the metamorphic rocks indicates that they formed during the Ordovician [51]. In the south Qiangtang area, the formation age of the basement is not clear because of overlaying of post-Ordovician sediments, but it is considered to be similar to the Himalaya and Lhasa blocks where the basement is of Pan-African character in terms of regional correlation [51]. The Pan-African tectono-thermal event is well developed in the pre-Ordovician basement of Gondwana. In the basement of the southern margin of the Euro-Asia continent, by contrast, this event has not been identified. Similar to the coetaneous sedimentary rocks in the India-Hymalaya area, the Wenquan quartzite contains many detrital zircons with Pan-African ages, suggesting that sediments come from the metamorphic basement of Gondwana, and therefore supporting a view that the south Qiangtang block belongs to the Gondwana [51]. It is notable that the detrital zircons of the Wenquan quartzite show an age peak of 625 Ma (Figure 4(b)), but the Paleozoic magma-metamorphic ages are

480–530 Ma in the India-Hymalaya-Lhasa blocks [15, 37, 43, 44, 47], either earlier or later than the typical Pan-African tectono-thermal event (520–570 Ma) [45]. However, many Pan-African magmatic rocks are slightly older than 600 Ma, with a strong 570–560 Ma tectonothermal overprint. Compared with late Pan-African event, early Pan-African activity was significantly more developed in the source region of the Wenquan quartzite. It is also interesting to note that the discordia that yields an upper intercept age of ca. 2.5 Ga has a lower intercept age of ca. 550 Ma, betraying influence of the Pan-African event on the source region of the ca. 2.5 Ga detrital materials. In the Rola Kangri Belt, north of the Lungmuco-Shuanghu Suture, low-grade metamorphic sedimentary rocks contain detrital zircons of 525–653, 794–975 and 1591–3217 Ma [52], similar to the age distribution model of the zircons from the Wenquan quartzite. Their relationship with the rocks described here remains to be determined.

6.2 Grenville-Jinning tectono-magmatic events (1100–800 Ma)

In recent years, Grenville-Jinning tectono-magmatic events have increasingly been identified in the Pan-African basement of Himalayas, including: 1) many inherited zircons of 1064–1144 and 636–776 Ma in intrusive rocks along the Lhaqênsangrag-Kangmar uplift Belt [13], 2) gneissic granitoids of 835–869 Ma in the Kangmar area [43], 3) abundant 780–1100 Ma zircons obtained from the pre-Ordovician Namche Barwa Complex in the eastern Himalaya [47], 4) many zircons of 900–1200 Ma identified in the pre-Ordovician Bhimphedi Group in the Himalaya area, western Nepal [37], 5) many inherited and detrital zircons in the Palaeozoic S-type granites and metamorphic sedimentary rock enclaves in the Kathmandu area, Nepal [45], and 6) many 800–1300 Ma detrital zircons in the gneisses of the metamorphic basement in the Eohimalayan area [11, 53]. In the Pan-African basement of the Lhasa block, on the other hand, ages of 748–787 Ma have been obtained only for metamorphosed intrusive rocks distributed in the Nyainqêntanglha Group, western margin of Nam Co [54]. In the Wenquan quartzite there are many detrital zircons of 800–1200 Ma, up to ca. 40% in all the zircons analyzed. The age peak of ca. 950 Ma is more obvious than the one of ca. 800 Ma, suggesting that in the source region, both the Grenville and Jinning tectono-magmatic events are important, with the former being more significant than the latter. The existence of many detrital zircons of 800–1100 Ma also suggests that the Wenquan quartzite was probably derived from the Himalaya basement and India Craton and therefore the south Qiangtang block belongs to Gondwana. This is supported by the detrital zircon age distribution of Carboniferous-Cretaceous (meta-)sedimentary rocks in the Himalaya, Lhasa, and south Qiangtang blocks [55, 56].

6.3 Early history of the metamorphic basement (>1200 Ma)

In the Wenquan quartzite there are some detrital zircons older than 1200 Ma. The age data show dispersed distribution in age histogram diagram, but with two small age peaks of 1800–1900 Ma and 2400–2500 Ma. The oldest detrital zircon has an age of 3180 Ma, and there are detrital zircons with the oldest t_{DM}(Hf) age up to 3.79 Ga. Most of the early Precambrian detrital zircons are probably formed as products of crustal recycling. They cannot provide important information on where they were derived, because of wide distribution of rocks with these ages in the North China Craton, South China Platform, and India Craton. In the Pan-African basement of the Tibetan Plateau, abundant early Precambrian rocks and zircons have recently been discovered, with ages mainly between 1800–2000 and 2400–2700 Ma [11, 45, 53, 57], respectively, to which the early Precambrian detrital zircons of the Wenquan quartzite are similar in age distribution. The detrital and residual zircons of >3000 Ma have also been reported in the Pan-African basement, including a ca. 4100 Ma detrital zircon grain from the Pulan quartzite [35, 55, 58]. It is evident that there are early Precambrian crustal materials in the Tibetan Plateau and adjacent areas.

The Lhasa-south Qiangtang block and Western Australia are similar in zircon age distribution spectra. In Western Australia, Archaean rocks are widely distributed, metasediments in the Jack Hills contain some detrital zircons of >4000 Ma [59], tectono-thermal events of 650–500 Ma are widely identified [60], and detrital zircons of Ordovician and younger sedimentary rocks are similar in age distribution and Hf isotope composition to ones of the (meta-) sediments [61, 62], including the Wenquan quartzite, in the Lhasa-south Qiangtang block. These may suggest that in the Ordovician, both the Lhasa-south Qiangtang block and Western Australia belonged to Gondwana, and the latter should be the source region for the Wenquan quartzite and other sediments in the Lhasa-south Qiangtang block. It is still debatable whether the South China Platform was a part of Gondwana [63, 64]. If so, it is also a possible source region for the Wenquan quartzite because the Grenville-Jinning tectono-magmatic events are well developed in the South China Platform [65–71]. Clearly, detrital zircons of the Pan-African ages can play more important roles than the ones of the Grenville-Jinning ages in determining source regions of sediments.

7 Conclusions

The most robust youngest detrital zircon age from the Wenquan quartzite is 525 Ma, providing geochronological evidence for a post Precambrian age for the widely distributed low-grade metamorphic sedimentary rocks in the south of the Lungmuco-Shuanghu Suture in the Qiangtang area. The age distribution model of the detrital zircons from the Wenquan quartzite suggests that significant Pan-African and Grenville-Jinning tectono-thermal events occurred in their source region, where there are also some continental materials of the early Precambrian. Hf isotope compositions of detrital zircons indicate that crustal recycling and addition happened in the source regions during different periods. This study supports the idea that the south Qiangtang block belongs to Gondwana.

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1 Li C, Li Y T, Lin Y X, et al. Sm-Nd dating of the protolith of blueschist in the Shuanghu area, Tibet (in Chinese). Chin Geol, 2002, 29: 355–359
2 Li C, Cheng L R, Zhang Y C, et al. Discovery of Ordovician-Devonian strata in the south of the Qiangtang area, Tibet (in Chinese). Reg Geol Chin, 2004, 23: 602–604
3 Li C, Cheng L R, Wang T W, et al. New results and major progress in regional geological survey of the Xainza County Sheet (in Chinese). Reg Geol Chin, 2004, 23: 479–483
4 Li C, Zhai Q G, Dong Y S, et al. Discovery of eclogite and its geological significance in Qiangtang area, central Tibet. Chin Sci Bull, 2006, 51: 1095–1100
5 Li C, Zhai Q G, Dong Y S, et al. Establishment of the Upper Triassic Wanghuling Formation at Guoganjianian Mountain, central Qiangtang, Qinghai-Tibet Plateau, and its significance (in Chinese). Reg Geol Chin, 2007, 26: 1003–1008
6 Li C, Dong Y S, Zhai Q G, et al. High-pressure metamorphic belt in Qiangtang, Qinghai-Tibet Plateau, and its tectonic significance (in Chinese). Reg Geol Chin, 2008, 27: 27–35
7 Li C, Zhai Q G, Chen W, et al. Geochronology evidence of the closure of Longmu CoShuanghu suture, Qinghai-Tibet plateau: Ar-Ar and zircon SHRIMP geochronology from ophiolite and rhyolite in Guoganjianian (in Chinese). Acta Petrol Sin, 2007, 26: 911–918
8 Li C. Question about the Basement of the Qiangtang Micro-plate (in Chinese). Geol Rev, 2003, 49: 5–9
9 Cheng L R, Chen S M. Discovery of Early Paleozoic strata in South of Qiangtang, northern Tibet and its significance (in Chinese). Earth Sci J, 2007, 32: 59–62
10 Garzanti E, Casnedi R, Jadoul F. Sedimentary evidence of a Cambro-Ordovicin orogenic event in the northwestern Himalaya. Sediment Geol, 1986, 48: 237–265
11 Gehrels G E, DeCelles P G, Martin A, et al. Initiation of the Himalayan Orogen as an early Paleozoic thin-skinned thrust belt. GSA Today, 2003, 13: 4–9
12 Liu W C, Liang D Y, Wang K Y, et al. The discovery of the Ordovician and its significance in the Kangmar area, southern Tibet (in Chinese). Earth Sci Front, 2002, 9: 247–248
13 Liu W C, Wan X J, Liang D Y, et al. New achievements and main progress in geological survey of the Gyangzê and Yadong sheets (in Chinese). Reg Geol Chin, 2004, 23: 444–450
14 Zhou Z G, Liu W C, Liang D Y. Discovery of the Ordovician and its basal conglomerate in the Kangmar area, southern Tibet-with a discussion of the relationof the sedimentary cover and unifying basement in the Himalayas (in Chinese). Reg Geol Chin, 2004, 23: 655–663
15 Li C, Xie Y W, Sha S L, et al. SHRIMP U-Pb zircon dating of the Pan-African granite in Baxoi County, eastern Tibet, China (in Chinese). Geol Bull Chin, 2008, 27: 64–68
16 Williams I S. U-Th-Pb geochronology by ion microprobe. In: McKibben M A, Shanks W C, Ridley W I, eds. Applications of Microanalytical Techniques to Understanding Mineralizing Processes. Rev Eco Geol, 1998, 7: 1–35
17 Wan Y S, Li R W, Wilde S A, et al. UHP metamorphism and exhuma- tion of the Dabie Orogen: Evidence from SHRIMP dating of zircon and monazite from a UHP granitic gneiss cobble from the Hefei Basin. Geochim Cosmochim Acta, 2005, 69: 4333–4348
18 Black L P, Kamo S L, Allen C M, et al. TEMORA 1: A new zircon standard for Phanerozoic U-Pb geochronology. Chem Geol, 2003, 200: 155–170
19 Ludwig K R. Squid 1.02: A user's manual. Berkeley Geochronology Centre, 2001, Spec 2: 1–19
20 Black L P, Kamo S L, Williams I S, et al. The application of SHRIMP to Phanerozoic geochronology: A critical appraisal of four zircon standards. Chem Geol, 2003, 200: 171–188
21 Yuan H L, Gao S, Dai M N, et al. Simultaneous determinations of U-Pb age, Hf isotopes and trace element compositions of zircon by excimer laser ablation quadrupole and multiple collector ICP-MS. Chem Geol, 2008, 247: 100–117
22 Bievre D P, Taylor P D. Table of the isotopic compositions of the elements. Int J Mass Spectrom Ion Process, 1993, 123: 149–166
23 Chu N C, Taylor R N, Chavagnac V, et al. Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: An evaluation of isobaric interference corrections. J Anal At Spectrom, 2002, 17: 1567–1574
24 Wu F Y, Yang Y H, Xie L W, et al. Hf isotopic compositions of the standard zircons and baddeleyites used in U-Pb geochronology. Chem Geol, 2006, 234: 105–126
25 Elhlou S, Belousova E, Griffin W L, et al. Trace element and isotopic composition of GJ red zircon standard by laser ablation. Geochim Cosmochim Acta, 2006, 70(Suppl): A158, doi: 10.1016/j.gca.2006.06.1383
26 Scherer E, Muenker C, Mezger K. Calibration of the lutetium-hafnium clock. Science, 2001, 293: 683–687
27 Blichert-Toft J, Albarede F. The Lu-Hf isotope geochemistry of chondrites and the evolution of the mantle-crust system. Earth Planet Sci Lett, 1997, 148: 243–258
28 Vervoort J D, Blichert-Toft J. Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. Geochim Cosmochim Acta, 1999, 63: 533–556
29 Hoskin P W. Trace-element composition of hydrothermal zircon and the alteration of Hadean zircon from the Jack Hills, Australia. Geochim Cosmochim Acta, 2005, 69: 637–648, doi: 10.1016/j.gca.2004.07.006
30 Wu Y B, Zheng Y F. Genesis of zircon and its constraints on interpretation of U-Pb age. Chin Sci Bull, 2004, 49: 1554–1569
31 Rubatto D. Zircon trace element geochemistry: Partitioning with garnet and the link between U-Pb ages and metamorphism. Chem Geol, 2002, 184: 123–138
32 Zheng Y F, Wu Y B, Zhao Z F, et al. Metamorphic effect on zircon Lu-Hf and U-Pb isotope systems in ultrahigh-pressure eclogite-facies metagranite and metabasite. Earth Planetary Sci Lett, 2005, 240: 378–400
33 Zheng Y F, Zhao Z F, Wu Y B, et al. Zircon U-Pb age, Hf and O isotope constraints on protolith origin of ultrahigh-pressure eclogite and gneiss in the Dabie orogen. Chem Geol, 2006, 231: 135–158
34 Gilloti J A, Nutman A P, Brueckner H K. Devonian to Carboniferous collision in the Greenland Caledonides: U-Pb zircon and Sm-Nd ages of high-pressure and ultrahigh-pressure metamorphism. Contrib Mineral Petrol, 2004, 148: 216–235, doi: 10.1007/s00410-004-0600-4
35 Kapp P, Yin A, Manning C E, et al. Tectonic evolution of the early

Mesozoic blueschist-bearing Qiangtang metamorphic belt, central Tibet. Tectonics, 2003, 22: 1043–1068
36 Pullen A, Kapp P, Gehrels G E, et al. Triassic continental subduction in central Tibet and Mediterranean-style closure of the Paleo-Tethys Ocean. Geology, 2008, 36: 351–354
37 Gehrels G E, DeCelles P G, Ojha T P, et al. Geologic and U-Pb geochronologic evidence for early Paleozoic tectonism in the Dadeldhura thrust sheet, far-west Nepal Himalaya. J Asian Earth Sci, 2006, 28: 385–408
38 Cenki B, Braun I, Brocher M. Evolution of the continental crust in the Kerala Khondalite Belt, southernmost India: Evidence from Nd isotope mapping, U-Pb and Rb-Sr geochronology. Precambrian Res, 2004, 134: 275–292
39 Collins A S, Santosh M, Braun I, et al. Age and sedimentary provenance of the Southern Granulites, South India: U-Th-Pb SHRIMP secondary ion mass spectrometry. Precambrian Res, 2007, 155: 125–138
40 Burg J P, Chen G M. Tectonics and structural formation of southern Tibet, China. Nature, 1984, 311: 219–223
41 Miller C, Thöni M, Frank W, et al. The early Palaeozoic magmatic event in the Northwest Himalaya, India: Source, tectonic setting and age of emplacement. Geol Mag, 2001, 138: 237–251
42 Zhang L L, Liao G Y, Geng Q R, et al. New results and major progress in regional geological survey of the Mêdog County Sheet (in Chinese). Reg Geol China, 2004, 23: 458–462
43 Xu Z Q, Yang J S, Liang F H, et al. Pan-African and Early Paleozoic orogenic events in the Himalaya terrane: Inference from SHRIMP U-Pb zircon ages (in Chinese). Acta Petrol Sin, 2005, 21: 1–12
44 Liu W C, Zhou Z H, Zhang X X, et al. SHRIMP zircon geochronological constraints on a Pan-African orogeny in the Yadong area, southern Tibet. Goldschmidt Conf Abst, 2006, A365
45 Cawood P A, Johnson M R W, Nemchin A A. Early Palaeozoic orogenesis along the Indian margin of Condwana: Tectonic response to Condwana assembly. Earth Planet Sci Lett, 2007, 255: 70–84
46 Zhang Z M, Wang J L, Zhao G C, et al. Geochronology and Precambrian tectonic evolution of the Namche Barwa complex from the eastern Himalayan syntaxis (in Chinese). Acta Petrol Sin, 2008, 24: 1627–1637
47 Zhang Z M, Wang J L, Shen K, et al. Paleozoic circum-Gondwana orogens:Petrology and geochronology of the Namche Barwa Complex in the eastern Himalayan syntaxis, Tibet (in Chinese). Acta Petrol Sin, 2008, 24: 1477–1487
48 Wang G Z, Wang C S. Disintegration and age of basement metamorphic rocks in Qiangtang, Tibet, China. Sci Chin Ser D-Earth Sci, 2001, 44: 86–93
49 Li Y T, Luo J N, Lu H N, et al. The stratum of Qinghai-Tibet Plateau (in Chinese). Beijing: Science Press, 2001. 10–30
50 Wang C S, Yin H S, Li Y, et al. Geological evolution and petroleum prospect of the Qiangtang basin, Tibet (in Chinese). Beijing: Geological Publishing House, 2001. 1–59
51 Li C. A Review on 20 Years' Study of the Longmu Co-Shuanghu-Lancang River Suture Zone in Qinghai-Xizang (Tibet) Plateau (in Chinese). Geol Rev, 2008, 54: 600–614
52 Yang Z J, Li X Y. SHRIMP U-Pb dating of zircons from low-grade metamorphic rocks in the Rola Kangri junction zone, northern Tibet, China (in Chinese). Geol Bull Chin, 2006, 25: 118–123
53 Yoshida M, Upreti B N. Neoproterozoic India within East Gondwana: Constraints from recent geochronologic data from Himalaya. Gondwana Res, 2006, 10: 349–356
54 Hu D G, Wu H Z, Jiang W, et al. SHRIMP zircon U-Pb age and Nd isotopic study on the Nyainqêntanglha Group in Tibet. Sci China Ser D-Earth Sci, 2005, 48: 1377–1386
55 Leier A L, Kapp P, Gehrels G E, et al. Detrital zircon geochronology of Carboniferous-Cretaceous strata in the Lhasa terrane, Southern Tibet. Basin Res, 2007, 19: 361–378
56 Gehrels G E, Kapp P, Pullen A, et al. U-Pb basement and detrital zircon geochronology of the southern Tibetan Plateau and Tethyan Himalaya. Abstract in Geological Society of America, 2008 Annual Meeting, Anonymous, 2008. 40: 329
57 Li D W, Zhang X H, Liao Q A, et al. New results and main progress in geological survey of the Dinggyê County and Chentang District sheets (in Chinese). Geol Bull Chin, 2004, 23: 438–443
58 Duo J, Wen C Q, Guo J C, et al. 4.1 Ga old detrital zircon in western Tibet of China. Chin Sci Bull, 2007, 52: 23–26
59 Wilde S A, Valley J W, Peck W H, et al. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Science, 2001, 409: 175–179
60 Veevers J J. Pan-Gondwanaland post-collisional extension marked by 650–500 Ma alkaline rocks and carbonatites and related detrital zircons: A review. Earth-Sci Rev, 2007, 83: 1–47
61 Veevers J J, Saeed A, Belousova E A, et al. U-Pb ages and source composition by Hf-isotope and trace-element analysis of detrital zircons in Permian sandstone and modern sand from southwestern Australia and a review of the paleogeographical and denudational history of the Yilgarn Craton. Earth-Sci Rev, 2005, 68: 245–279
62 Veevers J J, Belousova E A, Saeed A, et al. Pan-Gondwanaland detrital zircons from Australia analysed for Hf-isotopes and trace elements reflect an ice-covered Antarctic provenance of 700–500 Ma age, TDM of 2.0–1.0 Ga, and alkaline affinity. Earth-Sci Rev, 2006, 76: 135–174
63 Li Z X, Bogdanov S V, Collins A S, et al. Assembly, configuration, and break-up history of Rodinia: A synthesis. Precambrian Res, 2008, 160: 179–210
64 Yang Z Y, Sun Z M, Yang T S, et al. A long connection (750–380 Ma) between South China and Australia: Paleomagnetic constraints. Earth Planet Sci Lett, 2004, 220: 423–434
65 Zhou M F, Kennedy A K, Sun M, et al. Neoproterozoic arc-related mafic intrusions along the Northern Margin of South China: Implications for the accretion of Rodinia. J Geol, 2002, 110: 611–618
66 Li Z X, Li X H, Kinny P D, et al. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze Craton, South China and correlation's with other continents: Evidence for a mantle superplume that broke up Rodinia. Precambrian Res, 2003, 122: 85–109
67 Wan Y S, Liu D Y, Xu M H, et al. SHRIMP U-Pb zircon geochronology and geochemistry of metavolcanic and metasedimentary rocks in Northwestern Fujian, Cathaysia block, China: Tectonic implications and the need to redefine lithostratigraphic units. Gandwana Res, 2007, 12: 166–183
68 Li Z X, Li X H, Zhou H, et al. Grenville-aged continental collision in South China: New SHRIMP U-Pb zircon results and implications for Rodinia configuration. Geology, 2002, 30: 163–166
69 Li X H, Li Z X, Sinclair J A, et al. Revisiting the "Yanbian Terrane": implications for Neoproterozoic tectonic evolution of the western Yangtze Block, South China. Precambrian Res, 2006, 151: 14–30
70 Li X H, Li W X, Li Z X, et al. 850–790 Ma bimodal volcanic and intrusive rocks in northern Zhejiang, South China: A major episode of continental rift magmatism during the breakup of Rodinia. Lithos, 2008, 102: 341–357
71 Ye M F, Li X H, Li W X, et al. SHRIMP zircon U-Pb geochronological and whole-rock geochemical evidence for an early Neoproterozoic Sibaoan magmatic arc along the southeastern margin of the Yangtze Block. Gondwana Res, 2007, 12: 144–156