

Article

Mineralogy and Geochemistry of Early Triassic Granite in South China: Insights into Source Region Characteristics and REE Mineralization

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Abstract: Regolith-hosted rare-earth element (REE) deposits are some of the most important types of REE deposits. The relationship between Late Paleozoic and Early Mesozoic granite and regolith-hosted REE deposits is still poorly studied. Detailed geochronology, geochemistry, and rare-earth mineralogy analyses of Early Triassic granite in the South China Block were conducted. The geochronological results showed that four representative granite samples yielded formation ages of 245 ± 1 Ma, 244 ± 1 Ma, 244 ± 1 Ma, and 244 ± 2 Ma, respectively. The granites show geochemical affinity to A-type granite. They are characterized by enrichment in Rb, Th, and U, are depleted in Ba, Sr, P, and Ti, and show obvious negative Nb and Ta anomalies. They have high light rare-earth element (LREE) and low heavy rare-earth element (HREE) contents, with obvious negative Eu anomalies. They were derived from the partial melting of a sediment source and underwent intense fractional crystallization during the magma evolution process. They contain a certain number of rare-earth-element-bearing minerals, such as monazite, xenotime, apatite, and zircon. Their REE compositions and mineral associations are similar to those of the parent rocks from typical regolith-hosted REE deposits in South China. The highly weathered horizon at the ridge of the granite weathering crust profile has the highest REE content. A comprehensive analysis indicated that the degree of magma evolution, geomorphology, and weathering are important factors controlling the formation of regolith-hosted REE deposits in the area.

Keywords: regolith-hosted REE deposits; granite; REE mineralogy; zircon U-Pb dating; Early Triassic; Darongshan–Shiwandashan



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1. Introduction

The Tethys Ocean, which was named by Suess (1893) [1], was a trans-equatorial ocean between Eurasia, Africa, and India. Many studies have shown that the Tethys Ocean existed at different geological times and had different evolutionary processes [2]. Metcalfe (2021) divides the Tethys Ocean into the Late Silurian Prototethys, Devonian–Late Triassic Paleotethys, Middle Permian–Late Cretaceous Mesotethys, and Jurassic–Cretaceous Neotethys [3]. The Paleotethys was a Paleozoic ocean between the continents of Gondwana and Laurasia [4–7]. This has been well documented in Southeast Asia [8–14]. Previous studies have shown that the framework of the Eastern Paleotethys is complex. The main ocean basin is represented by the Changning–Menglian suture zone, which extends to

Thailand [15,16]. The branches of the ocean basin are represented by a series of suture zones, such as the Jinshajiang, Ailaoshan, Songma, and Hainan suture zones [17,18]. In addition, the Tethyan metallogenic domain is a world-famous metallogenic domain that includes different types of deposits, such as skarn Fe deposits, porphyry Cu–Mo–Au, sediment-hosted Pb–Zn deposits, granite-related Sn–W deposits, and so on [19]. In South China, there are numerous granite outcrops along the Tethyan tectonic domain. However, the relationship between the Late Paleozoic and Early Mesozoic granite and regolith-hosted REE deposits in South China is poorly studied.

The Darongshan–Shiwandashan granite belt, an important Late Paleozoic to Early Mesozoic granite belt in South China, is located at the intersection of the Paleo-Pacific and Paleotethys tectonic domains. A thick granitoid weathering crust that is preserved in the Darongshan–Shiwandashan area and some regolith-hosted REE deposits have been discovered [20–24]. The Darongshan–Shiwandashan granite belt provides an ideal location for revealing the Late Paleozoic to Early Mesozoic tectonic evolution of South China and discussing the relationship between granite and regolith-hosted REE deposits. In this study, petrography, zircon U–Pb geochronology, geochemistry, and REE mineralogical data of granites from the Darongshan–Shiwandashan granite belt are presented. Our aims are to (1) discuss the petrogenesis, source characteristics, and tectonic environment of the granite and (2) reveal the ore-controlling conditions of the regolith-hosted REE deposit.

2. Geological Background

The South China Block is composed of the Yangtze Block in the northwest and the Cathaysia Block in the southeast (Figure 1a). The Darongshan–Shiwandashan granite belt is located at the junction of the South China Block, Indochina Block, and Pacific Plate (Figure 1a). The granite belt has an NE trend and extends from Wuzhou in the northeast to the Beibu Gulf in the southwest, with a length of approximately 400 km and a width of approximately 20–75 km [25]. It is mainly controlled by the Bobai–Cenxi and Lingshan–Tengxian faults and is composed of Darongshan, Pubei, Taima, and Jiuzhou plutons (Figure 1b) [26,27]. Previous studies showed that the Taima pluton formed at 249–236 Ma [28–30]. The formation age of the Darongshan pluton is 251–243 Ma [31,32]. The Pubei pluton formed at 252–244 Ma [33,34]. Granites from the Jiuzhou pluton have LA-ICP-MS zircon U–Pb ages of 248–245 Ma [26]. Granites from the above plutons generally display obvious negative Nb–Ta anomalies, high Rb, Th, and U contents, low Ba and Sr contents, high Zr/Nb and Ba/Nb ratios, and low Th/Nb and Ta/La ratios [26,28,31,33]. In addition, a few volcanic rocks, such as 247–245 Ma dacite porphyry and ~246 Ma basalt, were reported in the Banba and Hengxian areas [35–37].

The wall rocks of the Darongshan–Shiwandashan granite are mainly Silurian, Devonian, Permian, Triassic, and Jurassic sedimentary and volcanic rocks (Figure 1c). The Silurian rocks are mainly composed of a set of shales. The Devonian rocks are composed of mudstone, sandstone, and siltstone and are in interdigitated or gradational contact with the Silurian. The Upper Permian is mainly composed of limestone and clastic limestone with a small amount of siliceous limestone. The Lower Permian strata are composed of carbonate, volcanic breccia, and mafic lava. The Lower Triassic rocks are mainly a set of sedimentary shallow marine carbonates and clastic rocks. The Middle Triassic rocks mainly consist of terrigenous clastic turbidite, and the Upper Triassic rocks are a suite of lithologic clastic rocks and terrigenous red beds. The Jurassic strata are mainly composed of argillaceous siltstone, breccia, and medium- to coarse-grained feldspar quartz sandstone [26].

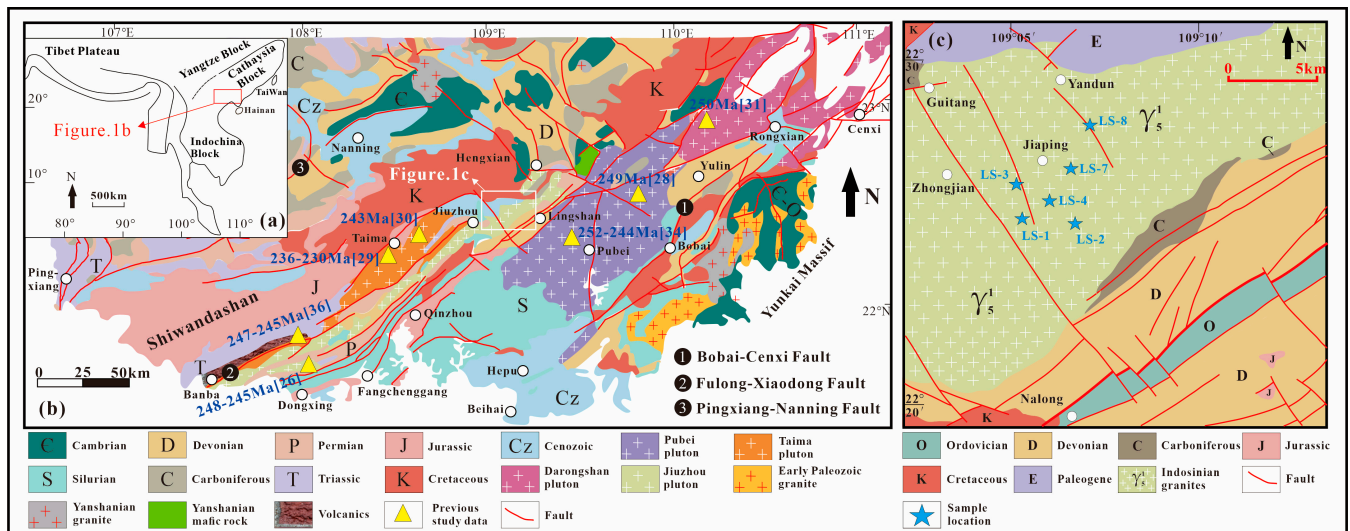


Figure 1. (a) Simplified tectonic map showing major tectonic units in Southeast Asia (modified after [38]). (b) Simplified geological map showing major plutons of Darongshan–Shiwandashan granite belt (modified after [26]). (c) Sketch of a geological map showing sampling locations.

3. Petrological Characteristics

Four granite samples (LS-3, LS-4, LS-7, and LS-8) from the Darongshan–Shiwandashan granite belt were selected for geochronological analysis (Figure 2). The sampling locations are shown in Figure 1c.



Figure 2. Field photographs showing the granite weathering crust from Darongshan–Shiwandashan, southeast Guangxi.

Sample LS-3 was biotite granite and was grayish-black with a medium-to coarse-grained texture and massive texture (Figure 3a). The main minerals were quartz, plagioclase, K-feldspar, and biotite (Figure 3b). The quartz (25–35 vol%) was euhedral to anhedral, with sharp contacts. The plagioclase (20–30 vol%) exhibited twinning lamellae. The biotite (10–15 vol%) was a dark-brown, flaky, and had semi-idiomorphic sheets. The K-feldspar (10–15 vol%) was idiomorphic with a grain size of 400–1000 μm .

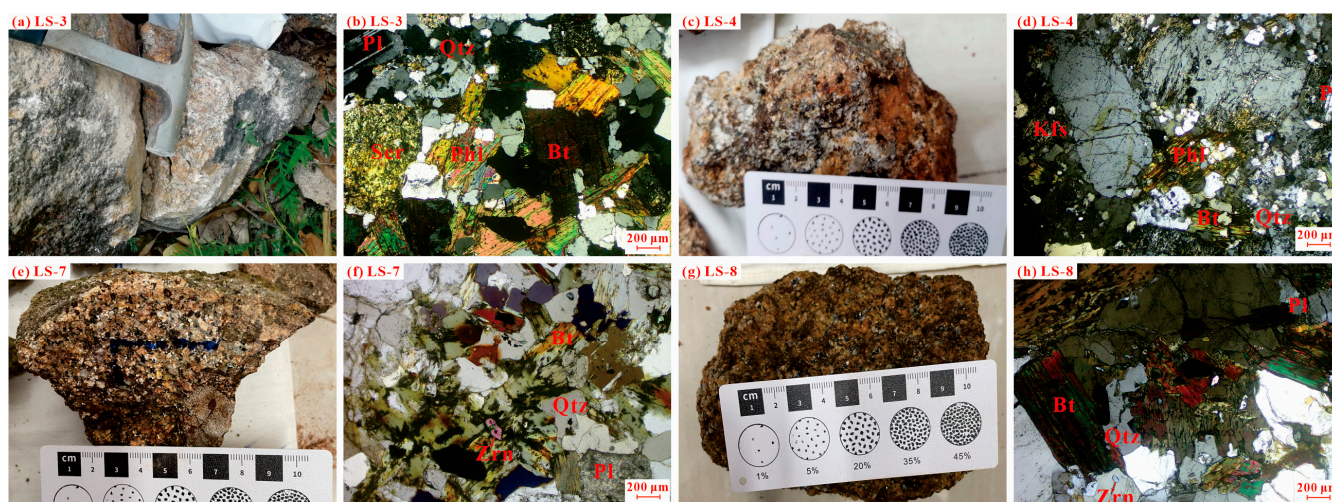


Figure 3. Field photographs (a,c,e,g) and photomicrographs (b,d,f,h) of granite from Darongshan-Shiwandashan, southeast Guangxi. Bt—biotite; Qtz—quartz; Pl—plagioclase; Kfs—K-feldspar; Phl—phlogopite; Ser—sericite; Zrn—zircon.

Sample LS-4 was biotite granite and was coarse-grained with a massive texture (Figure 3c). The main minerals were quartz, plagioclase, biotite, and K-feldspar (Figure 3d). The biotite (20–30 vol%) was dark brown with a 200–800 µm grain size. The K-feldspar (25–35 vol%) was euhedral to subhedral with a size of 300–1000 µm.

Sample LS-7 was biotite granite and was coarse-grained with a massive texture (Figure 3e). The main minerals were quartz, biotite, and plagioclase. The quartz (30–35 vol%) was irregular with a clean surface. The biotite (10–15 vol%) was dark brown with a size of 200–600 µm. The plagioclase (5–10 vol%) was dark gray with a grain size of 200–500 µm (Figure 3f).

Sample LS-8 was alkaline feldspar granite and was obtained from a spheroidal granite mass. It was grayish-black, and it had a coarse-grained and massive texture (Figure 3g). The main minerals were quartz (25–35 vol%), plagioclase (20–25 vol%), K-feldspar (10–15 vol%), and biotite (10–15 vol%) (Figure 3h).

4. Results

4.1. Zircon U-Pb Dating Results

The LA-ICP-MS zircon U-Pb analysis results are shown in Table 1. CL images show that most of the zircons were brown and idiomorphic, with lengths of 100–350 µm and widths of 90–150 µm (Figure 4). They were characterized by clear oscillating zones, indicating a magmatic source for the texture.

Twenty zircon grains from sample LS-3 were selected for U-Pb isotope testing, and the results showed that the U content was 223–2117 ppm, the Th content was 164–1385 ppm, and the Th/U ratio varied from 0.21 to 1.19 (Table 1). Among them, 16 zircons were located at or near the U-Pb age concordance and gave a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 245 ± 1 Ma (MSWD = 0.02, 1σ) (Figure 4a,b), representing the crystallization age.

The results of the analysis of 20 zircon grains from sample LS-4 showed that the U content ranged from 216–1583 ppm and the Th content ranged from 86–954 ppm, with the Th/U ratio ranging from 0.07 to 0.77 (Table 1). Fifteen grains yielded a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 244 ± 1 Ma (MSWD = 0.11, 1σ) (Figure 4c,d), representing the crystallization age.

Table 1. LA-ICP-MS zircon U-Pb isotope results of granite from Darongshan–Shiwandashan, south-east Guangxi.

Spot	Isotope Ratio						Age (Ma)			
	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ
Sample LS-3										
1	0.0999	0.0020	3.5422	0.0734	0.2572	0.0026	1537	16	1476	13
2	0.0816	0.0022	1.7865	0.0831	0.1593	0.0071	1041	30	953	39
3	0.0675	0.0011	1.1543	0.0213	0.1237	0.0009	779	10	752	5
4	0.0566	0.0028	0.2983	0.0147	0.0386	0.0007	265	11	244	5
5	0.0551	0.0027	0.2930	0.0147	0.0387	0.0007	261	12	245	5
6	0.0540	0.0030	0.2956	0.0317	0.0385	0.0023	263	25	244	14
7	0.0508	0.0011	0.2702	0.0060	0.0386	0.0003	243	5	244	2
8	0.0500	0.0008	0.2665	0.0043	0.0387	0.0003	240	3	245	2
9	0.0492	0.0044	0.2613	0.0226	0.0387	0.0008	236	18	245	5
10	0.0539	0.0089	0.2733	0.0401	0.0388	0.0010	245	32	246	6
11	0.0523	0.0025	0.2788	0.0131	0.0388	0.0006	250	10	245	4
12	0.0689	0.0011	1.4063	0.0639	0.1456	0.0058	892	27	876	33
13	0.0480	0.0026	0.2552	0.0133	0.0387	0.0007	231	11	245	4
14	0.0503	0.0025	0.2676	0.0125	0.0387	0.0005	241	10	245	3
15	0.0529	0.0020	0.2819	0.0109	0.0387	0.0004	252	9	245	3
16	0.0516	0.0015	0.2771	0.0089	0.0388	0.0004	248	7	245	3
17	0.0498	0.0022	0.2647	0.0115	0.0387	0.0004	238	9	245	2
18	0.0493	0.0010	0.2633	0.0052	0.0388	0.0004	237	4	245	2
19	0.0513	0.0016	0.2736	0.0086	0.0387	0.0004	246	7	245	3
20	0.0512	0.0011	0.2745	0.0067	0.0388	0.0004	246	5	245	2
Sample LS-4										
1	0.0541	0.0041	0.2866	0.0239	0.0382	0.0004	256	19	242	2
2	0.0530	0.0013	0.2829	0.0078	0.0387	0.0004	253	6	245	2
3	0.0485	0.0015	0.2578	0.0077	0.0386	0.0004	233	6	244	2
4	0.0501	0.0017	0.2658	0.0093	0.0386	0.0005	239	7	244	3
5	0.0502	0.0019	0.2672	0.0108	0.0386	0.0004	240	9	244	3
6	0.0543	0.0019	0.2891	0.0102	0.0386	0.0004	258	8	244	3
7	0.0694	0.0021	1.1172	0.0393	0.1172	0.0024	762	19	714	14
8	0.0517	0.0018	0.2771	0.0114	0.0387	0.0005	248	9	245	3
9	0.0669	0.0009	1.2181	0.0192	0.1320	0.0013	809	9	799	7
10	0.0487	0.0014	0.2590	0.0072	0.0386	0.0004	234	6	244	2
11	0.0568	0.0026	0.3013	0.0135	0.0387	0.0005	267	11	245	3
12	0.0484	0.0027	0.2583	0.0145	0.0388	0.0005	233	12	245	3
13	0.0758	0.0012	1.9556	0.0366	0.1875	0.0029	1100	13	1108	16
14	0.0719	0.0013	1.4987	0.0414	0.1507	0.0031	930	17	905	17
15	0.0500	0.0028	0.2654	0.0149	0.0386	0.0005	239	12	244	3
16	0.0485	0.0025	0.2588	0.0140	0.0387	0.0005	234	11	244	3
17	0.0709	0.0010	1.3233	0.0226	0.1355	0.0016	856	10	819	9
18	0.0509	0.0023	0.2708	0.0122	0.0386	0.0005	243	10	244	3
19	0.0497	0.0024	0.2655	0.0135	0.0387	0.0005	239	11	245	3
20	0.0485	0.0028	0.2599	0.0169	0.0386	0.0007	235	14	244	4
Sample LS-7										
1	0.0506	0.0011	0.2685	0.0060	0.0386	0.0006	242	5	244	4
2	0.0688	0.0008	1.3364	0.0163	0.1410	0.0011	862	7	850	6
3	0.0513	0.0009	0.2734	0.0051	0.0386	0.0002	245	4	244	1
4	0.0811	0.0009	1.3047	0.0227	0.1165	0.0012	848	10	710	7
5	0.0531	0.0022	0.2883	0.0116	0.0394	0.0003	257	9	249	2
6	0.0517	0.0013	0.2750	0.0084	0.0385	0.0004	247	7	243	3
7	0.0547	0.0011	0.2913	0.0064	0.0386	0.0003	260	5	244	2
8	0.0563	0.0010	0.5063	0.0101	0.0652	0.0006	416	7	407	4

Table 1. Cont.

Spot	Isotope Ratio						Age (Ma)			
	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ
9	0.0552	0.0013	0.3486	0.0117	0.0460	0.0014	304	9	290	9
10	0.0504	0.0013	0.2676	0.0079	0.0386	0.0007	241	6	244	4
11	0.0548	0.0013	0.2923	0.0079	0.0386	0.0004	260	6	244	2
12	0.0910	0.0010	3.1411	0.1258	0.2457	0.0082	1443	31	1416	43
13	0.0542	0.0018	0.2880	0.0103	0.0386	0.0006	257	8	244	4
14	0.0533	0.0010	0.2840	0.0057	0.0386	0.0003	254	5	244	2
15	0.0510	0.0016	0.2692	0.0079	0.0384	0.0007	242	6	243	4
16	0.0533	0.0014	0.2824	0.0074	0.0386	0.0007	253	6	244	4
17	0.0611	0.0016	0.7590	0.0244	0.0899	0.0015	573	14	555	9
18	0.0499	0.0014	0.2662	0.0088	0.0387	0.0007	240	7	245	4
19	0.0566	0.0021	0.2955	0.0106	0.0379	0.0005	263	8	240	3
20	0.0509	0.0013	0.2716	0.0076	0.0386	0.0003	244	6	244	2
Sample LS-8										
1	0.0487	0.0027	0.2569	0.0139	0.0385	0.0006	232	11	243	4
2	0.0480	0.0018	0.2540	0.0087	0.0386	0.0004	230	7	244	2
3	0.0564	0.0033	0.3033	0.0206	0.0387	0.0005	269	16	245	3
4	0.0493	0.0014	0.2634	0.0084	0.0386	0.0004	237	7	244	2
5	0.0494	0.0015	0.2643	0.0091	0.0386	0.0004	238	7	244	2
6	0.0691	0.0017	1.5486	0.0379	0.1625	0.0016	950	15	971	9
7	0.0702	0.0014	1.5980	0.0318	0.1656	0.0018	969	12	988	10
8	0.0689	0.0014	1.2455	0.0259	0.1312	0.0013	821	12	795	7
9	0.0604	0.0015	0.7899	0.0208	0.0947	0.0009	591	12	583	5
10	0.0593	0.0011	0.8226	0.0172	0.1005	0.0009	610	10	617	5
11	0.0543	0.0012	0.4771	0.0129	0.0639	0.0014	396	9	399	8
12	0.0553	0.0015	0.5245	0.0138	0.0689	0.0006	428	9	430	4
13	0.0563	0.0045	0.2992	0.0222	0.0394	0.0007	266	17	249	5
14	0.0602	0.0030	0.3264	0.0166	0.0397	0.0007	287	13	251	5
15	0.0508	0.0038	0.2716	0.0215	0.0387	0.0008	244	17	245	5
16	0.1595	0.0019	8.2178	0.1121	0.3735	0.0028	2255	12	2046	13
17	0.1615	0.0009	8.7021	0.1713	0.3902	0.0071	2307	18	2124	33
18	0.0514	0.0014	0.2732	0.0076	0.0386	0.0004	245	6	244	2
19	0.0532	0.0021	0.2817	0.0109	0.0385	0.0004	252	9	244	2
20	0.0529	0.0014	0.2802	0.0071	0.0385	0.0003	251	6	243	2

Twenty zircons from sample LS-7 were selected for U-Pb isotope analysis. The results showed that the U content ranged from 330–1437 ppm, and the Th content ranged from 161–618 ppm, with a Th/U ratio of 0.19 to 1.59 (Table 1). Thirteen zircons yielded a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 244 ± 1 Ma (MSWD = 0.20, 1σ) (Figure 4e,f), representing the crystallization age.

The results showed that twenty zircon grains from sample LS-8 had a U content of 314–1929 ppm and a Th content of 101–939 ppm, with a Th/U ratio of 0.17–1.31 (Table 1). Nine of the grains yielded a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 244 ± 2 Ma (MSWD = 0.05, 1σ) (Figure 4g,h), representing the crystallization age.

The trace element composition of zircons in granite showed that they were enriched in Th, U, Ta, Pr, and Hf and relatively depleted in Nb, La, Sr, Nd, and Ti. Additionally, they had high contents of heavy rare-earth elements (HREEs) and low contents of light rare-earth elements (LREEs), accompanied by notable negative Eu anomalies (Figure 5, Tables 2 and 3).

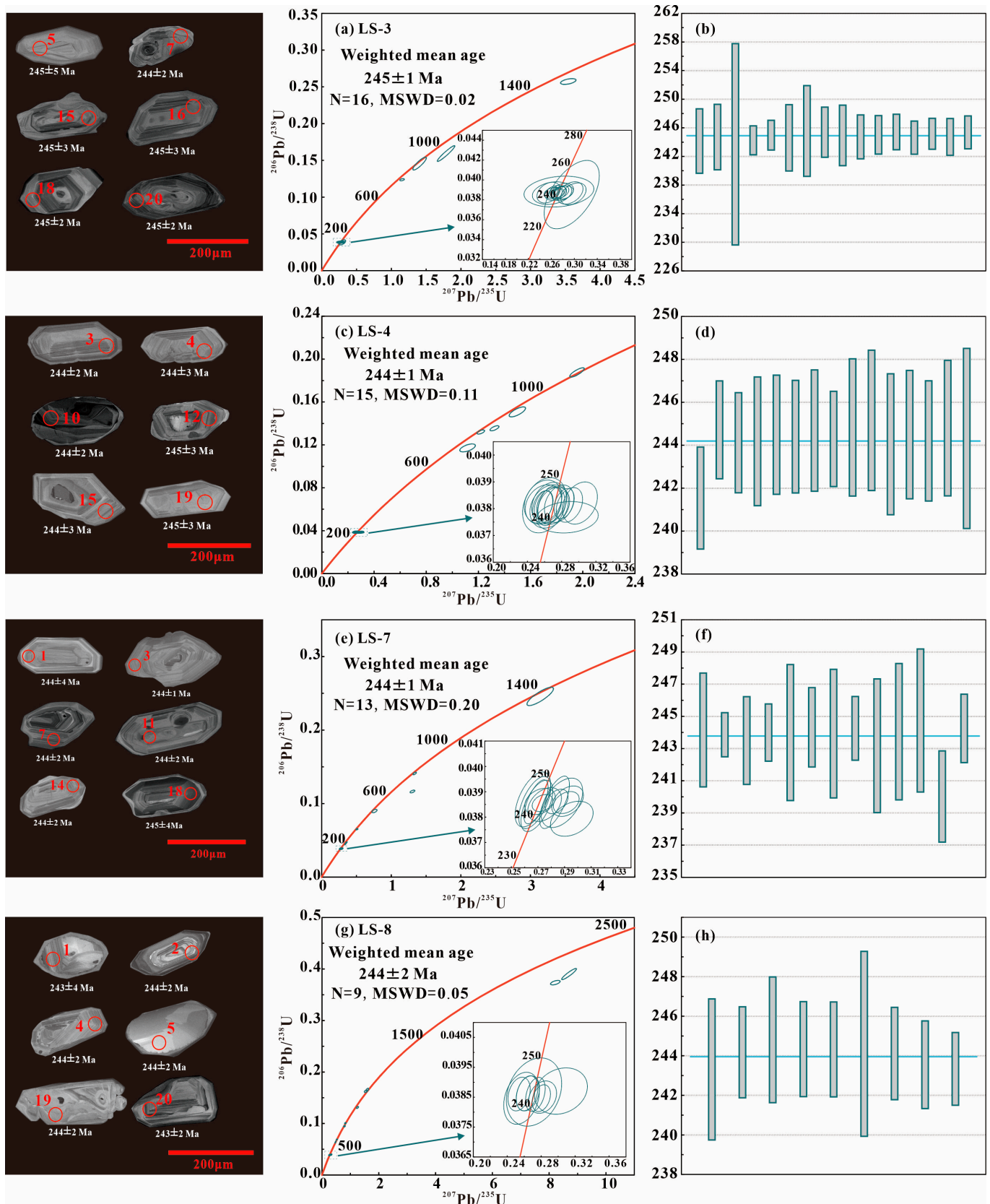


Figure 4. Cathodoluminescence images of representative zircons and plots of zircon U-Pb concordia and weighted mean age of sample (a,b) LS-3, (c,d) LS-4, (e,f) LS-7, and (g,h) LS-8 from Darongshan-Shiwandashan, southeast Guangxi.

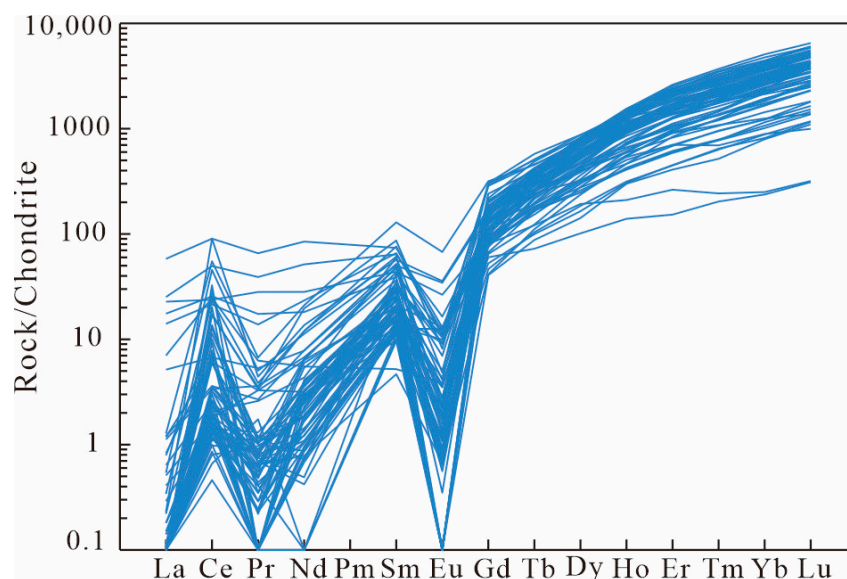


Figure 5. Chondrite-normalized REE distribution patterns of zircon from granite from Darongshan-Shiwandashan, southeast Guangxi.

Table 2. Trace element contents ($\times 10^{-6}$) of zircon from granite from Darongshan-Shiwandashan, southeast Guangxi.

Spot	Ti	Sr	Y	Nb	Hf	Ta	Th	U
Sample LS-3								
1	16.02	0.66	3415.07	5.94	36,285.96	2.77	403.50	248.48
2	18.04	0.45	2332.22	11.48	35,828.97	3.84	397.29	584.45
3	40.69	1.41	5938.22	7.76	34,708.51	3.90	1385.38	1168.20
4	29.42	2.91	7102.70	1.62	43,330.55	1.98	357.46	1227.92
5	23.48	3.07	6894.76	3.19	41,350.27	2.19	359.55	1310.39
6	32.70	0.73	7397.21	2.57	42,316.71	2.61	408.41	1163.66
7	20.28	0.76	7463.15	3.34	40,832.45	2.21	391.78	1845.89
8	21.86	1.02	7601.99	3.72	40,717.43	3.29	660.39	2116.91
9	17.09	0.49	2696.17	1.53	42,067.54	1.85	204.14	560.96
10	66.50	0.59	3104.57	1.84	33,066.26	1.07	164.29	222.63
11	39.22	0.75	7072.69	2.05	36,539.11	1.76	298.39	803.35
12	20.68	0.91	4711.55	5.17	38,742.47	3.64	372.86	1494.86
13	29.24	0.50	7276.29	2.34	39,248.61	2.11	256.58	1042.07
14	31.62	0.40	5309.05	1.57	41,428.61	0.94	273.81	689.79
15	28.51	1.58	6744.18	2.14	40,321.48	1.68	221.83	823.42
16	37.64	1.68	5107.88	2.13	39,232.64	1.63	291.85	755.58
17	33.29	0.35	4894.95	1.13	40,495.21	1.30	203.91	736.91
18	24.17	1.92	5273.35	6.15	40,866.41	4.47	899.62	2084.07
19	25.06	1.15	5225.81	2.03	41,904.34	1.87	247.49	913.45
20	21.95	1.06	3802.24	2.78	41,388.61	1.64	336.02	1167.46
Sample LS-4								
1	39.97	0.61	4687.48	2.38	39,629.59	0.37	200.12	732.85
2	22.38	1.93	6942.60	2.73	31,328.26	1.37	953.59	1238.51
3	18.75	0.79	3541.54	2.97	42,396.93	2.21	95.19	1277.53
4	25.21	0.47	7400.36	1.84	41,277.83	1.90	229.64	938.68
5	29.64	1.68	6262.68	1.05	39,574.41	2.34	254.68	865.42
6	27.90	1.21	6774.17	2.03	41,611.76	1.91	226.05	822.46
7	26.41	0.24	1357.71	5.77	32,359.66	2.16	85.91	215.93
8	24.31	0.82	4970.46	2.06	42,783.45	2.52	141.68	826.28

Table 2. Cont.

Spot	Ti	Sr	Y	Nb	Hf	Ta	Th	U
9	33.87	0.72	4430.67	10.39	34,581.06	6.01	915.99	1407.85
10	29.71	0.82	6532.83	2.03	41,360.48	2.03	213.49	857.87
11	29.08	1.02	5264.50	1.33	41,585.70	3.98	302.37	1085.31
12	27.97	0.64	5798.94	3.02	41,939.55	1.21	205.53	772.91
13	105.84	4.75	1394.44	7.65	32,826.19	3.68	433.78	778.27
14	20.10	0.00	1303.25	4.24	35,068.66	2.33	391.92	869.35
15	23.43	0.00	4575.70	1.90	42,350.65	2.12	207.21	866.00
16	21.31	0.32	2507.66	0.76	44,955.25	1.37	145.37	961.98
17	12.72	0.00	1145.92	4.35	41,097.37	4.47	480.62	1583.29
18	26.47	2.23	6566.34	2.25	41,409.00	0.90	220.21	765.22
19	30.26	1.23	5265.15	0.48	41,318.78	1.31	164.77	650.77
20	22.32	1.00	5431.69	1.16	41,714.42	0.79	174.98	715.41
Sample LS-7								
1	20.79	0.51	3994.29	2.00	33,533.17	1.74	219.82	946.90
2	19.92	0.51	668.06	2.83	33,995.09	1.77	250.05	633.27
3	27.24	0.97	6765.46	2.78	30,267.72	1.10	264.78	1026.42
4	37.89	0.82	3229.58	5.82	29,977.52	3.59	298.79	1437.43
5	70.02	0.73	4862.95	3.59	26,456.08	1.94	352.10	746.63
6	39.28	1.41	4051.94	1.99	22,866.98	1.10	291.29	708.98
7	39.66	1.21	5188.40	2.68	29,694.96	1.24	294.88	1010.19
8	13.01	0.64	2767.50	7.19	27,245.60	3.74	219.37	630.17
9	22.53	1.31	1985.15	4.30	30,895.28	3.47	173.98	878.37
10	24.42	0.83	6350.86	0.98	30,052.86	1.36	209.50	919.63
11	33.07	1.06	6029.14	4.43	28,357.20	1.60	618.05	829.02
12	22.65	6.31	2058.59	5.08	26,244.50	2.86	246.70	828.92
13	24.53	0.77	5169.57	1.01	31,728.21	1.65	234.49	961.33
14	28.74	0.71	5544.11	1.34	30,957.39	1.12	225.62	873.43
15	34.85	1.30	5494.83	1.54	33,091.26	0.94	188.21	699.83
16	28.26	0.74	5088.30	1.02	31,265.06	0.94	202.46	818.62
17	63.18	0.69	2880.95	7.71	24,914.42	3.01	522.39	329.55
18	19.44	0.99	7658.93	2.92	31,934.58	2.24	181.05	933.34
19	44.71	1.76	3375.30	3.19	20,453.63	0.97	253.36	431.27
20	25.77	0.29	4416.07	2.55	30,965.82	0.94	161.17	721.35
Sample LS-8								
1	23.32	0.55	4436.48	2.60	39,653.81	1.04	124.63	566.57
2	26.15	1.07	5105.89	1.32	42,187.94	1.52	182.04	665.70
3	37.16	2.13	8031.18	2.50	38,470.86	1.17	681.93	1380.40
4	27.34	1.22	7123.14	2.75	42,310.64	1.40	258.73	913.74
5	27.66	1.24	6220.90	1.40	39,460.02	1.55	291.34	916.66
6	10.58	0.41	2828.18	6.04	38,449.72	2.69	136.60	313.70
7	6.96	8.06	3183.31	9.07	39,689.68	3.75	165.83	424.42
8	9.63	0.62	2226.73	5.09	43,613.01	3.72	100.94	529.59
9	20.34	0.00	1887.85	5.26	33,511.00	2.91	195.72	698.73
10	35.21	1.13	4908.82	4.32	32,224.63	2.61	418.01	1049.32
11	3.05	1.28	2814.82	7.36	46,308.98	5.39	332.82	1928.85
12	10.98	0.30	4263.76	13.06	38,180.98	7.08	431.56	1342.76
13	40.48	0.43	3555.07	1.69	41,098.63	1.78	166.23	444.97
14	129.58	2.08	6184.30	2.57	34,772.64	1.77	320.47	652.75
15	40.13	1.75	5414.94	2.06	36,488.57	1.80	217.60	443.60
16	28.91	1.45	5215.68	7.93	24,440.27	5.69	939.27	717.12
17	24.78	0.72	3129.20	4.82	31,753.77	4.15	759.94	898.61
18	19.76	1.09	4679.96	1.17	42,457.75	1.29	167.06	955.20
19	24.74	0.60	6014.60	1.57	39,091.75	1.71	307.34	984.66
20	25.47	0.54	6965.97	1.46	38,094.75	1.12	338.48	1130.12

Table 3. REE element contents ($\times 10^{-6}$) of zircon from granite from Darongshan–Shiwandashan, southeast Guangxi.

Spot	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Sample LS-3														
1	0.00	51.02	0.18	2.95	12.96	1.86	63.53	25.51	305.01	117.46	487.09	100.50	859.15	170.94
2	0.00	57.82	0.00	1.26	5.60	2.10	50.96	16.52	222.31	82.75	336.71	70.14	603.47	133.19
3	0.23	41.58	1.06	16.19	33.82	1.80	178.67	54.77	600.35	223.43	869.48	166.55	1418.67	274.03
4	0.00	4.14	0.28	1.17	15.51	1.17	103.53	40.33	600.21	243.49	1097.89	226.94	2125.31	403.12
5	0.00	3.30	0.25	4.33	10.39	0.00	110.36	40.08	560.93	216.45	1032.34	226.74	2020.33	395.24
6	0.00	4.73	0.00	3.11	13.61	0.00	108.68	41.93	610.81	242.74	1082.91	234.42	1912.91	377.89
7	0.08	3.40	0.12	1.43	8.50	0.12	86.74	39.15	574.16	251.07	1135.57	255.93	2191.19	448.05
8	0.00	5.80	0.14	3.64	15.19	0.00	100.50	43.91	600.26	251.89	1165.67	244.68	2156.60	434.22
9	0.00	3.45	0.00	5.57	8.25	0.00	54.22	26.20	237.17	88.18	336.87	51.37	438.64	73.79
10	0.00	6.21	0.28	3.35	13.85	1.55	77.11	20.67	243.96	121.61	515.37	107.23	1080.12	210.48
11	0.00	3.18	0.91	4.29	15.09	0.69	117.71	41.86	579.96	216.08	978.88	213.28	1859.90	382.57
12	0.00	16.47	0.00	1.30	9.16	0.00	67.41	28.17	395.96	155.97	781.72	163.58	1469.90	303.18
13	0.00	1.17	0.48	0.00	11.69	0.46	120.69	44.86	580.83	234.36	1131.84	242.35	2043.00	413.70
14	0.09	4.62	0.22	5.31	10.32	0.85	89.87	34.25	461.64	183.80	813.00	162.32	1520.89	285.23
15	0.00	2.78	0.14	3.71	12.94	0.26	80.08	38.62	524.75	216.00	988.15	206.70	1820.98	361.77
16	0.00	5.32	0.06	4.47	8.61	0.59	75.55	35.17	429.40	176.05	798.08	163.60	1404.07	287.31
17	0.00	1.74	0.25	2.51	6.96	0.16	77.96	30.66	386.54	163.61	749.96	150.66	1371.57	276.03
18	12.04	45.40	4.81	24.58	17.35	0.12	78.19	33.21	454.46	182.16	814.80	165.25	1531.38	282.11
19	0.35	2.96	0.00	3.74	8.12	0.13	59.55	27.43	417.24	174.01	809.34	166.69	1530.95	297.06
20	0.00	3.54	0.00	1.02	5.48	0.32	44.73	23.23	298.16	128.30	596.62	130.76	1141.04	224.91
Sample LS-4														
1	0.12	2.61	0.10	4.09	6.65	0.73	62.19	27.10	380.45	152.26	721.19	142.68	1326.39	255.69
2	9.65	38.11	3.82	31.63	29.19	2.00	171.39	55.19	642.43	234.19	997.05	210.53	1776.23	322.64
3	0.12	4.67	0.19	0.57	5.88	0.18	39.93	17.73	266.47	120.24	615.46	145.37	1455.68	312.91
4	0.00	2.32	0.15	1.82	13.99	0.14	99.07	38.36	555.93	238.32	1090.57	223.32	2110.91	404.35
5	0.10	3.55	0.08	4.36	7.18	0.00	86.80	38.58	487.75	204.22	972.27	195.88	1818.87	350.68
6	0.00	2.59	0.07	3.94	8.95	0.00	80.91	35.12	551.15	212.47	1033.83	217.07	1959.96	386.65
7	0.07	11.55	0.11	0.00	4.26	0.32	27.65	11.22	136.17	51.62	214.68	46.85	434.81	87.02
8	0.00	2.12	0.08	1.41	6.45	0.15	73.63	28.49	397.20	165.81	794.43	170.56	1603.12	316.70
9	0.00	30.82	0.93	16.25	27.09	0.22	124.67	40.29	445.74	159.34	653.90	128.96	1117.04	209.42
10	0.00	3.17	0.17	3.37	7.26	0.11	88.51	39.33	524.51	212.16	971.12	206.23	1884.92	363.19
11	0.83	6.37	0.33	0.97	6.61	0.31	58.09	34.98	408.14	170.48	825.06	187.23	1668.24	329.93
12	0.00	3.20	0.16	1.84	7.30	0.00	82.65	31.16	447.07	199.85	908.13	177.21	1570.81	311.13
13	4.82	43.96	1.73	7.48	2.31	0.65	31.37	10.76	121.24	50.27	216.44	47.83	401.73	85.59
14	0.00	24.21	0.22	1.93	5.11	0.00	24.24	9.47	104.41	49.16	196.09	38.31	391.55	81.21
15	0.00	4.06	0.00	0.00	4.48	0.00	51.11	27.81	356.86	152.99	725.92	159.64	1344.01	296.01
16	0.00	1.52	0.00	0.92	5.22	0.59	52.99	19.34	237.10	76.10	328.91	70.97	600.20	121.62
17	0.57	10.85	0.90	8.56	8.95	0.42	47.94	13.07	142.02	34.47	126.47	17.97	123.31	23.58
18	0.20	2.81	0.16	7.27	11.32	0.29	94.01	36.91	512.95	211.31	996.85	205.72	1848.47	382.52
19	0.00	2.52	0.00	2.62	5.93	0.00	68.57	30.98	429.32	185.59	825.50	178.37	1630.12	318.84
20	0.00	1.77	0.00	3.81	4.32	0.00	67.75	28.31	450.58	175.36	805.83	180.65	1583.95	315.81
Sample LS-7														
1	0.00	2.04	0.11	1.66	6.29	0.20	48.47	21.50	322.13	128.66	616.92	132.47	1184.78	235.41
2	0.00	13.91	0.10	3.60	7.62	0.62	35.81	7.83	74.68	22.86	73.33	15.05	116.98	22.97
3	0.00	2.72	0.16	3.49	12.57	0.06	98.02	42.23	578.75	231.29	1010.09	213.53	1859.30	369.25
4	15.64	42.12	7.77	38.15	19.45	4.45	53.55	20.73	292.36	99.47	468.50	101.64	945.64	191.20
5	0.00	6.40	0.74	10.62	23.11	0.38	110.68	41.21	432.63	162.36	668.41	132.01	1215.00	235.19
6	3.54	11.96	1.47	10.54	20.95	0.21	90.83	33.99	390.03	140.23	605.31	121.00	1084.26	211.61
7	0.77	5.99	0.99	9.14	16.18	0.47	90.43	37.13	454.69	171.57	777.80	159.88	1459.41	279.07
8	0.54	17.88	0.21	1.64	7.62	1.55	45.76	18.71	231.40	91.60	436.56	90.65	831.48	169.74
9	0.00	10.63	0.19	1.48	5.84	1.67	57.37	19.70	203.41	67.31	288.63	57.60	567.05	112.96
10	0.00	2.53	0.36	4.82	11.60	0.36	92.64	37.13	511.62	206.98	975.75	210.62	1818.81	352.77
11	0.81	10.60	0.32	8.84	19.19	1.51	121.46	45.81	563.69	207.84	904.12	174.93	1523.82	274.95
12	17.32	88.13	10.77	69.73	28.47	2.76	67.72	18.08	182.49	69.82	295.08	58.38	527.11	107.17
13	0.00	2.85	0.13	5.05	10.17	0.24	64.26	31.81	428.85	169.76	794.66	170.80	1514.21	285.17
14	0.04	2.73	0.15	4.64	8.12	0.38	77.25	34.44	454.71	190.71	864.60	181.12	1540.52	313.49
15	0.00	1.96	0.31	3.63	9.10	0.33	74.23	33.63	465.53	177.81	874.28	179.43	1548.95	314.56
16	0.00	1.41	0.27	2.48	9.22	0.09	63.93	29.18	411.41	168.62	778.44	166.56	1462.03	281.36
17	0.15	159.99	1.22	18.41	25.28	6.00	104.89	28.22	290.54	96.91	395.28	78.83	707.29	134.43
18	0.00	3.31	0.00	0.98	13.55	0.15	95.05	41.43	592.98	253.61	1211.28	261.68	2342.72	441.33
19	0.00	5.73	0.29	4.82	14.13	1.75	79.22	27.16	313.43	117.69	504.25	98.88	953.19	184.23
20	0.28	2.15	0.06	1.25	5.17	0.11	64.54	24.95	346.00	146.97	670.86	140.84	1328.17	259.07
Sample LS-8														
1	0.00	0.81	0.00	2.35	7.14	0.12	48.71	24.08	328.74	149.84	694.53	153.97	1420.21	278.17
2	0.00	2.25	0.23	3.92	5.95	0.00	73.87	28.52	406.44	173.04	830.84	171.17	1607.92	313.12
3	0.44	4.38	0.17	8.06	9.19	0.32	130.31	52.64	606.73	252.06	1255.14	273.56	2503.92	480.67
4	0.00	2.14	0.07	2.30	11.82	0.12	103.58	44.36	569.28	227.00	1027.05	215.29	1901.18	365.74
5	0.00	2.66	0.07	5.45	11.58	0.00	100.46	37.73	527.05	218.49	989.81	199.40	1785.57	358.25
6	0.00	35.92	0.00	1.17	4.92	0.38	50.35	17.73	220.76	99.77	464.93	101.24	899.54	195.84
7	39.92	160.29	18.11	114.64	32.79	2.18	77.80	25.89	283.63	115.21	536.09	111.94	1059.02	226.33
8	0.15	23.80	0.18	1.06	2.07	0.11	24.70	12.00	174.21	76.08	402.88	92.11	930.34	203.35
9	0.00	20.15	0.33	2.53	10.95	0.61	46.85	18.12	191.30	67.06	282.27	57.35	499.28	101.48
10	0.08	30.25	0.97	26.54	38.47	1.37	170.81	49.68	515.12	177.76	721.84	136.83	1108.54	210.90
11	0.00	13.08	0.00	0.00	4.90	0.19	38.50	13.28	206.32	89.74	454.54	108.18	1175.25	281.02

Table 3. Cont.

Spot	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
12	0.00	22.83	0.29	2.54	9.36	2.18	58.57	28.40	356.74	148.52	699.75	155.62	1531.46	319.36
13	0.00	2.80	0.21	0.67	18.42	1.96	82.75	32.76	345.73	109.20	434.82	80.13	616.13	102.05
14	0.00	3.69	0.72	5.86	26.42	0.81	181.61	62.19	644.01	208.86	778.36	136.30	1048.55	190.46
15	0.00	4.13	0.21	8.62	21.60	0.40	143.70	43.21	513.93	187.71	822.46	151.58	1284.02	251.89
16	0.87	97.71	1.85	28.45	57.28	11.35	189.01	48.96	562.27	194.06	728.16	137.26	1271.49	258.31
17	0.37	81.00	1.39	15.25	22.31	5.78	98.69	28.49	307.54	104.98	445.11	88.89	816.01	171.13
18	0.00	2.34	0.07	1.91	5.41	0.00	68.95	28.52	379.34	159.17	715.41	152.28	1325.48	275.00
19	0.00	2.36	0.10	2.24	8.60	0.00	76.71	36.64	483.79	199.36	930.42	191.68	1736.57	349.66
20	0.00	2.79	0.24	2.79	9.47	0.22	97.84	44.14	573.81	225.67	1064.11	215.44	1902.84	369.54

4.2. Geochemical Characteristics

4.2.1. Major Elements

The SiO₂ content of the samples was 67.92 wt.%–69.76 wt.% (Table 4). The total alkali (Na₂O + K₂O) content ranged from 5.59 wt.% to 6.35 wt.%. They were rich in K₂O (K₂O/Na₂O = 0.39–0.63) and belonged to the high-K calc-alkaline series (Figure 6a; [39]). The Al₂O₃ content was 13.96 wt.%–15.62 wt.%, and the aluminum saturation index (A/CNK) was high (1.17–1.63), as it belonged to peraluminous rock (Figure 6b; [40]). The differentiation index (DI) ranged from 72.8 to 76.4, indicating a high degree of magma differentiation.

Table 4. Compositions of major (wt.%), trace, and REEs ($\times 10^{-6}$) in granite from Darongshan–Shiwandashan, southeast Guangxi.

Sample	LS-1	LS-2	LS-3	LS-4	LS-7	LS-8
SiO ₂	69.76	69.52	67.92	68.64	69.68	68.63
TiO ₂	0.72	0.79	0.80	0.85	0.76	0.73
Al ₂ O ₃	13.96	14.22	14.97	15.38	14.76	15.62
Fe ₂ O ₃ ^T	5.15	5.93	5.55	5.99	5.19	5.92
MgO	1.68	1.76	1.67	1.71	1.52	1.81
CaO	2.44	1.70	2.50	1.33	1.61	1.51
K ₂ O	3.72	3.93	3.91	4.27	4.23	3.68
Na ₂ O	2.34	1.94	2.43	1.66	2.05	1.91
MnO	0.07	0.08	0.07	0.07	0.06	0.06
P ₂ O ₅	0.16	0.13	0.17	0.10	0.13	0.12
LOI	1.17	1.80	1.32	2.83	2.05	2.21
Total	99.13	99.32	99.97	99.51	99.78	99.94
Mg [#]	43.16	40.89	41.27	39.96	40.63	41.63
FeO ^T /MgO	2.76	3.03	2.98	3.15	3.06	2.94
Na ₂ O + K ₂ O	6.06	5.87	6.35	5.93	6.28	5.59
K ₂ O/Na ₂ O	0.63	0.49	0.62	0.39	0.48	0.52
A/CNK	1.17	1.39	1.21	1.61	1.40	1.63
Sc	11.18	17.34	14.05	13.40	12.45	16.82
Rb	182.69	205.22	205.36	203.05	208.55	285.70
Sr	86.97	77.00	98.29	63.16	88.66	86.14
Y	36.99	43.82	38.32	38.94	44.45	54.72
Zr	294.16	280.56	309.39	313.05	276.48	388.40
Nb	12.44	14.75	14.91	14.56	14.49	15.89
Cs	6.51	7.71	8.76	7.98	9.17	13.12
Ba	579.33	585.95	702.74	687.83	843.72	1508.39
La	54.10	56.09	57.88	54.04	63.41	62.49
Ce	107.90	102.56	102.27	96.95	110.77	99.89
Pr	10.84	11.25	11.31	10.77	12.66	12.48
Nd	40.08	42.00	41.70	39.23	47.00	45.61
Sm	7.71	7.91	7.99	7.39	9.16	9.11
Eu	1.24	1.23	1.41	1.23	1.76	1.81

Table 4. Cont.

Sample	LS-1	LS-2	LS-3	LS-4	LS-7	LS-8
Gd	7.94	8.20	8.14	7.74	9.42	10.27
Tb	1.06	1.16	1.09	1.00	1.27	1.47
Dy	6.02	7.34	6.51	6.33	7.61	9.05
Ho	1.14	1.42	1.21	1.26	1.42	1.81
Er	3.12	3.81	3.20	3.58	3.84	4.89
Tm	0.44	0.55	0.38	0.49	0.53	0.66
Yb	2.84	3.55	2.92	3.47	3.65	4.65
Lu	0.41	0.48	0.40	0.50	0.50	0.66
Hf	7.06	6.82	7.56	7.66	6.78	9.94
Ta	0.79	0.97	0.93	0.95	0.93	1.10
Th	20.73	22.42	21.97	21.81	21.52	21.37
U	3.57	4.74	4.08	3.75	3.84	5.40
ΣHREE	22.97	26.51	23.86	24.36	28.25	33.46
ΣLREE	221.86	221.03	222.56	209.61	244.77	231.39
ΣREE	244.83	247.54	246.41	233.98	273.02	264.85
Y/Nb	2.97	2.97	2.57	2.67	3.07	3.44
Nb/Ta	15.74	15.22	16.04	15.31	15.58	14.49
Zr/Hf	41.66	41.11	40.93	40.87	40.78	39.07
Zr + Nb + Ce + Y	451.49	441.69	464.89	463.49	446.19	558.89
Th + U	24.30	27.15	26.05	25.56	25.36	26.77
Rb/Sr	2.10	2.67	2.09	3.21	2.35	3.32
La/Nb	4.35	3.80	3.88	3.71	4.38	3.93
Th/La	0.38	0.40	0.38	0.40	0.34	0.34
Y/Ta	46.79	45.20	41.23	40.94	47.80	49.89
T(°C)	848	861	853	885	860	908

In the Harker diagrams (Figures 7 and 8), Al_2O_3 , K_2O , MgO , TiO_2 , CaO , Na_2O , MnO , P_2O_5 , Ba, Rb, and SiO_2 showed negative correlations, indicating that fractional crystallization played a role during magma evolution.

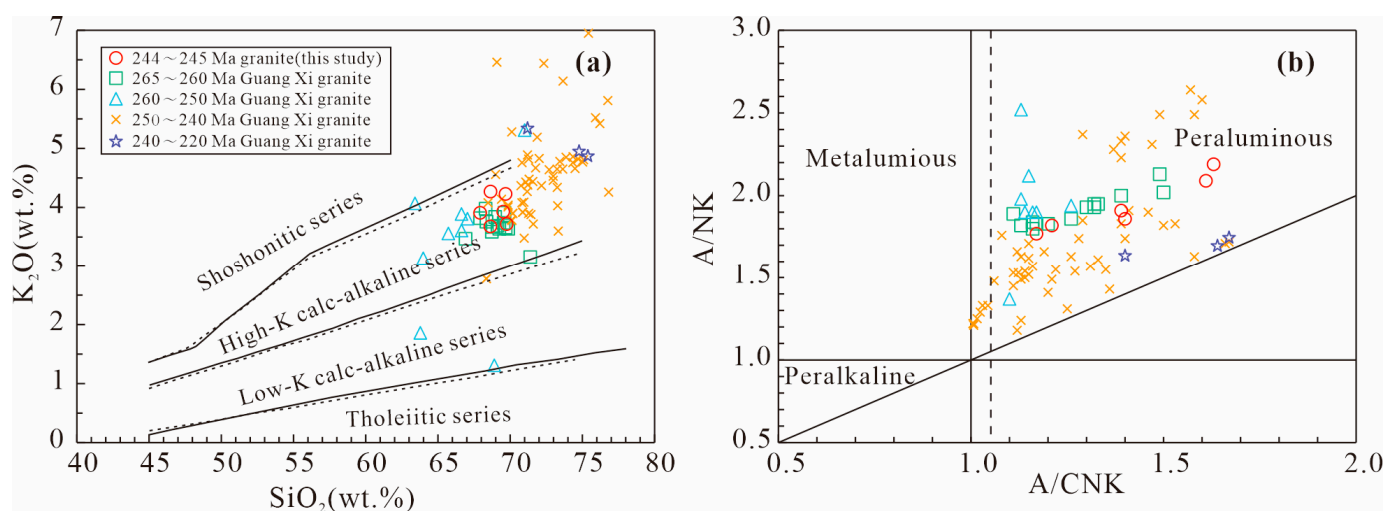


Figure 6. Plots of (a) K_2O versus SiO_2 and (b) A/NK versus A/CNK in granite from Darongshan–Shiwandashan, southeast Guangxi. Data source: 265–260 Ma granites: [41]; 260–250 Ma granites: [42]; 250–240 Ma granites: [26,43–45]; 240–220 Ma granites: [46].

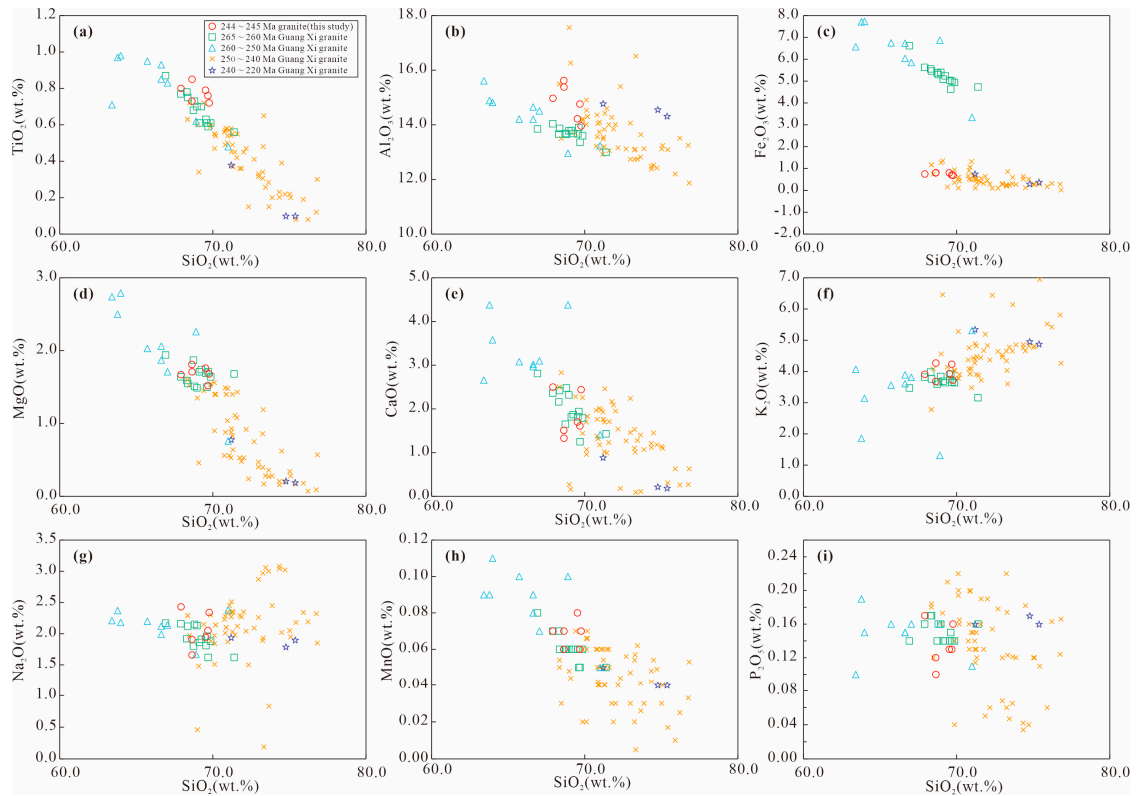


Figure 7. Plots of (a) TiO_2 , (b) Al_2O_3 , (c) Fe_2O_3 , (d) MgO , (e) CaO , (f) K_2O , (g) Na_2O , (h) MnO , and (i) P_2O_5 versus SiO_2 in granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6.

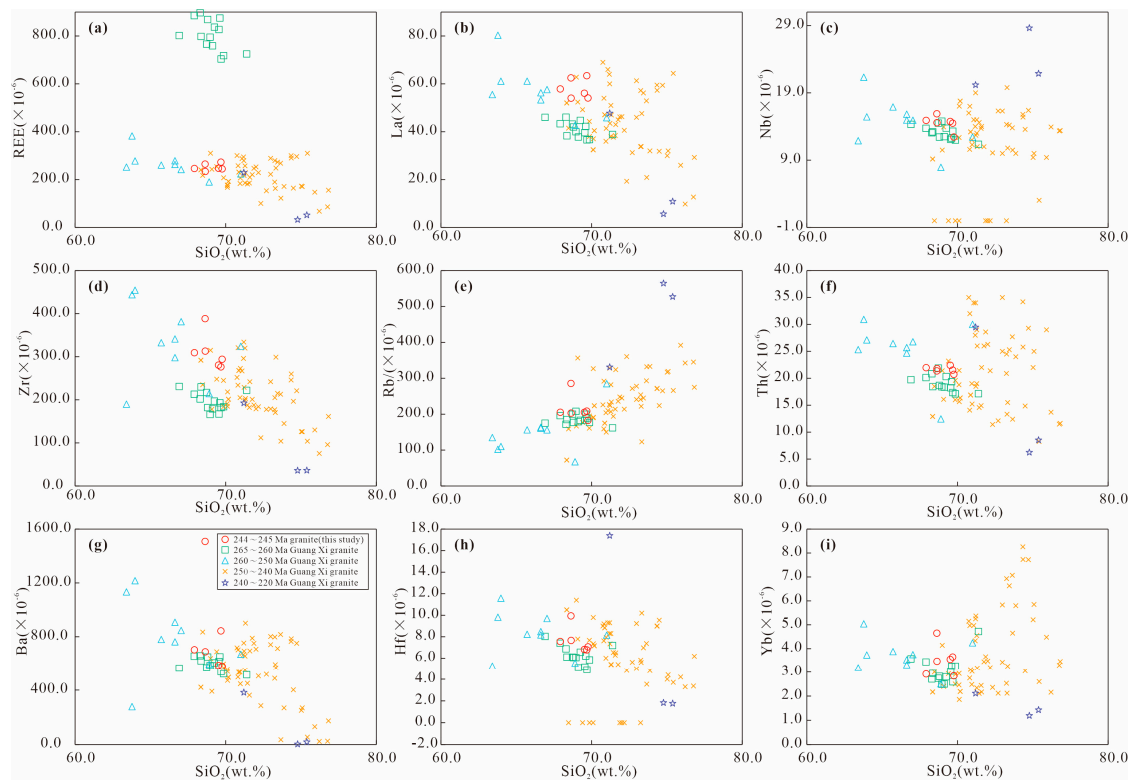


Figure 8. Plots of (a) REE, (b) La, (c) Nb, (d) Zr, (e) Rb, (f) Th, (g) Ba, (h) Hf, and (i) Yb versus SiO_2 in granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6.

4.2.2. Trace and REE Elements

The granite samples were rich in Rb, Th, and U and depleted in Ba, Nb, Ta, Sr, P, and Ti (Figure 9a). The LREE and HREE contents of the samples were 210.0×10^{-6} – 245.0×10^{-6} and 23.0×10^{-6} – 33.0×10^{-6} , respectively, indicating that LREEs were relatively enriched. The REE contents were 234.0×10^{-6} – 273.0×10^{-6} , with an average of 252.0×10^{-6} , which was much higher than that in the original mantle (7.43×10^{-6}). The $(\text{La}/\text{Sm})_{\text{N}}$ and $(\text{Gd}/\text{Yb})_{\text{N}}$ ratios are 4.43–4.72 and 1.82–2.31, respectively, with obvious negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.15$ – 0.18) (Figure 9b).

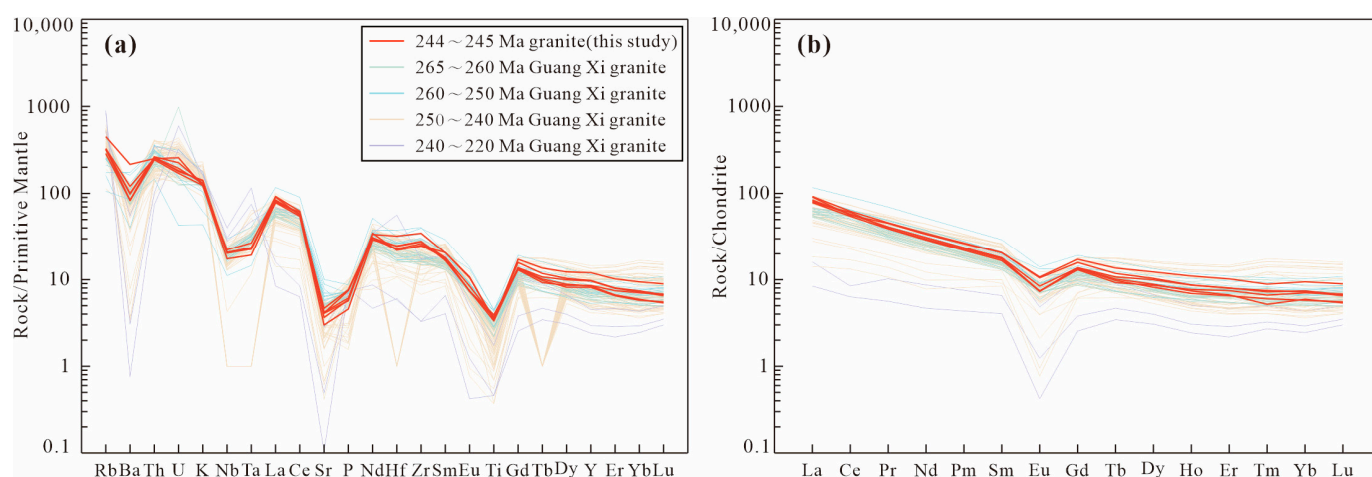


Figure 9. (a) Chondrite-normalized REE distribution patterns and (b) primitive-mantle-normalized multi-element diagrams of granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6.

4.2.3. Characteristics of Rare-Earth Minerals

Previous studies have shown that rare-earth elements in granite occur primarily in two types: (1) primary REE-bearing minerals and (2) REE replacements in secondary minerals [47,48]. Scanning electron microscopy (SEM) analyses of the granite samples revealed that the samples primarily contained REE-bearing minerals, such as monazite, xenotime, zircon, and apatite. Zircon and apatite were primarily formed through magma crystallization and occurred in rock-forming minerals, such as biotite (Figure 10). Xenotime was distributed along the edges or fractures of apatite (Figure 10a), indicating that they were mainly formed through hydrothermal alteration. These REE-bearing minerals had relatively high rare-earth element contents and were the main carriers of rare-earth elements in the parent rock, as shown by energy-dispersive spectroscopy (EDS) in Figure 11 and Table 5.

Xenotime (YPO_4) is a phosphate mineral and one of the most important carriers of rare-earth elements. It mainly occurs as granular grains between plagioclase and quartz, with particle sizes ranging from 40 to 100 μm (Figure 10a). Its Y_2O_3 , Gd_2O_3 , and Dy_2O_3 contents are 47.40 wt.%, 2.53 wt.%, and 4.42 wt.%, respectively (Figure 11a, Table 5).

Zircon ($\text{Zr}[\text{SiO}_4]$) is a silicate mineral and a common accessory mineral in granite. It primarily occurs as euhedral grains that are interstitial or enclosed in minerals, such as feldspar, biotite, and quartz, with grain sizes ranging from 50 to 100 μm (Figure 10b). It is mainly composed of ZrO_2 (69.19 wt.%) and SiO_2 (30.81 wt.%) (Figure 11b, Table 5).

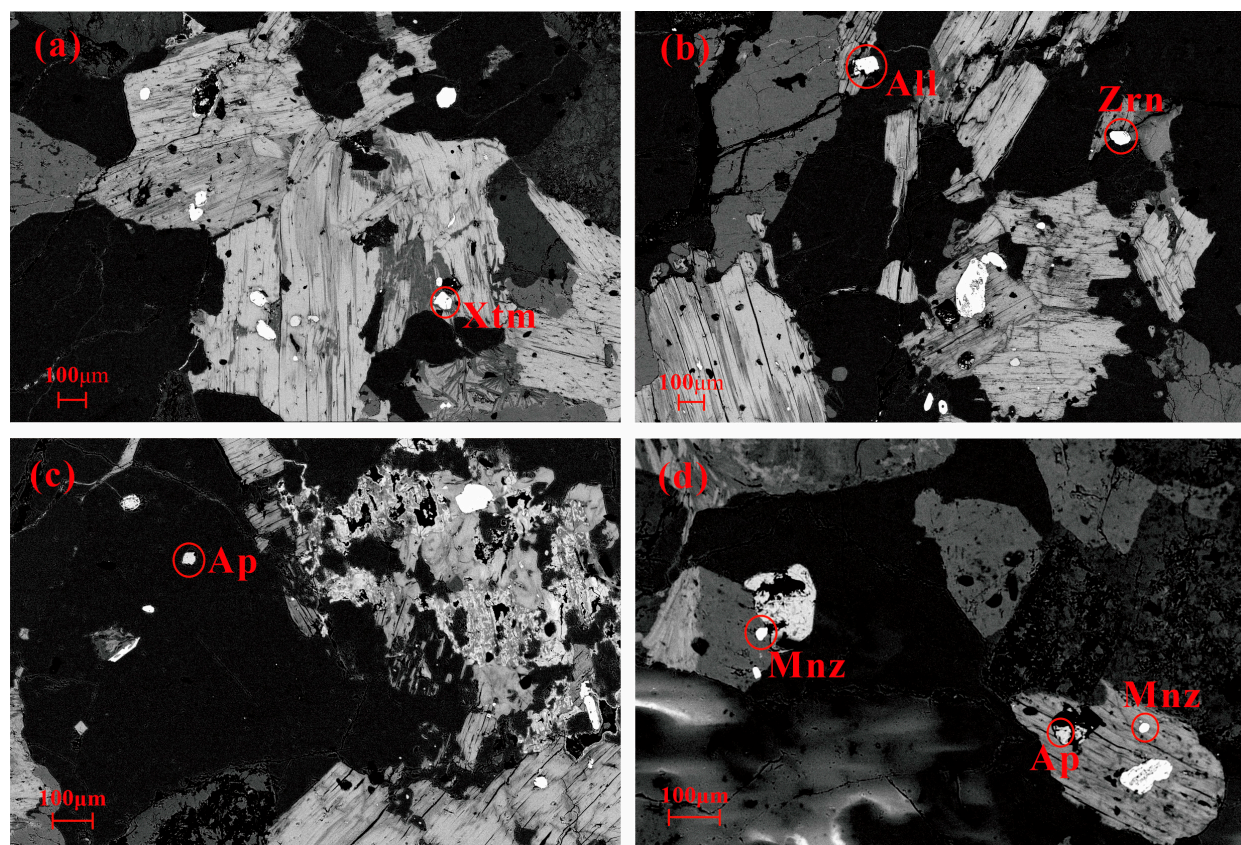


Figure 10. SEM images (a–d) of granite from Darongshan–Shiwandashan, southeast Guangxi. Xtm—Xenotime; Ap—Apatite; Mnz—Monazite; Zrn—Zircon; All—Allantite.

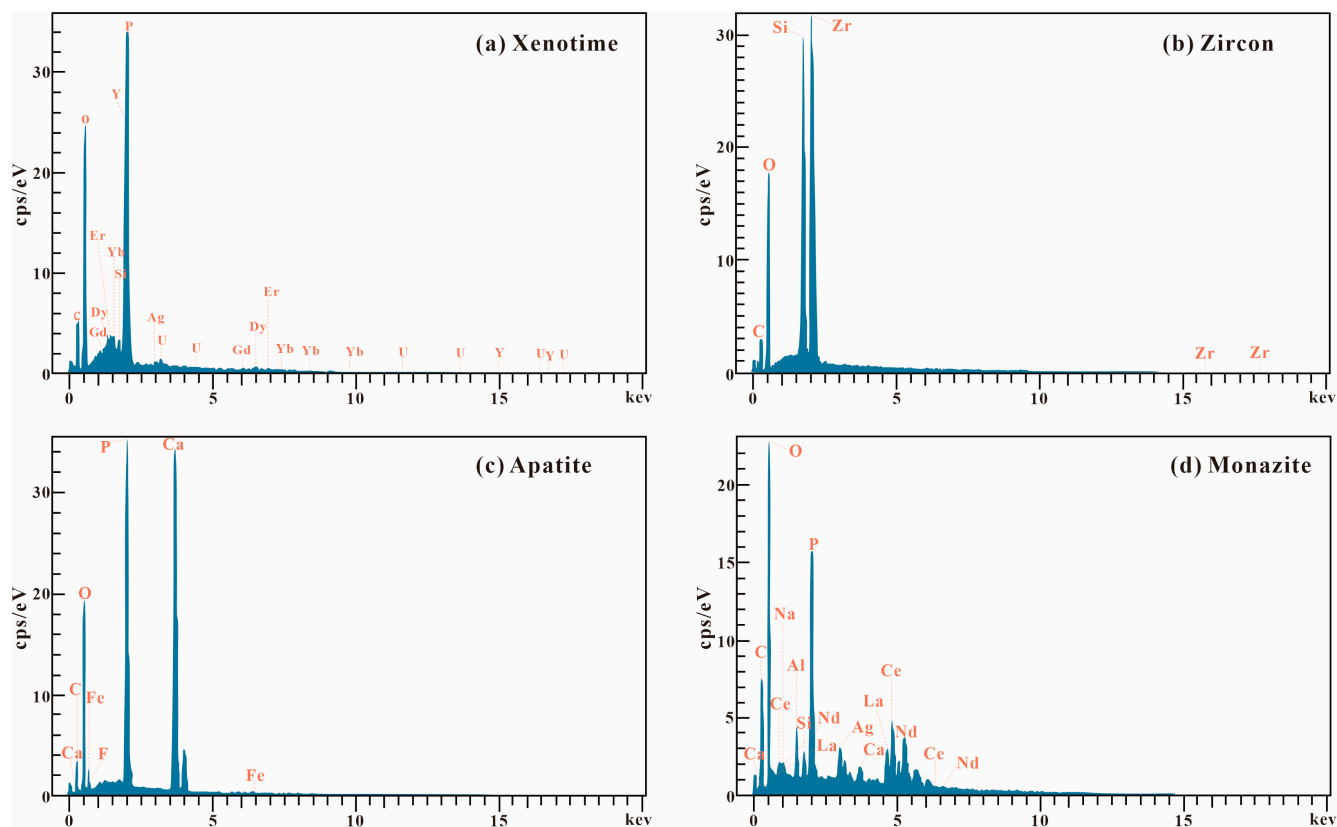


Figure 11. Spectrogram of energy analysis of (a) xenotime, (b) zircon, (c) apatite, and (d) monazite in granite from Darongshan–Shiwandashan, southeast Guangxi.

Table 5. Results of energy spectrum analysis of REE-bearing minerals in granite from Darongshan–Shiwandashan, southeast Guangxi.

REE Minerals	Oxide	Content (wt.%)
Monazite	P ₂ O ₅	27.18
	La ₂ O ₃	15.34
	Ce ₂ O ₃	30.25
	Nd ₂ O ₃	11.49
	SiO ₂	2.58
Xenotime	P ₂ O ₅	34.57
	Y ₂ O ₃	47.40
	Gd ₂ O ₃	2.53
	Dy ₂ O ₃	4.42
Zircon	SiO ₂	30.81
	ZrO ₂	69.19
Apatite	P ₂ O ₅	42.69
	CaO	52.51
	FeO	1.05

Apatite from the granite samples mainly occurred as euhedral or subhedral grains with sizes ranging from 20 to 110 μm (Figure 10c). It is always enclosed by minerals such as quartz and feldspar. Its P₂O₅, CaO, and FeO contents are 42.69 wt.%, 52.51 wt.%, and 1.05 wt.%, respectively (Figure 11c, Table 5).

In this study, monazite was mainly distributed within minerals such as feldspar and quartz (Figure 10d). It was rich in rare-earth elements, with La₂O₃ content of 15.34 wt.%, Ce₂O₃ content of 30.25 wt.%, and Nd₂O₃ content of 11.49 wt.% (Figure 11d, Table 5).

5. Discussion

5.1. Rock Type

The genetic type of igneous rock is closely related to geodynamic processes [49]. Research indicates that determining the genesis type of granite is of great significance for studying magma evolution processes and the characteristics of magma source regions. According to its genesis and properties, granite can be classified into the A-, S-, I-, and M-types [50–52]. I-, S-, and M-type granite classification mainly emphasizes the difference in the magma source region, while A-type granites mainly reflect the specific geodynamic background. Mineralogy is an important indicator for distinguishing A-, S-, and I-type granites. S-type granite contains peraluminous minerals (such as cordierite). I-type granite most commonly contains hornblende. A-type granite is characterized by alkaline ferromagnesian minerals [50,53]. M-type granite is produced through the differentiation of basic magma and is a mantle-derived granite [50]. In addition, the aluminum saturation index (A/CNK) of I-type granite is less than 1.1, and it is mainly produced by crust–mantle interactions. S-type granite is derived from crust-derived sediments, and its A/CNK ratio is greater than 1.1 [51,52]. A-type granite is formed through magma crystallization at relatively high temperatures and under alkaline, anhydrous, and anorogenic conditions (“3A”), and it is characterized by $\text{Zr} > 250 \times 10^{-6}$, $(\text{Zr} + \text{Ce} + \text{Nb} + \text{Y}) > 350 \times 10^{-6}$, $\text{FeO}^{\text{T}}/\text{MgO} > 16$, and $10,000 \times \text{Ga}/\text{Al} > 2.5$ [51,52].

Compared with I-type granite, the samples in this study showed high A/CNK ratios (>1.1, Table 4), and there was no hornblende in the photomicrographs, indicating that they were not I-type granite. The P₂O₅ content was low (0.10–0.17 wt.%; Table 4), and SiO₂ was negatively correlated with P₂O₅ (Figure 7i), indicating that they were different from S-type granite. They showed obvious negative Eu anomalies (Figure 9b), high

$10,000 \times \text{Ga}/\text{Al}$ values (2.16–5.37, average = 3.42), and high $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ contents (441.69×10^{-6} – 558.89×10^{-6} , average = 471.11×10^{-6}). These features are similar to those of A-type granites. In the discriminant diagrams proposed by Whalen (1987), all samples fell into the area of A-type granite [54] (Figure 12a,b). These data indicate that the samples in this study were A-type granite.

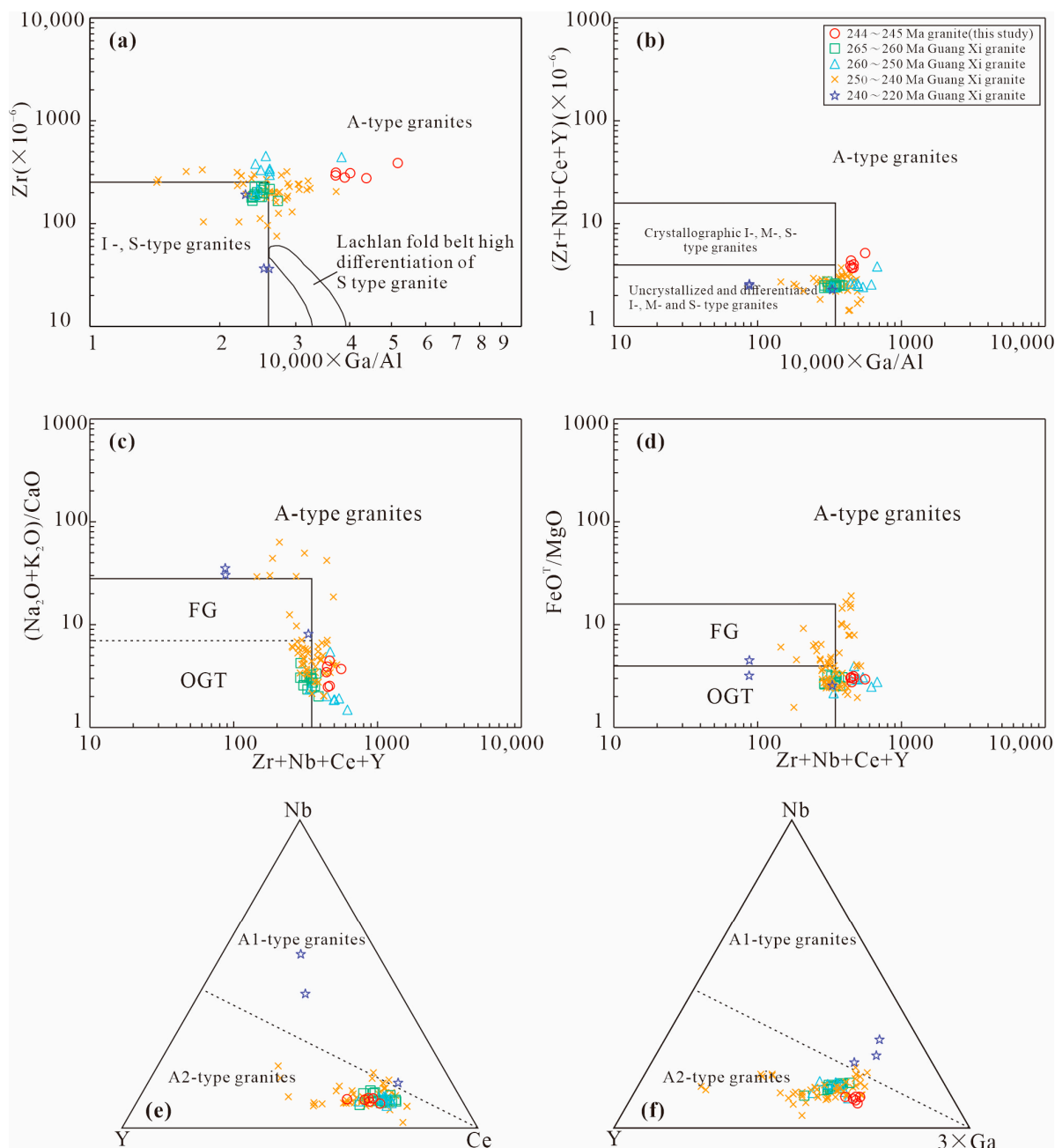


Figure 12. Plots of (a) $10,000 \times \text{Ga}/\text{Al}$ versus Zr , (b) $10,000 \times \text{Ga}/\text{Al}$ versus $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$, (c) $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ versus $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$, (d) $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ versus $(\text{FeO}^T/\text{MgO})$, (e) Nb–Y–Ce, and (f) Nb–Y– $3 \times \text{Ga}$ for granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6.

It is worth noting that highly differentiated I-type, S-type, and A-type granites have similar geochemical characteristic. The P_2O_5 content of S-type granite is commonly greater than 0.20%, and is positively correlated with the degree of crystallization differentiation [55]. Wang et al. (2000) proposed that FeO^T content and formation temperature can distinguish between highly differentiated I-type and A-type granite. The FeO^T content of highly

differentiated I-type granite is less than 1.00%, and the formation temperature is lower (764 °C) [56]. A-type granite has higher FeO^{T} content (>1.00%) and forms at higher temperatures (>800 °C). Whalen et al. (1987) and Eby (1992) proposed a series of diagrams to further distinguish highly differentiated I-type, S-type, and A-type granites [54,57] (Figure 12c,d).

The P_2O_5 content of the granite samples is low (0.10%–0.16%), and the FeO^{T} content ranges from 4.63% to 5.39%, which is significantly different from S-type granite ($\text{P}_2\text{O}_5 > 0.20\%$) and highly differentiated I-type granite ($\text{FeO}^{\text{T}} < 1.00\%$). The saturation temperature of zircon determines the formation temperature of granite to be 848–908 °C, with an average temperature of 869 °C (Table 4), which is greater than 764 °C. In the highly differentiated granite type discrimination diagrams (Figure 12c,d), all the samples also fall within the A-type granite area.

A-type granite can be further subdivided into A1- and A2-type granites [57]. The geochemical composition of A1-type granite is consistent with oceanic island basalt (OIB), and it is mainly formed in anorogenic environments, such as intraplate rifting, mantle plumes, or hotspot activities [57]. The geochemical composition of A2-type granite is similar to that of continental crust and island arc basalt, and it is mainly derived from back-arc basins, post-collision areas, or post-orogenic extension environments [57]. The samples in this study were characterized by low Nb and high Y contents that were similar to those of A2-type granite. In the Nb-Y-Ce discrimination diagram, all of the samples fell into the area of A2-type granite (Figure 12e,f). This evidence indicates that the granite samples were A2-type granite.

5.2. Characteristics of the Source Region

According to the geochemical characteristics, the granite samples had high Al_2O_3 (13.96 wt.%–15.62 wt.%) and alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 5.59 \text{ wt.\%} - 6.35 \text{ wt.\%}$) contents. Their $\text{Mg}^{\#}$ values were 40–43, lower than that of mantle-derived magma ($\text{Mg}^{\#} > 45$). The Nb/Ta (14.49–16.04), Zr/Hf (39.07–41.66), and Rb/Sr (2.09–3.32) ratios were similar to those of continental crust (Nb/Ta = 12, Zr/Hf = 33, Rb/Sr > 0.5). In the δEu versus $(\text{La}/\text{Yb})_{\text{N}}$ and Ce/Nb versus Y/Nb diagrams, the samples fell within the area of the crust type or average crustal composition (Figure 13a,b). The isotopic data of contemporaneous granites in the study area showed that the granites had enriched Nd isotopic and zircon Hf isotopic compositions ($\epsilon_{\text{Nd}}(\text{t})$ and $\epsilon_{\text{Hf}}(\text{t})$ values of -13.6 to -11.9 and -21.9 to -8.8 , respectively, [41]).

All of the above evidence suggests that the samples were mainly derived from crustal material. The geochemical compositions of the samples further indicated that their A/MF, C/MF, and $\text{CaO}/\text{Na}_2\text{O}$ ratios were similar to those of metasediment or sandy source rock (Figure 13e,f). This suggests that the granites originated from partial melting of sandy source rock.

In the Harker diagrams, the contents of Al_2O_3 , K_2O , MgO , TiO_2 , CaO , Na_2O , MnO , P_2O_5 , Ba, and Rb showed a negative correlation with SiO_2 (Figures 7 and 8). In the La-La/Sm diagram (Figure 14a), the samples showed an obvious trend of fractional crystallization. Additionally, they had a high differentiation index ($\text{DI} = 72.8\text{--}76.4$). This evidence indicates that fractional crystallization occurred during magma evolution. In the related diagrams, fractional crystallization of plagioclase and accessory minerals (such as monazite and allanite) can be observed (Figure 14b–d). The depletion of P and Ti (Figure 9a) indicates the crystallization of phosphorus- and titanium-bearing minerals. The negative anomalies of Eu and Sr (Figure 9b) are related to the crystallization of plagioclase (Figure 14b,c).

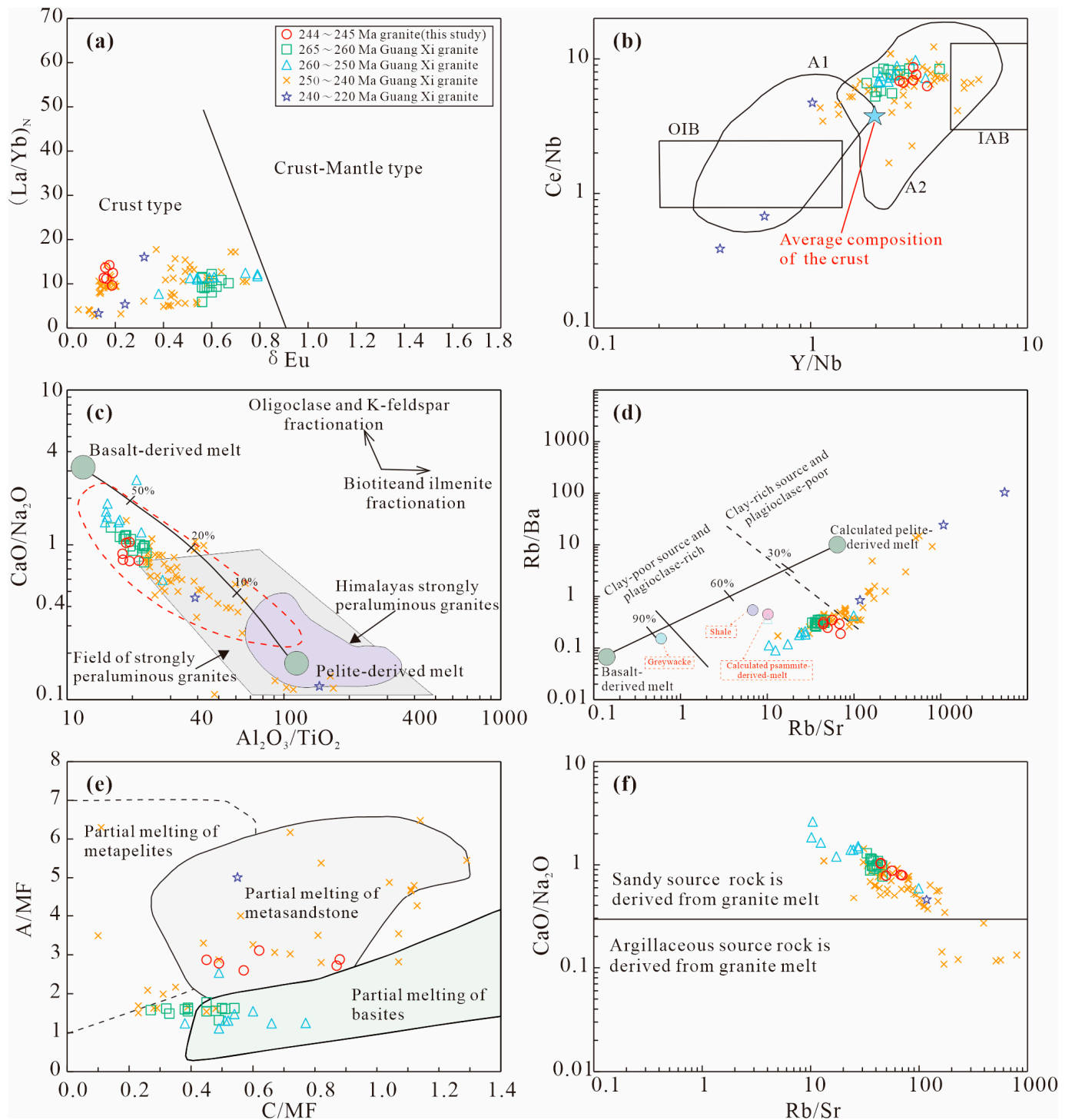


Figure 13. Plots of (a) δEu versus $(La/Yb)_N$, (b) Y/Nb versus Ce/Nb , (c) Al_2O_3/TiO_2 versus CaO/Na_2O , (d) Rb/Sr versus Rb/Ba , (e) C/MF versus A/MF , and (f) Rb/Sr versus CaO/Na_2O for granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6.

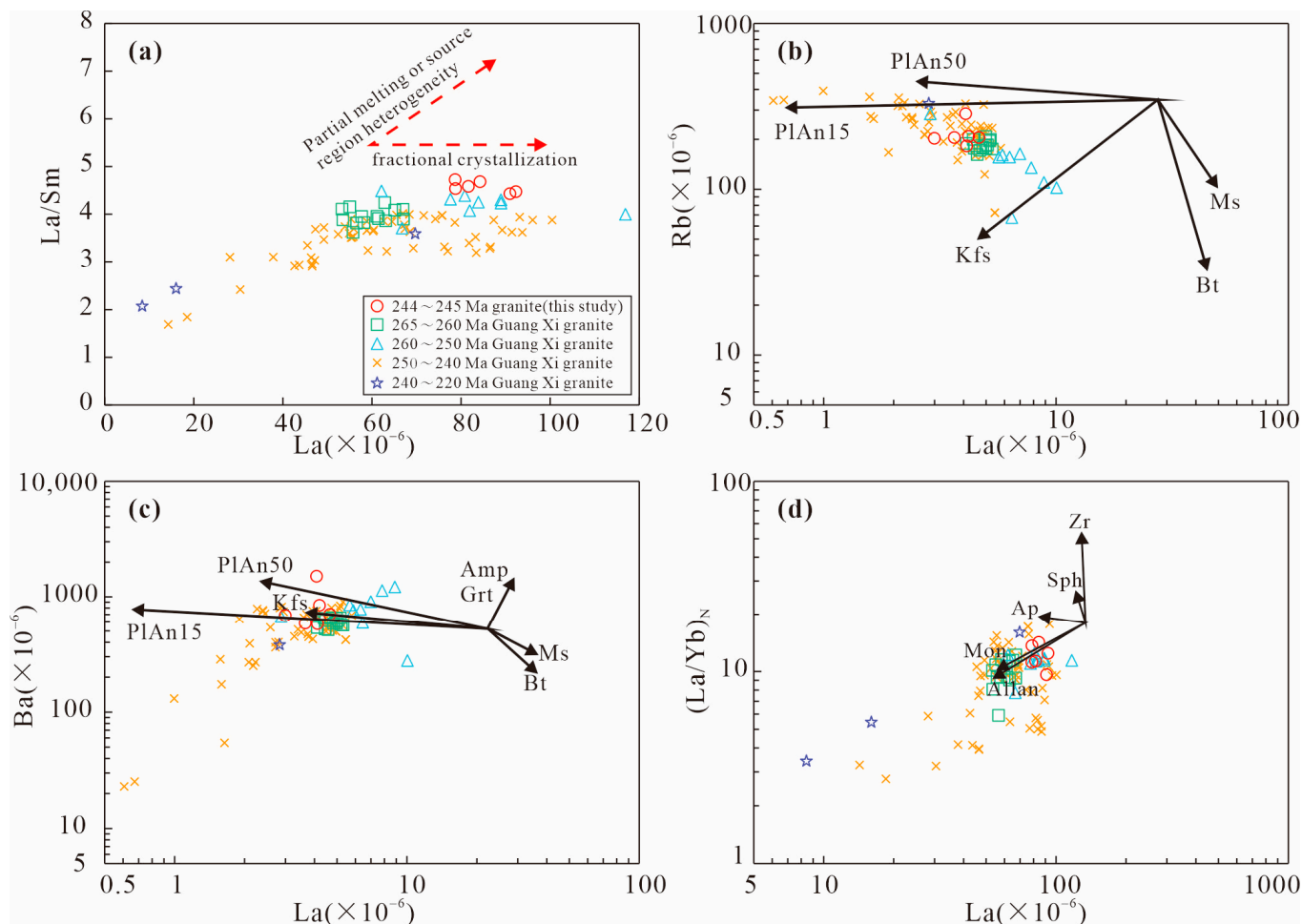


Figure 14. Plots of (a) La versus La/Sm, (b) La versus Rb, (c) La versus Ba, and (d) La versus $(\text{La}/\text{Yb})_N$ for granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6. Pl—plagioclase; Kfs—K-feldspar; Bt—biotite; Ms—muscovite; Amp—amphibolite; Grt—garnet; Zr—zircon; Sph—sphaerocobaltite; Ap—apatite; All—allanite; Mon—monazite.

5.3. Tectonic Environment

As discussed above, the formation age of the granite samples in this study was 244–245 Ma, and they were A2-type granite. Previous studies have shown that A-type granite forms in an extensional tectonic environment [57,58]. This indicates that the samples were formed in an extensional environment. In addition, they fell into the area of within-plate granite (WPG) (Figure 15a,b), further indicating that they formed in an extension setting.

Extensive magmatism occurred in the South China and Indochina blocks during the Late Paleozoic to Early Mesozoic periods. The Jinshajiang suture zone outcropped 247–246 Ma rhyolite that was formed by a collision event caused by the subduction of the Paleotethys oceanic crust [59]. In addition, 253–247 Ma granite and volcanic rocks were reported in the Ailaoshan suture zone, and their tectonic settings were syn-collision or arc-continent collision [60–62]. Roger et al. (2012) and Wang et al. (2014) proposed that the formation of Early Triassic (248 Ma) granite in northern Vietnam (Indochina block) was related to continental collision or arc-continent collision resulting from the subduction of the Paleotethys oceanic crust [63,64].

Granite from the Darongshan–Shiwandashan granite belt is considered to have been formed through the subduction of the Paleotethys oceanic crust [42]. Recent studies have revealed that contemporaneous basalt (250–248 Ma), diabase (247 Ma), and dacite porphyry

(247–245 Ma) were preserved in the Darongshan–Shiwandashan area [65,66], and their formation was related to the evolution of Paleotethys [38]. These data indicate that the Late Paleozoic to Early Mesozoic tectonic evolution of the Darongshan–Shiwandashan area was influenced by the evolution of Paleotethys.

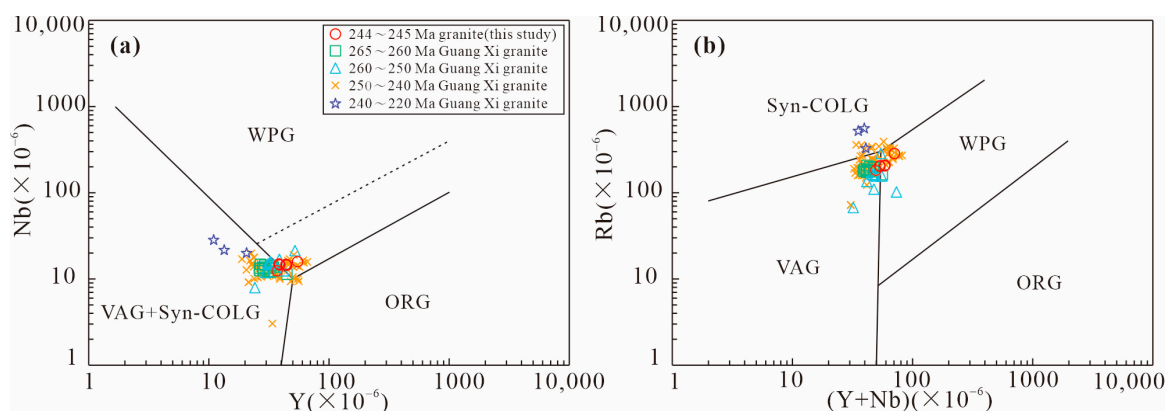


Figure 15. Plots of (a) Y versus Nb and (b) Y + Nb versus Rb of granite from Darongshan–Shiwandashan, southeast Guangxi. Data sources are the same as in Figure 6.

Considering the above, it is suggested that records of Paleotethys are well preserved in the South China and Indochina blocks (Figure 16), and the Early Triassic A-type granite in the Darongshan–Shiwandashan area was formed in an extensional tectonic background, which was related to the evolution of Paleotethys.

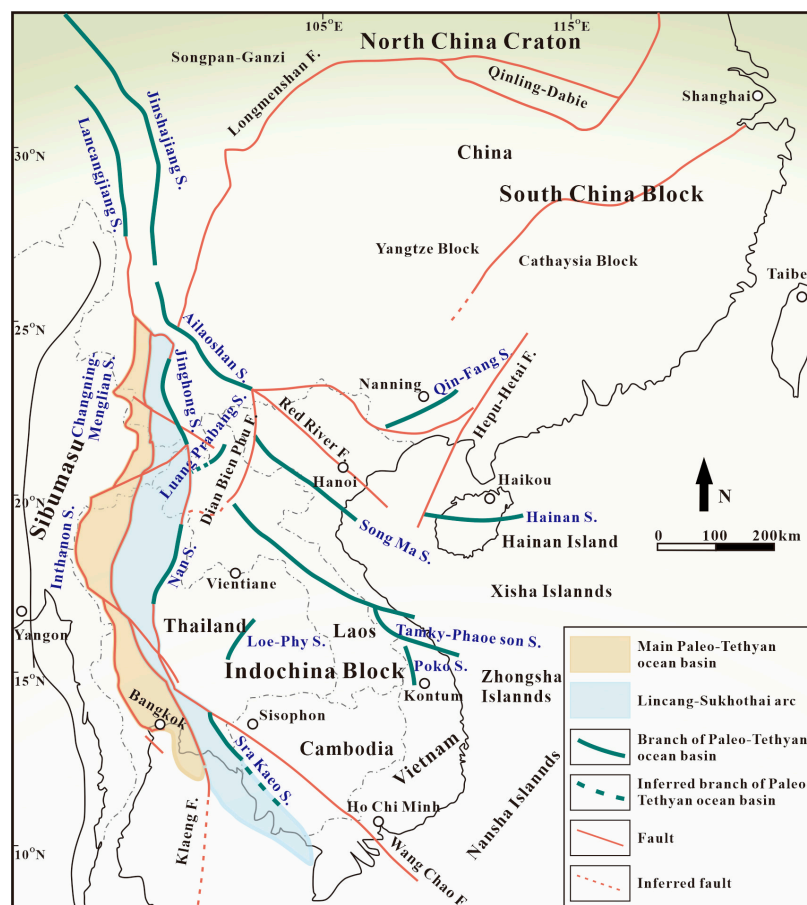


Figure 16. Spatiotemporal framework of main and branched Paleotethyan ocean basin in SE Asia. Modified from [26].

5.4. Ore-Controlling Factors of Regolith-Hosted REE Deposits

5.4.1. Parent Rock Properties

Previous studies have shown that the formation and scale of regolith-hosted REE deposits are directly related to the content of rare-earth elements in the parent rocks [67,68]. Weathering of parent rocks enriched in light rare-earth elements results in light rare-earth regolith-hosted REE deposits, whereas weathering of those enriched in heavy rare-earth elements forms heavy rare-earth regolith-hosted REE deposits [67,69]. The parent rocks of regolith-hosted light REE deposits are mainly biotite monzonite granite, muscovite granite, granite-porphyry, two mica granite, syenite, tuff, and rhyolite, which contain accessory minerals enriched in light rare-earth elements such as bastnaesite, monazite, apatite, titanite, and allanite. The parent rocks of regolith-hosted heavy REE deposits are mostly medium-fine-grained two-mica granite and muscovite granite, which contain accessory minerals enriched in heavy rare-earth elements such as fergusonite, gadolinite, xenotime, euxenite, polycrase, thorite, and zircon [67,70].

The granite samples in this study contain REE-bearing minerals such as xenotime, monazite, apatite, and zircon that are enriched in rare-earth elements. The energy spectrum results show that the content of rare-earth oxides in monazite and xenotime is relatively high (Table 4). The total amount of rare-earth elements (234.0×10^{-6} – 273.0×10^{-6}) in the granite samples was much higher than the lower limit values of the parent rock (132.0×10^{-6}) [71]. In addition, the ratios and contents of rare-earth elements, together with the rare-earth mineral associations of the samples, are similar to those in the ore-forming parent rocks in Jiangxi and Yunnan (Table 6; Figure 17). This evidence indicates that the granites in this area show a good material basis for forming regolith-hosted REE deposits.

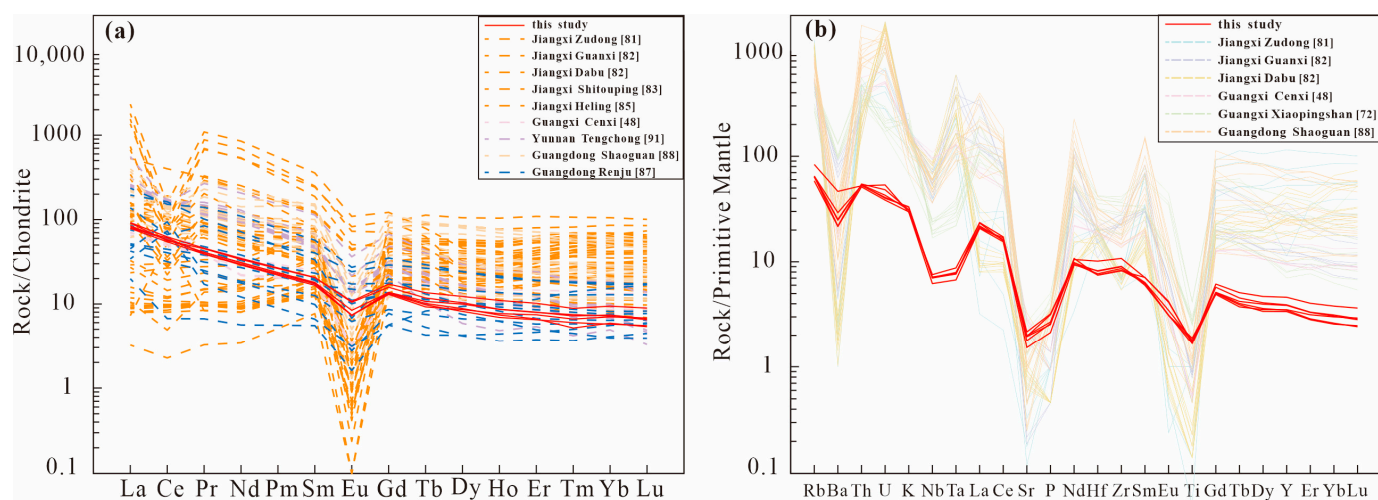


Figure 17. (a) Chondrite-normalized REE distribution patterns and (b) primitive-mantle-normalized multi-element diagrams of parent rocks of some typical regolith-hosted REE deposits in South China.

The distribution of regolith-hosted REE deposits/mineralization in the Darongshan–Shiwandashan area is closely related to the lithology. Outcrops of biotite granite, muscovite granite, and two-mica granite show higher total rare-earth element (REE) content (206×10^{-6} – 343×10^{-6} , this study; [71]), and regolith-hosted REE deposits/mineralization are also distributed in the above lithologic areas. In contrast, the Yong’an pluton, a part of the Darongshan–Shiwandashan granite belt, is mainly composed of granodiorite, and its REE content is 175×10^{-6} – 241×10^{-6} [45], which is obviously different from the above lithologic areas. At present, no regolith-hosted REE deposits have been found in the Yong’an area. One of the main reasons for this is that the Yong’an pluton underwent relatively weak magma evolution.

Previous studies have shown that strong fractional crystallization favors the crystallization of REE-bearing minerals such as zircon, sphene, apatite, monazite, and xenotime, which are easily decomposed and adsorbed during later weathering processes, thus providing a material basis for the enrichment of rare-earth elements [72–74]. Studies have further pointed out that the fractionation and leaching of rare-earth elements in the parent rock must have a high degree of magma evolution [75–77]. The granite in this study underwent fractional crystallization (Figures 7, 8 and 14). Therefore, strong fractional crystallization of parent rocks may be favorable for the formation of regolith-hosted REE deposits.

Table 6. Comparison of parent rocks of typical regolith-hosted REE deposits in South China.

Name of Deposit	Parent Rock/Age	Rare-Earth Minerals	ΣREE ($\times 10^{-6}$)	ΣLREE ($\times 10^{-6}$)	ΣHREE ($\times 10^{-6}$)	$\Sigma\text{LREE}/\Sigma\text{HREE}$	Reference
Guangxi Qinfang	granite	Apatite, zircon, xenotime, monazite	252	225	27	8.58	this study
Jiangxi Dafuzu	granite (226 Ma)	Apatite, xenotime	328–414	199–242	82–107	1.2–2.4	[78]
Jiangxi Wulitin	Biotite monzonitic granite (238 Ma)	Apatite, allanite	354–453	305–407	46–48	6.3–8.9	[79]
Jiangxi Shangyou	Medium coarse-grained porphyritic biotite granite	Zircon, xenotime	148	61	87	0.63	[80]
Jiangxi Zudong	Biotite potassium feldspar granite	Xenotime, monazite	261	75	187	0.51	[81]
Jiangxi Guanxi	Alkaline feldspar granite (190 Ma)	Xenotime, monazite	469	419	50	8.38	[82]
Jiangxi Dabu	Muscovite granite (155 Ma)	Xenotime, monazite	125	55	70	0.79	[82]
Jiangxi Shitouping	granite	Xenotime, monazite, bastnaesite	685	351	334	1.2	[83]
Jiangxi Qingxi	Biotite granite (230 Ma)	Xenotime	398	356	42	8.5	[84]
Jiangxi Heling	Granite porphyry	Apatite, zircon, bastnaesite	808	724	84	8.6	[85]
Guangdong Renju	Granodiorite	Xenotime, zircon	338	287	51	5.61	[86]
Guangdong Renju	Quartz diorite	Apatite, zircon, sphene, bastnaesite	298	267	31	9.44	[87]
Guangdong Shaoguan	Biotite granite (162 Ma)	Xenotime	297	205	20	6.7	[88]
Guangxi Huashan	Biotite granite	Sphene	323	245	78	3.12	[89]
Guangxi Cenxi	Granite (155 Ma)	Apatite, zircon, monazite, bastnaesite	279	199	79	2.55	[48]
Guangxi Dazhou	Biotite granite	Allanite	299	217	82	2.65	[90]
Guangxi Xiaopingshan	Biotite monzonitic granite	Apatite, zircon, monazite	343	228	114	2	[72]
Yunnan Tengchong	granite	Xenotime, zircon	783	87	12	7.9	[91]
Yunnan Chahe	Biotite monzonitic granite	Xenotime	257	202	55	3.67	[92]
Yunnan Lincang	Biotite monzonitic granite	Xenotime	361	300	64	5.55	[93]

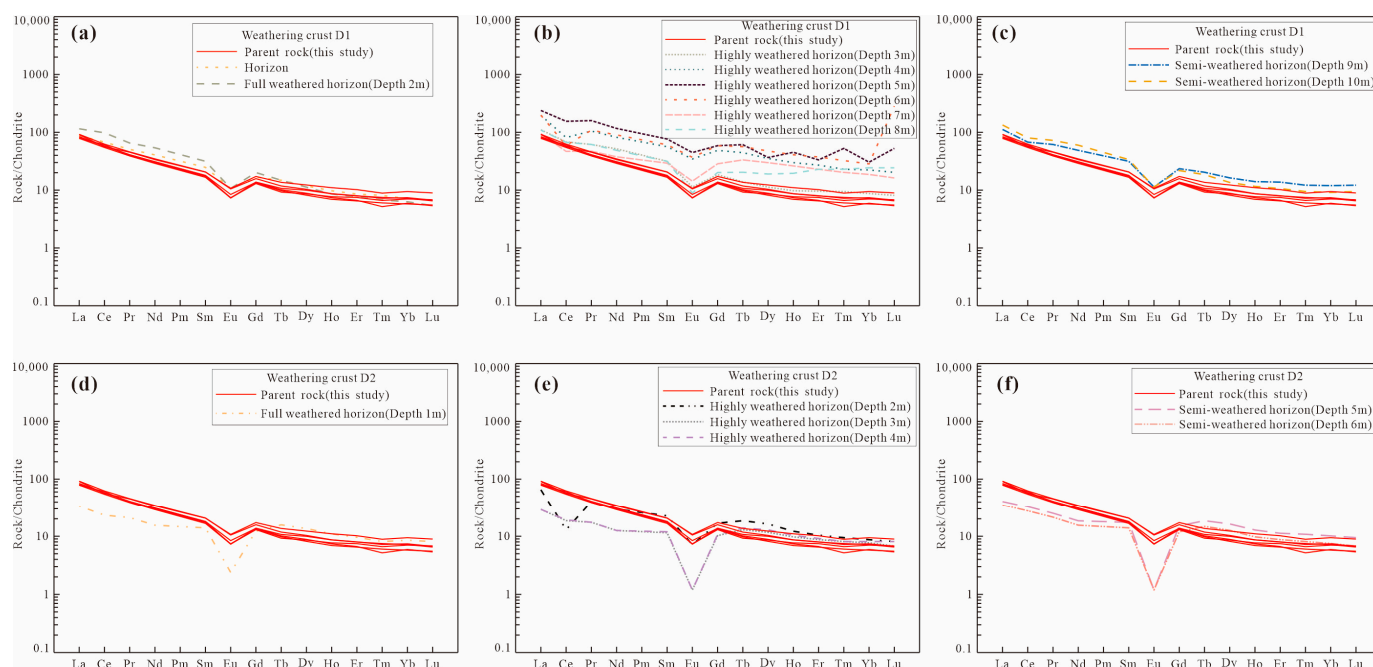
5.4.2. Geomorphology

The geomorphology of the study area mainly consists of mountains and hills. The rare-earth element contents from two weathering crust profiles showed that the top, upper, middle, and lower parts had REE contents of 329×10^{-6} and 178×10^{-6} , 369×10^{-6} – 929×10^{-6} and 155×10^{-6} – 226×10^{-6} , 402×10^{-6} – 436×10^{-6} and 184×10^{-6} – 224×10^{-6} , and 343×10^{-6} and 131×10^{-6} , respectively (Figure 18, Table 7). This indicates that different parts of the weathering crust profile show different rare-earth element contents. More specifically, the middle and upper parts showed the highest REE contents, whereas the top and lower parts were characterized by lower REE contents. This indicates that geomorphology is an important ore-controlling factor of the regolith-hosted REE deposits in the area, and the ridge area in the middle and upper parts is a favorable position for the enrichment of rare-earth elements. In contrast, the steep terrain lacks good conditions for the storage of rare-earth elements, and thus, it is difficult for deposits to be formed.

Table 7. REE compositions of granite and weathering crust from Darongshan–Shiwandashan, south-east Guangxi.

Type	Sample Number	REE	LREE	HREE	LREE/HREE	δEu	δCe
Parent rock	LS-1	245	222	23	9.66	0.16	1.06
	LS-2	248	221	27	8.34	0.15	1.03
	LS-3	246	223	24	9.33	0.18	1.00
	LS-4	234	210	24	8.60	0.16	1.05
	LS-7	273	245	28	8.66	0.19	1.03
	LS-8	265	231	33	6.92	0.19	1.02
Full weathered horizon	D1-1	329	262	67.6	8.48	0.50	0.99
	D1-2	421	360	63.0	11.75	0.41	1.10
Highly weathered horizon	D1-3	368	300	68.6	9.38	0.48	0.79
	D1-4	581	450	221	4.87	0.65	0.54
	D1-5	929	683	247	2.79	0.67	0.47
	D1-6	733	426	326	3.58	0.61	0.39
	D1-7	424	227	196	3.26	0.50	0.66
	D1-8	433	293	142	5.00	0.35	0.79
Semi-weathered horizon	D1-9	401	296	106	6.60	0.41	0.79
	D1-10	437	352	83.9	9.12	0.39	0.78
Full weathered horizon	D2-1	178	97	80.8	3.14	0.18	0.86
Highly weathered horizon	D2-2	226	130	95.6	3.57	0.35	0.25
	D2-3	155	80	74.8	2.99	0.13	0.80
	D2-4	159	81	77.7	2.84	0.09	0.85
Semi-weathered horizon	D2-5	223	126	98.0	3.38	0.08	1.00
	D2-6	184	106	77.6	3.74	0.09	0.97

Weathering crust data are from [72].

**Figure 18.** Chondrite-normalized REE distribution patterns of parent rocks and (a,d) full weathered horizon, (b,e) highly weathered horizon, and (c,f) semi-weathered horizon of weathering crust D1 and D2. Comparison data are sourced from [72].

5.4.3. Weathering

The development, integrity, and thickness of the weathering crust are all affected by the intensity of weathering [94]. Typical weathering crust profiles, from top to bottom, can be divided into a fully weathered horizon, highly weathered horizon, semi-weathered horizon, weakly weathered horizon, and parent rock. The rare-earth element contents in the fully weathered horizon, highly weathered horizon, and semi-weathered horizon of the two weathering profiles are 329×10^{-6} – 423×10^{-6} , 369×10^{-6} – 929×10^{-6} , and 402×10^{-6} – 436×10^{-6} and 178×10^{-6} , 155×10^{-6} – 226×10^{-6} , and 184×10^{-6} – 224×10^{-6} , respectively (Figure 18, Table 7). It can be seen that the maximum REE content in both profiles occurs in the highly weathered horizon. Theoretically, a higher degree of weathering is more conducive to the precipitation of rare-earth elements [95]. However, the maximum REE content did not occur in the fully weathered horizon, indicating that the degree of weathering is not directly proportional to the enrichment of REE. In addition, the fully weathered horizon in the study area is located at the top of the hillside, with a steep terrain and large slope, which is not conducive to the storage of rare-earth elements. In contrast, the highly weathered horizon is located at a relatively wide and slow terrain and undergoes strong vertical and lateral leaching, thus having the highest rare-earth element content.

The LREE/HREE ratio of the two weathering crust profiles gradually decreased from the fully weathered horizon to the semi-weathered horizon (Table 6; Figure 18), indicating that there is a differentiation of light and heavy rare-earth elements from the upper to lower parts of the weathering crust. The differentiation of light and heavy rare-earth elements may be related to the stability of rare-earth complexes and ligand complexation in soil solutions [96,97]. For instance, surface water contains anions such as carbon and phosphate ions. The complexation between these anions and heavy rare-earth elements leads to stronger mobility of heavy rare-earth elements, thus resulting in the accumulation of heavy rare-earth elements at the lower part of the weathering profile. Furthermore, prolonged and intense weathering and leaching facilitate the differentiation of light and heavy rare-earth elements, resulting in the accumulation of heavy rare-earth elements in the lower section of the weathering crust.

It is worth noting that the formation of regolith-hosted REE deposits is complex and results from the mutual influence and interaction of multiple factors. For example, geomorphology affects the migration and storage of rare-earth elements and the infiltration and leaching of surface water. This further affects the enrichment of rare-earth elements in the vertical section of the weathering crust profile. Moreover, it is difficult for mineralization to occur with a single factor; for example, the Darongshan and Yong'an plutons, both belonging to the Darongshan–Shiwandashan granite belt, have similar geomorphologies and climate conditions. However, only the former exhibits good regolith-hosted REE mineralization. The possible reasons are as follows: (1) The lithology and the degree of magma evolution are different. The Yong'an pluton is dominated by granodiorite and shows a low degree of magma evolution; (2) the degree of weathering is different. The weathered horizon of the Yong'an pluton is thin. Spherically weathered residual bodies are common, and even some fresh rock outcrops can be observed. In addition to the ore-controlling factors mentioned above, climate, hydrodynamic conditions, PH value, hydrothermal metamorphism, and microbial interactions are all influencing factors of regolith-hosted REE deposits [98,99]. These factors should be comprehensively considered in studies on the formation and differentiation mechanisms of regolith-hosted REE deposits.

6. Conclusions

(1) Geochemical data indicate that some Early Triassic (244–245 Ma) granite in the Darongshan–Shiwandashan granite belt belongs to A-type granite.

(2) The granite belongs to high-potassium calc-alkaline rock and is the product of the partial melting of sandy source rocks. Fractional crystallization of plagioclase, apatite, monazite, and epidote occurred during magma evolution. This formed in an extension tectonic background, which was related to the evolution of the Paleotethys.

(3) The granite is enriched in light rare-earth elements (LREE) and depleted in heavy rare-earth elements (HREE), and it contains certain REE-bearing minerals, such as xenotime, monazite, apatite, and zircon. These characteristics are comparable with those of the parent rocks of typical regolith-hosted REE deposits in South China. The highly weathered horizon located at the mountain ridge showed the highest concentration of rare-earth elements. The formation of regolith-hosted REE deposits in the Darongshan–Shiwandashan areas is primarily controlled by the degree of magma evolution, geomorphology, and weathering processes.

Supplementary Materials: Analytical methods can be downloaded at: <https://www.mdpi.com/article/10.3390/min15050530/s1>.

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