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Detrital Zircon U-Pb Geochronology and Lu-Hf Isotopic Compositions of the Wuliangshan Metasediment Rocks in SW Yunnan (China) and Its Provenance Implications

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ABSTRACT: The Wuliangshan Group occurs to the east of the Lancang giant igneous zone in SW Yunnan, and is mainly composed of low-grade metamorphosed sedimentary rocks. The group has been considered as the syn-orogenic product of the Baoshan with Simao-Indochina blocks. However, its depositional time and provenance remain to be poorly constrained. This paper presents zircon U-Pb dating and Lu-Hf-isotopic data for five representative sandstone samples from the Wuliangshan Group. The detrital grains yield a major age-peak at ~259 Ma, and four subordinary age-peaks at ~1 859, ~941, ~788, and ~447 Ma, respectively. Our results suggest that the Wuliangshan metasedimentary sequence was deposited after Middle Triassic rather than previously-thought Cambrian. The detrital zircon age spectrum, along with in-situ Lu-Hf isotopic data suggest that the Wuliangshan Group might be a syn-collisional sedimentary product related to the collision of Baoshan with Simao-Indochina blocks. It is inferred that the provenance of the Wuliangshan Group is mainly from the Simao/Yangtze blocks to the east rather than the Baoshan Block or Lancang igneous zone to the west.

KEY WORDS: detrital zircon U-Pb dating, Lu-Hf isotopic composition, Wuliangshan sandstone sequence, Middle Triassic, Simao-Indochina.

0 INTRODUCTION

The SE Asia has been assembled by a series of collision and accretion processes involving numerous continental blocks or fragments separated from the East Gondwana since the Paleozoic (Faure et al., 2014; Metcalfe, 2006). The catchment areas of the Lancang, Jinsha and Nujiang rivers (also named Sanjiang in Chinese literature) in SW Yunnan (SW China) have preserved abundant paleotethyan heritages (e.g., the Lincang giant igneous zone) at which kilometer-thick Triassic volcanic rocks and Upper Triassic/Lower Jurassic molasse sediments are considered to have resulted from closure of the Paleotethys main ocean and subsequent continental collision (Peng et al., 2008, 2006; Jian et al., 2003a, b; Mo et al., 1998; Zhong, 1998; Cong et al., 1993; Mahawat et al., 1990; Liu et al., 1989; Zhang et al., 1985).

It has been commonly accepted that the Paleotethys main ocean was closed by an eastward subduction beneath the Indochina-Simao Block in the Permian–Triassic (Zaw et al., 2014; Wang et al., 2010). However, the precise timing of the initial collision of the Baoshan and Simao-Indochina blocks remains to be disputed. Previous studies focused on the origin of the Triassic igneous rocks along the Lancangjiang tectonic zone. Little attention has been paid to the coeval sedimentary rocks which preserved abundant geological records on the Paleotethyan tectonic evolution. The sedimentary rocks can provide key information to the time of closure of the Paleotethyan Ocean and subsequent collision of the Baoshan and Simao-Indochina blocks. The Wuliangshan Group occurs to the east of the Lancang giant igneous zone. It is mainly composed of low-grade metamorphosed sedimentary rocks. This group is likely syn-orogenic product of the Paleotethyan orogeny although its depositional time and provenance are still disputed. In this paper, we have carried out comprehensive detrital zircon U-Pb dating and Lu-Hf isotope analyses on the Wuliangshan metamorphic sandstones in SW Yunnan. Our results indicate that the Wuliangshan Group was deposited at the Middle Triassic, and the provenance was from the Simao and western Yangtze blocks, most likely the Ailaoshan tectonic zone, rather than the Baoshan Block or Lancangjiang igneous zone, and further constrain the collision of the Baoshan and Simao-Indochina blocks occurring at Middle Triassic period.

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1 GEOLOGICAL BACKGROUND

The Tethyan-Himalaya tectonic domain is located between the Gondwana and Eurasia continents. The Sanjiang area in SW Yunnan (SW China) has preserved abundant Tethyan geological records and is considered an important segment of the eastern Tethyan-Himalaya tectonic domain. This region involves, from east to west, the western margin of the Yangtze Craton, the Lanping-Simao and Baoshan blocks, which are separated by the Jinshajiang-Ailaoshan, and Lancangjiang-Changning-Menglian suture zones (Figs. 1a–1b; Liu et al., 2009; Zhong, 1998; Metcalfe, 1996). The Simao Block is considered to have an affinity to the Yangtze Block, which consists of Archean to Paleoproterozoic crystalline basement and Neoproterozoic to Paleozoic and marine sediments (Cawood et al., 2013; Wang et al., 2013; Gao et al., 1999), and to represent the northern extension of the Indochina Block (Zhong, 1998; Metcalfe, 1996), In the Simao Block, Lower Paleozoic metasedimentary rocks are overlain by the Middle Devonian conglomerates by an unconformity (Feng et al., 2000; Zhong, 1998; Yunnan BGMR, 1990). The Ailaoshan suture zone comprises structurally juxtaposed successions of variably metamorphosed Proterozoic and younger rock assemblages. The Baoshan Block to the west of the study area is a component of the Sibumasu fragment with an affinity to the Gondwana land, and the basement comprises the Ximeng, Lancang and Gaoligong metamorphic complexes (e.g., Metcalfe, 2002, 1996; Zhong, 1998; Yunnan BGRM, 1990).

The Wuliangshan area is situated to the east of the Lancang River or the Lancang giant igneous zone, and belongs to the western Simao Block (Figs. 1b–1c). The Paleozoic and Lower Triassic strata are composed of low-grade metamorphosed clastic, volcanic and carbonatite rocks, which are unconformably overlain by the Upper Triassic–Lower Jurassic sedimentary rocks. The dominant feature of the area is the development of a low-grade metamorphic sequence that has been mapped as the Wuliangshan Group and previously believed to be of Cambrian or Triassic origin (e.g., Yunnan BGMR, 1979, 1975). The Wuliangshan Group is divided into five segments from bottom to top (Figs. 1c and 2). Segment I at the bottom has a thickness of over 1 300 m and is composed lithologically of leptite, quartzite and quartz schist. Segment II, with a thickness of ~670 m, comprises quartz schist, quartz microcrystalline schist, metasandstone and slate. Segment III is characterized by gray-green metamorphic calcareous sandstones, mica microcrystalline schist and phyllite. Segment IV is in conformable contact with the Segment III and is composed of carbonaceous slate, calcareous slate and sandy slate with a thickness of ~500 m. Segment V is marked by dolomitic limestone, carbonaceous slate and schist. Our samples 09YN-8 and 09YN-3 in this study were taken from segments I and IV,

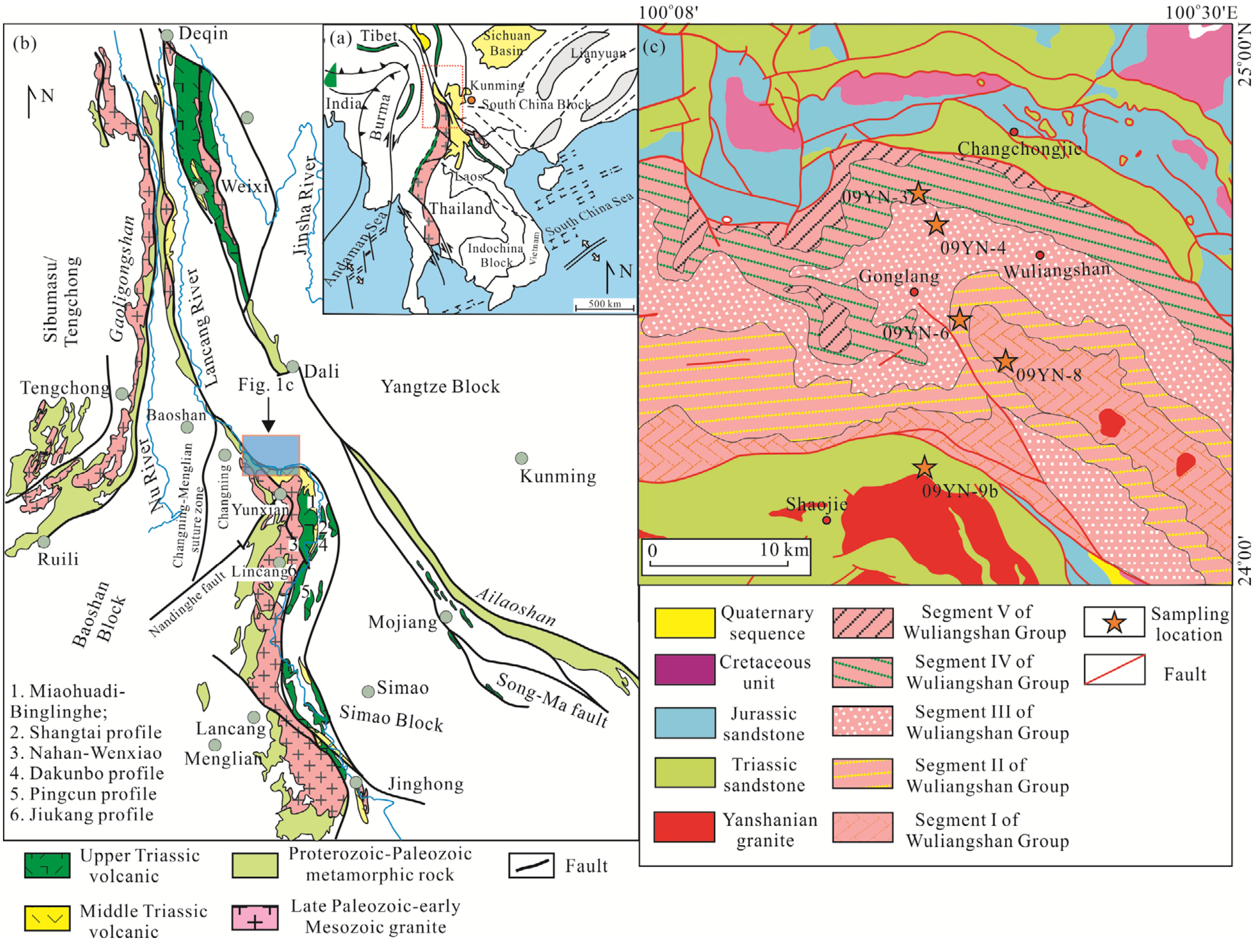

Figure 1. (a) Tectonic outline of Southeast Asian; (b) simplified geological map of SW Yunnan; (c) geological map of the Wuliangshan area (revised from 1 : 200 000 geological map of Weishan, Yunnan).

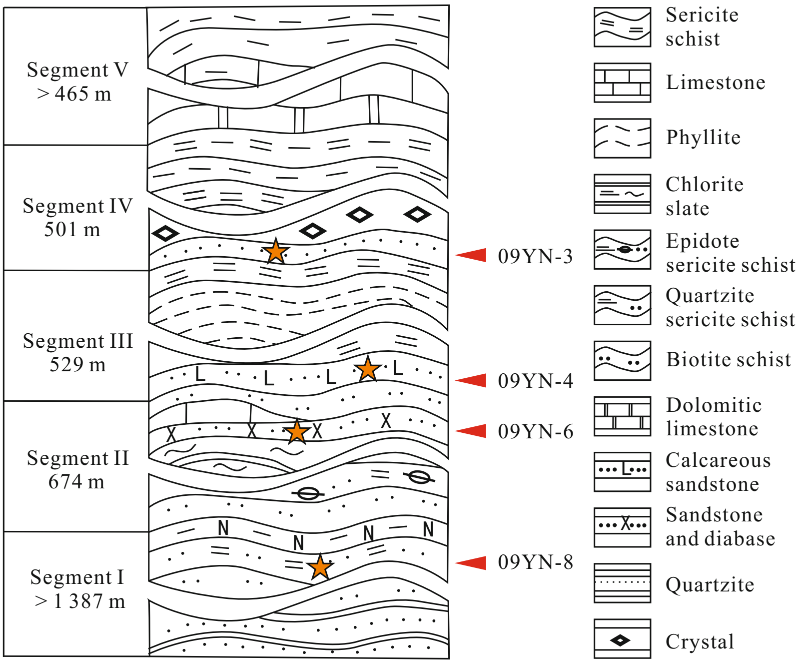

Figure 2. Stratigraphic column of the Wuliangshan Group (revised from 1 : 200 000 geological map of Weishan, Yunnan, BGMR, 1975).

respectively, and 09YN-6 and 09YN-4 from Segment II and Segment III, respectively. Sample 09YN-9b is a calcareous sandstone sample from the sandstone interlayer in the Upper Triassic volcanic sequence that overlies the Wuliangshan Group. All the samples from Wuliangshan Group have similar mineral assemblages including quartz, mica and plagioclase with minor rutile, epidote, zircon and apatite (Fig. 3). The sampling locations and stratigraphic assemblages are shown in Fig. 1c and Fig. 2.

2 ANALYTICAL METHODS

2.1 LA-ICP-MS Zircon U-Pb Dating

Zircon grains are separated by conventional heavy liquid and magnetic techniques, and then handpicked under a binocular microscope. They were mounted in epoxy, polished and coated with gold and then photographed in transmitted and reflected light. To examine their internal texture, cathodoluminescence (CL) images were obtained on a JEOL JXA-8100 electron microprobe at the Institute of Geology and Geophysics (IGG), Chinese Academy of Sciences (CAS). The U, Th and Pb isotopes measurements for the studied samples 09YN-3, 09YN-4, 09YN-6, 09YN-8, and 09YN-9b were conducted using an Agilent 7200a quadruple (Q)-ICPMS attached with a Geolas laser-ablation system equipped with a 193 nm Ar-F-excimer laser in the IGGCAS. The data acquisition mode involved peak jumping and raw count rates were measured for ^{29}Si, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, and ^{235}U, U, Th and Pb concentrations were calibrated using ^{29}Si. CN92-1, 91500, GJ-1 and Plesovice. The instrumental settings and detailed analytical procedures have been described by Xia et al. (2011), Wu et al. (2006) and Yuan et al. (2004). Common Pb correction was in accordance with the method of Andersen (2002). U-Pb ages and concordia diagrams were prepared using ISOPLOT3.00 (Ludwig, 2001). Individual analyses in the data table and concordia plots are presented with 1σ errors, and uncertainties in weighted mean ages are quoted at the 95% confidence level (2σ). The analytical results are listed in Table S1. The zircons are mostly euhedral, subhedral and columnar with well-developed oscillatory zoning, typical of an igneous origin (Figs. 4–5). The U-Pb ages for these grains are mostly concordant or only slightly disconcordant (Figs. 4–5 and Table S1), and only grains with less than 10% discordance are considered in this study. ^{207}Pb/^{206}Pb ages are used for zircons older than 1 000 Ma and ^{206}Pb/^{238}U ages for younger grains.

2.2 Zircon In-Situ Lu-Hf Isotopic Analyses

Zircon in-situ Lu-Hf isotopic ratio analysis was carried out using a Geolas-193 laser-ablation microprobe, attached to a Neptune multi-collector ICP-MS at the University of Hong Kong. External calibration was made by measuring zircon standard 91500 during the analyses to evaluate the reliability of the analytical data, which yielded a weighted mean ^{176}Hf/^{177}Hf ratio of 0.282 307±0.000 031 (2σ). The instrumental conditions and detailed analysis of the process were performed according to Yuan et al. (2008). The interference of ^{176}Yb on ^{176}Hf was corrected by measuring the interference-free ^{173}Yb isotope and using the ratio ^{176}Yb/^{173}Yb=0.793 810 to calculate ^{176}Yb/^{177}Hf. Similarly, the relatively minor interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of the interference-free ^{175}Lu isotope and using the recommended ratio ^{176}Lu/^{175}Lu=0.026 560 (Blichert-Toft and Albarede, 1997) to calculate ^{176}Lu /^{177}Hf. The calculation of the initial Hf isotope values used the ^{176}Lu decay constant of 1.865×10^{-11} a^{-1} (Schärer et al., 2001). The ratio of ^{176}Yb/^{172}Yb (0.588 700) was applied for the Yb correction. The calculated model ages (T_{DM}) are based on the depleted mantle model described by Griffin et al. (2000). The analytical results for zircon in-situ Lu-Hf isotopic compositions are listed in Table 2.

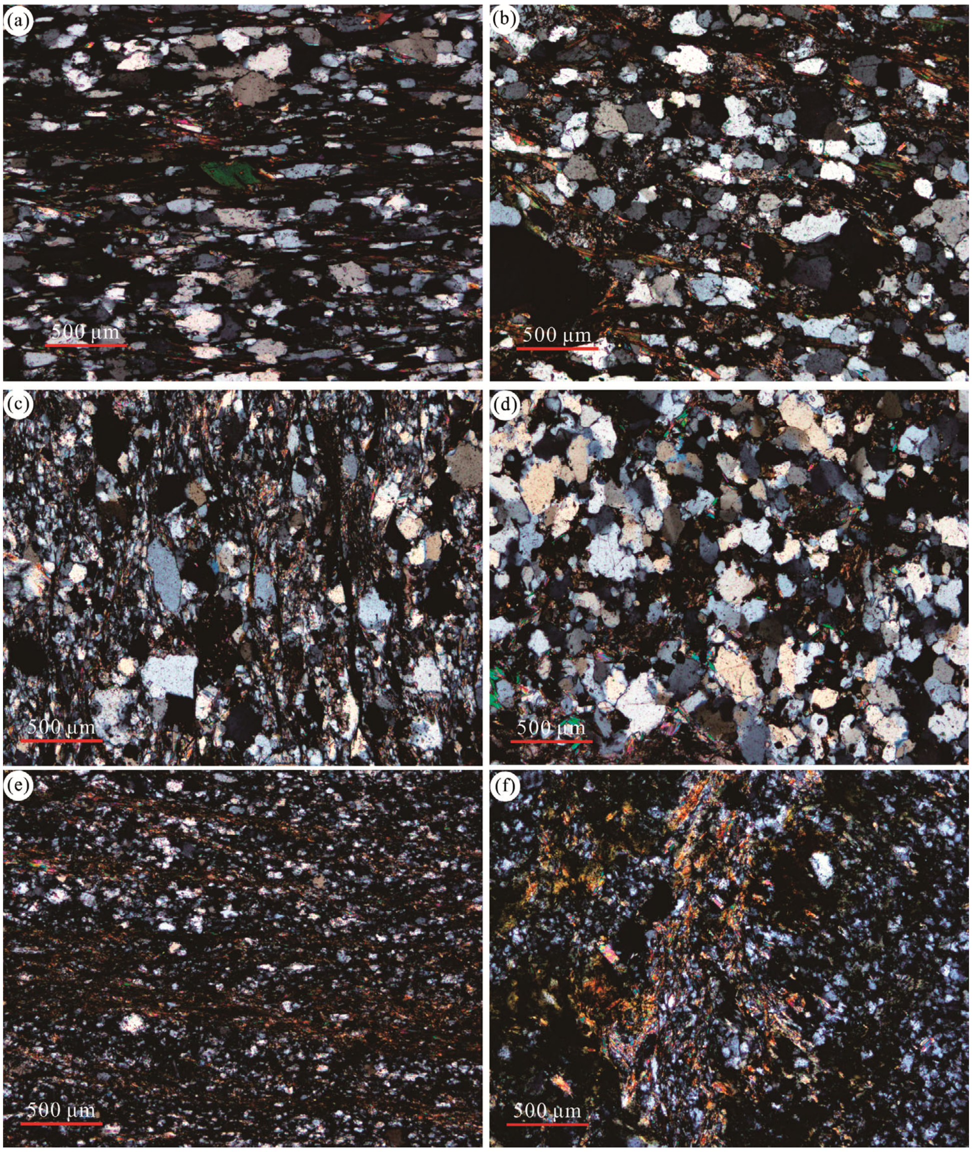

Figure 3. The microscope photos of metamorphic sandstone samples from the Wuliangshan Group, SW Yunnan. (a) Sample 09YN-3; (b) sample 09YN-4; (c) sample 09YN-6; (d) sample 09YN-8 and (e)–(f) sample 09YN-9b.

3 RESULTS

Calcareous sandstone 09YN-8: This sample, representative of Segment I of the Wuliangshan Group, comes from north of Banqiao Village. The youngest apparent age is 248±8 Ma given by spot 09YN-8-21 (Fig. 4a). Among the 48 analyzed grains, spot 09YN-8-12 gives the oldest age of 3 424±52 Ma. Five major age peaks are ~1 800, ~976, ~600, ~471, and ~259 Ma (Fig. 4b).

Calcareous phyllite 09YN-6 is a calcareous phyllite from the Segment II of the Wuliangshan Group at southeast of Gonglang Town. Forty-two grains from this sample were selected for the U-Pb dating (Table S1 and Fig. 4c). Spot 09YN-4-40 gives the youngest U-Pb apparent age of 243±6 Ma. The main age group, accounting for half of the analyzed spots, ranges from 304 to 243 Ma with peak at ~269 Ma (Fig. 4c). Smaller age-peaks include ~957, ~751, ~498, and ~437 Ma (Fig. 4d).

Calcareous sandstone 09YN-4: This sample, taken from about 200 m south of sample 09YN-3, is the representative of the Segment III of the Wuliangshan Group. The oldest and youngest grains give the apparent age of 3 456±16 (spot 09YN-4-27) and 241±8 Ma (spot 09YN-4-36), respectively (Fig. 4e). Forty-nine spots yield three main age-peaks at ~929, ~424, and ~247 Ma and three secondary age-peaks of ~2 471, ~1 671, and ~741 Ma (Fig. 4f).

Phyllite 09YN-3: Fifty-five detrital zircon grains were analyzed for this sample from Segment IV of the Wuliangshan Group (Table S1). The majority of the analytical spots plot along or near the concordia curve (Fig. 5a). The oldest spot gives a $^{207}Pb/^{206}Pb$ age of 2 739±34 Ma (spot 09YN-3-9), whereas the youngest grain yields a $^{206}Pb/^{238}U$ apparent age of 255±5 Ma (spot 09YN-3-13). All the analyses define four major age-peaks at ~1 065, ~785, ~447, and ~266 Ma (Fig. 5b). Zircon in-situ Lu-Hf isotopic compositions for 39 grains are also measured (Table 2 and Fig. 6). The $^{176}Hf/^{177}Hf$ values for these analyses range from 0.282 638 to 0.280 942, and the

^{176}Lu/^{177}Hf values are from 0.001 816 to 0.000 211. The corresponding $\varepsilon_{\rm Hf}(t)$ values have wide variations ranging from -20.1 to +2.5, with most grains giving negative $\varepsilon_{\rm Hf}(t)$. The model ages ($T_{\rm 2DM}$) are from 3.6 to 1.2 Ga.

Calcareous sandstone 09YN-9b: This sample was collected from the sandstone interlayer in the Upper Triassic volcanic sequence. Twenty-nine grains were analyzed for this sample. The youngest apparent age of 230±5 Ma is given by spot 09YN-9b-8. More than 68% spots give the ^{207}Pb/^{206}Pb apparent age of older than 1 700 Ma (Fig. 5c). The smallest age group consists of three grains with age at 230–288 Ma. The age-peaks mainly are at ~2 495, ~2 380, and ~1 853 Ma (Fig. 5d).

4 DISCUSSION

4.1 Constraints on the Deposition Time of the Wuliangshan Group

The Wuliangshan Group has experienced low-grade metamorphism and is characterized by leptite, quartzite, schist, metasandstone, phyllite, slate, dolomitic limestone. The depositional time of this group has been hotly disputed, as manifested

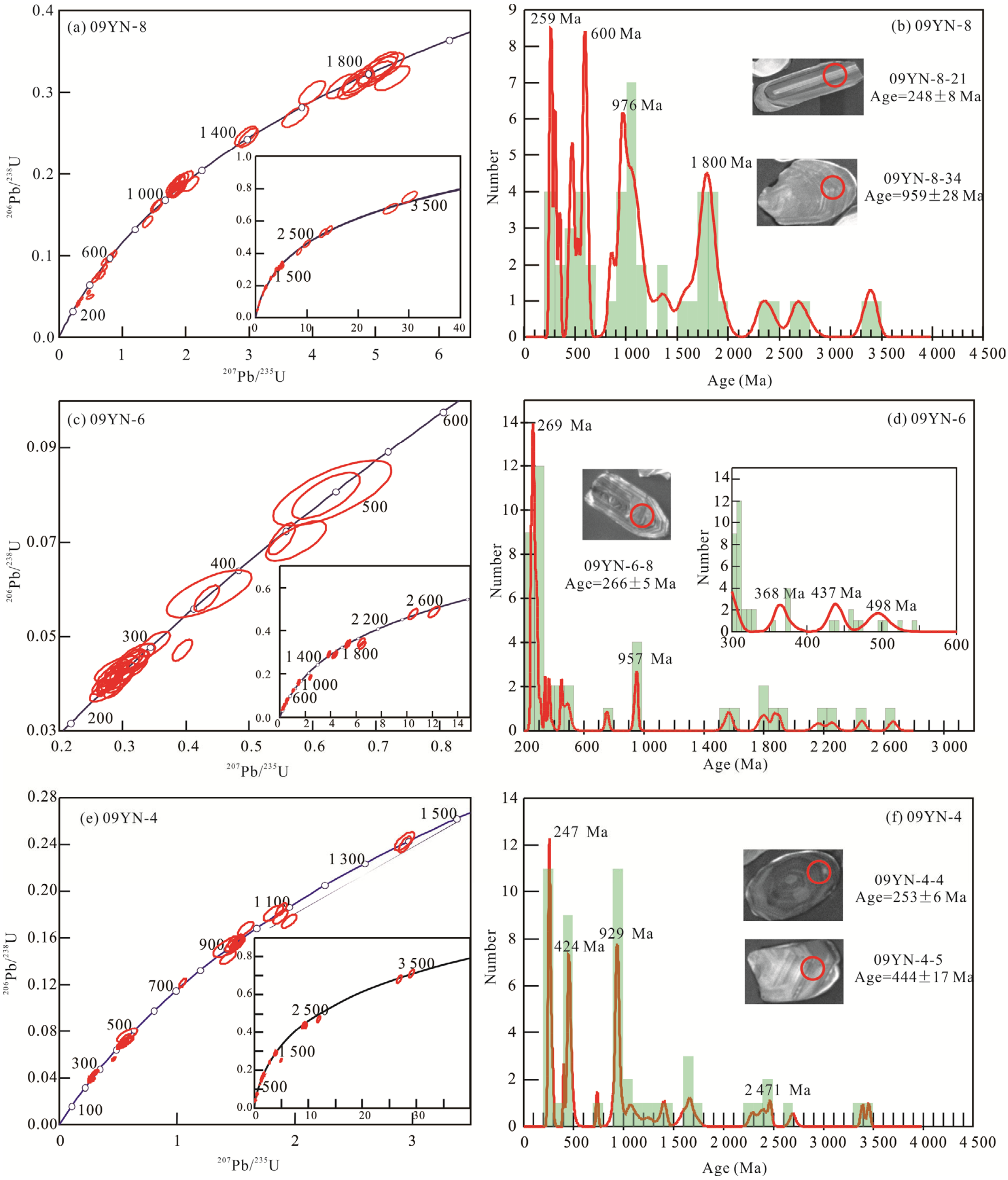

Figure 4. Concordia diagrams ((a) 09YN-3, (c) 09YN-4, and (e) 09YN-6), frequency patterns and representative cathodoluminescence images ((b) 09YN-3, (d) 09YN-4, and (f) 09YN-6) of detrital zircon U-Pb data for the Wuliangshan metasandstone samples.

by the conflicting ages assigned to this unit on different geological maps. For example, on the 1 : 200 000 Weishan Regional Geological Map of the People's Republic of China, it is defined as Cambrian sequence (Yunnan BGMR, 1975), whereas on the 1 : 200 000 Yongping (Yunnan BGMR, 1979) and Baoshan geological maps, it is mapped as the Lower Cretaceous and Middle Jurassic sequence, respectively.

Our geochronological data show that the youngest age peaks for 09YN-3, 09YN-4, 09YN-6, and 09YN-8 are at ~266, ~247, ~269, and ~259 Ma, respectively, suggestive of the maximum deposition age of the Wuliangshan Group should be less than ~247–269 Ma. Their youngest ages of the detrital zircons are at 255±5, 241±8, 243±6, and 248±8 Ma. It is general the youngest age peak (at least three grains; Dickinson and Gehrels, 2009) of detrital zircons to constrain the deposition age. The youngest age peak for our samples is at 247 Ma given by 09YN-4. Thus our data suggest the deposited age is similar to or slightly younger than 241–255 Ma. Sample 09YN-9b is from a sandstone interlayer in the Upper Triassic volcanic sequence that overlies the Wuliangshan Group, yields a youngest detrital zircon U-Pb age of 230±5 Ma. Taken together, this provides an upper limit for the underlying Wuliangshan Group. Therefore, the deposition of the Wuliangshan Group occurred during the time window at 241–230 Ma, confirming it a Middle Triassic rather than Paleozoic or Cretaceous as previously thought.

4.2 Provenance and Tectonic Implications

In order to better evaluate the provenance of the Wuliangshan Group, it is statistically synthesized for the reported detrital zircon U-Pb ages for Late Paleozoic sedimentary rocks from the Yangtze, Cathaysia Block and the Ailaoshan and Tethys-Himalayan tectonic zones (Li D P et al., 2015; Nie, 2015; Wang Q F et al., 2014; Usuki et al., 2013; Wang Y J et al., 2013, 2007; Li X H et al., 2012, 2009, 2008; Dong et al., 2011; Duan et al., 2011; Yan Y et al., 2011; Zhu et al., 2011; Li R B et al., 2010; Myrow et al., 2010; Yu et al., 2010; Wan et al., 2010, 2007; Wang G S et al., 2009; McQuarrie et al., 2008; She, 2007; Yan D P et al., 2006; Zhang et al., 2006; Zheng et al., 2006; Xu et al., 2005; Gehrels et al., 2003), as shown in Fig. 7. Our data for four samples from the Wuliangshan Group and one sample from Upper Triassic strata give similar age spectra of detrital zircons, which is characterized by a main age-peak at ~259 Ma and four subordinate age-peaks at ~447, ~788, ~941, and ~1 859 Ma. Only several grains have the Archean (older than 2 500 Ma) and Carboniferous (~365 Ma) ages (Figs. 6a, 7a).

There are abundant Paleoproterozoic (~1 884–1 846 Ma) detrital zircons in the Cathaysia and Yangtze blocks and the Ailaoshan and Tethyan-Himalaya tectonic belts. Our samples share the pronounced age-peaks of ~730–900 Ma and similar Lu-Hf isotopic compositions with negative and positive $\varepsilon_{\mathrm{Hf}}(t)$

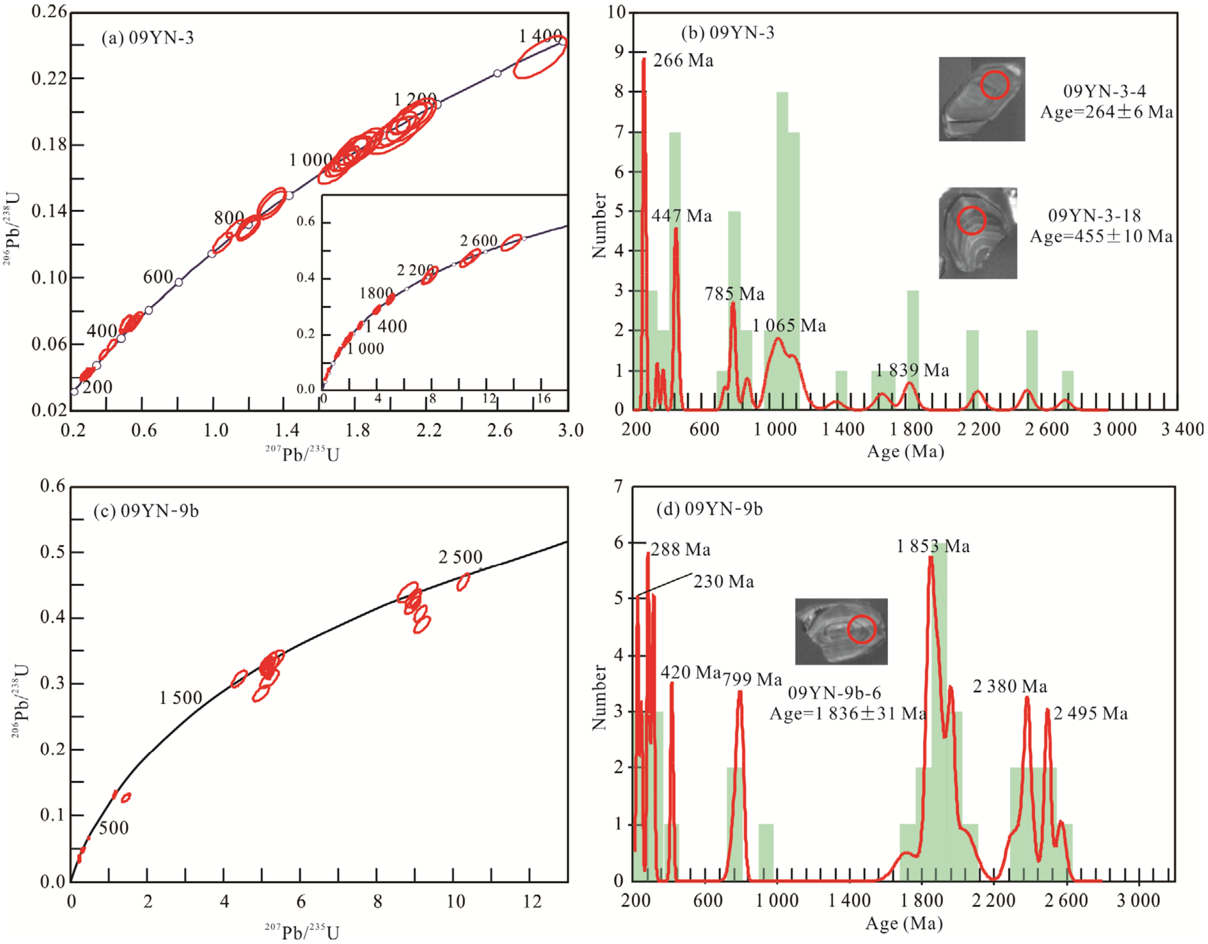

Figure 5. Concordia diagrams ((a) 09YN-8 and (c) 09YN-9b), frequency patterns and representative cathodoluminescence images ((b) 09YN-8 and (d) 09YN-9b) of detrital zircon U-Pb data for the Wuliangshan metasandstone samples.

Table 2 In-situ Lu-Hf isotopic analytical results of detrital zircons of the Wuliangshan sandy sequence in SW Yunnan

Sample spot	Age (Ma)	^{176}Yb/^{177}Hf	^{176}Lu/^{177}Hf	^{176}Hf/^{177}Hf	±1σ	$\mathrm{H_{fi}}$	$\varepsilon_{\mathrm{Hf}}(t)$	T_{2DM} (Ga)
09YN-3								
09YN-3-1	453	0.017 866	0.000 751	0.282 088	0.000 068	0.282 082	-14.5	2.4
09YN-3-2	865	0.013 250	0.000 491	0.281 865	0.000 035	0.281 857	-13.3	2.6
09YN-3-4	264	0.014 803	0.000 611	0.282 249	0.000 061	0.282 246	-12.8	2.1
09YN-3-5	1 144	0.015 428	0.000 667	0.281 836	0.000 074	0.281 822	-8.3	2.5
09YN-3-7	783	0.030 606	0.001 273	0.282 035	0.000 088	0.282 016	-9.5	2.3
09YN-3-8	264	0.032 907	0.001 326	0.282 638	0.000 060	0.282 632	0.8	1.2
09YN-3-9	2 739	0.030 105	0.001 158	0.280 942	0.000 049	0.280 881	-5.4	3.6
09YN-3-11	1 681	0.024 957	0.001 074	0.281 820	0.000 036	0.281 786	2.5	2.2
09YN-3-12	261	0.026 995	0.001 140	0.282 119	0.000 055	0.282 113	-17.6	2.4
09YN-3-13	255	0.032 137	0.001 274	0.282 354	0.000 138	0.282 348	-9.4	1.9
09YN-3-14	1 168	0.013 036	0.000 559	0.281 567	0.000 033	0.281 555	-17.2	3.1
09YN-3-15	1 830	0.034 013	0.001 366	0.281 665	0.000 043	0.281 618	-0.1	2.5
09YN-3-16	1 392	0.020 936	0.000 879	0.281 867	0.000 042	0.281 844	-1.9	2.3
09YN-3-17	1 049	0.015 781	0.000 638	0.281 976	0.000 026	0.281 963	-5.4	2.2
09YN-3-18	455	0.029 131	0.001 244	0.282 238	0.000 056	0.282 227	-9.3	2.0
09YN-3-19	875	0.020 162	0.000 800	0.281 992	0.000 065	0.281 979	-8.7	2.3
09YN-3-20	272	0.024 313	0.001 022	0.282 416	0.000 050	0.282 411	-6.8	1.7
09YN-3-21	1 166	0.021 690	0.000 846	0.281 928	0.000 066	0.281 910	-4.7	2.3
09YN-3-23	449	0.029 876	0.000 993	0.282 130	0.000 196	0.282 122	-13.1	2.3
09YN-3-25	442	0.018 960	0.000 777	0.282 336	0.000 045	0.282 329	-5.9	1.8
09YN-3-26	1 066	0.022 106	0.000 925	0.281 979	0.000 052	0.281 961	-5.1	2.2
09YN-3-27	791	0.014 268	0.000 490	0.281 930	0.000 072	0.281 923	-12.6	2.5
09YN-3-28	789	0.042 718	0.001 816	0.282 201	0.000 075	0.282 174	-3.7	1.9
09YN-3-31	787	0.022 897	0.000 894	0.282 061	0.000 061	0.282 048	-8.3	2.2
09YN-3-32	1 040	0.010 763	0.000 441	0.281 941	0.000 046	0.281 932	-6.7	2.3
09YN-3-33	1 145	0.013 047	0.000 577	0.281 825	0.000 079	0.281 813	-8.6	2.5
09YN-3-34	1 044	0.005 952	0.000 211	0.281 986	0.000 073	0.281 982	-4.9	2.2
09YN-3-35	1 142	0.039 764	0.001 726	0.282 097	0.000 134	0.282 060	0.1	2.0
09YN-3-36	263	0.020 416	0.000 905	0.282 047	0.000 056	0.282 043	-20.0	2.5
09YN-3-38	447	0.013 203	0.000 623	0.282 309	0.000 036	0.282 303	-6.7	1.9
09YN-3-41	1 144	0.038 593	0.001 566	0.281 524	0.000 085	0.281 490	-20.1	3.2
09YN-3-42	277	0.019 097	0.000 765	0.282 141	0.000 034	0.282 137	-16.4	2.3
09YN-3-45	1 165	0.014 235	0.000 559	0.281 582	0.000 051	0.281 570	-16.8	3.1
09YN-3-47	1 044	0.023 183	0.000 930	0.281 970	0.000 066	0.281 952	-5.9	2.3
09YN-3-49	1 019	0.018 486	0.000 688	0.281 652	0.000 065	0.281 638	-17.6	3.0
09YN-3-50	2 228	0.030 458	0.001 205	0.281 121	0.000 068	0.281 070	-10.4	3.5
09YN-3-51	1 648	0.026 959	0.001 130	0.281 754	0.000 083	0.281 719	-0.6	2.4
09YN-3-52	737	0.019 575	0.000 659	0.282 069	0.000 084	0.282 060	-8.9	2.2
09YN-3-55	2 225	0.019 263	0.000 798	0.281 367	0.000 067	0.281 333	-1.2	2.9

values, but mostly negative values (Figs. 6b–6c). Along the western Yangtze Block and the Ailaoshan tectonic belt, there are a lot of Neoproterozoic igneous intrusions (Cai et al., 2014; Qi et al., 2012; Zhao and Zhou, 2008; Zhu et al., 2008; Zhao and Zhou, 2007; Zhou et al., 2006; Li et al., 2002). Detrital zircon populations from sandstone samples along the Ailaoshan tectonic belt display a major Neoproterozoic (730–900 Ma) cluster, similar to that of detrital zircons of the western Yangtze Block (Figs. 7b–7d). The counterpart igneous plutons with the age of ~940 Ma have not been recognized in the Indochina/Simao Block. However, during the Paleozoic period, the Indochina/Simao and Yangtze blocks were located along the northern margin of East Gondwana, at which the Rayner-Eastern Ghats belt in India and Antarctic recorded extensive ~900–990 Ma magmatic event (Burrett et al., 2014; Metcalfe, 2013; Usuki et al., 2013). In addition, it is poorly reported for the Neoproterozoic magmatism in the Baoshan Block to west of the Lancang tectonic zone. Thus, the Neoproterozoic detrital zircons for the Wuliangshan Group probably represent exotic input from the adjacent Ailaoshan tectonic belt of the Yangtze Block.

The significant signature is the presence of the detrital zircon U-Pb age peak of ~544 Ma in the Paleozoic sedimentary rocks from the Baoshan, Tengchong blocks and Tethyan-Himalaya belt (Fig. 7e; Dong et al., 2013; Gehrels et al., 2006; Godin et al., 2001; DeCelles, 2000; DeCelles et al., 1998). These Cambrian–Ordovician detrital zircons are also observed in the Pan-African orogenic belts associated with the formation of the Gondwana supercontinent (Wang et al., 2012; Xu et al., 2012). Such signature is inconsistent with our data from the Wuliangshan sandstones, suggestive of the impossibility of the provenance from the Gondwana fragments to west of the Lancang teconoic zone. Our data show the secondly main age-peak of ~447 Ma and negative $\varepsilon_{\rm Hf}(t)$ values. In the Simao Block (e.g., Mojiang-Lüchun area), the Ordovician–Silurian mafic and felsic rocks (418–459 Ma) with an arc-like affinity have been found, which show mostly negative $\varepsilon_{\rm Hf}(t)$ values (Fig. 6c; Nagy et al., 2001). In addition, the majority of ~450 Ma detrital zircons in this study have subhedral morphology (Figs. 4f and 5b), suggestive of short-distant transportation from the source region. Therefore, it is most likely that the provenance of the ~450 Ma grains is from the Indochina-Simao Block. In fact, detrital zircon analyses on Silurian–Triassic siliciclastics and modern river sediments from the Indochina Block give two pronounced age-peaks of ~439 and ~957 Ma (Burrett et al., 2014; Usuki et al., 2013), similar to our data. As a result, the Wuliangshan Group may share the same detrital provenance with the Paleozoic siliciclastic rocks in the Indochina-Simao Block, e.g., Mojiang-Lüchun area of the Ailaoshan tectonic zone. Several grains from the Wuliangshan sandstone give the apparent age of ~365 Ma, rarely observed in the sedimentary rocks in the Tethyan-Himalaya orogenic belt. On the contrary, the igneous rocks with the age of 337–371 Ma have been observed along the Ailaoshan tectonic zone (Chen et al., 2013; Jian et al., 2009a, b). Abundant detrital grains with the Carbonferious (~360 Ma) origin are commonly discovered for the sandy rocks at Da Rang River (Indochina Block) and Permian sandstone in the southern Yangtze and eastern Cathaysia blocks (Liang et al., 2013; Li et al., 2012; Yokoyama et al., 2010).

The main age-peak of detrital zircons for the Wuliangshan Group is ~259 Ma with the apparent age ranging from 277 to 241 Ma (Fig. 7). The igneous rocks with such an age-peak are usually observed along the Yuanjiang-Mojiang area of the Ailaoshan tectonic zone and Banpo area of the western Simao Block (Wen et al., 2013; Fan et al., 2010; Hennig et al., 2009; Jian et al., 2008; Li and Li, 2007; Li et al., 2006; Xie et al., 2006; He et al., 2003a, b). In addition, along the Ailaoshan-Song Ma tectonic zone, abundant Permian and Early Triassic granitic rocks are reported (Chen et al., 2013; Li et al., 2012; Liu et al., 2009). In contrast, the Lancang giant igneous rocks easterly adjacent to the Wuliangshan area mainly formed at ~230 Ma with seldom data yielding zircon U-Pb age of older than 245 Ma (Peng et al., 2013; Wang et al., 2010). Available data show that the Suyi blueschists, which originated from a seamount, give a zircon U-Pb age of 260±4 Ma and glaucophane minerals formed during prograde metamorphism yield a ^{40}Ar/^{39}Ar plateau age of 242±5 Ma (Fan et al., 2015). The associated ophiolite and volcanic rocks along the Changning-Menglian suture and Lancangjiang tectonic zone suggest a switch from the eastward subduction of the Paleotethyan main ocean to the collision of the Baoshan with Simao-Indochina blocks most likely occurring at ~240 Ma (Fan et al., 2015). The Lincang granitic batholith and related igneous rocks represent the derivation of the mantle wedge in a post-collisional setting at 210–232 Ma (Wang et al., 2010). As discussed above, the Wuliangshan Group might deposit at Middle Triassic period, slightly younger than the youngest age-peak of ~241–255 Ma for detrital zircons for the Wuliangshan Group. The synthesis of all these data suggests the provenance of the Wuliangshan Group is from the Simao-Indochina and western Yangtze blocks, especially the Ailaoshan tectonic zone of the western Yangtze Block, rather than the Baoshan/Tengchong blocks to west of the Lancang igneous zone.

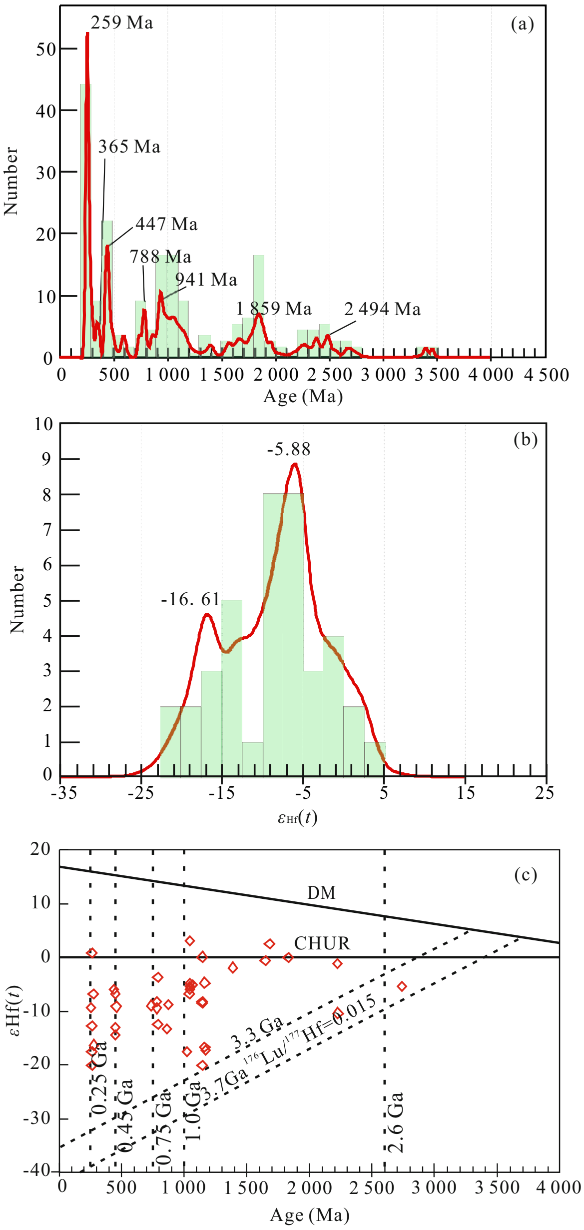

Figure 6. Intergrated frequency of (a) detrital zircon U-Pb ages; (b) and (c) Age (Ma) vs. $\varepsilon_{\rm Hf}(t)$ for the analytical samples from the Wuliangshan Group, SW Yunnan.

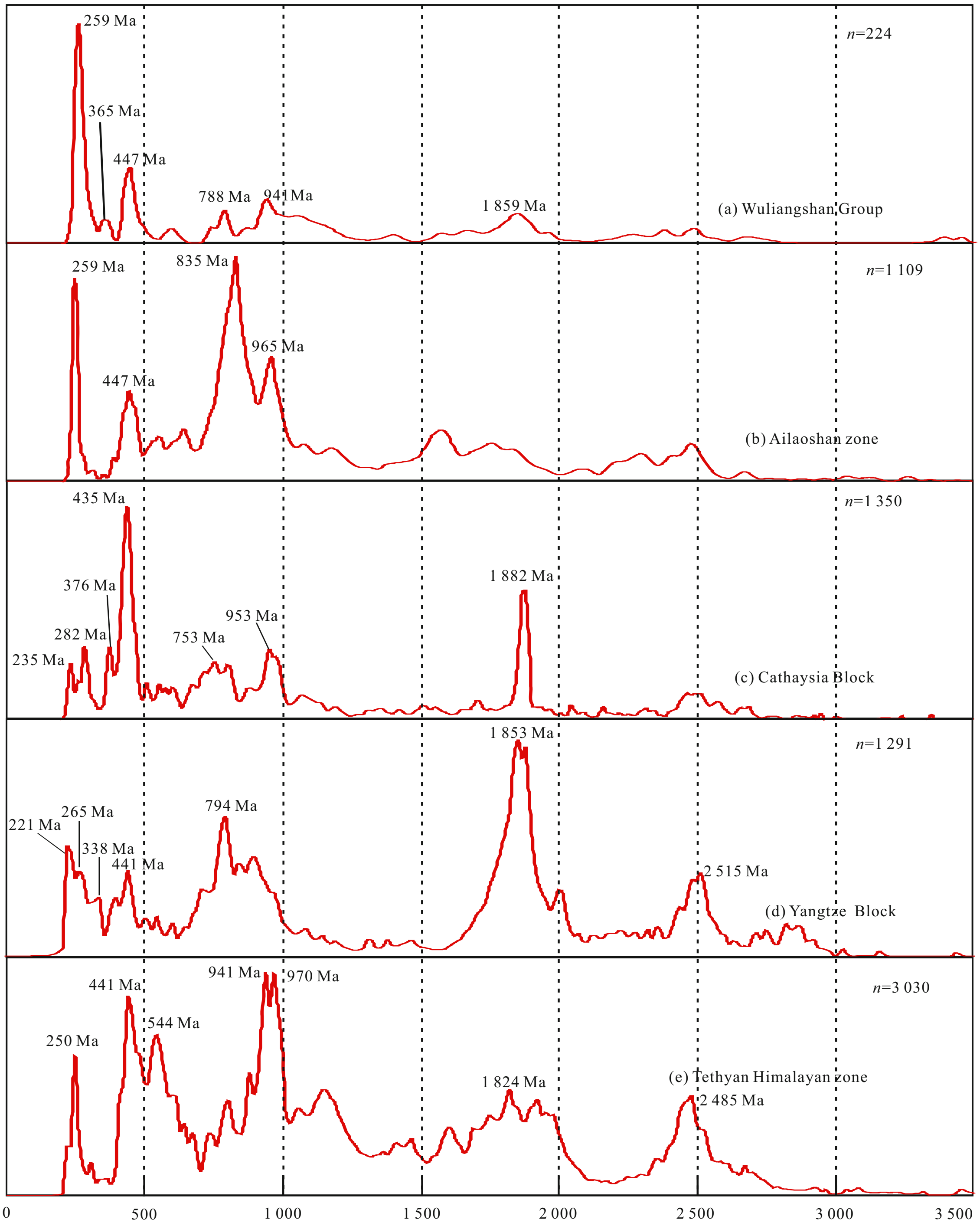

Figure 7. Frequency pattern of detrital zircon U-Pb ages for the sedimentary rocks from the Cathaysia (data are from Li et al., 2012; Yu et al., 2010; Wan et al., 2010, 2007; Wang G S et al., 2009; Wang Y J et al., 2007; Yan et al., 2006; Xu et al., 2005) and Yangtze Block (data are from Duan et al., 2011; Yan et al., 2011; Li R B et al., 2010; Li X H et al., 2009, 2008; She, 2007; Zhang et al., 2006; Zheng et al., 2006), Tethyan-Himalaya (data are from Li et al., 2015; Usuki et al., 2013; Wang et al., 2013; Dong et al., 2011; Zhu et al., 2011; Myrow et al., 2010; McQuarrie et al., 2008; Gehrels et al., 2003) and Ailaoshan tectonic zone (data are from Nie, 2015 and Wang et al., 2014), along with Wuliangshan Group (this study).

5 CONCLUSION

(1) Detrital zircon U-Pb geochronological data from four samples from the Wuliangshan Group in SW Yunnan suggest the Wuliangshan Group deposited at 241–230 Ma rather than previously-thought Cambrian or Jurassic–Cretaceous sequence.

(2) The provenance of the Wuliangshan Group is from the Simao-Indochina and western Yangtze blocks, especially the Ailaoshan tectonic zone, rather than the Baoshan/Tengchong blocks to west of the Lancanjiang igneous zone.

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