Zircon U–Pb and Hf isotope constraints from the Ailao Shan–Red River shear zone on the tectonic and crustal evolution of southwestern China

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A B S T R A C T

The Ailao Shan–Red River (ASRR) shear zone, one of the most prominent geologic strike-slip shear zones in Southeast Asia, consists of high-grade metamorphic complexes that provide a rare opportunity to sample the mid-crustal rocks along the western margin of the Yangtze Block of South China. Here we report combined, in-situ analyses of zircon U–Pb and Lu–Hf isotopes of eight gneisses from the Diancang Shan and Ailao Shan segments of the ASRR shear zone. Our zircon U–Pb data indicate that the rocks contain abundant magmatic zircons ranging in age from 1785 to 25 Ma, with peak ages at ca. 770, 350 and 240 Ma, suggesting three major periods of protolith formation. The 350-Ma zircons, observed only in an orthogneiss from the Diancang Shan, show uniform initial Hf isotopic ratios marked by high and positive εHf(T) values from +16 to +10. This is in contrast with the other two zircon populations that are more common, occurring in both the Diancang Shan and Ailao Shan, and overall delineate very heterogeneous Hf isotopic compositions, with εHf(T) values ranging from +15 to −16. Many zircons reveal distinctive core-rim age variations. Zircon rims, formed between ca. 34 and 26 Ma, show significant variations in Th/U ratios (5–0.01) and εHf(T) values (+14 to −10) that suggest complicated magmatic and metamorphic zircon overgrowth during the Oligocene. The presence of both metamorphic and magmatic overgrowths on zircons suggests that the metamorphism reached upper amphibolite facies, corresponding to mid-crustal level P–T conditions, as also suggested by structural and petrologic data. Our data furthermore suggest that the ASRR gneisses were not produced solely by shear heating during the Tertiary strike-slip faulting, but are uplifted, mid-crustal basement rocks that formed essentially during two major stages of magmatism, represented by the Neo-proterozoic Kangding Complex and Late Permian Emeishan large igneous province. As a result of the India–Asia collision, these basement rocks underwent regional magmatic and metamorphic overprinting in the Oligocene that, based on our relevant work (Searle et al., 2010, Geosphere, 6, 1–23), predated the initial left-lateral movement along the ASRR shear zone. The 350-Ma protolith, which requires a dominant depleted-mantle input in the petrogenesis, cannot be linked to any major magmatic events in South China but may be interpreted as part of the Paleotethys remnants that were later incorporated into the ASRR shear zone.

1. Introduction

As one of the most significant strike-slip shear zones in Southeast Asia (Fig. 1), the Ailao Shan–Red River (ASRR) shear zone has been repeatedly invoked as a key structure accommodating crustal deformation resulting from the convergence between India and Asia since the early Cenozoic (e.g., Tapponnier et al., 1982, 1990; Leloup et al., 1995, 2001; Morley, 2002; Yeh et al., 2008). Several previous studies suggested that the left-lateral movement along the ASRR shear zone absorbed the main intracontinental deformation, and thus the Indochina Block was extruded southeastward relative to the South China Block (cf. Leloup et al., 1995; for details). Nonetheless, controversies persist and recent discussions on the evolution of the ASRR shear zone focus on the timing of the shearing, the amounts of the offset, the depth of the faults, and the degree of metamorphism and melting produced by the strike-slip motion (Searle et al., 2010; for a recent review). In contrast to the “end-member” interpretation that regards all the metamorphic and igneous rocks in the shear zone as products of shear heating during Tertiary left-lateral strike-slip motion (Tapponnier et al., 1982, 1990; Leloup and Kienast, 1993;
Leloup et al., 1995, 2001), an alternative hypothesis correlates these rocks to earlier magmatic and metamorphic events, with the latter being unrelated to the mylonites in the shear zone formed by the left-lateral shearing (Chung et al., 1997; Jolivet et al., 2001; Searle, 2006; Anczkiewicz et al., 2007; Chung et al., 2008; Yeh et al., 2008; Searle et al., 2010).

In order to better constrain the tectonic evolution of the ASRR shear zone, and the pre-Cenozoic crustal history of the region, this study reports the first combined, in-situ analyses of zircon U–Pb and Lu–Hf isotopes for gneissic samples from the Diancang Shan and Ailao Shan areas, the northern and middle segments of the shear zone (Fig. 1). The results suggest that the ASRR gneisses were not formed by shear heating during the Tertiary strike-slip faulting, but represent the uplifted, mid-crustal basement rocks that resulted essentially from regional magmatic activities in three distinct stages.

2. Tectonic setting

The ASRR shear zone in Yunnan is located in the margin of the Yangtze Block (Chung et al., 1997), a complicated Precambrian continental block that combined with the Cathaysia Block to form the South China Block (Fig. 1). Neoproterozoic magmatic rocks have been reported within the region around the Yangtze Block (e.g. Li et al., 1999, 2003a, 2003b; Zheng et al., 2007) versus subduction (Zhou et al., 2002, 2006; Sun et al., 2008, 2009) associated with the breakup of the Rodinia supercontinent (Wang et al., 2010; for a review) were proposed for the formation of these Neoproterozoic magmatic rocks. Detrital zircons from Precambrian basins around the Yangtze Block have been investigated with a combination of U–Pb and Lu–Hf isotopes (Sun et al., 2009). A dominance of negative $\varepsilon_{\text{Hf}}(T)$ values in the detrital zircons points to reworking of early Paleoproterozoic to Archean basement rocks, and suggests the presence of old continental crust in the western Yangtze Block. Nevertheless, Neoproterozoic magmatism at ~830 and 740 Ma with high positive $\varepsilon_{\text{Hf}}(T)$ values was recognized, suggesting an important period of juvenile crustal growth in this region (Wang et al., 2010).

The western Yangtze Block experienced another stage of large-scale magmatism as evidenced by the emplacement of the Emeishan large igneous province (LIP) started with basaltic eruptions at ~260 Ma, with magmatic activity lasted until ~240 Ma (Shellnutt et al., 2008; Xu et al., 2008). Wide range of $\varepsilon_{\text{Nd}}(T)$ and $\varepsilon_{\text{Hf}}(T)$ isotopic values from rocks within the Emeishan LIP implies a significant input of the juvenile mantle during magma genesis which intensified basaltic underplating of the lower continental...
crust (Xu et al., 2001, 2004; Zhong et al., 2007; Shellnutt et al., 2009; Zhong et al., 2009). This was followed shortly afterwards by voluminous “synorogenic” granitoid formation during the Middle Triassic. During the Upper Triassic, these rocks were overlain by molasse and later exposed along the Jinshajiang–Ailao Shan suture zone as a result of collision/suturing between the Simao, South China

Fig. 2. Geological map of (a) Diancang Shan and (b) Ailao Shan after the Geological Map of Yunnan, scale 1:500,000, showing the sample localities and distribution of major geologic units.
and Indochina Blocks (Wang et al., 2000b; Jian et al., 2008; Hennig et al., 2009). The collision/suturing event is interpreted to be the Indosinian Orogeny, which is considered responsible for the widespread tectonometamorphism identified throughout all of Southeast Asia (Carter and Clift, 2008; Hoa et al., 2008).

3. Geological background

The ASRR shear zone in Yunnan, SW China, is composed of two main massifs, namely, the Diancang Shan (Fig. 2a) and Ailao Shan (Fig. 2b). The two massifs are separated by the 80 km long sedimentary Midu Gap (Tapponnier et al., 1990). The Diancang Shan massif, which lies in the northwestward projected trend of the Ailao Shan, is a NW–SE aligned mountain range approximately 80 km long and 10–15 km wide. The Ailao Shan massif, which is ~20 km wide and >300 km long (Bureau of Geology and Mineral Resources of Yunnan, 1983), may extend southeastward to the DayNuiConVoi (DNCV) metamorphic complex, NW Vietnam.

Both Diancang Shan and Ailao Shan massifs consist largely of high-grade metamorphic complexes with main rock types including paragneiss, augen gneiss, mica schist, hornblende schist, marl, and leucogranite (Leloup et al., 1995). Schistosity is common and parallel to the strike of the ASRR shear zone; and stretching lineations are nearly always horizontal. All kinematic indicators show left-lateral to the strike of the ASRR shear zone, but occurred as a regional response to the India collision between the Simao, South China and Indochina Blocks (Zhang et al., 1994, 1995; Jian et al., 1998; Metcalfe, 1996; Wang et al., 2000b; Metcalfe, 2002).

Moreover, left-lateral ductile shear fabrics clearly occurred during the Tertiary by shear heating along the ASRR shear zone, as constrained by the U–Pb ages of early deformed leucogranites and later cross-cutting leucogranite dykes (Searle et al., 2010).

5. Analytical methods

Zircons were separated from ~3 kg rock samples using conventional heavy-liquid and magnetic separation techniques, and then were cast with zircon standards in epoxy mounts that were polished to section the crystals for analysis. Cathodoluminescence (CL) images (Figs. 3 and 4) were taken at the Institute of Earth Sciences, Academia Sinica, Taipei for examining the internal structures of individual zircon grains and selecting suitable positions for U–Pb and Lu–Hf isotope determinations. In addition to the 3-D thin section petrographic analyses (Yeh et al., in prep.), six out of the eight samples were powdered and subjected to major element determinations using the X-ray fluorescence (XRF) method at the Department of Geosciences, National Taiwan University. The whole-rock XRF results are listed as an Appendix table.

5.1. Zircon U–Pb geochronology

Zircon U–Pb isotopic analyses were performed using a New Wave UP213 laser ablation system combined with an Agilent 7500 s quadrupole ICPMS (inductively coupled plasma mass spectrometer) housed at the Department of Geosciences, National Taiwan University. The LA-ICPMS operating conditions and analytical procedures were the same as those reported in Chiu et al. (2009). Given that in LA-ICPMS zircon U–Pb isotopic analysis, precise age measurements using 206Pb/238U and 207Pb/206Pb ratios are feasible usually only for zircons older than ~800 Ma, due essentially to the fact that 238U comprises less than 1% of natural U and thus relatively little 238U can be produced in the Phanerozoic (cf. Ireland and Williams, 2003), the weighted means of pooled 206Pb/238U ages are used to represent the ages of the young zircons dated. The analytical results are summarized in Appendix Table 1.
Fig. 3 (continued).
5.2. Zircon Lu–Hf isotopic measurements

In-situ Lu–Hf isotopic measurements were subsequently performed by the LA-MC-ICPMS method using a Thermo Finnigan Neptune multicollector-ICPMS and a Geolas CQ 193 nm laser ablation system housed at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Detailed descriptions for the analytical techniques can be found in Wu et al. (2006a). The Lu–Hf isotopes were measured on the dated spots of individual zircons to minimize zoning effects but the laser ablation size is ~50–65 μm, slightly larger than that of preexisting pits (~30 μm), made by the U–Pb dating. The external analytical error of the method is about 4 ε unit (Wu et al., 2006a).

6. Results

6.1. Zircon U–Pb age results

The zircon U–Pb age results are summarized in Appendix Table 1 and plotted using concordia diagrams and histograms in Figs. 3 and 4.
respectively, together with Th/U ratios, a “proxy” for distinguishing zircons of igneous and metamorphic origin (Rubatto, 2002). These results include 206Pb/238U ages of the eight samples, based on a total of 258 individual zircon analyses.

6.1.1. Diancang Shan

6.1.1.1. DS07-08 (Figs. 3a–b, 4a): augen gneiss. The zircons are characterized by euhedral, short prismatic shape with diameters ranging from 150 to 300 μm. In CL images they display oscillatory bands characterized by variation in CL-emission, as commonly observed in magmatic zircons. A few zircons have unzoned rims, which surround oscillatory-zoned cores. Occasionally, cores have features similar to those of detrital zircons, such as rounded crystal shape and diverse internal zoning-patterns. Both these crystallographic domains were analyzed and they gave different results with respect to U- and Th-contents and U–Pb ages. The rims are richer in U (8243–336 ppm) than the cores, which contain ~500 ppm of the element. Both cores and rims have Th/U ratios higher than 0.1, which are characteristic of magmatic zircons (Rubatto and Gebauer, 2000).

A total of 28 spots were analyzed on both cores and rims of the zircon separates. Among these data, 23 analyses form a concordant cluster yielding a mean 206Pb/238U age of 28.7±0.3 Ma (2σ; MSWD=1.5), which, with Th/U ratios of 5–0.13, is interpreted to represent the crystallization or recrystallization age of the zircons from the host magma. Five cores give much older and slightly discordant ages (682–931 Ma), considered to represent inherited zircons that may have experienced certain degrees of Pb loss. Two zircon grains (grains 01 and 14) contain both cores and rims, with Neoproterozoic cores of 708 and 881 Ma and Oligocene rims of 27.7 and 27.9 Ma, respectively (Fig. 3a and Appendix Table 1).

6.1.1.2. DS07-10 (Figs. 3c–d, 4b): biotite gneiss. The zircon separates are irregular in shape, with lengths ranging from 150 to 400 μm, and display unzoned or cloudy-zoned CL image patterns. Most zircons have relatively thick rims (up to 50 μm) that are slightly brighter than the cores. Surfaces of some grains are rounded by resorption, partly underlain by narrow bright seams with dimensions unsuitable for laser-ablation dating. Even so, these zircons have rather uniform U concentrations (237–1476 ppm), and Th/U ratios (0.175–1.020) that are clearly higher than those of zircons of a metamorphic origin (Rubatto and Gebauer, 2000).

A total of 25 analyses on cores and rims form a concentrated and concordant cluster yielding a mean 206Pb/238U age of 769.7±5.1 Ma (2σ; MSWD=0.7), which is interpreted to represent the crystallization age of the zircons, and their host magma, in the Neoproterozoic. Some analyses that plot slightly below the concordia line show younger ages, probably due to radiogenic Pb loss. The two high-U zircon rims (grains 30 and 31, Fig. 3g) exhibit very low Th/U ratios (0.006 and 0.010), similar to the zircons crystallizing at high metamorphic grade (Williams, 1996), and yield 206Pb/238U ages of ~24 Ma, which we interpret as indicating the age of a metamorphic overgrowth event.

6.1.1.5. DS07-20 (Figs. 3i–j, 4c): augen gneiss. The CL images show irregular grains of 100–250 μm in length of the gneiss sample DS07-20A with marginal overgrowth domains and occasional relict cores with different chemical compositions. Most zircons have patchy-diffuse zoning cores with low U contents (60–392 ppm) and medium Th/U ratios (0.328–0.943). Some crystals show latest growth rims with lower luminescence and lower Th/U ratios (0.007–0.080), typical of metamorphic zircons (Rubatto and Gebauer, 2000).

38 analyzed spots on both cores and rims of the zircons yielded two concordant age clusters. The younger cluster gave a mean 206Pb/238U age of 348.4±4.5 Ma (2σ; MSWD=2.4), with high Th/U ratios (0.328–0.943) typical of magmatic zircons, which is interpreted as the age of crystallization and protolith magma emplacement. The younger cluster gave a mean 206Pb/238U age of 33.9±0.7 Ma (2σ; MSWD=1.9), with low Th/U ratios (0.007–0.058) typical of metamorphic zircons, and is thus interpreted as the age of zircon overgrowth or recrystallization during Oligocene metamorphism. A typical metamorphic rim may be represented by grain 06 that yielded 206Pb/238U age of 32.5±0.8 Ma, whereas its core yielded 346.0±7.0 Ma (Fig. 3i).

6.1.2. Ailao Shan

6.1.2.1. AL07-12A (Figs. 3k–l, 4f): biotite gneiss. The zircons are mostly euhedral and of long to short prismatic forms, with lengths of 200–300 μm. CL images of the cores show inherited features such as patchy zoning patterns that appear to have experienced resorption and are surrounded by planar growth banding rims. The inherited cores have diverse U contents ranging from 78 to 693 ppm, with Th/U ratios of 0.065–0.787. The rims, in general, have higher U contents (426–1531 ppm) and variable Th/U ratios (0.218–1.923). Note that all rims show Th/U apparently higher than 0.1 (Fig. 4f), except for one spot that shows very low Th/U of 0.014 (Th = 16 ppm; U = 1139 ppm), perhaps indicative of the presence of Th-rich minerals, e.g., monazite, titanite or allanite, accompanying the zircon crystallization (Rubatto and Gebauer, 2000).

17 analyses from the rims form a concordant cluster yielding a mean 206Pb/238U age of 34.4±0.4 Ma (2σ; MSWD=1.6). Given the high Th/U ratios and zircon structure, this age is interpreted to represent the age of magmatic zircon crystallization, rather than of metamorphic overgrowth. Another 17 analyses of inherited cores yielded slightly discordant 206Pb/238U ages from 164 to 614 Ma. Grain 09, for example, has an Oligocene (33.8±0.6 Ma) rim and a Triassic (228±5 Ma) core (Fig. 3k). Ages of the inherited cores appear to concentrate in two groups around the Permo–Triassic (228–285 Ma; n=7) and early Paleozoic (~500 Ma; n=3), with the former being more abundant and thus implying the involvement of Indosinian crustal material in the magma genesis.
6.1.2.2. AL07-24A (Figs. 3m–n, 4g): biotite gneiss. The sample contains mostly euhedral, transparent, colorless to pale brown zircons, with average crystal lengths being ~150–300 μm and length-to-width ratios from 2:1 to 3:1. CL images show that most zircons have complex internal structures. The cores show oscillatory and sector zoning patterns with highly variable U from 54 to 923 ppm and Th/U ratios from 0.22 to 1.12. Some zircons contain rims displaying oscillatory bands characterized by a strong variation in CL-emission, as commonly observed in magmatic zircons (Rubatto and Gebauer, 2000). Some peripheral domains that show weaker CL-intensity are characterized by higher U concentrations from 280 to 4913 ppm, coupled with Th/U from 0.11 to 1.01, which can also be interpreted as of magmatic origin.

34 spots on 33 zircon grains were analyzed, among which 22 analyses were on rims and yielded a weighted mean 206Pb/238U age of 239 ± 0.3 Ma (2σ; MSWD = 2.0), which is interpreted as the age of zircon crystallization from a host magma during the late Oligocene. The remaining 12 spots were on cores and gave scattered 206Pb/238U ages ranging from 239 to 818 Ma, implying these are inherited zircons derived from a sedimentary source that was involved in the magma generation at ca. 26 Ma to form the protolith of this sample. The rim of grain 29 yielded a 206Pb/238U age of 27.5 ± 0.6 Ma, whereas its core gave 724.0 ± 12.0 Ma (Fig. 3m).

6.1.2.3. AL07-26A (Figs. 3o–p, 4h): augen gneiss. Zircons are dominated by clear to brownish, rounded to short prismatic, partly irregular grains, ranging in size between ~100 and 300 μm. Most zircons reveal oscillatory zoning in CL images, a feature typical of magmatic zircons. Small rounded cores are sometimes preserved. The U contents range from 328 to 1704 ppm, with Th/U ratios of 0.061 ± 0.095. These data suggest that this gneiss sample served in magmatic zircons (Rubatto and Gebauer, 2000). Some parts in 104 deviation of initial 176Hf/177Hf isotopic ratios between −1.4 to +2.2, leading to TDM ages of 1538–1701 Ma, consistent with a simple magmatic source.

6.2. Zircon Hf isotopic results

A total of 249 dated zircon grains from the eight samples were analyzed for 176Hf/177Hf isotopic ratios. The results are listed in Appendix Table 2 and plotted in Figs. 5 and 7. The εHf(T) value, i.e., parts in 10^4 deviation of initial 176Hf/177Hf isotopic ratios between the sample and the chondritic uniform reservoir was calculated after Patchett and Tastumoto (1981) by utilizing the 176Lu/177Hf decay constant reported in Scherer et al. (2000). The zircon Hf isotope crustal model age, TDM, was calculated based on a depleted-mantle source and an assumption that the protolith of the zircon’s host magma has the average continental crust 176Lu/177Hf ratio of 0.015 (Griffin et al., 2002). All calculations are made with following equations:

\[
\epsilon_Hf(T) = \epsilon_Hf(0) - \frac{1}{\lambda_{Lu-Hf}} \times \left( \frac{176\text{Hf}}{177\text{Hf}} \right)^{T_{Sample}} \times \left( \frac{176\text{Hf}}{177\text{Hf}} \right)^{T_{CHUR}} - 1 \\
\times 10^4 \quad (\text{Patchett and Tastumoto, 1981})
\]

\[
T_{DM} = \frac{1}{\lambda} \times \ln \left( \frac{(f_{Hf}^{176\text{Hf}})^{Sample}}{(f_{Hf}^{176\text{Hf}})^{DM}} \right) \\
- \left( \frac{176\text{Lu}}{177\text{Hf}} \right)_{DM}
\]

\[
f_{Hf}^{176\text{Lu}} = \left( \frac{176\text{Lu}}{177\text{Hf}} \right)_{Source} \times \left( \frac{176\text{Lu}}{177\text{Hf}} \right)_{CHUR} - 1
\]

\[
176\text{Hf} / 177\text{Hf} \quad \text{DM} = 0.0384 \quad (\text{Griffin et al., 2000})
\]

\[
176\text{Hf} / 177\text{Hf} \quad \text{DM} = 0.28325 \quad (\text{Nowell et al., 1998})
\]

\[
176\text{Lu} / 177\text{Hf} \quad \text{mean runt} = 0.015 \quad (\text{Griffin et al., 2002})
\]

\[
f_{Hf}^{176\text{Lu}} = \frac{(f_{CC})_{Continental ~Crust} - 0.015}{0.0332} - 1 = -0.5482
\]

\[
f_{Hf}^{176\text{Lu}} = \frac{(f_{DM}^{Depleted ~Mantle}) - 0.0384}{0.0332} - 1 = 0.1566
\]

If alternative decay constants proposed by other subsequent studies were used, our conclusions would not be significantly affected. Note that zircons can effectively preserve the initial Hf isotope ratios of their host magmas, thus allowing their Hf isotope compositions to be utilized in much the same way as whole-rock Nd isotopes have been utilized as a powerful geochemical tracer for petrogenesis. For example, assuming that the protolith of a zircon’s host magma had the 176Lu/177Hf ratio of the average continental crust (0.015), its Hf crustal model age, or TDM, may give a reasonable estimate of the elapsed time since the host magma was derived from a presumed depleted mantle source.

6.2.1. Diancang Shan

6.2.1.1. DS07-08 (Fig. 5a). The inherited zircon cores exhibit various Hf isotope ratios, with εHf(T) values ranging from −2.8 to +11, yielding TDM ages between 1062 and 1842 Ma. The rims, which gave a mean Oligocene age of 28.7 ± 0.3 Ma, in contrast, have more uniform U-Pb ages, and Hf isotopes from rims (Fig. 5a). This requires a petrogenic process capable of homogenizing the Hf isotopic composition when the zircon rims were crystallized in the Oligocene, consistent with a magmatic origin.

6.2.1.2. DS07-10 (Fig. 5b). Zircon Hf isotopic compositions of this sample are very uniform. 24 analyses of the Neoproterozoic zircons yield εHf(T) values from −1.4 to +2.2, leading to TDM ages of 1538–1701 Ma, consistent with a simple magmatic source.
6.2.1.3. DS07-16 (Fig. 5c). The zircon rims that gave a mean Indosinian U–Pb age (243.0±1.7 Ma) show negative ε$_{\text{Hf}}$(T) values ranging from $-14.9$ to $-8.0$, yielding T$_{\text{DM}}$ ages from 1778 to 2172 Ma. More heterogeneous Hf isotope ratios are observed in the inherited zircon cores, with ε$_{\text{Hf}}$(T) values varying from $+7.3$ to $-23.3$ and T$_{\text{DM}}$ ages from 1806 to 2960 Ma. The Hf isotope data support the notion that the inherited zircons were derived from a Proterozoic crustal rock and were captured by the protolith magma when the latter was emplaced in the Triassic.

6.2.1.4. DS07-19A (Fig. 5d). The Indosinian magmatic zircons (234.9±1.8 Ma) from this sample have high, positive and uniform ε$_{\text{Hf}}$(T) values from $+10.2$ to $+13.5$, yielding young T$_{\text{DM}}$ ages of 394–617 Ma, suggesting dominant mantle input in the petrogenesis of protolith magma. High and positive ε$_{\text{Hf}}$(T) values are also present in the two metamorphic rims.

6.2.1.5. DS07-20 (Fig. 5e). Both the magmatic cores (348.4±4.5 Ma) and metamorphic rims (33.9±0.7 Ma) show high and uniform Hf isotope ratios. The zircon cores have ε$_{\text{Hf}}$(T) values from $+10.9$ to $+15.7$, corresponding to T$_{\text{DM}}$ ages from 339 to 665 Ma that overlap with their U–Pb ages. The rims have ε$_{\text{Hf}}$(T) values from $+6.7$ to $+11.9$ and T$_{\text{DM}}$ ages from 348 to 684 Ma, implying that an isotopic equilibrium was achieved during the Oligocene metamorphism.

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**Fig. 5.** Plots of ε$_{\text{Hf}}$(T) values versus U–Pb ages of zircons from each sample in the Diancang Shan and Ailao Shan massif. 2σ error bars of individual analyses are smaller than the symbols. Data are shown with circles and diamonds when respective analyses in rim and core in one zircon grain can be done, otherwise in squares if core-rim structure was not observed. Dashed tie-lines are shown when both core and rim of the same zircon grain were analyzed.
6.2.2. Ailao Shan

6.2.2.1. AL07-12A (Fig. 5f). Both the magmatic zircon rims (34.4 ± 0.4 Ma) and inherited cores (aged from 164 to 614 Ma) are heterogeneous in Hf isotopic compositions. The cores have εHf(T) values from +14.8 to −12.0, corresponding to TDM ages of 357–2119 Ma. In comparison, the rims have εHf(T) values from +10.1 to −2.3, yielding a relatively narrower range of TDM ages from 577 to 1262 Ma. The −12±6 εHf units of Hf isotopic variation observed in the zircon rims, significantly larger than the external analytical errors of the method (−4±6 unit; Wu et al., 2006a), imply a heterogeneous isotopic composition of the Oligocene protolith magma.

6.2.2.2. AL07-24A (Fig. 5g). A large range of εHf(T) values from −10.6 to +10.9 was observed in the inherited zircon cores from this sample, yielding TDM ages between 1074 and 1938 Ma. The magmatic rims, gave a mean U–Pb age of 26.2 ± 0.3 Ma, in comparison, show a less variable εHf(T) values from −4.8 to +1.4, with TDM ages of 1078–1371 Ma, in general correspondence with those of the inherited zircon cores.

6.2.2.3. AL07-26A (Fig. 5h). Most zircons from this sample have negative εHf(T) values from −13.4 to +0.7, leading to TDM ages of 1491–2327 Ma. The Indosinian magmatic zircons (239.4 ± 1.9 Ma) and the four Oligocene metamorphic rims (−29 to 34 Ma) display similar εHf(T) values between −2.4 and −10.7, yielding TDM ages between 1263 and 1937 Ma.

7. Discussion

7.1. Ages and petrogenesis of protoliths

Zircon U–Pb data indicate that the ASRR gneissic samples have a wide range in age distribution (Fig. 6), and thus a complex history of protolith petrogenesis, which may be divided into several major stages as follows:

7.1.1. Neoproterozoic (ca. 770 Ma)

Along with sporadic grains of Mesoproterozoic ages, an old Neoproterozoic zircon age cluster from ca. 650 to 1000 Ma and peaking at 769 ± 8 Ma can be noted (Fig. 6). This age peak composed of 28 dates from samples DS07-08, DS07-10 and AL07-24A (Appendix Table 1 and Fig. 4), is identical to the magmatic protolith age of sample DS07-10 (769.7 ± 5.1 Ma; Fig. 3d). In South China, Neoproterozoic gneissic rocks emplaced from ca. 830 to 740 Ma are widespread (Fig. 1: Wang et al., 2010 and references therein) and range in composition from mafic to felsic. Some authors have related these Neoproterozoic rocks to mantle-plume activities that provoked not only the breakup of Rodinia but also an orogenic event leading to major crustal formation or cratonisation of the Yangtze Block (Li et al., 1999,2003a,2003b; Wang et al., 2010). Zircon Hf isotope data obtained from these Neoproterozoic intrusive bodies or granitoids show a significant variation in εHf(T) values from +12.4 to −24.1 (Fig. 7: Chen et al., 2007b; Wu et al., 2006b; Zhang et al., 2008; Zheng et al., 2007, 2008; Zhao et al., 2008; Wang et al., 2010). This can be interpreted as evidence for binary mixing of magmas derived from two major source components: (1) Neoproterozoic juvenile crust produced by melting of mantle during the breakup of Rodinia (cf. Li et al., 2003a; Zheng et al., 2008) and (2) Mesoarchean Yangtze crust that remelted during the tectonic collapse of a thickened intracontinental orogen (cf. Zhang et al., 2008). Based on our data, the Neoproterozoic zircons within the ASRR, show markedly variable εHf(T) values (Fig. 7, Appendix Table 2), with those of magmatic zircons from sample DS07-10 being uniform and close to zero while other inherited zircons from samples DS07-08 and AL07-24A display values varying from +10 to −3, suggesting the involvement of both components of the crustal source material.

7.1.2. Cambrian (ca. 520 Ma)

Inherited zircons dated at the early to middle Cambrian (535–500 Ma) are occasionally observed from samples DS07-16, AL07-12A, AL07-24A and AL07-26A (Fig. 6). These zircons show markedly heterogeneous Hf isotopic compositions, with εHf(T) values varying from 1 to −15 (Fig. 7, Appendix Table 2). These Cambrian zircons, given their inherited origin, may be correlated with the Early Paleozoic (ca. 500 Ma) granitoids emplaced in western Yunnan, in the Gaoligong, Baoshan and Tengchong areas (Chen et al., 2007a; Song et al., 2007; Liu et al., 2009), located within the northern Sibumasu terrane, west of the ASRR shear zone (Fig. 1). Major magmatic activity of Pan-African age, between ca. 570 and 510 Ma (e.g., Cawood and Buchan, 2007), has not yet been documented in the western Yangtze or other parts of the South China Block.

7.1.3. Devonian–Carboniferous (ca. 350 Ma)

A specific stage of protolith formation during the Devonian–Carboniferous boundary is observed in sample DS07-20 that gave an age cluster of zircon cores at ca. 350 Ma (Fig. 3j), coupled with positive and high εHf(T) values (Fig. 5e). The highly positive εHf(T) requires a dominating depleted mantle input during the petrogenesis and is difficult to link to any major magmatic events in South China. We note, however, that coeval zircon U–Pb ages have been reported for plagiogranites from the Jinshajiang–Ailaoshan ophiolites (Wang et al., 2000b; Jian et al., 2003, 2008), interpreted as relics of the oceanic crust from a branch of the Paleo-Tethys (Zhang et al., 1995; Metcalfe, 1996). This part of the Paleo-Tethys branch may have evolved diachronously, with main seafloor spreading taking place earlier in the Ailaoshan segment (ca. 387–377 Ma) and slightly
later in the Jinfojiang segment (ca. 346–341 Ma) (Jian et al., 2009).

We therefore attribute the protolith of sample DS07-24A to have played a role in the magma generation. Consequently, these samples into two subgroups: (1) magmatic zircons that have apparently lower and mostly negative $\epsilon_{\text{Hf}}(T)$ values to +13.5), and those from samples DS07-16 (ca. 243 Ma) and (2) metamorphic zircons that have lower Th/U and little internal structure (e.g., sample DS07-20).

Along the ASRR shear zone, there exist numerous small-volume Oligocene granitic bodies that consist of two major rock types: (1) alkaline rocks largely of monzonite–syenite lithologies, and (2) leucogranites crystallized from crustal melts (Zhang and Schärer, 1999; Leloup et al., 2001; Searle, 2006; Searle et al., 2010). The petrogenesis of both rock types has long been a subject of debates (e.g., Leloup et al., 2007; Searle, 2007; Chung et al., 2008), which will be reiterated in more detail in the following section. Here we relate crystallization of the Oligocene magmatic zircons (rims and cores) to the alkaline magmatism that was active during ca. 35 to 24 Ma within and outside of the ASRR shear zone (Chung et al., 1997; Zhang and Schärer, 1999; Liang et al., 2007; Chung et al., 2008). This is perhaps best exemplified by sample AL07-12A with whole-rock SiO$_2$ and K$_2$O contents of ~60 and 7.4 wt.%, respectively (Appendix Table 3), suggesting a protolith magma of intermediate and highly potassic composition that crystallized at ca. 34 Ma and captured older inherited zircons from the host crustal rocks.

The alkaline magmas have been generally considered as originating from a metasomatized lithospheric mantle source (Chung et al., 1997; Zhang and Schärer, 1999; Xu et al., 2001), which existed prior to the India–Asia collision. They show outcrops away from the ASRR and thus have little to do with the ASRR sinistral shearing (Chung et al., 2008). In the ASRR shear zone, the ubiquitous left-lateral kinematic indicators are low-temperature fabrics, implying that the fault was purely a crustal structure (Searle, 2006) that could hardly induce partial melting of the lithospheric mantle. Moreover, the left-lateral fabrics were superimposed on all earlier formed metamorphic rocks and associated granitoids (Yeh et al., 2008; Searle et al., 2010). In the cases of samples DS07-08 and AL07-24A, with higher SiO$_2$ contents of ~70 wt.%, remelting of greater amounts of the host rocks seems to have played a role in the magma generation. Consequently, these two samples have apparently lower and mostly negative $\epsilon_{\text{Hf}}(T)$ values in their Oligocene magmatic zircons (Figs. 5 and 7).

7.1.5. Oligocene

Another principal group of zircon results yielded age clusters between ca. 35 and 26 Ma in the Oligocene, which may be divided into two subgroups: (1) magmatic zircons that have apparently higher Th/U ratios and oscillatory zoning (e.g., samples DS07-08, AL07-12A and AL07-24A) and (2) metamorphic zircons that have lower Th/U and little internal structure (e.g., sample DS07-20).
rocks have apparently older protoliths that cannot have been produced by the Tertiary shear heating. Many zircons from the rocks reveal core-rim structures, with core ages peaking at ca. 770, 350 and 240 Ma while the rims ages are between ca. 34 and 26 Ma (Fig. 6). The zircon rims show significant variations in Th/U ratios (5–0.01) and εHf(T) values (+14 to −10), suggesting complicated magmatic and/or metamorphic overgrowths during the Oligocene. The occurrence of both magmatic and metamorphic overgrowths of zircons may suggest that the ASRR gneisses underwent regional metamorphism to the upper amphibolite facies, corresponding to mid-crustal level P–T conditions, as suggested by the structural and petrologic data (e.g., Leloup et al., 1995). However, our recent work (e.g., Searle et al., 2010) demonstrated that in the ASRR shear zone the left-lateral fabrics are low-temperature (<550°C) and late features that crosscut and postdate all other metamorphic and magmatic lithologies. Under such a framework, our new data suggest that the gneisses underwent regional magmatic and metamorphic overprinting in the Oligocene before the initial left-lateral movement along the ASRR shear zone and the sinistral, ductile deformation may have only partly reset the zircon U–Pb isotope systematics. Besides, there is no spatial and temporal correlation between the sample localities and their age records. Therefore, the Diancang Shan and Ailaoshan massifs represent two fragmentary and inhomogeneous belts, in which high-grade metamorphic rocks did not undergo a complete isotopic resetting by the collision-related thermal/tectonic events prevailing in Southeast Asia.

7.3. Implications for crustal evolution in SW China

The ASRR gneisses that represent exposed, mid-crustal basement rocks may serve as rare samples for studying the crustal evolution at depth along the southwestern margin of the Yangtze Block of South China. In addition to U–Pb dating, zircons can effectively preserve the initial Hf isotope ratios of their host magmas. Thus, their Hf isotopic compositions have been utilized as a geochemical tracer of magmatic origin in the same way as whole-rock Nd isotope data, and may provide an even more powerful tool than Nd isotopes for detailed petrogenetic studies (cf. Griffin et al., 2002; Chiu et al., 2009). Hf crustal model ages of zircons, denoted as TDMc, representing a minimum age for the source of the host magma, may offer reasonable estimates of the crustal residence time since which the host magmas were derived from the presumed depletions–mantle source (Griffin et al., 2002), especially in the case where juvenile crustal reworking occurs (e.g., Zhang et al., 2006). However, zircon Hf model ages do not necessarily have a chronological significance but, as the whole-rock Nd model ages (cf. Arndt and Goldstein, 1987), often reflect mixtures between older and younger material.

Our U–Pb results indicate that the ASRR gneissic rocks have four magmatic zircon age clusters at ca. 770, 350, 240, and 34–26 Ma, respectively, suggesting four principal stages of protolith formation. The Hf isotopes of these zircons, moreover, yield three model ages that are consistent with magma generation by remelting of the Neoproterozoic crust with the εHf(T) values of the associated inherited zircons (Fig. 5). Their TDMc ages, therefore, overlap in part those of the Neoproterozoic Kanding granitoids (Fig. 7) and detrital zircons from Neoproterozoic strata of the western Yangtze Block (Sun et al., 2009). The latter have been used to define two older stages of main igneous events coupled with crustal formation around 1700–1900 and 2300–2500 Ma, respectively, in the Yangtze Block. In this study, however, no zircons of such old ages are observed from the ASRR gneisses. The zircon U–Pb age spectra of both Diancang Shan and Ailaoshan rocks resemble in general the age distribution of detrital zircons from riverbank sediments in the Red River, NW Vietnam (Hoang et al., 2009); but the latter have a more complex U–Pb age spectrum and Hf TDMc ages that may be attributed to more heterogeneous sources.

8. Concluding remarks

Zircon U–Pb dating results of gneisses from the Diancang Shan and northern Ailaoshan segments of the ASRR shear zone show diverse age spectra implying that the rocks have undergone complicated magmatic and tectonic histories. Combined zircon U–Pb and Hf isotopic data suggest that the protoliths resulted from multiple magmatic events, related to the Neoproterozoic magmatism in South China, the Pan-African orogeny associated with Gondwana assembly, the Emeishan LIP formation, and the Palaeogene alkaline magmatism and metamorphism in Yunnan. Moreover, some rocks may be remnants of the Paleo-Tethys now exposed in the Jinhaijiang–Ailaoshan suture zone.

Cenozoic ductile deformation along the ASRR shear zone may have only partly reset the zircon U–Pb isotope systematics. Judging from the absence of spatial and temporal correlation between the sample localities and their age records, we conclude that the Diancang Shan and Ailaoshan massifs are fragmentary and inhomogeneous belts in which high-grade metamorphic rocks have not experienced a complete isotopic resetting by the Cenozoic thermal/tectonic event prevailing in Southeast Asia.

Zircon TDMc model ages of the gneisses vary from the Paleozoic to Palaeoproterozoic, two samples from the Diancang Shan (DS07-20 and DS07-19A) have the youngest TDMc model ages of 400–600 Ma, implying higher proportions of juvenile mantle input than that of the eoaeal Emeishan LIP during their petrogenesis. Sample DS07-10, which has TDMc model ages of ~1700 Ma plotting in the model age gap of the Neoproterozoic granitoids, may represent binary mixing of melting product sourced from the juvenile mantle/crust and the old Yangtze continental crust.

Lastly, this study exemplifies the usefulness of in-situ LA-ICPMS analysis of the ASRR shear zone that, exposed in several high-grade
metamorphic massifs, provides a rare opportunity to sample the mid-crustal rocks of the southwestern margin of the Yangtze Block of South China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.chemgeo.2011.11.011.

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