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SHRIMP zircon U-Pb ages and tectonic implications for Indosinian granitoids of southern Zhuguangshan granitic composite, South China

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The large southern Zhuguangshan granitic batholith composite consists of granites with ages varying from the Caledonian through Indosinian to Yanshanian. Based on K-Ar dating data, the ages of the major parts of this composite were previously regarded as Yanshanian. In this study, the SHRIMP zircon U-Pb dating method has been adopted for six plutons, Ledong, Longhuashan, Dawozi, Zhaidi, Baiyun and Jiangnan, in the southern Zhuguangshan composite, in which the four plutons other than Baiyun and Jiangnan were previously regarded as Yanshanian granites. Magmatic zircons from these six plutons, dated by this study, have yielded ages of 239±5 Ma (MSWD = 2.5), 239±5 Ma (MSWD = 2.5), 239±2 Ma (MSWD = 1.7), 239±4 Ma (MSWD = 3.2), 231±2 Ma (MSWD = 0.81) and 231±3 Ma (MSWD = 1.8), respectively. The results indicate that these plutons were formed by early Indosinian magmatism. Geochemical characteristics suggest that these granites were formed in an extensional tectonic environment. Therefore, the Indosinian period granites in the southern Zhuguangshan composite were formed by partial melting of the Paleo- Mesoproterozoic crustal components during the collapse of thickened lithosphere after the collision between the South China and Indosinian plates.

granites, SHRIMP zircon U-Pb dating, early Indosinian period, southern Zhuguangshan

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The Zhuguangshan granitic batholith composite is located in the mountain ranges at the juncture of northern Guangdong, southeastern Hunan and southwestern Jiangxi regions. These granitic ranges, lie between the longitudes of 113°10′ and 114°23′E and the latitudes of 25°00′ and 26°10′N. The total outcrop area of the composite is larger than 2500 km^2. The composite granites are controlled by both the E-W-trending deep faults of the Nanling Range and the N-S-trending Zhuguangshan structure. Several granitic plutons (e.g. Zhaiqian, Tanghu, Dongluo and Exing plotons) are distributed in a N-S orientation along the boundary region between Hunan and Jiangxi Provinces. In northern Guangdong Province, granitic plutons (including Jiufeng, Changjiang, Fuxi, Baiyun and Longhuashan) are distributed in an E-W direction (Figure 1), in or near the cities of Lechang, Renhua and Nanxiong, with a total outcrop area of >1500 km^2. These plutons, which is referred to as the southern Zhuguangshan composite (thereafter SZC) [1,2], constitute an important part of "the Qitianling-Zhuguangshan granitic zone", one of the three large-scale E-W-trending granitic zones in the Nanling Range. In the SZC, most plutons have emplaced into Cambrian-Ordovician-Devonian strata. The contact boundaries between the plutons and surrounding wall rocks are sharp, with either wavy or irregular geome-

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tries.

The SZC can be divided into two parts (Figure 1). The western part, consisting of the Jiufeng, Sanjiangkou and Changjiang bodies, is distributed in an E-W direction and is Yanshanian in age. The eastern part is composed of plutons distributed in a N-S direction, where the Baiyun, Jiangnan and Longhuashan plutons have been dated as the Indosinian Period. A Caledonian stock, the Fuxi body, is located on the southern side of the boundary between these two parts. In addition, in the SZC, aplite, granitic porphyry, diabase and lamprophyre are widely developed. Therefore, the SZC is considered being consisting of Caledonian (Fuxi granite and Lanhe migmatite), Indosinian (Baiyun, Ledong, Jiangnan, Longhuashan, Dawozi, Zhaidi, Guting and Tangdong plutons) and Yashanian plutons (Changjiang, Jiufeng, Sanjiangkou, Hongshan, Qiling, Chashan, Chikeng, Rizhuang and Baishun granitoids).

Previous studies have indicated that uranium mineralization widely distributed in the SZC, has a close genesis relationship with the granitoids of the region [2,7–17]. However, in previous studies, some granitic geochronological data, including K-Ar, Rb-Sr and conventional U-Pb dating results, are imprecise. For example, dates determined for the formation of the Baiyun pluton differ: the K-Ar age of biotite is 205–235 Ma; the U-Pb age of zircon is 205–214 Ma [6] and the Rb-Sr isochron age of whole rocks is 225 Ma [2]. Similar case is for the Fuxi granite which yielded a U-Pb age of 400 Ma and a Rb-Sr whole rock isochron age of 548 Ma [1]. Formation ages of other granites were also based on imprecise conventional U-Pb dating results, such as 226 Ma for the Youdong pluton [6], 255 Ma for the Jiangnan pluton [6], and >424 Ma for the Lanhe migmatite [1]. These age data suggest that distinct age uncertainties occur in the granitoids in the studied area.

In the eastern part of the SZC, all rocks were previously considered belonging to the Yanshanian period, except the

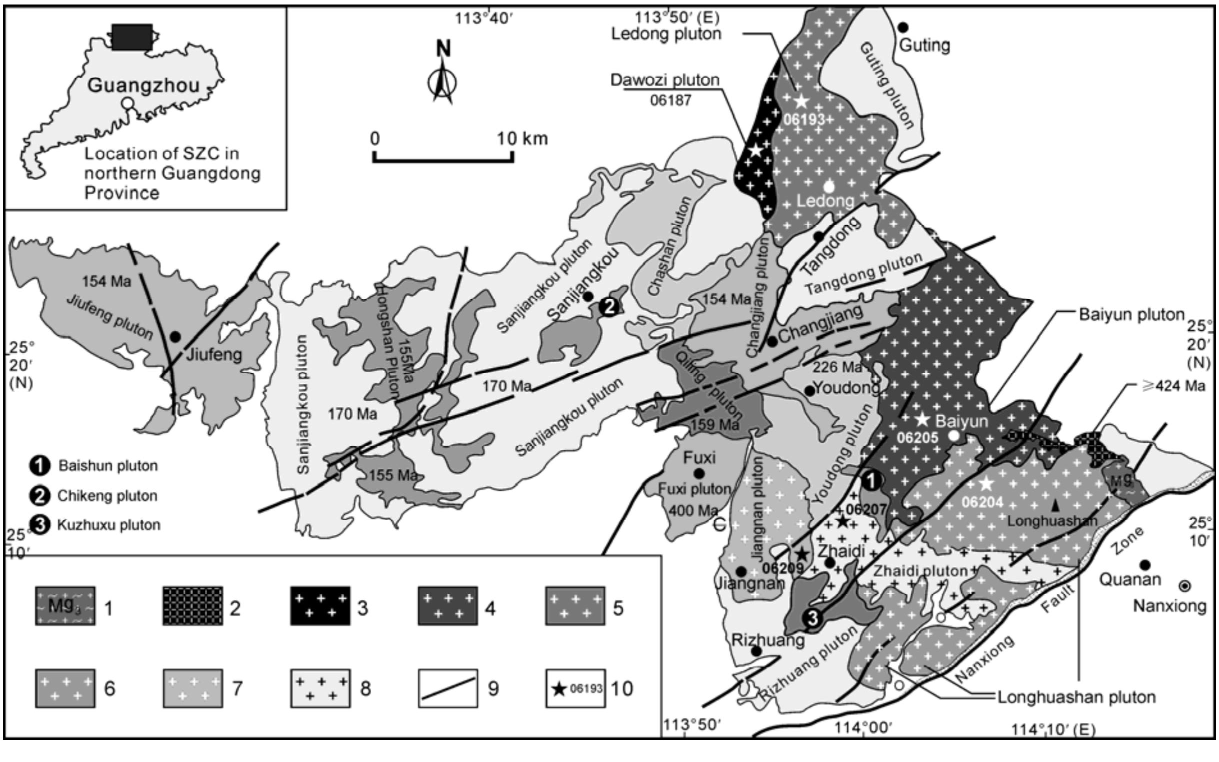

Figure 1 Geological sketch map showing the distribution of Indonisian plutons and the sampling locations in the southern Zhuguangshan composite (SZC). 1, Migmatic granite; 2, zoned migmatite; 3, Dawozi pluton; 4, Baiyun pluton; 5, Ledong pluton; 6, Longhuashan pluton; 7, Jiangnan pluton; 8, Zhaidi pluton; 9, fault; 10, sampling locations. Previous age data: (1) Yanshanian period: the Changjiang medium grained biotite granite, U-Pb age of zircon, 164±12 Ma and Rb-Sr isochron age, 171±4 Ma [1]; the Jiufeng medium-coarse grained biotite granite, U-Pb age of zircon, 154±0.6 Ma [2]; the Sanjiangkou medium-coarse grained porphyroid biotite granite, U-Pb age of zircon, 170 Ma [3]; the Hongshan fined-grained biotite granite, U-Pb age of zircon, 155±2 Ma [4]; the Qiling medium-grained two-mica granite, U-Pb age of zircon, 159 Ma [5]; the Chashan, medium-grained biotite granite; the Chikeng, medium-grained two-mica granite; the Rizhuang and Baishun plutons, medium-coarsed grained biotite granites (no age data available). (2) Indosinian period: the Baiyun coarsed-grained porphyroid biotite granite, U-Pb age of zircon, 205–214 Ma [6]; the Jiangnan coarsed-grained porphyroid biotite granite, U-Pb age of zircon, 255 Ma [6]; the Youdong medium-grained two-mica granite, U-Pb age of zircon, 226 Ma [6]; the Guting and Tangdong coarsed-grained porphyroid biotite granites (no age data available). SHRIMP zircon U-Pb age data obtained by this study for plutons of the SZC are as follows: the Baiyun coarse-grained porphyroid biotite granite, 239±5 Ma; the Ledong medium-grained two-mica granite, 239±5 Ma; the Jiangnan coarse-grained porphyroid biotite granite, 239±2 Ma; the Longhuashan coarse-grained porphyroid biotite granite, 239±4 Ma; the Dawozi coarse-grained porphyroid biotite granite, 231±2 Ma and the Zhaidi medium-grained two-mica granite, 231±3 Ma. (3) Caledonian period: the Fuxi granodiorite, U-Pb age of zircon, 400 Ma and the Lanhe migmatite, U-Pb age of zircon, > 424 Ma [1].

K-Ar and U-Pb ages for the Baiyun granite [6], the U-Pb age for the Youdong pluton [6] and the U-Pb age for the Jiangnan pluton [6]. In this study, we use the advanced SHRIMP zircon U-Pb dating method to obtain precise isotopic dating for the Baiyun, Ledong, Jiangnan, Longhuashan, Dawozi and Zhaidi plutons. Our new age data suggest that these six granitoids were formed in the Indosinian period, rather than in the Yanshanian period. The genesis and tectonic settings of these plutons are discussed below.

1 Petrological features

The Ledong and Zhaidi plutons are both two-mica granites that have a granitic texture and a massive structure. Their main mineral contents are as follow: K-feldspar (35%–40%), consisting mainly of microcline (2.0–5.0 mm in size); plagioclase (10%–20%, An = 8–25), with a sub-euhedral column-plate shape and obvious rim structure; quartz (25%–35%), transparent and sub-euhedral; biotite (3%–4%), plate shaped with black or brown color, and muscovite (2%–3%), transparent and plate shaped sometimes with some biotite remains. Accessory minerals include zircon, apatite, titanite and allanite.

The Baiyun, Jiangnan, Longhuashan and Dawozi plutons are biotite granites that have coarse-grained, granitic and porphyroid textures and massive structure. Main minerals include K-feldspar (30%–40%), plagioclase (20%–35%), quartz (25%–30%) and biotite (3%–7%). Accessory minerals consist principally of ilmenite, zircon and apatite. Phenocrysts are mainly K-feldspar, microline, quartz and biotite; K-feldspar and microline have sub-euhedral, column-plate and irregular shapes. The size of phenocrysts is generally around 1.0–3.5 cm, although some can exceed 5 cm. The content of phenocrysts is variable (5%–30%). Plagioclase as matrix minerals, are sub-euhedral with a column-plate shape and zoning structure; the K-feldspar and quartz matrix minerals show irregular plate or granular shapes. These plutons have undergone alteration to various extents, such as sericitization, muscovitization, choritization and kaolinization.

2 Sample preparation and dating method

The sampling locations for SHRIMP zircon U-Pb dating are shown in Figure 1. Separation of zircon minerals was carried out at the Langfang Geological Survey Lab, Hebei Province. Rock samples were crushed and ground into fine sands and zircon minerals were concentrated on a shaking table. Then, zircon grains that met the criteria of being euhedral and transparent without cracks or inclusions were separated out under a binocular microscope for U-Pb dating.

Separated zircon grains were fixed on glass sheets by epoxy resin and polished down to half section for observing their inner structures. Before U-Pb dating, photographs were taken of each zircon under transmitted light, reflected light, and cathode luminescence (Figure 2). The cathodeluminescence (CL) images were obtained in the Electron Probe Laboratory at the Mineral Resources Institute in Chinese Academy of Geological Science (CAGS). The SHRIMP zircon U-Pb dating was conducted on a SHRIMP-II instrument at the Beijing Ion Microprobe Center. RSES standard zircon (age = 417 Ma [18]) was applied for fractionation correction among different elements; RSES standard zircon SL13 (age = 572 Ma, uranium contents: 238×10^{-6}, average ratio of Th/U= 0.09 [19]) was adopted to measure the contents of U, Th and Pb of zircon samples studied. Age calculations and diagrams were accomplished using the software package SQUID (1.02) of Ludwig [20] and ISOPLOT. The principles and processes of the analytical method are similar to those described by Song et al. [21] and Jian et al. [22]. Common lead correction was carried out using measured ^{204}Pb. Weighted mean ^{206}Pb/^{238}U ages with 2σ error are at 95% confidence. The results are listed in Table 1.

Table 1 SHRIMP zircon U-Pb dating results for the granitic plutons of the southern Zhuguangshan composite[a)]

Sample	U (×10^{-6})	Th (×10^{-6})	Th/U	^{206}Pb$_c$ (%)	^{206}Pb* (×10^{-6})	^{207}Pb/^{206}Pb	±%	^{207}Pb/^{235}U	±%	^{206}Pb/^{238}U	±%	*t* (Ma) ^{206}Pb/^{238}U	*t* (Ma) ± 1σ
Baiyun (06205) 239±4 Ma MSWD = 3.2													
1.1	1451	248	0.18	0.33	45.7	0.0511	2.9	0.2577	3.2	0.0366	1.5	231.7	3.3
2.1	654	242	0.38	0.69	20.8	0.0485	4.5	0.2450	4.8	0.0367	1.5	232.6	3.5
3.1	1725	140	0.08	1.32	57.4	0.0504	3.2	0.2654	3.6	0.0382	1.4	241.8	3.4
4.1	727	315	0.45	0.37	23.2	0.0491	3.0	0.2499	3.3	0.0369	1.5	233.8	3.4
5.1	448	284	0.66	0.41	14.3	0.0505	3.2	0.2579	3.6	0.0371	1.5	234.7	3.6
6.1	3020	213	0.07	0.06	98.1	0.0506	0.9	0.2635	1.7	0.0378	1.4	239.1	3.3
7.1	427	271	0.65	0.25	13.5	0.0515	3.4	0.2605	3.8	0.0367	1.6	232.1	3.6
8.1	2690	413	0.16	0.15	89.6	0.0507	1.2	0.2707	1.9	0.0387	1.4	244.8	3.4
9.1	1727	134	0.08	0.12	56.3	0.0500	1.2	0.2614	1.8	0.0379	1.4	239.9	3.4
10.1	3133	252	0.08	1.96	108.0	0.0501	3.3	0.2714	3.6	0.0393	1.4	248.5	3.5
11.1	4104	235	0.06	0.24	138.0	0.0511	1.1	0.2750	1.8	0.0391	1.4	247.0	3.4
13.1	2720	368	0.14	0.97	99.9	0.0523	3.8	0.3050	4.0	0.0424	1.4	267.4	3.8

(*To be continued on the next page*)

(*Continued*)

Sample	U ($\times10^{-6}$)	Th ($\times10^{-6}$)	Th/U	$^{206}Pb_c$ (%)	$^{206}Pb^*$ ($\times10^{-6}$)	$^{207}Pb/^{206}Pb$	±%	$^{207}Pb/^{235}U$	±%	$^{206}Pb/^{238}U$	±%	*t* (Ma) $^{206}Pb/^{238}U$	± 1σ
Ledong (06193) 239±5 Ma MSWD = 2.5													
1.1	175	284	1.68	0.31	12.4	0.0568	5.1	0.6410	5.3	0.0818	1.6	507.0	7.7
2.1	804	57	0.07	0.08	25.4	0.0508	1.8	0.2573	2.3	0.0367	1.4	232.4	3.3
3.1	1551	146	0.10	0.07	50.3	0.0507	1.3	0.2637	1.9	0.0377	1.4	238.7	3.3
4.1	999	654	0.68	0.14	34.3	0.0508	1.9	0.2794	2.3	0.0399	1.4	252.2	3.5
5.1	202	152	0.78	0.34	6.5	0.0503	5.7	0.2570	5.9	0.0371	1.6	234.8	3.8
6.1	769	244	0.33	0.01	278.0	0.1379	0.3	8.0000	1.4	0.4210	1.4	2265	27
7.1	1297	139	0.11	–	42.1	0.0510	1.0	0.2656	1.7	0.0378	1.4	238.9	3.3
8.1	2045	374	0.19	0.24	67.5	0.0500	1.3	0.2646	1.9	0.0384	1.4	242.6	3.3
9.1	2459	126	0.05	0.08	83.1	0.0505	0.1	0.2734	1.6	0.0393	1.4	248.5	3.4
10.1	772	27	0.04	0.12	34.3	0.0533	1.7	0.3799	2.2	0.0517	1.4	324.7	4.5
11.1	1530	190	0.13	0.40	49.5	0.0493	2.0	0.2551	2.5	0.0375	1.4	237.5	3.3
12.1	1467	113	0.08	0.31	55.7	0.0507	1.8	0.3079	2.3	0.0440	1.4	277.9	3.8
13.1	1954	460	0.24	0.50	59.8	0.0511	2.0	0.2499	2.4	0.0354	1.4	224.5	3.1
14.1	1055	202	0.20	0.24	32.3	0.0519	1.4	0.2544	2.0	0.0356	1.4	225.3	3.1
Jiangnan (06209) 239±2 Ma MSWD = 1.7													
1.1	955	338	0.37	0.18	31.0	0.0500	1.6	0.2600	2.1	0.0377	1.4	238.8	3.3
2.1	2044	335	0.17	0.12	67.0	0.0513	1.2	0.2695	1.8	0.0380	1.4	241.0	3.3
3.1	4992	1083	0.22	3.77	171.0	0.0511	4.2	0.2710	4.5	0.0385	1.4	243.5	3.3
4.1	794	242	0.31	–	25.4	0.0518	1.4	0.2665	2.0	0.0373	1.4	236.2	3.3
5.1	1678	237	0.15	0.03	55.2	0.0506	1.0	0.2666	1.7	0.0383	1.4	242.0	3.3
7.1	2576	373	0.15	0.17	84.4	0.0511	1.4	0.2682	2.0	0.0381	1.4	240.8	3.3
8.1	526	312	0.61	11.50	18.9	0.0882	10.0	0.4490	10.0	0.0370	1.8	234.1	4.2
9.1	1831	229	0.13	0.13	60.7	0.0506	1.1	0.2689	1.8	0.0385	1.4	243.7	3.3
10.1	427	327	0.79	0.86	13.4	0.0501	4.9	0.2500	5.1	0.0362	1.5	228.9	3.4
11.1	703	332	0.49	0.18	22.6	0.0500	1.9	0.2573	2.4	0.0373	1.4	236.0	3.3
12.1	2290	202	0.09	0.09	74.8	0.0510	0.9	0.2671	1.7	0.0380	1.4	240.5	3.3
Longhuashan (06204) 236±2 Ma MSWD = 1.3													
1.1	2180	296	0.14	2.22	76.7	0.0491	4.7	0.2710	4.8	0.0401	1.2	253.3	2.9
3.1	3277	494	0.16	3.94	116.0	0.0526	5.5	0.2870	5.7	0.0395	1.2	249.9	2.9
4.1	1151	181	0.16	0.14	37.0	0.0503	1.5	0.2593	1.9	0.0374	1.1	236.6	2.6
5.1	1445	542	0.39	0.47	46.7	0.0537	5.7	0.2770	5.8	0.0375	1.1	237.1	2.7
6.1	372	130	0.36	0.53	11.9	0.0470	2.9	0.2394	3.1	0.0370	1.2	234.0	2.8
7.1	766	248	0.34	0.08	24.7	0.0515	2.0	0.2664	2.3	0.0375	1.2	237.3	2.7
8.1	451	244	0.56	0.34	14.2	0.0492	4.3	0.2470	4.4	0.0364	1.2	230.6	2.8
9.1	1304	341	0.27	0.34	42.9	0.0505	2.6	0.2658	2.9	0.0382	1.1	241.6	2.7
10.1	772	231	0.31	0.09	24.7	0.0507	2.7	0.2600	2.9	0.0372	1.2	235.4	2.7
11.1	476	139	0.30	0.07	28.9	0.0554	1.3	0.5394	1.7	0.0706	1.2	440.0	5.0
12.1	483	332	0.71	0.03	15.3	0.0531	2.8	0.2694	3.0	0.0368	1.2	233.1	2.8
13.1	1420	218	0.16	0.44	45.9	0.0512	1.9	0.2648	2.2	0.0375	1.1	237.3	2.6
14.1	456	310	0.70	0.25	14.3	0.0500	2.1	0.2514	2.4	0.0365	1.2	231.0	2.8
15.1	1401	312	0.23	0.10	44.7	0.0512	1.4	0.2617	1.8	0.0371	1.1	234.9	2.6
Dawozi (06187) 231±2 Ma MSWD = 0.81													
1.1	3348	167	0.05	0.48	111.0	0.0508	2.6	0.2694	2.9	0.0385	1.4	243.3	3.4
2.1	2095	202	0.10	0.09	69.2	0.0509	1.6	0.2693	2.2	0.0384	1.4	242.8	3.4
3.1	1191	163	0.14	0.10	37.0	0.0510	1.4	0.2542	2.0	0.0361	1.5	228.7	3.3
5.1	1029	189	0.19	0.06	32.2	0.0510	1.7	0.2561	2.2	0.0364	1.5	230.6	3.3
6.1	1949	222	0.12	0.13	63.0	0.0498	1.4	0.2581	2.1	0.0376	1.6	238.0	3.6
7.1	1309	181	0.14	0.07	40.7	0.0505	1.4	0.2517	2.0	0.0362	1.4	229.2	3.3
8.1	690	216	0.32	0.12	21.3	0.0516	1.8	0.2547	2.4	0.0358	1.5	226.9	3.3
9.1	1227	210	0.18	0.73	39.0	0.0513	3.1	0.2599	3.5	0.0367	1.5	232.5	3.3
10.1	1093	153	0.14	0.60	34.2	0.0494	2.9	0.2467	3.2	0.0363	1.5	229.5	3.3
11.1	1453	218	0.15	0.19	45.7	0.0501	1.3	0.2526	2.0	0.0366	1.5	231.6	3.5
12.1	987	168	0.18	0.04	30.8	0.0516	1.6	0.2582	2.2	0.0363	1.5	230.0	3.3
Zhaidi (06207) 231±3 Ma MSWD = 1.8													
2.1	390	101	0.27	0.66	12.6	0.0506	4.4	0.2610	4.6	0.0374	1.3	236.9	3.0
3.1	267	276	1.07	0.93	8.4	0.0489	5.3	0.2450	5.5	0.0364	1.3	230.3	3.0
4.1	564	688	1.26	0.46	17.5	0.0499	2.9	0.2471	3.1	0.0359	1.2	227.3	2.7
5.1	1139	434	0.39	0.11	36.7	0.0512	1.3	0.2641	1.7	0.0374	1.1	236.9	2.6
6.1	1011	181	0.19	0.20	32.0	0.0510	1.8	0.2586	2.2	0.0368	1.1	232.8	2.6
7.1	263	236	0.93	1.04	8.2	0.0465	2.8	0.2294	3.1	0.0358	1.3	226.4	2.9
8.1	284	217	0.79	0.86	8.9	0.0506	3.7	0.2530	4.1	0.0363	1.8	229.5	4.0
9.1	1054	418	0.41	0.24	32.8	0.0490	1.7	0.2444	2.1	0.0362	1.1	229.0	2.6
11.1	914	154	0.17	0.34	28.8	0.0492	2.2	0.2478	2.5	0.0365	1.1	231.3	2.6
12.1	839	340	0.42	0.35	25.8	0.0488	2.3	0.2400	2.5	0.0357	1.1	226.1	2.5
13.1	471	295	0.65	0.53	14.8	0.0503	4.0	0.2520	4.2	0.0364	1.2	230.2	2.8

a) $^{206}Pb_c$ and $^{206}Pb^*$ represent common Pb and radioactive Pb, respectively.

3 Dating results

Most of the zircon grains chosen for U-Pb dating are euhedral and transparent or partly translucent, with columnar or prism shapes and oscillatory zoning structure, and without core-rim structures or cracks. This indicates they are typical magmatic zircons. The dating points are positioned within the closed rhythmic rings of zoning structures and kept away from cores (Figures 2b, 3b, 4b, 5b, 6b and 7b). Zircon U-Pb analysis yields three age groups: $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and $^{207}Pb/^{206}Pb$. For young zircons, which contain only minor quantities of radiogenic ^{207}Pb, the $^{206}Pb/^{238}U$ value should reflect the crystallization age much more accurately than $^{207}Pb/^{235}U$ or $^{207}Pb/^{206}Pb$ values, because the abundance of ^{235}U is much lower than ^{238}U. For this reason, we have determined the crystallization time of various plutons on the basis of the $^{206}Pb/^{238}U$ age values. Generally speaking, the ages on the Concordia curves reflect crystallization ages of zircons that have not been affected by later tectono-magmatic events after the magma crystallization and thus without Pb loss [23]. Therefore, we adopt Concordia ages corresponding to the age of magma crystallization.

3.1 Baiyun pluton (06205)

The Baiyun pluton was sampled at a site along the road from Lanhe to Baishun, in the district of Nanxiong City, Guangdong Province (sampling location: 114°04′58.5″E, 25°14′47.6″N). Sample 06205 is a coarse-grained porphyroid biotite granite. From Table 1, the uranium content of zircon grains is observed to vary widely (427.4×10^{-6}–4104×10^{-6}); thorium content varies within a small range (133.7×10^{-6}–412.7×10^{-6}); and the Th/U values are between 0.06-0.63, with most values above 0.4. All but one of the twelve zircons dated show ages concentrated between 231.7±3.3 and 248.5±3.5 Ma (Table1) (the age of Spot 13.1 is a little greater at 267.4 Ma which is not included in mean age calculation). These ages are located on the concordia curve, suggesting that the U-Pb isotope system remained closed after the crystallization of these zircon grains. The eleven closely clustered $^{206}Pb/^{238}U$ ages yield an average of 239±4 Ma (MSWD = 3.2), indicating that the Baiyun pluton was formed during the early Indosinian period.

3.2 Ledong pluton (06193)

Sample 06193, a medium-grained two-mica granite, was collected from the roadside near Reshui Town in the district of Rucheng City (sampling position: 113°57′25.6″E, 25°32′23.3″N). As shown in Table 1, uranium and thorium contents vary widely from 175.2×10^{-6} to 2459×10^{-6} and from 27.15×10^{-6} to 653.7×10^{-6}, respectively. The ratio of Th/U varies between 0.04 and 1.63, with most around 0.11–0.75. In the dating data of fourteen zircons, $^{206}Pb/^{238}U$ ages vary from 224.5±3.1 to 507.0±7.7 Ma, reflecting that some zircon grains were derived from early magmatic events. In Figure 3, seven zircon grains (2.1, 3.1, 5.1, 7.1, 8.1, 9.1 and 11.1) which are located on the concordia curve (232.4±3.3–248.5±3.4 Ma) yielded an average $^{206}Pb/^{238}U$ age of 239±5 Ma (MSWD = 2.5), suggesting that the Ledong pluton was also formed during the early Indosinian period.

3.3 Jiangnan pluton (06209)

Sample 06209, a biotite granite with coarse-grained and porphyroid textures, was taken from the roadside between Renhua City and Baishun Town, near the city of Nanxiong (sample position: 113°56′24.5″E, 25°08′10.7″N). The uranium content of zircons from this pluton varies widely (427×10^{-6}–4992×10^{-6}), thorium content varies within a small range (202×10^{-6}–1083×10^{-6}), and the Th/U values lie in the range between 0.09 and 0.77. Eleven spot analyses, (i.e. all except Spot 10.1 which has an age of 228.9±3.4 Ma), yield ages between 234.1±4.2 and 243.7±3.3 Ma. These

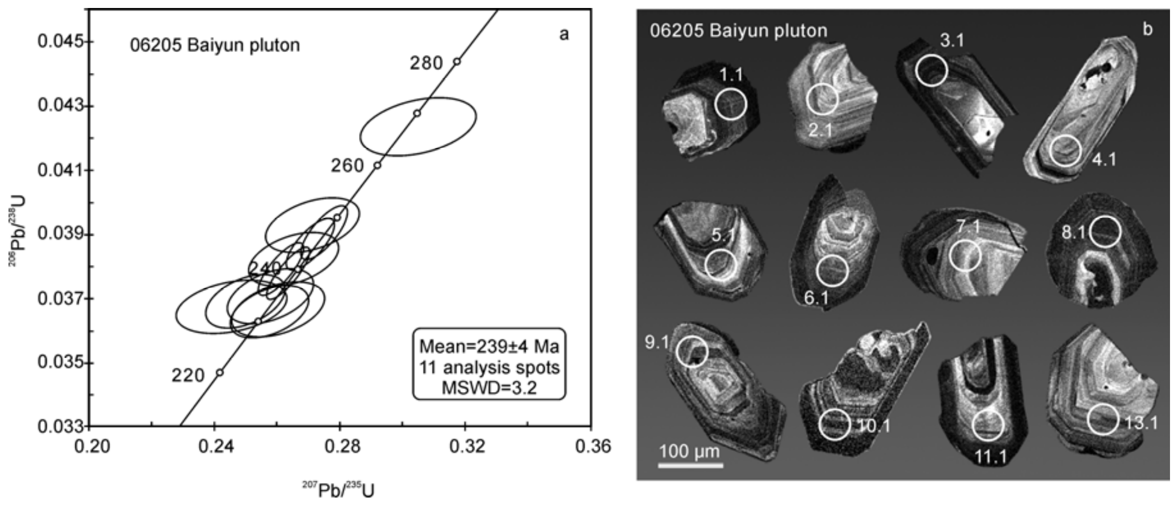

Figure 2 U-Pb age concordia diagram (a) and CL image (b) of zircons from the Baiyun pluton.

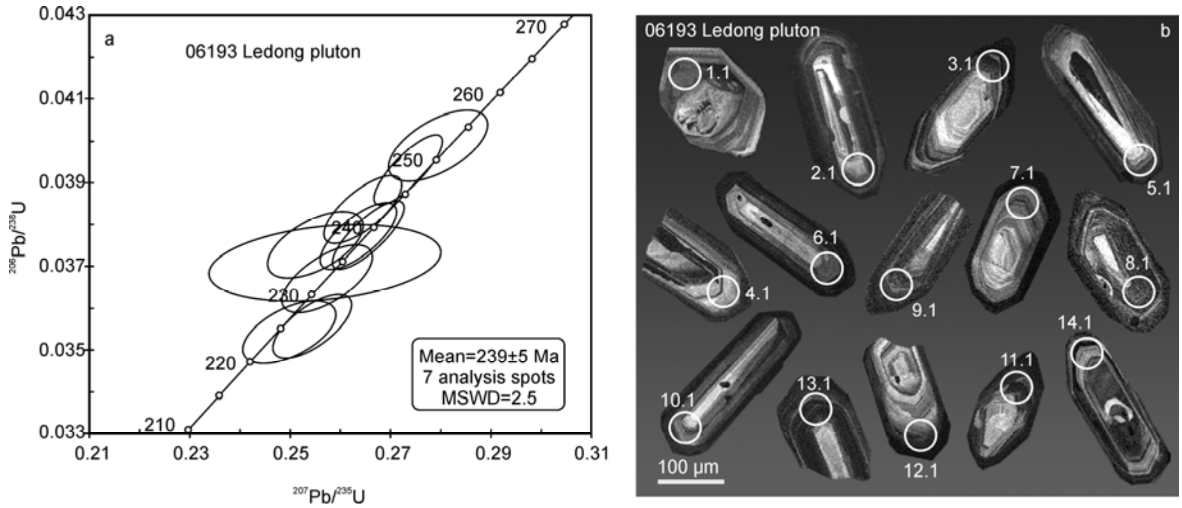

Figure 3 U-Pb age concordia diagram (a) and CL image (b) of zircons from the Ledong pluton.

ages are located on the concordia curve and generate an average age of 239±2 Ma (MSWD = 1.7). They also indicate the formation of the pluton by the early Indosinian tectono- thermal event.

3.4 Longhuashan pluton (06204)

Sample 06204, a coarse-grained porphyroid biotite granite, collected from the roadside between Nanxiong and Lanhe (sample position: 114°07′08.4″E, 25°13′04.8″N). Uranium content of the zircon grains varies widely (371.9×10^{-6} to 3277×10^{-6}), the thorium content varies within a small range (129.5×10^{-6} to -494.5×10^{-6}), and the ratio of Th/U is 0.14–0.69. The dating of eleven of fourteen zircons shows ages that cluster between 230.6±2.8 and 241.6±2.7 Ma (Table 1). Spots 1.1, 3.1 and 11.1 are older (249.9–440.0 Ma). In Figure 5, the ages of the eleven clustered zircons are plotted on the concordia curve, reflecting a closed U-Pb isotope system of zircons after their crystallization. A weighted average age of 236±2 Ma (MSWD = 1.3) was obtained, indicating that the Longhuashan pluton was formed during the early Indosinian period.

3.5 Dawozi pluton (06187)

Sample 06187, a biotite granite with coarse-grained and porphyroid textures, was collected from the roadside between the towns of Jiangkou and Reshui (sample position: 113°54′11.0″E, 25°29′37.8″N). From Table 1, note that the uranium content of zircon minerals varies widely (690.3×10^{-6}–3348×10^{-6}), the thorium content of the zircons varies within a small range (153.0×10^{-6}–222.1×10^{-6}), and the ratio of Th/U is between 0.10 and 0.31. With the exception of one zircon with a Th/U value of 0.05, eleven of the zircons belong to magmatic zircon. Nine of the twelve spot analyses, project onto the concordia curve (Figure 6), defining concordant ages of 226.9±3.3 to 238.0±3.6 Ma averaging at 231±2 Ma (MSWD = 0.8). The ages of Spots 1.1 and 2.1

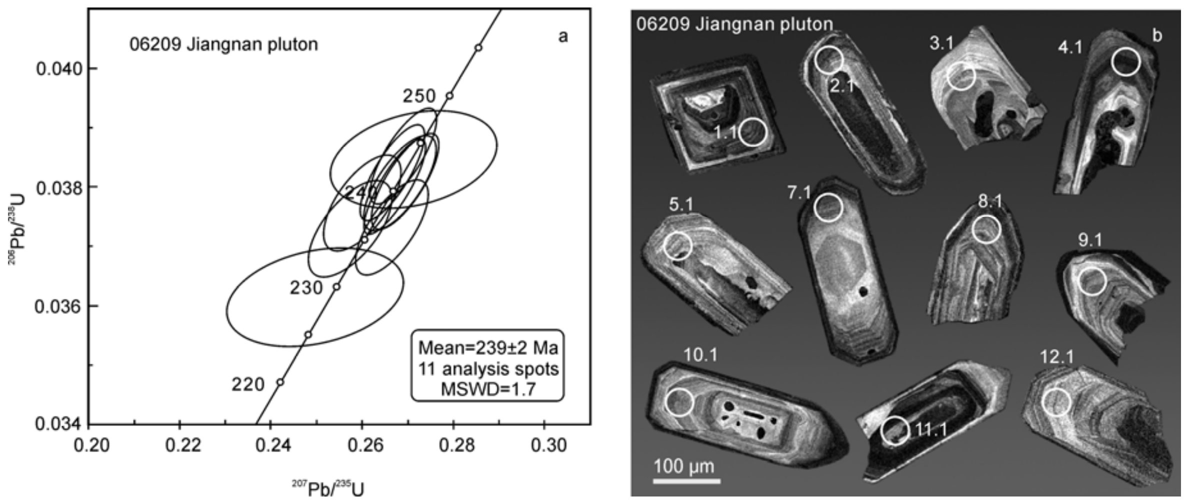

Figure 4 U-Pb age concordia diagram (a) and CL image (b) of zircons from the Jiangnan pluton.

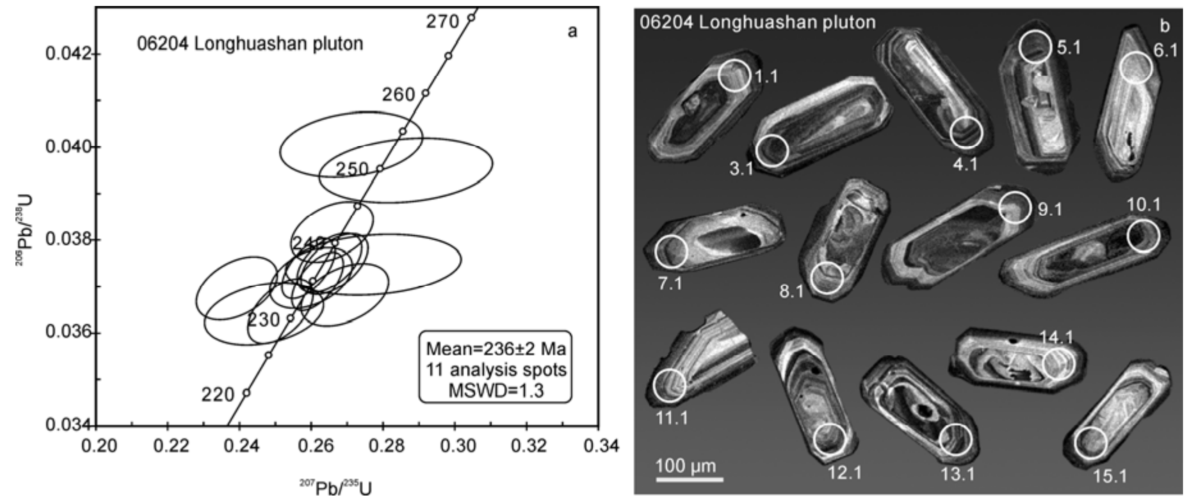

Figure 5 U-Pb age concordia diagram (a) and CL image (b) of zircons from the Longhuashan pluton.

are a little greater (242.8–243.3 Ma). The results indicate that the Dawozi pluton was formed during the early Indosinian period.

3.6 Zhaidi pluton (06207)

Sample 06207, a medium-grained two-mica granite, was collected from the roadside between Renhua and Baishun (sample location: 25°10′40.8″N, 113°59′23.5″E). The uranium content of the zircons is between 263×10^{-6} and 1139×10^{-6}, the thorium content is between 161×10^{-6} and 688×10^{-6}, and the ratio of Th/U is 0.17–1.21 (Table 1). The ages of all eleven zircon grains are concentrated between 226.1±2.5 Ma and 236.9±3.0 Ma (Table 1) distributing on the concordia curve (Figure 7), suggesting that the U-Pb isotope system has remained closed after formation of these zircon grains. Thus, the weighted average age of 231±3 Ma (MSWD = 1.8), representing the formation time of the Zhaidi pluton, also corresponds to the early Indosinian period.

4 Discussion and conclusions

As mentioned above, all of the plutons in the eastern part of the SZC were considered belonging to the Yanshanian Period, with exception of the Baiyun, Jiangnan and Youdong plutons that had been previously reported as Indosinian [24]. However, by adopting the SHRIMP zircon U-Pb dating method, the formation ages of six plutons in the eastern part of the SZC have been determined to lie around 231–239 Ma, indicating that most of the plutons in this region are the result of tectono-magmatism in the early Indosinian period. Their time of formation was slightly later than the initial collision between the South China Plate and the Indosinian Plate (258–243 Ma) [25]. The structure of these plutons,

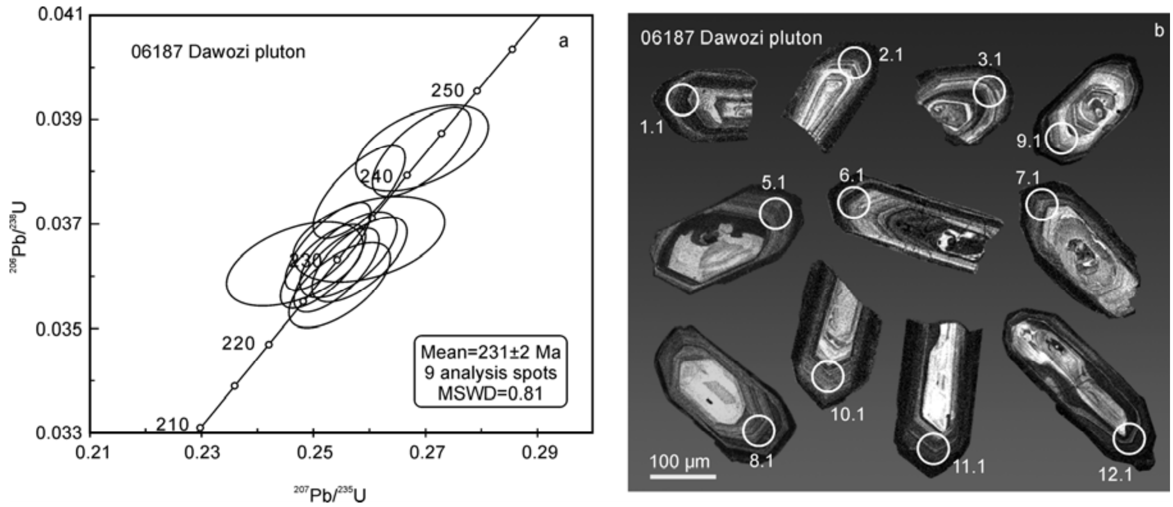

Figure 6 U-Pb age concordia diagram (a) and CL image (b) of zircons from the Dawozi pluton.

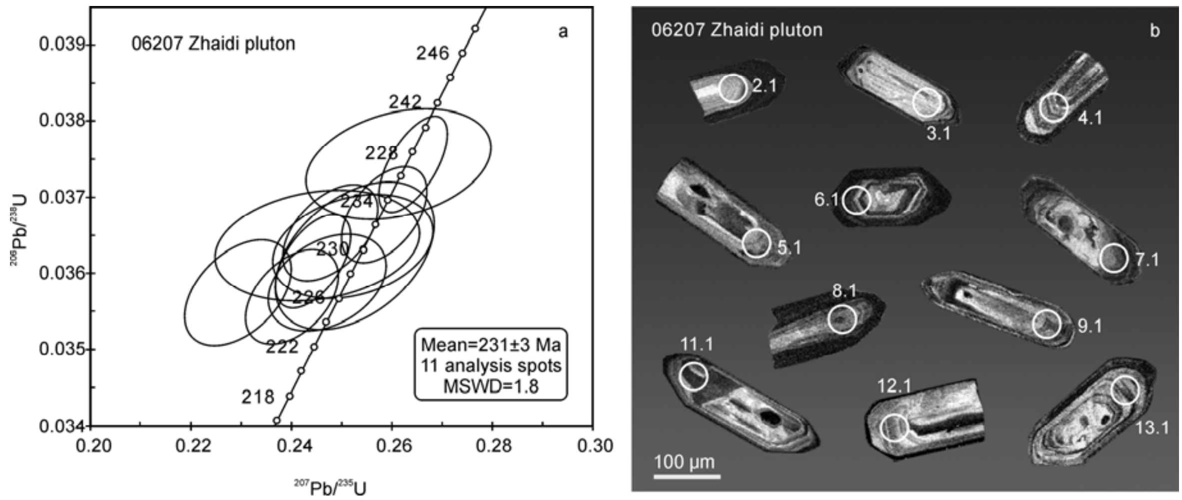

Figure 7 U-Pb age Concordia diagram (a) and CL Image (b) of zircons from the Zhaidi pluton.

formed during magma crystallization, is massive rather than compressive, reflecting that the magmatic emplacement was controlled by faults. The petrochemical compositions of the granitic samples indicate that A/NKC [i.e. mol values $Al_2O_3/(Na_2O+K_2O+CaO)$] vary from metaluminous granite to strongly peraluminous granite (0.99–1.17). From the Rb vs. Y+Nb diagram, most of the samples are observed to fall in the post-collision area, although a few fall in the syn-collision area (Figure 8a). Recent researches show that granite samples that fall in the syn-collision area might also be the results of post-collision [27,28]. From the SiO_2-Al_2O_3 diagram, all samples fall in the post-orogenic granite region, except for a few samples where the SiO_2 content is below 70.5%. Research on other Indosinian period plutons in the Nanling Range also supports the hypothesis that the granites formed in an extensional structural environment [30]. Thus the magmatic emplacement of the Indosinian-period plutons in the eastern part of the SZC occurred in an extensional tectonic environment [31,32].

Over the last decade, along with the discovery and in-depth research of Indosinian granites in southern China, several hypotheses for the tectonic environment under which the granites formed have been proposed. These include the collision orogenic model [33–35], the intracontinental orogenic subduction model [36], a model involving extension, lithospheric thinning and basic magma underplating [37,38], the model of continental collision and crustal thickening [10,31,39–42], and the model of flat-slab subduction [43].

Wang et al. [44,45] acquired SHRIMP U-Pb age data for alkaline syenites from Mingxi Yangfang (242±4) and Zhenghe Tieshan (254±4 Ma). Xie et al. [46] acquired a SHRIMP U-Pb age date of 244±7 Ma for garnet augite syenite from Sanya, Hainan Province. Those ages are almost the same as the period of collision between the South China and Indosinian plates (258–243 Ma) [25]. Moreover, all the peralkaline magmatic rocks formed in an extentional environment [47,48]. Wang et al. [45] suggested that these

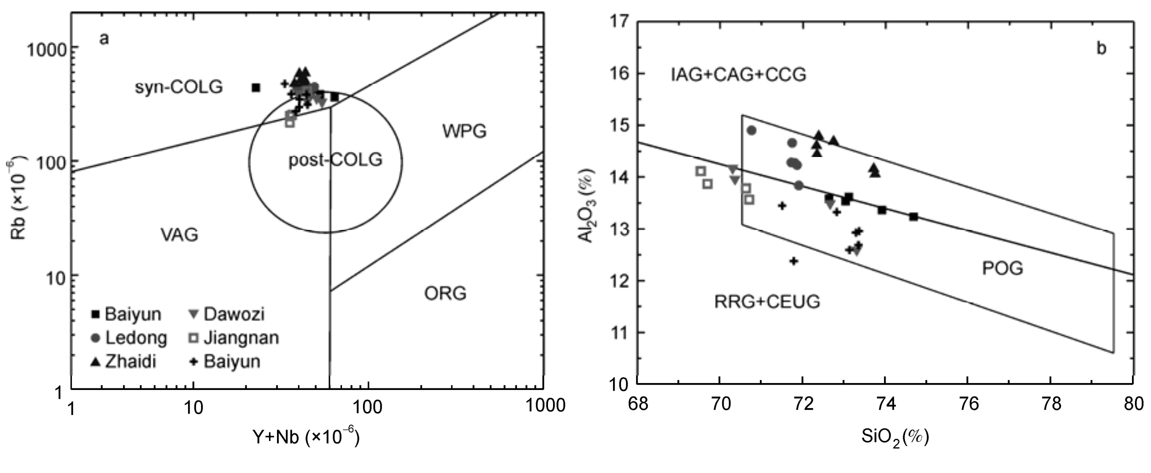

Figure 8 Plottings of Indosinian granites from the southern Zhuguangshan composite in diagrams of Rb vs. Y+Nb. a, After Pearce [26] and SiO_2 vs. Al_2O_3; b, after Maniar & Piccoli [29].

peralkaline magmatic rocks were formed under the transtensional activity of the NE-SW directed strike-slip fault. These researches indicate that a local extensional structural environment existed in southeastern China during the collision between the South China and Indosinian plates.

Granites of the Indosinian period in southern China are distributed mainly in inland regions such as the provinces of Hunan, Guangxi, Hainan, Guangdong and Jiangxi, whereas in the coastal regions, Indosinian granites are rare. The spatial distribution of these Indosinian granites shows no preferred geometrical alignment, which is different from the NE-SW oriented distribution of the Yanshanian granites. The formation ages of these Indosinian granites appear not to show a trend of becoming younger inland in south China (e.g. in the center of Hunan Province, the U-Pb age of zircons from many Indosinian granites is around 239–244 Ma [49]). The Indosinian granites are rich in biotite and high-aluminum minerals such as muscovite and even garnet, which is typical of S-type granites. This characteristic is distinctively different from the calc-alkaline granite in coastal areas related to oceanic plate subduction, and also different from alkaline syenite found in Fujian and Hainan provinces. Moreover, volcanic rocks accreting with Indosinian granites have not been found so far. Based on the above evidence, we suggest that the model of continent collision and crust thickening would be more reasonable than other models for interpreting the genesis of the granites of the Indosinian Period in southern China.

The Indosinian tectono-activity was caused by the collision between the South China and Indosinian plates, and resulted in the closure and disappearance of the eastern Tethys sea, Songpan. The collision of the two plates happened during 258–243 Ma [25], which led to the thickening of crust of the South China Plate (reaching about 50 km [40, 41]). The crust thickness soon started to reduce naturally after disappearing of the collisional stress, in an isostatic response to its over-thickened state [50]. Such effects would result in the extension and thinning of the lithosphere. This change was previously regarded to have taken place after about 20 Ma [40,41,50,51]. However, Carter et al. [25] pointed out that, at the end of the Indosinian orogenesis in Southeast Asia, the regional stress field might have changed from compression to extension. Currently, it has been found that many prealuminous granites in southern China had already formed by the end of the period of collision between the South China and Indosinian plates. For example, the SHRIMP U-Pb ages of the zircons from granitic plutons of Weishan, Tangshi and Longtan, in Hunan Province, are 244±4 Ma, 239±3 Ma and 243±3 Ma, respectively [49]; the LA-ICPMS U-Pb ages of the zircons from plutons of Luxi and Xiazhuang of the Guidong granitic composite in north Guangdong Province are 239±5 Ma and 236±8 Ma [52], respectively; the SHRIMP U-Pb ages of the zircons from Darongshan, Jiuzhou and Taima plutons in southeastern Guangxi, are 233±5 Ma, 230±4 Ma and 236±4 Ma, respectively [10]; the LA-ICPMS U-Pb ages of the zircons from Longyuanba pluton in North Guangdong are 241.0±1.3 Ma [53]; the isotope dilution U-Pb ages of the individual zircon grains from Wuliting pluton in South Jiangxi are 238.9±1.5 Ma [54]; the SHRIMP U-Pb ages of the zircons from Jianfengling pluton in Hainan are 249±5 Ma [55]; the LA-ICPMS U-Pb ages of the zircons from Nanfucheng pluton in southeastern Jiangxi are 239±17 Ma [56]. Also, as found in this paper, the SHRIMP U-Pb ages of the zircons from the six Indosinian granites in the SZC, are 231–239 Ma. All the geochemical characteristics of the granites listed above, indicate that they were formed in a post-collisional tectonic environment. Sylvester [32] suggested that post-collision granites were emplaced in an extensional environment after the maximum compression of crust; Zhou [31] also pointed out that the Early Mesozoic granites were formed under the mechanics of crustal attenuation and decompression melting.

In summary, the investigation presented here shows that the plutons of the SZC, such as Baiyun, Ledong, Jiangnan, Longhuashan, Dawozi and Zaidi, were produced by magmatic activities in the early Indosinian Period. They formed shortly after the collision between the South China and Indosinian plates, during a period when the thickened lithosphere collapsed. The plutons were formed by the partial melting of argillaceous-arenaceous sedimentary metamorphic rocks of the Paleoproterozoic-Mesoproterozoic middle-lower crust, under the integrated influence of geothermal increase, decompression and water-conduction which were caused by the extension and attenuation of the lithosphere.

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