Research Article

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The Cretaceous igneous rocks in southeastern Guangxi and their implication for tectonic environment in southwestern South China Block

<https://doi.org/10.1515/geo-2020-0160>

received January 9, 2020; accepted May 13, 2020

Abstract: Southeastern Guangxi is located in the southwestern South China Block and to the northwest of the South China Sea (SCS), with abundant records of the Cretaceous magmatism. A detailed study of igneous rocks will contribute to a better understanding of the late Mesozoic tectonic environment. Zircon U–Pb dating yields ages of 93.37 ± 0.43 Ma for Yulin andesites and 107.6 ± 1.2 Ma for Luchuan granites. Yulin andesites are hornblende andesites, of which $w(\text{MgO})$ is between 7.72% and 8.42%, and $\text{Mg\#}$ is between 66.7 and 68.0, belonging to high magnesian andesites (HMAs) from peridotite sources. Luchuan granites are medium- to fine-grained monzogranites. Monzogranites and clastoporphyratic lava are high-K calc-alkaline series and metaluminum to weakly peraluminous series, which belong to the I-type granites. Those are enriched in Rb, Th, K and LREEs and depleted in Nb, Ta, P and Eu, showing the geochemical characteristics related to subduction. Unlike the contemporary “bimodal igneous rock assemblages” in Zhejiang and Fujian, the intermediate-acid magmatites in the southeastern Guangxi imply the compressive tectonic environment. The assemblage of HMAs and adakitic rocks indicates that the southwestern South China Block was under the Neo-Tethyan subduction during Cretaceous, and slab melting contributed to the magma in this area.

Keywords: high-magnesian andesites 1, I-type granite 2, clastoporphyratic lava 3, Neo-Tethyan Subduction 4, Southwestern South China Block 5

1 Introduction

South China Block lies between the Tethyan tectonic belt and Pacific tectonic belt [1]. It is a crucial period for magmatic rocks and mineralization in southwestern South China Block in Cretaceous, especially in the range of 100–90 Ma [2]. These magmatic rocks are a key to study the tectonic evolution in this region. More research has been done by predecessors, including Kunlun batholith, Dali rock mass and Dachang dike group with concealed rock mass, Sanchaichong rock mass, Chehe rock mass, Michang rock mass, Songwang rock mass and acidic volcanic rocks in Shuiwen basin and so on [2–15]. Because of eye-catching polymetallic ore deposits there, those mineralization-related granitoids and ore-forming process become main objectives, especially in western Guangxi and eastern Yunnan [3–6]. Besides, some little rock masses are seldom studied in eastern Guangxi [7–11], and the Luchuan batholith, the biggest Cretaceous rock body in Guangxi, is much less studied. Conversely, there are a lot of other types of igneous rocks, such as andesites in Guangxi and Guangdong, which are also poorly studied. As to the magmatic activity, mineralization characteristics and tectonic setting in the Cretaceous period, discussion is still continuing. Most studies proposed that southwestern part of the South China Block is influenced by Pacific’s subduction [2,3,6–15]. There are a few studies on Tethyan subduction as well [4,5]. Without a comprehensive study of different types of igneous rocks, it is difficult to make an accurate judgment of the characteristics of the Cretaceous magmatic activities and tectonic setting.

There are abundant Cretaceous magmatic records in Southeastern Guangxi, such as Luchuan batholith and

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Figure 1: Maps of the Southeastern Guangxi (modified after reference 1): (a) the studied area in the context of the South China Block; (b) geological map of the studied area. The location of porphyroclastic lava samples in Shuiwen Basin is considered from Ref. 2. (1) Cretaceous acid volcanic rocks; (2) Cretaceous andesites; (3) Cretaceous granites; (4) Jurassic granites; (5) Indosinian granites; (6) Hercynian granites; (7) Caledonian granites; (8) neoproterozoic granites; (9) quaternary; (10) Paleogene sedimentary rocks; (11) Cretaceous sedimentary rocks; (12) late Paleozoic sedimentary rocks; (13) early Paleozoic sedimentary rocks; (14) faults; and (15) sample location.

intermediate-acidic volcanic rocks. In this article, we present the U–Pb dating of zircon, mineralogical and geochemical compositions of the Luchuan granites and andesites in Yulin during Cretaceous. By combining with the study of late Cretaceous acidic magmatites in the Shuiwen basin [2], the petrogenesis and tectonic setting of Cretaceous magmatites in southeastern Guangxi are analyzed to have a better understanding of the tectonic setting of the southeastern Guangxi. Moreover, the influence of Tethyan subduction on the northern continental margin of the SCS during Cretaceous is discussed.

2 Geological setting

2.1 Regional geology

Guangxi lies in South China and on the northwest margin of the South China Sea (SCS). Besides, Guangxi lies on the south margin of Nanling, which is a critical metallogenic province. The study area is located at the southwest margin of the Cathaysia orogenic belt, where the Tethyan tectonic belt meets the Pacific tectonic belt and therefore is the crucial area for the research of the east extension of the

Figure 2: (a) Hand specimen of andesites from Yulin; (b and c) photomicrographs of andesites, containing phenocryst of hornblende, pyroxene, and plagioclase, with matrix displaying andesitic texture. (d) Hand specimen of monzogranites from Luchuan; (e and f) photomicrographs of monzogranites, containing semi-euhedral plagioclase, alkali feldspar and granular quartz with minor biotite. Abbreviations: Pl, plagioclase; Hb, hornblende; Px, clinopyroxene; Qtz, quartz; Kfs, potassium feldspar; Bi, biotite.

Tethyan tectonic belt [16]. In that area, the outcropping strata are from Mesoproterozoic to Quaternary strata (Figure 1) [1]. Besides, there are plenty of granite records from Neoproterozoic to Cretaceous (Figure 1) [1].

2.2 Local geology

Volcanic activities, occurring in the Xidong Formation of the Upper Cretaceous in southeastern Guangxi, are one of the most remarkable volcanic activities in the continental margins in the northern SCS. Along the Bobai-Cenxi deep fault belt, there is an intermediate-acidic volcanic rock belt with 360 km length and 10–60 km width in the northeast-southwest direction [1]. Volcanic rocks are mainly acidic and intercalated with intermediate volcanic rocks with a thickness of 102–738 m. The volcanic rocks in Shuiwen Basin have the most extensive distribution area, which is mainly composed of tuff breccia, felsophyre, quartz porphyry and tuff. Andesites are mainly distributed in the Yulin-Bobai basin, Santan, Wangmao. It is unconformable over Devonian and Silurian Systems and is covered by sediments of Luowen Formation of the upper Cretaceous system and Paleogene system. The area of andesitic

outcropping is about 38 km² with a thickness of over 481 m. Volcanic rocks in the Yulin-Bobai basin are mainly andesites with a small amount of dacite, rhyolite and acidic tuff breccia.

The outcropping area of Luchuan batholith is 372 km² with N-S distribution and intruded into the lower Paleozoic and Caledonian migmatite [1]. The outer contact zone is characterized by amphibolitization, greisenization, marmorization and silicatization. The batholith comprises a marginal fine-grained monzogranite and a central medium-grained monzogranite. Subsequently, felsic dykes were emplaced with several meters and lengths of several kilometers. The Rb–Sr age data of Luchuan granites is 116 Ma, belonging to the late Yanshanian plutonic rocks [1].

3 Samples and analytic methods

3.1 Petrology of the igneous rocks

The andesites in Yulin are porphyritic with phenocryst (11%–16%) of hornblende (50%–65%), pyroxene (20%–35%),

Table 1: U–Pb data of zircon crystals from andesite sample (15LC1-1) and monzogranite sample (15LC8-1)

	²³² Th (ppm)	²³⁸ U (ppm)	Th/U	Isotopic ratios				Age (Ma)							
				²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ
15LC1-1															
101	369.9031	1097.415	0.337068	0.069394	0.000946	1.479264	0.022043	0.154699	0.001383	910.185	27.78	921.9289	9.03	927.2479	7.72
102	351.6855	814.3251	0.431874	0.073216	0.001017	1.542407	0.023326	0.152604	0.001137	1020.37	28.55	947.4655	9.32	915.5426	6.36
103	5.788257	722.0978	0.008016	0.151631	0.001552	8.842395	0.097376	0.422511	0.002668	2364.51	18.36	2321.876	10.05	2271.869	12.09
105	359.8538	1970.83	0.18259	0.060137	0.000686	0.842628	0.010756	0.10139	0.000711	609.28	24.07	620.5946	5.93	622.5516	4.16
106	375.3026	1075.682	0.348897	0.089175	0.000967	2.883195	0.032698	0.234226	0.001542	1409.26	20.83	1377.528	8.55	1356.609	8.05
107	213.9288	722.0371	0.296285	0.070226	0.001039	1.500139	0.025399	0.154576	0.001463	1000	29.63	930.4427	10.32	926.5634	8.17
109	570.043	870.8691	0.654568	0.072671	0.001129	1.533127	0.027094	0.152402	0.001352	1005.555	31.48	943.7524	10.86	914.4118	7.57
111	613.8774	895.8791	0.685223	0.097284	0.001131	3.59895	0.046454	0.267513	0.002156	1572.53	21.76	1549.3	10.26	1528.167	10.96
114	2118.73	662.169	3.199681	0.064143	0.001041	0.993233	0.015529	0.112186	0.000638	746.3	33.33	700.3685	7.91	685.4325	3.70
115	536.4898	506.6273	1.058944	0.059697	0.00111	0.838994	0.016053	0.101737	0.00075	592.31	40.73	618.5903	8.86	624.5806	4.39
116	432.4318	551.2917	0.784397	0.064711	0.001099	1.103915	0.019405	0.12353	0.000941	764.82	236.11	755.242	9.37	750.8499	5.40
1104	778.0538	659.6152	1.179557	0.052943	0.002028	0.105863	0.00426	0.01455	0.000162	327.835	87.03	102.174	3.91	93.11836	1.03
108	215.2011	319.4118	0.673742	0.055402	0.005689	0.106484	0.00931	0.014642	0.000365	427.825	226.82	102.744	8.54	93.70662	2.32
110	784.9412	647.1618	1.212898	0.048431	0.002114	0.095819	0.004078	0.014437	0.00016	120.46	103.69	92.90974	3.78	92.40299	1.02
112	661.9847	887.1498	0.746193	0.052819	0.002251	0.105023	0.004352	0.014548	0.000155	320.43	98.14	101.4028	4.00	93.1057	0.98
113	51.65246	563.106	0.091728	0.047487	0.004553	0.095395	0.009201	0.014721	0.000308	72.315	214.79	92.51632	8.53	94.20726	1.95
117	807.3268	1006.848	0.801836	0.048714	0.001889	0.097236	0.003751	0.014577	0.000148	200.075	97.21	94.22184	3.47	93.29211	0.94
118	288.3278	1657.861	0.173916	0.048054	0.001621	0.097694	0.003339	0.014783	0.000153	101.94	84.25	94.64546	3.09	94.60189	0.97
15LC8-1															
B1-01	1224.02	2189.7	0.55899	0.05096	0.00135	0.11958	0.00349	0.01702	0.00041	239	60.16	114.7	3.17	108.8	2.58
B1-02	240.82	205.99	1.169086	0.05012	0.00339	0.11282	0.00759	0.01633	0.00046	200.3	149.9	108.5	6.93	104.4	2.89
B1-04	377.21	541.61	0.696461	0.05019	0.00226	0.10167	0.00464	0.01469	0.00038	203.6	101.27	98.3	4.28	94	2.4
B1-05	1185.13	1832.22	0.646827	0.05097	0.00135	0.12122	0.00353	0.01725	0.00041	239.4	59.92	116.2	3.2	110.2	2.61
B1-06	927.78	1686.72	0.55005	0.04853	0.00154	0.11615	0.00391	0.01736	0.00042	125.3	73.06	111.6	3.56	110.9	2.68
B1-07	500.14	727.1	0.687856	0.0474	0.00179	0.10642	0.00415	0.01628	0.0004	68.8	87.96	102.7	3.81	104.1	2.57
B1-08	309.7	517.63	0.598304	0.04942	0.0025	0.11305	0.00575	0.01659	0.00044	167.8	114.11	108.8	5.25	106.1	2.77
B1-11	500.86	398.46	1.256989	0.0681	0.00443	0.14706	0.00944	0.01566	0.00045	871.5	129.29	139.3	8.36	100.2	2.88
B1-12	233.53	282.46	0.826772	0.04427	0.00449	0.09972	0.01005	0.01634	0.00048	0.1	136.52	96.5	9.28	104.5	3.08
B1-13	703.94	1152.84	0.610614	0.04828	0.00187	0.11383	0.00454	0.0171	0.00043	112.8	88.86	109.5	4.14	109.3	2.71
B1-14	491.27	671.18	0.73195	0.04844	0.00228	0.10967	0.00522	0.01642	0.00043	121	107.39	105.7	4.78	105	2.7
B1-15	696.33	960.37	0.725064	0.05266	0.00208	0.12145	0.00492	0.01672	0.00042	314.2	87.28	116.4	4.45	106.9	2.66
B1-16	1127.74	1979.13	0.569816	0.04781	0.00153	0.11456	0.00388	0.01738	0.00042	89.1	75.26	110.1	3.54	111.1	2.68
B1-17	549.77	391.71	1.403513	0.05741	0.00565	0.1359	0.01309	0.01717	0.00059	507	203.5	129.4	11.7	109.7	3.72
B1-18	415.41	258.21	1.608807	0.05492	0.00507	0.1218	0.01102	0.01608	0.00053	408.8	194.25	116.7	9.97	102.9	3.35
B1-19	924.99	1745.1	0.53005	0.05128	0.00172	0.11495	0.00405	0.01626	0.0004	253.5	75.49	110.5	3.69	104	2.53
B1-20	845.93	2001.5	0.422648	0.05076	0.00156	0.11992	0.00394	0.01713	0.00041	230.1	69.69	115	3.57	109.5	2.63
B1-21	411.87	661.11	0.622998	0.04843	0.00229	0.11506	0.00551	0.01723	0.00044	120.4	107.71	110.6	5.01	110.1	2.8

	²³² Th (ppm)	²³⁸ U (ppm)	Th/U	Isotopic ratios				Age (Ma)							
				²⁰⁷ Pb/ ²⁰⁶ Pb ±1σ	²⁰⁷ Pb/ ²³⁵ U ±1σ	²⁰⁶ Pb/ ²³⁸ U ±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb ±1σ	²⁰⁷ Pb/ ²³⁵ U ±1σ	²⁰⁶ Pb/ ²³⁸ U ±1σ						
B1-22	892.02	1638	0.544579	0.04929	0.00181	0.11203	0.00425	0.01648	0.00041	161.7	83.51	107.8	3.88	105.4	2.6
B1-23	919.05	2210.6	0.415747	0.05108	0.00149	0.12198	0.00382	0.01732	0.00042	244.4	65.84	116.9	3.46	110.7	2.64
B1-24	484.64	446.11	1.086369	0.04966	0.00235	0.11423	0.00549	0.01668	0.00043	179.3	106.88	109.8	5	106.6	2.7
B1-25	372.44	316.27	1.177601	0.04944	0.0036	0.11618	0.00838	0.01704	0.00048	168.8	161.55	111.6	7.62	108.9	3.07

The samples from Luchuan batholith are reddish, and the granitic texture is medium to fine grained (0.5–3 mm; Figure 2d–f). The minerals present include plagioclase (30%–35%), alkali feldspar (25%–30%) and quartz (20%–30%). Besides, trace amounts (<1%) of magnetite, apatite and zircon also occur. The plagioclase is semi-euhedral with the development of polysynthetic twinning and zoning textures, and some plagioclase is partially sericitized or kaolinized. The alkali feldspars are mainly microcline and perthite.

Zircon grains were separated by conventional magnetic and density techniques from approximately 10 kg per sample. Then, under a binocular microscope, zircons were selected by hand-picking. By using CL images and transmitted as well as reflected light micrographs of the polished zircon grains, potential analytical spots were selected. At the Laboratory Center, Xi'an Center of Geological Survey, Xi'an, China, U–Pb isotopic analysis of the monzogranite sample was carried out with Agilent 7500a quadrupole ICP-MS. A 193 nm excimer laser was focused on the surface of the zircon grains with an energy density of 10 J/cm². The laser beam diameter was 24 μm, and the repetition rate was 5 Hz. Helium, as a carrier gas, transported the ablation aerosol to the laser ablation inductively coupled plasma mass spectrometer (ICP-MS). Harvard zircon 91500 was used as an external standard for zircon U–Th–Pb analyses, and NIST610 was used as an external standard to calculate the contents of U, Th and Pb. Details of the analytical procedures and data processing methods are presented in Refs. [17,18]. Table 1 presents the zircon U–Pb dating results.

Major elements were analyzed by X-ray fluorescence (Axios max) at the Hebei Institute of Geology and Mineral Resources, China Geological Survey. Analytical precision was generally better than 5% for most oxides. Trace element data were also measured by an ICP-MS

Table 2: Major element (wt%) and trace element (ppm) compositions of the Cretaceous magmatic rocks in Southeast Guangxi

	Andesites				Monzogranites			
	15LC1-1	15LC4-1	15LC2-1	15LC2-2	15LC7-1	15LC8-1	15LC-H2	15LC-H3
SiO ₂	54.67	54.07	54.39	54.31	77.17	75.72	78.04	77.80
Al ₂ O ₃	15.72	15.16	15.48	15.46	12.34	12.88	11.41	12.16
TiO ₂	0.81	0.80	0.80	0.80	0.08	0.14	0.14	0.08
Fe ₂ O ₃	3.44	3.58	4.35	4.48	0.33	0.42	0.48	0.24
FeO	3.32	3.72	3.02	2.96	0.20	0.42	0.33	0.23
CaO	7.83	7.54	7.35	7.32	0.61	0.95	0.61	0.51
MgO	7.61	8.28	7.84	7.85	0.07	0.19	0.19	0.09
K ₂ O	2.06	2.02	2.05	2.09	4.56	5.22	4.95	4.53
Na ₂ O	2.80	2.88	2.83	2.88	3.90	3.40	2.95	3.80
MnO	0.13	0.12	0.13	0.12	0.071	0.041	0.031	0.044
P ₂ O ₅	0.17	0.17	0.17	0.17	0.011	0.022	0.023	0.011
LOI	1.24	1.47	1.37	1.33	0.64	0.57	0.77	0.49
Total	99.80	99.80	99.77	99.77	99.99	99.96	99.92	99.99
FeO ^T	6.42	6.94	6.93	6.99	0.50	0.79	0.77	0.45
Mg#	67.88	68.03	66.85	66.67	20.89	29.98	30.55	25.44
A/CNK	0.75	0.73	0.76	0.76	0.99	0.99	1.01	1.01
Sc	22.2	23.2	25.4	20.3	6.64	2.95	2.69	5.92
V	174	163	146	142	8.01	12.6	18.9	8.02
Cr	369	353	424	415	0.49	12.0	2.96	1.43
Co	33.1	34.3	34.6	33.8	0.084	2.10	0.62	0.09
Ni	147	148	134	128	0.074	4.37	0.78	0.17
Ga	16.7	16.7	17.8	17.3	17.6	15.9	13.4	19.8
Rb	61.3	65.0	66.2	65.1	432	250	233	488
Sr	530	533	509	515	12.8	102	76.9	12.9
Zr	164	125	167	164	58.7	90.6	103	58.6
Hf	4.51	3.35	4.40	4.30	4.41	4.99	5.68	4.45
Nb	8.97	8.73	8.04	8.27	57.5	18.3	13.4	37.2
Ta	0.90	0.50	0.51	0.51	3.47	1.31	1.05	2.61
Th	8.00	7.89	7.51	7.36	26.2	38.0	40.8	28.1
U	1.81	1.73	1.59	1.48	30.5	9.20	7.62	19.8
Pb	12.7	12.4	13.0	11.0	72.0	45.2	41.5	65.5
Ba	570	589	549	556	28.7	176	185	38.3
Y	16.5	13.1	17.2	17.5	28.7	12.4	9.87	17.2
La	28.7	24.3	27.0	26.7	20.0	38.6	33.8	19.5
Ce	51.8	40.6	49.9	50.7	41.5	59.4	56.1	36.9
Pr	6.44	5.25	6.13	6.12	4.88	6.59	6.00	4.05
Nd	24.5	19.5	24.0	23.4	15.3	20.2	18.3	11.8
Sm	4.41	3.51	4.38	4.39	2.98	2.91	2.49	1.99
Eu	1.11	0.87	1.23	1.25	0.06	0.41	0.36	0.08
Gd	3.51	2.89	3.77	3.82	2.58	2.66	2.34	1.90
Tb	0.62	0.49	0.58	0.60	0.51	0.39	0.31	0.32
Dy	3.19	2.50	3.25	3.27	3.20	1.85	1.50	1.93
Ho	0.63	0.50	0.62	0.62	0.82	0.42	0.32	0.49
Er	1.73	1.35	1.76	1.77	2.78	1.25	1.02	1.68
Tm	0.31	0.25	0.28	0.27	0.69	0.26	0.20	0.43
Yb	1.80	1.52	1.81	1.82	4.86	1.54	1.23	3.09
Lu	0.45	0.40	0.26	0.27	0.89	0.25	0.22	0.63
ΣREE	129.15	104.00	125.05	125.05	100.96	136.67	124.14	84.77
δEu	0.84	0.81	0.90	0.91	0.06	0.45	0.45	0.13
LREE/HREE	9.55	9.50	9.13	9.06	5.19	14.86	16.38	7.11
(La/Yb) _N	6.80	6.54	10.97	10.65	2.41	16.23	16.28	3.35
Rb/Sr	0.12	0.12	0.13	0.13	33.68	2.44	3.03	37.97
Ba/La	19.88	24.22	20.31	20.80	1.44	4.57	5.47	1.96
Zr/Hf	36.48	37.25	38.02	38.21	13.30	18.16	18.17	13.18
Sr/Y	32.09	40.82	29.53	29.34	0.45	8.25	7.79	0.75

with the use of a X Serise 2 machine. The analytical precisions for most trace elements are higher than 3%. Table 2 presents samples' major and trace elemental data.

4 Results

4.1 Zircon U–Pb ages

Zircon CL images reveal that the zircon crystals were mostly colorless and semi-euhedral. Most are of short-column or sub-rounded shape with a length-to-width ratio of about 1:1–1:3. The zircons display typical magmatic oscillatory zoning and rhythmically zoned texture. The Th/U ratios of the five youngest zircon crystals are between 0.09 and 1.21 (Table 1), six of which are bigger than 0.10 and are within the range of typical igneous zircons [19]. The seven youngest zircon crystals together yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 93.38 ± 0.83 Ma (2σ) (MSWD = 0.47; Table 1 and Figure 3), the early stage of late Cretaceous.

Zircons are abundant in the studied monzogranite samples. Zircons are euhedral and range up to 100 μm in size; most of them are transparent to light brown in color and exhibit magmatic oscillatory zoning. Twenty-five grains were analyzed from sample 15LC8-1, of which 19 may be pooled to yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 107.6 ± 1.2 Ma (2σ) (MSWD = 0.96; Table 1 and Figure 4). The other Cretaceous igneous rocks' ages are from 113 to

83 Ma in southeastern Guangxi [2,7,10,20], indicating that the Cretaceous igneous rocks crystallized from late early Cretaceous to early late Cretaceous in the studied area.

4.2 Whole-rock major and trace elements

These monzogranites are compositionally similar to each other and are characterized by high SiO_2 and low Al_2O_3 , FeO^T , P_2O_5 , TiO_2 , MgO and CaO . Total alkalis and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ values of samples are high, with the characteristic of high-K calc-alkaline rocks (Figure 5a and b). They are metaluminous-weakly peraluminous with A/CNK values (molar $\text{Al}_2\text{O}_3/[\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O}]$, 0.99–1.04, Figure 5c). Andesites fall within the range of basaltic andesites (Figure 5a), with low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ values. They are high-magnesian andesites (HMAs), significantly characterized by high MgO and high Mg contents. The HMAs are calc-alkaline similar to clastoporphyratic lava (Figure 5b).

The $\sum \text{REE}$ of the monzogranites and HMAs are lower than that of clastoporphyratic lava. LREE/HREE ratios of the monzogranites and HMAs vary between 5.16 and 16.38. The $(\text{La}/\text{Yb})_N$ values of the monzogranites and HMAs range from 2.41 to 16.28, which are less negative than the clastoporphyratic lava (Figure 5a; $(\text{La}/\text{Yb})_N = 18.98\text{--}22.04$). The chondrite-normalized REE patterns of Cretaceous igneous rocks show a gently right-inclined “V” shape characterized by the LREE enrichment with apparent negative Eu anomalies (Figure 6a). Moreover, the monzogranites' negative Eu anomalies are more strong than that of volcanics.

Figure 3: Cathodoluminescence images and U–Pb ages of zircons from Yulin andesites. The red circles indicate the analytical area for U–Pb dating, and age error is given at 2 sigma level.

Figure 4: Cathodoluminescence images and U–Pb ages of zircons from Luchuan monzogranites. The red circles indicate the analytical area for U–Pb dating, and age error is given at 2 sigma level.

In the primitive-mantle-normalized spidergram, all the samples have similar distribution patterns (Figure 6b), showing enrichment in large ion lithophile elements (LILEs; such as Rb, Th and K) while depletion or negative anomaly in high-field strength elements (HFSEs; such as Nb, Ti, Sr and P). The phenomenon of the “TNT (Ti–Nb–Ta) anomaly” was most characteristic of island arc volcanics and the continental crust in general [21].

5 Discussion

5.1 Samples’ tectonic implications

The ratios of HFSEs in magmatic rocks can accurately reflect the characteristics of the magmatic sources. With high Rb/Sr ratios, and low Ba/La as well as Zr/Hf ratios, monzogranites and clastoporphyritic lava are mainly crust derived. Granitic rocks can be categorized into the following four main genetic types: M-type, I-type, S-type and A-type. With low $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ and A/CNK

values, the monzogranites and clastoporphyritic lava are similar to I-type granites without alkaline dark-colored minerals (Figure 7a). Moreover, I-type granites are formed by partial melting of intermediate-basic metamorphic igneous rocks of the crust [22]. In the Rb versus $(\text{Yb} + \text{Ta})$ discriminant diagrams (Figure 7b), monzogranites and clastoporphyritic lava samples are plotted in the volcanic arc granites and syn-collisional granites, which indicates that the formation of monzogranites and clastoporphyritic lava is closely related to the subduction.

HMA s are mostly formed in a convergent plate boundary. HMA s in Yulin share similar geochemical characteristics with bajaites in Baja California Peninsula, Mexico, such as the high fractionation of light and heavy rare earth elements and the high contents of Sr, Cr, Ni, V and Co. It indicates that the HMA s in Yulin, like the bajaites, was formed in a convergent tectonic environment with probable origin by melting of mantle peridotites previously metasomatized by slab melts [23]. Besides, magmatites with similar geochemical characteristics of HMA s are found in Gangdese Belt contemporaneously [24,25], which means that Neo-

Figure 5: (a) Geochemical classification diagrams for Cretaceous magmatic rocks in southeastern Guangxi: plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 (after reference 26). The green line between alkaline and sub-alkaline igneous rocks is taken from Ref. 27; (b) diagram of SiO_2 versus K_2O (after reference 28); and (c) A/NK versus A/CNK diagram (after reference 29). A/NK : molar $\text{Al}_2\text{O}_3/[\text{K}_2\text{O} + \text{Na}_2\text{O}]$; A/CNK : molar $\text{Al}_2\text{O}_3/[\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O}]$. The data of porphyroclastic lava are from Reference 2.

Tethys extended to the present location of SCS and the tectonic environment in the northern margin of SCS was

affected by the subduction of Neo-Tethys during Cretaceous.

Figure 6: (a) Chondrite-normalized REE patterns and (b) the primary-mantle-normalized trace elements spider diagrams for Cretaceous magmatic rocks in southeastern Guangxi. Normalizing values are taken from Ref. 30.

Figure 7: Tectonic discriminant diagrams of Cretaceous monzogranites and clastoporphyrific lava in southeastern Guangxi: (a) $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ versus FeO^T/MgO plot for the identification of A-type granites from I- and S-type granites (after Ref. 31); (b) $\text{Yb} + \text{Ta}$ versus Rb plot for discriminating syn-collisional granites, volcanic-arc granites, within-plate granites and ocean-ridge granites (after Ref. 32).

The ratios of HFSEs in magmatic rocks can accurately reflect the characteristics of magmatic source. HMAs have lower Rb/Sr ratios, higher Ba/La and Zr/Hf ratios. In Figure 8a, showing the picture of $(\text{La}/\text{Yb})_N$ versus δEu , the magma source of HMAs is crust mantle derived, while the clastoporphyrific lava and monzogranites are mainly crust derived. The differentiation degree of monzogranites' magma, especially the medium-grained monzogranites', is much higher with lower $(\text{La}/\text{Yb})_N$. These geochemical characteristics indicate that the andesitic magma is obviously mixed with mantle source. Besides, the HMAs in Yulin have low FC3MS values lower than 0.65, suggesting peridotitic sources (Figure 8b).

5.2 Cretaceous magmatism's geochronology and regional tectonics in southwestern South China Block

Beside the magmatism in southeastern Guangxi, there are numerous igneous rocks in Cretaceous, which can be found in the surrounding area, such as Yangchun Basin, western Guangxi, eastern Yunnan and northern Vietnam [4,35–41]. The ages of those rocks are from 113 to 70 Ma, similar to samples in southeastern Guangxi. Furthermore, Cretaceous ore mineralization is often related to those igneous rocks, especially granitoids. So it is a meaningful period for magma and mineralization from

Figure 8: Origin discriminant diagrams of Cretaceous igneous rocks in southeastern Guangxi: (a) $(\text{La}/\text{Yb})_N$ versus δEu (after reference 33) and (b) FC3MS versus MgO plot for HMAs (after Ref. 34). $\text{FC3MS} = \text{FeO}^T/\text{CaO} \cdot 3\text{MgO}/\text{SiO}_2$.

Figure 9: (a) Sr/Y versus Y diagrams (after Ref. 65), Hainan granites' data are taken from Refs. 39–41. (b) Schematic diagram of the tectonic setting of magmatic activities in northern margin of SCS during late early Cretaceous to early late Cretaceous.

late early Cretaceous to early late Cretaceous in southwestern South China Block.

The volcanic rocks during this period in the northern continental margin of the SCS are mainly concentrated in the Yunkai region at the border of Guangdong and Guangxi, and there are a lot of extrusive rocks in Hainan island mainly in early Cretaceous. Most of them are most intermediate-acid volcanic rocks and seldom basic volcanic rocks, which do not conform to the “bimodal igneous rock assemblages” in Southeastern China, especially in late Cretaceous. Besides, according to zircon solubility simulation formula at 700–1,300°C [42], the diagenetic temperature of clastoporphyrific lava in Shuiwen basin clastoporphyrific lava is 764–812°C, much lower than that of the clastoporphyrific lava in Zhejiang (803–820°C) and rhyolite in Fujian (861–930°C) [43,44]. Moreover, the diagenetic temperature of monzogranites in Luchuan is 706–754°C, much lower than the average diagenetic temperature of I-type granites (781°C) [45]. Cretaceous S-type granites have also been discovered in southeastern Guangxi in recent years, such as Youmapo muscovite granites [46], which is also different from the assemblages of I-type and A-type granites in Zhejiang and Fujian. From late early Cretaceous to early late Cretaceous, the subduction of the paleo-Pacific plate only influences the area east of Wuyi Mountain [35,47]. Therefore, it may not be suitable to mechanically apply the tectonic model in Zhejiang and Fujian to the southeastern Guangxi during this period. The assemblage of I- and S-type granites is

suggested the symbol of convergent environment [48], which also differs from the extensional environment in Southeast China.

In recent years, studies on the influence of the Tethyan subduction on the northern continental margin of the SCS increased [36,49–54]. In the northern part of the SCS and nearby area, there was an E-W trending magmatic belt, and the northern continental margin of the SCS was in the tectonic environment of the Tethyan subduction in Cretaceous [35,37,38,55]. These Cretaceous igneous rocks in Guangxi and Hainan islands are the product of northward subduction of Neo-Tethys. Moreover, HMAs in Guangxi and adakitic rocks in Hainan should form in subduction settings and be produced by partial melting of subducting young and hot slabs followed by interaction with the overlying mantle during ascent [56–61] (Figure 9). Due to the relatively young and high temperature of the subducted oceanic crust when Tethyan ridge subducted underneath South China Block [38,55], or tearing and breaking off, the subducted oceanic crust would melt, and the melt replaced mantle wedge and crustal materials in southeastern Guangxi to form Cretaceous magmatic rocks in this region, which share similarities with HMAs and adakitic rocks in Gangdese magmatic arc at a similar time [24,25,62–64]. In this case, andesites in Yulin were characterized by high magnesium content, almost at the same time that adakitic rocks formed in Hainan island. As the same with those igneous rocks in Gangdese belt, magmatism from both southwestern South China Block and Gangdese

magmatic arc may generate under the subduction of Neo-Tethyan ridge during the middle period of Cretaceous. Neo-Tethyan subduction influences both magmatic activity and mineralization in southwestern South China Block.

6 Conclusions

Yulin andesites and Luchuan monzogranites are emplaced at 93.37 ± 0.43 Ma and 107.6 ± 1.2 Ma, respectively. There is intense magmatic activity occurring in the late early Cretaceous to early late Cretaceous in southeastern Guangxi. The andesites exhibit high MgO and Mg#, enriched in Sr, Cr, Ni, V and Co, which imply that Cretaceous andesites belong to HMAs with similarity with bajaites. Luchuan granites are monzogranites and are highly differentiated I-type granites. These Cretaceous magmatic rocks are enriched in LREEs and LILEs, but depleted in HFSEs. The formation of Yulin HMAs, Luchuan batholith and Shuiwen clastoporphyratic lava is associated with subduction. Different from the NE-trending magmatic belt under the subduction of paleo-Pacific along the east coast of the South China Block, the northern continental margin of the SCS is in the tectonic environment of the Tethyan subduction during the Cretaceous. The subduction of Neo-Tethyan ridge may contribute to magmatism.

Acknowledgments: This research was supported by the National Natural Science Foundation of China (Grant No. 41572207, 41276047, 41030853). The authors acknowledge Yongyang Huang from the Institute of Guangzhou Marine Geological Survey and Guangxi Institute of Marine Geological Survey their support during the field investigation. The authors are grateful to the editor and the anonymous referees for constructive review comments. The authors thank Hailing Zhao and Dapeng Li from the China University of Geosciences, Beijing, for their helpful discussions.

Conflict of interest: No potential conflict of interest was reported by the authors.

Author contributions: Yang Liu: fieldwork; analysis of petrology, U–Pb ages and geochemical data of samples; and original draft. Nianqiao Fang: fieldwork; funding acquisition; and review and editing of manuscript. Menglin Qiang: methodology and analysis of petrology, U–Pb ages and geochemical data of samples. Lei Jia:

fieldwork and analysis of petrology of samples. Chaojie Song: visualization and curation of data.

Data availability statement: All data related to the research have appeared in the article and can be available upon request to the corresponding author.

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