Article

Geochronology and Geochemistry of the Zengudi and Tuobake Granite Porphyries in the Sanjiang Region, SW China: Petrogenesis and Tectonic Significance

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Abstract: The boundary between the Gondwana and Yangtze plate is still controversial. In southwest China, the Sanjiang region marks the collision zone which accreted several blocks coming from the northern Gondwana margin. In this region, subduction of the Paleo-Tethys Ocean and associated continental blocks during the Triassic Period led to the formation of an N–S trending complex involving intrusive and volcanic rocks. The intrusive rocks are important for constraining the evolution of the Paleo-Tethyan in southwestern China. This study presents new geochronological, geochemical, and Sr–Nd–Hf isotopic data of granite porphyries from northern Lancangjiang, in order to discuss the origin of these granites and their tectonic significance. Representative samples of the Zengudi and the Tuobake granite porphyries from the Yezhi area yielded weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 247–254 Ma and 246 Ma, respectively. The Zengudi granite porphyries display zircon $\epsilon_{\text{Hf}}(\text{t})$ values of -12.94 to -2.63 , $\epsilon_{\text{Nd}}(\text{t})$ values of -14.5 to -9.35 , and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.708 to 0.716. The Tuobake granite porphyries have zircon $\epsilon_{\text{Hf}}(\text{t})$ values of -14.06 to -6.55 , $\epsilon_{\text{Nd}}(\text{t})$ values of -10.9 to -9.41 , and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.716 to 0.731. Both the Zengudi and Tuobake granite porphyries exhibit strongly peraluminous signatures with high A/CNK $n\text{Al}_2\text{O}_3/(\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ ratios (1.07–1.86 and 0.83–1.33, respectively). These granites are enriched in Rb and Th, and depleted in Ti, Nb, Ta, Sr, and P, with negative Eu anomalies ($\text{Eu}/\text{Eu}^* < 0.61$). These geochemical and isotopic data indicate that the primary magma of the granite porphyries originated from partial melting of ancient continental crust as a result of basaltic magma underplating and underwent fractionation crystallization during their emplacement. We propose that the Triassic subduction of the Paleo-Tethys Ocean led to crust shortening and thickening in the Sanjiang region, while the northern Lancangjiang area was involved in the continental collision after the subduction of the Paleo-Tethys Ocean before 254 Ma.

Keywords: zircon U–Pb dating; granite porphyry; northern Lancangjiang; southern China; tectonic evolution; Paleo-Tethys

1. Introduction

The convergent subduction zone is an important window for understanding the interaction between the crust and mantle as well as deciphering the relationship between the magmatic rocks and their tectonic environment [1–3]. In subduction zones, the variability of plate tectonic processes, magma sources, thermal states, and crust thicknesses in the volcanic arc constrained the magmatic activity and led to the segmentation, heterogeneity, and differences of igneous rocks [4–7]. Nowadays, exploring the plate tectonic processes by studying the origin and evolution of igneous rocks in orogenic belts is a hot topic for the tectonic history of continents [8–11].

At the Paleo-Tethys stage, the Lhasa, West and East. Qiangtang, Songpan-Ganzi blocks became merged in North Sanjiang, while West. Burma Sibumasu and Indochina blocks became merged in the south of Sanjiang, which related the accreted orogenic process. During the late Cretaceous to Paleogene, continent–continent collision from the India block to south China block led to an orogenic belt collision in the Sanjiang area. Previous research has demonstrated that the magmatism of the Sanjiang area was related to the opening of the Paleo-Tethys Ocean, which occurred between 272 and 207 Ma [12–25]. In this framework, the Paleo-Tethys magmatism mainly occurred from Late Permian to Late Triassic in the Sanjiang region [15–17,19–22]. Magmatic rocks define distinct spatial distribution in the southern and northern segments of this region [21], with relatively late stage of magmatism identified in the southern part compared to the northern portion [17]. Many of these studies were focused on the volcanic rocks of the northern segment of this region [12,19,20], while little research was conducted on granitic rocks. Although the temporal evolution of magma in the arc volcanic belts of the Sanjiang region and the deep dynamic processes have been intensely studied and discussed [6,12–20,22,23], no consensus has been reached on the accurate timing and location of these volcanic arcs related to the Paleo-Tethys. On the other hand, the boundary of the Paleo-Tethys suture zone between the Baoshan and Simao blocks at the Yeshi area is not clear. Thus, a systematic geochemical study of the granitic rocks from specific areas would shed new insight into the tectonic evolution of the Sanjiang region.

The Yezhi area is located at the junction of the Chongshan shear zone and the Jinshajiang fault zone in the northern section of the Jiangda-Weixi volcanic arc belt (Figure 1a,b). Volcanic and granitic rocks generated by variable tectonic processes are exposed in this area, with complex contact relationships due to a strong collision and extrusion during the closure of the Paleo-Tethys Ocean. Exploring the petrogenesis of these rocks is very important to understand the geodynamic setting, subduction, and collision processes of the Yezhi area. In this paper, we present new zircon U–Pb age and Hf isotopic data as well as whole-rock major, trace element, and Sr–Nd isotopic data of the Zengudi and Tuobake granite porphyries from the Yezhi area, aiming to: (1) constrain their formation age, (2) characterize their magma source and petrogenesis, and (3) investigate their tectonic setting and provide implications for the Paleo-Tethys evolution.

2. Geological Setting

The Sanjiang region in southwest China has been generally considered a convergent margin subduction zone, which was involved during the tectonic evolution process of the Tethys (Figure 1a) [6]. This region can be further regarded as an excellent natural laboratory for studying the subduction-related tectonic processes. In the accretionary orogenic process caused by the collision of archipelagic arc-basin systems during Early Devonian to Middle Triassic [25], the Sanjiang region has experienced ocean–crust subduction and continent–continent collision [16,21], followed by complex thermal magmatism and metamorphism. Previous works on the tectonic history of this region have documented the formation of the Ganzi-Litang suture zone between the south China and Zhongza blocks [16,26,27], the Lancangjiang-Changning-Menglian suture zone between the Baoshan and Simao blocks [28,29], the Jinshajiang [12,30–32] and the Ailaoshan-Songma suture zones between the Simao and Yangtze blocks [33–35] (Figure 1b,d). The Lancangjiang-Changning-Menglian and the Jinshajiang-Ailaoshan Oceans were opened during the Early–Middle Devonian and closed at Middle Triassic. While the Ganzi-Litang and Songma Oceans (southern extension of the Ailaoshan Ocean) were opened during the Early–Middle Devonian and closed at late Triassic. The remnant of the oceanic crust distributed in these suture zones has been systematically studied [6]. Three volcanic arc belts related to the subduction of the Paleo-Tethys Ocean were delineated in the Sanjiang region: the Yushu-Yidun belt formed during Late Triassic (230–200 Ma) [25], the Jiangda-Weixi belt formed during Late Permian to Triassic (270–200 Ma) [21,36], and the Yunxian-Lvchun-Ailaoshan belt formed during Permian to Early–Middle Triassic (285–265 Ma and 260–230 Ma) [20,21].

Among these belts, the Jiangda-Weixi belt is the most complex volcanic arc characterized by fragmented blocks [6], which explains that its tectonic evolution is still unclear.

Figure 1. (a) Distribution of main continental blocks and sutures of the East Tethyan belt (modified from [26]); (b) tectonic framework of the Sanjiang region in southwest China showing the major terranes, suture zones, arc volcanic belts, Cenozoic igneous rocks, and location of the Yezhi area (modified from [24]); (c) Simplified geological map showing the Zengudi and Tuobake granite porphyries in the Yezhi area. (a) the east of India Myanmar block (b) the west of Litang suture zone. (d) An E-W vertical cross-section of the Sanjiang area.

The Zengudi and Tuobake granite porphyries are located in the Yezhi area in the north of the Sanjiang region. The Yezhi area is situated between the Jinshajiang suture zone and the Biluoxueshan-Chongshan shear zone and connects the Zhongzan and Lanping-Simao Blocks on the east and west, respectively (Figure 1a,b). The Yezhi area has undergone intense orogenic events in the East Tethyan tectonic zone as results of oceanic subduction and continental collision from Paleozoic to Mesozoic [16,19,21]. These orogenic activities were developed together with a remarkable volume of magmatic movements. Ophiolite and mafic rocks were crystallized in the Late Permian, whereas basic-acidic bimodal volcanic rocks and pyroclastic rocks were formed in the Early–Middle Triassic [16]. A series of ultrabasic, intermediate, and alkaline rocks are also exposed in the area [16,17]. Granitic rocks are mostly distributed on the west side of the study area. This region has alternatively experienced multiple periods of magmatism and sedimentation, which led to volcanoclastic successions [21,34]. Besides magmatic rocks, the exposed strata encompass Early to Middle Permian metamorphic sandstone, slate, and red sandstone (Figure 1c). The sedimentary succession is characterized by flysch and molasse [25].

The granite porphyries in the Yezhi area are distributed along the east side of the Jiangda-Weixi volcanic arc (Figure 1c). They form a long strip shape from south to north. The Zengudi granite porphyry intrudes into the Triassic Pantiang Formation volcanic rocks

with an ellipsoid shape and is adjacent to the Triassic Shanglan formation metamorphic–sedimentary rocks on the west (Figures 1c and 2a). The Tuobake granite porphyry displays an irregular long strip shape at the surface, intrusively connected to the Shanglan Formation (Figures 1c and 2b).

Figure 2. Field occurrences (a,b) and photomicrographs (c–f) of the Zengudi and Tuobake granite porphyries. (a) The Zengudi granite porphyry shows a massive structure; (b) the Tuobake granite porphyry displays a massive structure and has an intrusive contact with the Shanglan formation; (c) the plagioclase (Pl) is carlsbad-albite twin; (d) the quartz (Qtz) phenocryst is surrounded by plagioclase; (e) the quartz phenocrysts are subcircular due to dissolution; and (f) the plagioclase is a polysynthetic twin.

3. Samples and Analytical Methods

3.1. Sample Description

The crystals are mainly composed of quartz, plagioclase, K-feldspar, chlorite, and minor opaque minerals (Figure 2c). The quartz is xenomorphic granular and partly clastic with a particle size ranging between 0.3 to 2.0 mm (Figure 2d). Most plagioclase crystals occur as automorphic or subhedral laths (0.4–1.5 mm in size) showing polysynthetic and carlsbad-albite twins, with weakly sericitization and argillization. K-feldspar is mainly characterized by 0.2 to 1.5 mm automorphic or subhedral carlsbad twinning laths, and

some crystals are xenomorphic granular. Chlorite has a lamellar shape with a size ranging between 0.2 and 2.0 mm.

The Tuobake granite porphyry samples also have a phanerocrystalline texture with a large amount of felsic minerals (approximately 80%) and less phenocrysts (approximately 10%) of the matrix. The crystals mostly comprise quartz, plagioclase, and K-feldspar. Most quartz crystals (0.4–2.5 mm in size) are rounded, resulting from excessive melting corrosion (Figure 2e). Plagioclase often occurs as automorphic or subhedral laths with a particle size ranging between 0.5 and 2.0 mm, displaying polysynthetic and carlsbad-albite twins (Figure 2f). K-feldspar crystals also appear as automorphic or subhedral carlsbad-albite twinning laths (0.4–1.5 mm in size), and some crystals are granular.

3.2. Analytical Procedures

We selected ten rock samples (five Zengudi and five Tuobake granite porphyries) for whole-rock geochemical analyses. Major element concentrations were determined using an X-ray fluorescence (XRF) instrument (Primus II, Rigaku, Japan) at the Wuhan Sample Solution Analytical Technology Co., Ltd. (Wuhan, China). The detailed sample digestion procedure was as follows: (1) the sample powder (200 mesh) was dried in an oven at 105 °C for 12 h; (2) approximately 1 g of dried sample was accurately weighed and placed in the ceramic crucible and then heated in a muffle furnace at 1000 °C for 2 h. After cooling to 400 °C, this sample was placed in the drying vessel and weighed again to calculate the loss on ignition (LOI); (3) 0.6 g sample powder was mixed with 6 g co-solvent ($\text{Li}_2\text{B}_4\text{O}_7\text{:LiBO}_2\text{:LiF} = 9\text{:}2\text{:}1$) and 300 mg oxidant (NH_4NO_3) in a Pt crucible, which was placed in the furnace at 1150 °C for 14 min. Then, the air quenching was applied to the sample for 1 min to produce flat discs on the fire brick for the XRF analyses.

Trace element compositions were also obtained at the Wuhan Sample Solution Analytical Technology Co., Ltd. using an Agilent 7700e ICP-MS instrument. The detailed sample digestion procedure was as follows: (1) the sample powder (200 mesh) was dried in an oven at 105 °C for 12 h; (2) 0.05 g sample powder was accurately weighed and placed in a Teflon bomb; (3) 1 mL HNO_3 and 1 mL HF were slowly added into the Teflon bomb; (4) the Teflon bomb was put in a stainless steel pressure jacket and heated at 190 °C in an oven for >24 h; (5) after cooling, the Teflon bomb was opened and placed on a hot plate at 140 °C to dry the sample. The 1 mL HNO_3 was added to the sample, which was dried again; (6) 1 mL HNO_3 , 1 mL MQ water, and internal standard solution (1 ppm) were added to the sample and the Teflon bomb was resealed and placed in the oven at 190 °C for >12 h; (7) the final solution was transferred to a polyethylene bottle and diluted to 100 g by adding HNO_3 (2%).

Whole-rock Sr and Nd isotope measurements were carried out at the Isotope Laboratory of Wuhan Geological Survey Center, China Geological Survey. The Sr and Nd isotopic compositions were analyzed by thermoelectric ionization mass spectrometer using a Triton instrument. Sr and Nd single element solution from Alfa (Alfa Aesar, Karlsruhe, Germany) was used to optimize the instrument operating parameters. An aliquot of the international standard solution of $200\text{ }\mu\text{g}\cdot\text{L}^{-1}$ NIST SRM 987 and $200\text{ }\mu\text{g}\cdot\text{L}^{-1}$ JNdi-1 were regularly used for evaluating the reproducibility and accuracy of the instrument, respectively. Typically, the signal intensities of ^{88}Sr in NIST SRM 987 were > approximately 4.0 V, and the signal intensities of $^{144}\text{Nd}^+$ in JNdi-1 were > approximately 2.5 V. The rare earth element (REE) solution from the Sr column was evaporated to incipient dryness and taken up with 0.18 M HCl. The converted REE solution was loaded into an ion-exchange column packed with LN resin. After the completion of draining the sample solution, the columns were rinsed with 0.18 M HCl to remove undesirable matrix elements. Then, the Nd fraction was eluted using 0.3 M HCl and gently evaporated to dryness prior to mass-spectrometric measurement. The Sr and Nd isotopic data were acquired in a static mode at low resolution. The routine data acquisition consisted of ten blocks of 10 cycles (4.194 s integration time per cycle). The mass fractionation corrections for Sr and Nd isotopic ratios were normalized to

$^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. The detailed analytical procedures can be found in [37,38].

Zircon grains were extracted from four rock samples (two Zengudi and two Tuobake granite porphyries), using electromagnetic selection and flotation at the Langfang Diyan Mineral Separation Company (Hebei, China). About 500 zircon grains were selected from each sample, then handpicked under a binocular microscope, mounted in epoxy resin, and finally polished to expose the grain core. Cathodoluminescence (CL) images of zircon grains were obtained at the Wuhan Sample Solution Analytical Technology Co., Ltd., using a scanning electron microscope coupled with an energy dispersive spectroscopy (EDS) system and a CL^{3+} detector under operating conditions of 15 kV and 4 nA. These CL images were examined for selecting zircon grains without cracks and inclusions, which were further analyzed in the same laboratory by laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS). Zircon U–Pb dating and trace element analyses were performed using a 193 nm ArF excimer (COMPexPro) with laser power of 8 J/cm² coupled with an Agilent 7700e ICPMS instrument. The spot size and frequency of the laser were set as 32 μm and 5 Hz, respectively. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction can be found in [39–41]. Zircon 91500 and GJ-1 were used as external standards for U–Pb dating and trace element calibration, respectively. Concordia diagrams and weighted mean calculations were performed with Isoplot/Ex_ver3 (Isoplot4 by Kenneth R. Ludwig of American).

Subsequently, in situ Hf isotope measurements were performed on the same zircon grain or spot that was previously analyzed for U–Pb dating at the Wuhan Sample Solution Analytical Technology Co., Ltd., Hubei, China. Zircon Lu–Hf isotope analyses were conducted using a Neptune Plus MC-ICP-MS in combination with a Geolas HD excimer laser ablation system. Detailed operating conditions for the laser ablation system and the MC-ICP-MS instrument and analytical method are the same as described by Hu et al. 2012 [42]. All analyzed spots used a beam diameter of 44 μm and pulse frequency of 8 Hz with the GJ-1 zircon standard. The $^{179}\text{Hf}/^{177}\text{Hf}$ and $^{173}\text{Yb}/^{171}\text{Yb}$ ratios were used to calculate the mass bias of Hf (β_{Hf}) and Yb (β_{Yb}), which were normalized to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ and $^{173}\text{Yb}/^{171}\text{Yb} = 1.132685$ [43] using an exponential correction for mass bias. Interference of ^{176}Yb on ^{176}Hf was corrected by measuring the interference-free ^{173}Yb isotope and using $^{176}\text{Yb}/^{173}\text{Yb} = 0.79639$ [43] to calculate $^{176}\text{Yb}/^{177}\text{Hf}$. Similarly, the relatively minor interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of the interference-free ^{175}Lu isotope and using the recommended $^{176}\text{Lu}/^{175}\text{Lu} = 0.02656$ [44] to calculate $^{176}\text{Lu}/^{177}\text{Hf}$.

4. Results

4.1. Whole Rock Major and Trace Element Compositions

The whole rock major and trace element analytical results are shown in Table 1.

Table 1. Major (wt.%) and trace element (ppm) compositions of the Zengudi and Tuobake granite porphyries. LREE, light rare earth element; HREE, heavy rare earth element; A/CNK, $n\text{Al}_2\text{O}_3/(\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{K}_2\text{O})$.

Sample	Zengudi Granite Porphyry					Tuobake Granite Porphyry				
	SC-H1	SC-H2	SC-H3	SC-H4	SC-H5	YZ-H1	YZ-H2	YZ-H3	YZ-H4	YZ-H5
SiO ₂	87.61	80.32	81.96	68.04	69.68	71.07	72.97	77.75	72.42	73.84
TiO ₂	0.264	0.230	0.299	0.771	0.727	0.545	0.493	0.333	0.486	0.417
Al ₂ O ₃	5.55	9.25	9.12	13.18	13.33	13.98	13.09	9.21	12.80	11.38
Fe ₂ O ₃	1.38	2.18	2.18	4.51	5.16	2.67	2.99	2.24	3.62	3.72
MnO	0.072	0.031	0.022	0.063	0.057	0.042	0.035	0.064	0.035	0.050
MgO	0.42	0.97	0.91	1.54	2.10	0.68	0.68	0.38	0.74	0.70
CaO	0.71	1.02	0.22	2.15	0.72	1.71	1.54	2.66	1.57	2.06
Na ₂ O	0.06	1.86	2.76	2.38	3.95	1.89	1.91	2.76	1.71	1.72

Table 1. Cont.

Sample	Zengudi Granite Porphyry					Tuobake Granite Porphyry				
	SC-H1	SC-H2	SC-H3	SC-H4	SC-H5	YZ-H1	YZ-H2	YZ-H3	YZ-H4	YZ-H5
K ₂ O	1.48	1.97	1.60	4.11	2.52	4.16	3.62	1.63	3.48	2.96
P ₂ O ₅	0.043	0.069	0.076	0.157	0.160	0.171	0.156	0.106	0.143	0.115
LOI	2.39	2.03	1.13	3.17	1.95	3.01	2.84	2.99	2.91	3.13
Total	99.96	99.95	100.27	100.07	100.35	99.94	100.32	100.12	99.91	100.10
Li	55.0	9.22	7.10	11.6	16.6	14.8	13.9	8.35	14.3	13.0
Be	0.92	1.32	1.09	1.35	2.46	3.37	3.20	1.57	3.15	2.49
Sc	3.64	4.36	5.19	10.9	11.8	8.13	7.30	4.71	7.92	6.59
V	31.7	27.5	29.9	52.1	56.8	29.6	29.0	17.6	28.9	25.5
Cr	13.3	20.4	21.9	33.7	31.4	16.6	14.6	10.8	14.7	12.7
Co	1.94	3.61	4.35	4.76	9.19	3.62	4.19	4.33	5.16	6.09
Ni	4.94	9.09	9.14	15.0	15.7	5.71	6.56	7.14	7.75	7.70
Cu	2.64	3.12	1.09	2.92	12.0	5.61	12.4	2.60	16.6	12.5
Zn	7.66	22.4	21.6	41.5	46.7	31.9	36.4	26.1	43.9	73.7
Ga	7.80	11.0	10.6	16.5	18.4	19.7	19.0	9.61	19.0	16.9
Rb	80.7	98.0	66.0	169	74.0	248	224	96.2	219	183
Sr	37.4	41.3	40.6	76.8	63.3	81.5	69.9	65.4	67.1	68.2
Y	13.7	16.2	20.5	34.3	40.0	51.5	48.5	35.9	44.4	43.1
Zr	138	121	151	300	291	289	276	181	254	235
Nb	6.67	6.39	7.77	15.6	14.6	15.0	13.7	9.57	13.2	11.7
Sn	2.67	2.44	2.18	4.75	4.53	6.33	5.94	3.89	5.49	4.94
Cs	6.76	2.85	2.65	1.53	1.59	9.39	9.01	2.91	8.78	7.83
Ba	157	276	318	765	515	785	594	240	582	546
La	21.1	15.0	37.3	20.5	43.5	51.9	49.8	32.2	46.1	40.7
Ce	39.8	28.7	67.5	42.2	85.9	104	100	64.9	91.3	82.0
Pr	4.54	3.20	6.98	4.93	9.60	11.6	11.2	7.25	10.1	9.11
Nd	15.9	11.9	24.0	19.5	36.0	43.7	41.5	27.9	38.1	34.2
Sm	3.02	2.45	4.21	4.68	7.61	9.56	9.23	6.02	8.52	7.25
Eu	0.34	0.45	0.72	0.52	1.06	1.33	1.03	0.89	1.06	0.90
Gd	2.23	2.15	3.06	4.55	6.41	8.23	7.58	5.50	7.26	6.77
Tb	0.35	0.44	0.54	0.84	1.13	1.43	1.33	0.95	1.26	1.21
Dy	2.39	2.55	3.41	5.38	6.93	8.65	8.36	5.79	7.59	7.26
Ho	0.46	0.56	0.66	1.15	1.38	1.73	1.65	1.15	1.53	1.43
Er	1.38	1.51	1.87	3.41	3.83	4.90	4.56	3.35	4.35	4.01
Tm	0.23	0.23	0.30	0.54	0.59	0.71	0.71	0.50	0.63	0.62
Yb	1.41	1.41	1.68	3.31	3.42	4.37	4.09	2.80	3.76	3.65
Lu	0.21	0.23	0.26	0.47	0.54	0.70	0.60	0.45	0.61	0.56
Hf	3.61	3.13	4.00	7.82	7.66	7.71	7.24	4.70	6.60	6.29
Ta	0.54	0.56	0.58	1.16	1.10	1.13	1.02	0.76	1.01	0.91
Tl	0.64	0.46	0.35	0.89	0.41	1.28	1.11	0.54	1.10	0.94
Pb	41.0	1.82	2.05	9.12	2.11	15.0	29.3	16.9	33.5	27.8
Th	11.7	12.3	16.9	24.8	23.6	29.0	26.4	19.0	25.6	23.1
U	2.90	3.10	3.30	4.99	5.20	6.74	5.87	4.30	5.95	5.24
ΣREE	93.4	70.8	152	112	208	252	242	160	222	200
LREE	84.8	61.7	141	92.4	184	222	213	139	195	174
HREE	8.65	9.07	11.78	19.65	24.23	30.72	28.88	20.50	26.99	25.51
LREE/HREE	9.80	6.80	11.94	4.70	7.58	7.22	7.37	6.79	7.24	6.83
La _N /Yb _N	10.7	7.62	15.95	4.45	9.12	8.53	8.74	8.24	8.81	8.00
Eu/Eu*	0.40	0.59	0.61	0.35	0.47	0.46	0.38	0.47	0.41	0.39
Ce/Ce*	1.00	1.02	1.03	1.03	1.03	1.03	1.04	1.04	1.04	1.04
Na ₂ O + K ₂ O	1.54	3.83	4.36	6.49	6.47	6.06	4.39	5.19	4.68	5.53
K ₂ O/Na ₂ O	25.05	1.06	0.58	1.73	0.64	2.20	1.89	0.59	2.04	1.72
A/CNK	1.86	1.31	1.37	1.07	1.27	1.30	1.33	0.83	1.36	1.16
Y/Yb	9.66	11.46	12.21	10.37	11.71	11.78	11.86	12.83	11.82	11.79
(Ho/Yb) _N	10.69	7.62	15.95	4.45	9.12	8.53	8.74	8.24	8.81	8.00

The Zengudi granite porphyry samples have high contents of SiO₂ (68.04–87.61%), Al₂O₃ (5.55–18.33%), Na₂O (0.06–3.95%), K₂O (1.48–4.11%), and Na₂O + K₂O (1.54–6.49%)

(Figure 3a). The K_2O/Na_2O ratios vary between 0.58 and 25.05. Except for sample SC-H1, most of the Zengudi granites plot in the peraluminous field ($A/CNK = 1.07$ – 1.86 ; Figure 3b). In addition, these granitic rocks contain low contents of P_2O_5 (0.043–0.16%), CaO (0.71–2.15%), TiO_2 (0.23–0.77%) and $Fe_2O_3^T$ (1.38–5.16%). The Zengudi granite porphyries are medium-to-high K and calc-alkaline rocks (Figure 3c,d). The CIPW standard mineral calculation shows that the contents of corundum range between 1.20 and 3.18, and high differentiation index (DI) from 78.74 to 90.99. The total rare earth element contents (ΣREE) of the granite porphyry samples vary from 70.75 to 207.93 ppm, with high LREE/HREE ratios of 4.70–11.94. The La_N/Yb_N ratios range between 4.45 and 15.95. These granitic rocks show a negative Eu anomaly with Eu/Eu^* ratios ranging from 0.35 to 0.61.

Figure 3. Geochemical classification diagrams of the Zengudi and Tuobake granite porphyries. (a) SiO_2 versus $(K_2O + Na_2O)$ [45], (b) A/CNK versus A/NK [46,47], (c) SiO_2 versus K_2O [48], and (d) SiO_2 versus AR [49].

The Tuobake granite porphyry samples have high concentrations of SiO_2 (71.07–77.75%), Al_2O_3 (9.21–13.98%) and $Na_2O + K_2O$ (4.39–6.06%), and low contents of $Fe_2O_3^T$ (2.24–3.72%) and P_2O_5 (0.106–0.171%). In the SiO_2 versus $(K_2O + Na_2O)$ diagram (Figure 3a), all samples plot in the granite field. Except for sample YZ-H3, most of the Tuobake granites plot in the peraluminous field ($A/CNK = 0.83$ – 1.36 , average = 1.20) (Figure 3b). In the SiO_2 vs. K_2O diagram (Figure 3c), these granite samples plot in the field of low-to-high K calc-alkaline series, whereas they mostly cluster within the field of calc-alkaline series in the diagram of

SiO_2 versus $\text{AR}((\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})/(\text{Al}_2\text{O}_3 + \text{CaO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})))$ (Figure 3d). In both diagrams (Figure 3a,b), the Tuobake granites exhibit high silica and aluminum contents. According to the CIPW standard mineral calculation, the contents of corundum vary between 1.88 and 3.79. The ΣREE contents of these granite porphyry samples range from 159.62 to 241.79 ppm, with high LREE/HREE ratios of 6.79–7.37. These granitic rocks display $\text{La}_\text{N}/\text{Yb}_\text{N}$ ratios ranging from 8.00 to 8.81, and negative Eu anomaly with Eu/Eu^* ratios of 0.38–0.47.

The chondrite-normalized REE patterns of the Zengudi and Tuobake granite porphyries show LREE enrichment and obvious negative Eu anomalies (Figure 4a). The primitive mantle-normalized trace element spider diagram shows that these rocks are significantly depleted in Sr, Ba and high field strength elements (HFSE such as Ta, Nb, and Ti), but enriched in large ion lithophile elements (LILE such as Rb, U, K, and Th) (Figure 4b).

Figure 4. (a) Chondrite-normalized REE patterns and (b) primitive mantle-normalized trace element spider diagram of the Zengudi and Tuobake granite porphyries. The normalized values are from [50].

4.2. Whole Rock Sr–Nd Isotopes

The whole rock Sr–Nd isotopic data of the studied granite porphyries is presented in Table 2. All the Zengudi granite porphyry samples have low contents of Rb (80–110 ppm) and Sr (68–92 ppm), but high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.708462–0.715748, average = 0.7115980). The initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios range between 0.511574 and 0.511837 (average = 0.511742) and the $\epsilon_{\text{Nd}}(t)$ values are low (−14.49 to −9.35, average = −11.21). The calculated Nd model ages ($T_{\text{DM}2}$) of the Zengudi granite porphyries vary from 1.78 to 2.46 Ga.

The Tuobake granite porphyry samples have relatively high contents of Rb (190–240 ppm) but low contents of Sr (66–83 ppm). These granite porphyry samples display relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7160803–0.7309865, average = 0.720591), low initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (0.511763–0.511839, average = 0.511785) and low $\epsilon_{\text{Nd}}(t)$ values (−10.9 to −9.41, average = −10.47). The calculated Nd model ages ($T_{\text{DM}2}$) of the Tuobake granite porphyries range from 1.79 to 1.90 Ga.

Table 2. Whole rock Sr–Nd isotopic compositions of the Zengudi and Tuobake granite porphyries.

Sample No.	Location	Age (Ma)	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	$\epsilon_{\text{Nd}}(t)$	$T_{\text{DM}}(\text{Ma})$
SC-Y1	Zengudi	254	170.0	75.0	3.02	15.9	0.723590	0.00005	0.7024524	0.51201	0.00002	0.511822	−9.65	1980
SC-Y2	Zengudi	254	157.0	56.0	4.21	11.9	0.728050	0.00003	0.7033351	0.51196	0.00006	0.511609	−13.8	2050
SC-Y3	Zengudi	254	98.0	47.0	4.68	24.0	0.722480	0.00003	0.7040523	0.511928	0.00004	0.511735	−11.34	1944
SC-Y4	Zengudi	254	135.0	61.0	7.61	19.5	0.721900	0.00003	0.7092388	0.511932	0.00005	0.511547	−15.01	2313
YZ-Y1	Tuobake	246	240.0	83.0	9.23	43.7	0.745380	0.00005	0.7160803	0.511976	0.00005	0.51177	−10.76	1892
YZ-Y2	Tuobake	246	223.0	71.0	6.02	41.5	0.748340	0.00002	0.7165142	0.51198	0.00002	0.511839	−9.41	1787
YZ-Y3	Tuobake	246	215.0	66.0	8.52	38.1	0.751790	0.00002	0.7187814	0.51198	0.00003	0.511763	−10.9	1903
YZ-Y4	Tuobake	246	190.0	70.0	7.25	34.2	0.758490	0.00003	0.7309865	0.511974	0.00003	0.511768	−10.8	1896

4.3. Zircon CL Images

Zircon CL images are presented in Figure 5. All the zircons from the Zengudi (samples SC1801 and SC1802) and Tuobake (samples YZ1803 and YZ1804) granite porphyries show similar morphology. They mostly show euhedral prismatic grains with a length of 80–120 μm and length-to-width ratios between 1:1 and 3:1. All the zircon grains display clear oscillatory zoning, suggesting a magmatic origin [51–54].

Figure 5. Zircon CL images of representative zircon grains for (a,b) the Zengudi granite porphyry and (c,d) the Tuobake granite porphyry. The orange and white circles are the sites for in situ U–Pb isotope dating and Hf isotope analyses, respectively.

4.4. Zircon U–Pb Ages

The zircon U–Pb dating results for the four granite porphyry samples are shown in Table 3. Zircons from the Zengudi granite porphyries (samples SC1801 and SC1802) have Th/U ratios = 0.12–0.52 (average = 0.35), which are comparable to those of typical magmatic zircons [55]. The $^{206}\text{Pb}/^{238}\text{U}$ ages of twenty-four zircon grains from sample SC1801 range between 243.9 Ma and 261.7 Ma, giving a weighted mean age of 253.8 ± 2.2 Ma (MSWD = 4.4) (Figure 6a). One zircon from this sample has a $^{206}\text{Pb}/^{238}\text{U}$ age of 462.8 Ma (Table 1), which is regarded as the age of inherited zircon grain. Twenty-five zircon grains from sample SC1802 yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 242.9 to 259.0 Ma, with a weighted mean age of 246.6 ± 0.54 Ma (MSWD = 5.3) (Figure 6b). Overall, the crystallization age of the Zengudi granite porphyries is estimated at 254–247 Ma.

Figure 6. Concordia diagrams for the zircon U–Pb dating data of (a,b) the Zengudi granite porphyry and (c,d) the Tuobake granite porphyry.

Zircons from the Tuobake granite porphyries (samples YZ1803 and YZ1804) have relatively high Th/U ratios = 0.15–0.69 (average = 0.48), which are similar to those of typical magmatic zircons [53]. The $^{206}\text{Pb}/^{238}\text{U}$ ages of twenty-five zircon grains from sample YZ1803 vary between 236.4 and 263.2 Ma, with a weighted mean age of 245.9 ± 2.6 Ma (MSWD = 3.3) (Figure 6c). One zircon from this sample yields a $^{206}\text{Pb}/^{238}\text{U}$ age of 430.8 Ma (Table 1), which is considered as the age of inherited zircon grain. For the sample YZ1804, twenty-three zircon grains yield a $^{206}\text{Pb}/^{238}\text{U}$ age varying from 241.1 to 257.8 Ma, with a weighted mean age of 245.8 ± 1.8 Ma (MSWD = 2.1) (Figure 6d). Consequently, the crystallization age of the Tuobake granite porphyries is estimated at 246 Ma, similar to that of the Zengudi granite porphyries.

Table 3. LA-ICPMS zircon U–Pb analytical results of the Zengudi and Tuobake granite porphyries.

Spot No.	Contents (ppm)			Th/U	Isotope Ratios						Age (Ma)					
	Pb	Th	U		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	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ
SC1801, Zengudi Granite Porphyry																
SC1801-01	11.43	78.0	130	0.60	0.6340	0.0316	0.0744	0.0010	0.0625	0.0033	499	19.7	462.8	6.2	692	312
SC1801-02	31.22	289	680	0.42	0.3032	0.0094	0.0410	0.0004	0.0534	0.0015	269	7.3	259.1	2.6	346	64.8
SC1801-03	27.95	140	648	0.22	0.3030	0.0093	0.0405	0.0003	0.0541	0.0017	269	7.3	256.2	2.0	376	68.5
SC1801-04	10.05	91.7	224	0.41	0.2850	0.0138	0.0399	0.0005	0.0524	0.0026	255	10.9	252.1	3.4	302	111
SC1801-05	11.39	90.2	253	0.36	0.2990	0.0136	0.0411	0.0005	0.0532	0.0025	266	10.6	259.5	3.2	345	103
SC1801-06	34.89	221	778	0.28	0.3027	0.0077	0.0414	0.0004	0.0529	0.0014	269	6.0	261.7	2.5	324	62.0
SC1801-07	14.13	146	309	0.47	0.2982	0.0125	0.0403	0.0005	0.0536	0.0022	265	9.8	254.6	3.0	354	99.1
SC1801-08	21.87	246	479	0.51	0.2772	0.0092	0.0393	0.0004	0.0512	0.0018	248	7.3	248.6	2.6	256	77.8
SC1801-09	19.20	205	417	0.49	0.2949	0.0115	0.0401	0.0004	0.0537	0.0022	262	9.0	253.4	2.5	367	94.4
SC1801-10	22.06	132	517	0.26	0.2878	0.0098	0.0394	0.0004	0.0529	0.0018	257	7.8	249.3	2.4	324	77.8
SC1801-11	36.46	273	824	0.33	0.2890	0.0091	0.0406	0.0004	0.0516	0.0016	258	7.2	256.4	2.2	333	72.2
SC1801-12	19.66	212	431	0.49	0.2855	0.0108	0.0397	0.0004	0.0520	0.0020	255	8.5	250.7	2.6	287	87.0
SC1801-13	18.39	210	407	0.52	0.2795	0.0106	0.0390	0.0004	0.0520	0.0020	250	8.4	246.7	2.6	283	87.0
SC1801-14	104.4	795	2261	0.35	0.2971	0.0065	0.0419	0.0003	0.0512	0.0011	264	5.1	264.6	2.0	250	51.8
SC1801-15	10.76	120	244	0.49	0.2746	0.0124	0.0386	0.0005	0.0518	0.0023	246	9.8	243.9	3.2	276	104
SC1801-16	14.43	113	331	0.34	0.2824	0.0108	0.0397	0.0004	0.0517	0.0020	253	8.5	250.7	2.4	272	86.1
SC1801-17	40.23	310	881	0.35	0.2960	0.0082	0.0413	0.0005	0.0519	0.0015	263	6.4	261.2	3.1	280	64.8
SC1801-18	19.88	276	423	0.65	0.2803	0.0106	0.0393	0.0004	0.0516	0.0020	251	8.4	248.7	2.7	333	88.9
SC1801-19	26.98	252	594	0.42	0.2731	0.0088	0.0404	0.0004	0.0488	0.0016	245	7.0	255.0	2.3	139	77.8
SC1801-20	26.82	224	593	0.38	0.2930	0.0087	0.0403	0.0004	0.0526	0.0016	261	6.9	254.6	2.4	322	70.4
SC1801-21	25.10	164	580	0.28	0.2781	0.0094	0.0396	0.0004	0.0508	0.0018	249	7.5	250.6	2.4	232	88.0
SC1801-22	26.18	212	595	0.36	0.2772	0.0087	0.0392	0.0004	0.0514	0.0017	248	7.0	247.8	2.5	257	77.8
SC1801-23	20.08	204	445	0.46	0.2719	0.0101	0.0392	0.0004	0.0503	0.0020	244	8.0	248.0	2.5	209	90.7
SC1801-24	32.77	209	728	0.29	0.2882	0.0088	0.0404	0.0004	0.0516	0.0017	257	7.0	255.3	2.4	333	74.1
SC1801-25	7.89	66.1	173	0.38	0.2805	0.0154	0.0400	0.0005	0.0514	0.0031	251	12.2	252.9	3.4	257	132
SC1802, Zengudi Granite Porphyry																
SC1802-01	12.22	73.4	287	0.26	0.2743	0.0115	0.0384	0.0005	0.0515	0.0021	246	9.2	243.0	3.0	265	99.1
SC1802-02	14.15	141	315	0.45	0.2819	0.0111	0.0391	0.0004	0.0522	0.0021	252	8.8	247.4	2.6	295	94.4
SC1802-03	11.95	73.5	285	0.26	0.2763	0.0134	0.0384	0.0005	0.0522	0.0026	248	10.7	242.7	2.8	295	108
SC1802-04	13.42	82.5	317	0.26	0.2648	0.0117	0.0388	0.0004	0.0494	0.0022	239	9.4	245.5	2.5	165	138
SC1802-05	20.88	151	492	0.31	0.2650	0.0099	0.0387	0.0004	0.0493	0.0018	239	8.0	244.9	2.6	161	91.7
SC1802-06	21.53	147	497	0.30	0.2855	0.0102	0.0393	0.0004	0.0527	0.0020	255	8.0	248.6	2.5	317	85.2

Table 3. Cont.

Spot No.	Contents (ppm)			Th/U	Isotope Ratios						Age (Ma)					
	Pb	Th	U		$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ
SC1802-07	17.47	117	411	0.28	0.2850	0.0108	0.0389	0.0004	0.0530	0.0021	255	8.6	246.2	2.7	332	88.9
SC1802-08	20.30	129	481	0.27	0.2732	0.0102	0.0388	0.0004	0.0509	0.0019	245	8.1	245.1	2.6	239	88.9
SC1802-09	25.03	159	598	0.27	0.2695	0.0083	0.0385	0.0003	0.0505	0.0016	242	6.7	243.7	2.1	220	78.7
SC1802-10	12.19	73.6	281	0.26	0.2886	0.0125	0.0397	0.0004	0.0526	0.0024	257	9.9	251.0	2.7	309	99
SC1802-11	13.99	91.2	336	0.27	0.2694	0.0100	0.0385	0.0005	0.0505	0.0019	242	8.0	243.6	2.9	220	87.0
SC1802-12	23.82	66.8	572	0.12	0.2935	0.0089	0.0398	0.0004	0.0532	0.0017	261	7.0	251.4	2.5	345	72.2
SC1802-13	19.11	153	416	0.37	0.2883	0.0102	0.0410	0.0005	0.0508	0.0019	257	8.1	259.0	3.0	235	85.2
SC1802-14	21.89	156	513	0.30	0.2629	0.0084	0.0384	0.0004	0.0494	0.0016	237	6.8	242.9	2.3	165	77.8
SC1802-16	13.88	91.7	328	0.28	0.2736	0.0109	0.0386	0.0004	0.0513	0.0021	246	8.7	244.1	2.6	254	88.0
SC1802-17	20.70	138	485	0.28	0.2778	0.0106	0.0391	0.0004	0.0512	0.0019	249	8.5	247.3	2.5	250	91.7
SC1802-18	23.04	169	534	0.32	0.2736	0.0100	0.0390	0.0004	0.0509	0.0019	246	7.9	246.8	2.4	235	87.0
SC1802-19	15.49	121	361	0.33	0.2728	0.0109	0.0386	0.0004	0.0516	0.0022	245	8.7	244.1	2.8	265	101
SC1802-20	13.39	89.5	314	0.28	0.2872	0.0125	0.0390	0.0004	0.0535	0.0024	256	9.8	246.9	2.7	350	100.0
SC1802-21	13.26	98.0	311	0.32	0.2885	0.0120	0.0385	0.0005	0.0546	0.0023	257	9.4	243.6	2.8	394	94.4
SC1802-22	13.22	74.7	310	0.24	0.2844	0.0131	0.0394	0.0004	0.0525	0.0025	254	10.4	249.0	2.7	309	107
SC1802-23	10.98	83.8	253	0.33	0.2782	0.0118	0.0392	0.0004	0.0519	0.0024	249	9.4	247.8	2.6	280	106
SC1802-24	20.32	152	474	0.32	0.2680	0.0100	0.0390	0.0004	0.0500	0.0019	241	8.0	246.6	2.6	195	90.7
SC1802-25	12.65	65.5	301	0.22	0.2812	0.0124	0.0394	0.0005	0.0522	0.0024	252	9.8	249.2	2.9	300	104
SC1802-26	17.47	113	411	0.27	0.2642	0.0102	0.0391	0.0004	0.0490	0.0019	238	8.2	247.0	2.4	146	90.7
YZ1803, Tuobake Granite Porphyry																
YZ1803-01	10.99	93.9	229	0.41	0.3016	0.0144	0.0417	0.0007	0.0533	0.0029	268	11.2	263.2	4.4	339	122
YZ1803-02	11.91	131	268	0.49	0.2637	0.0122	0.0374	0.0005	0.0514	0.0025	238	9.8	236.4	3.1	261	113
YZ1803-03	10.48	128	227	0.57	0.2698	0.0119	0.0384	0.0005	0.0511	0.0023	243	9.5	242.8	3.2	256	73.1
YZ1803-04	7.84	95.6	172	0.56	0.2695	0.0150	0.0384	0.0006	0.0507	0.0029	242	12.0	242.9	3.5	233	133
YZ1803-05	10.73	120	236	0.51	0.2753	0.0128	0.0393	0.0005	0.0508	0.0024	247	10.2	248.4	3.2	232	114
YZ1803-06	6.58	76.0	138	0.55	0.2764	0.0174	0.0403	0.0007	0.0502	0.0032	248	13.8	254.5	4.0	211	145
YZ1803-07	13.56	141	299	0.47	0.2854	0.0124	0.0395	0.0004	0.0523	0.0023	255	9.8	249.5	2.6	298	102
YZ1803-08	6.32	72.9	137	0.53	0.2670	0.0164	0.0394	0.0006	0.0497	0.0033	240	13.2	249.3	3.7	189	154
YZ1803-11	8.41	116	178	0.65	0.2842	0.0149	0.0390	0.0005	0.0527	0.0028	254	11.8	246.6	3.2	317	122
YZ1803-12	13.55	113	312	0.36	0.2766	0.0112	0.0383	0.0004	0.0521	0.0021	248	8.9	242.2	2.8	300	95.4
YZ1803-13	6.76	97.4	147	0.66	0.2703	0.0150	0.0378	0.0006	0.0527	0.0032	243	12.0	239.1	4.0	317	139
YZ1803-15	13.39	157	284	0.55	0.2858	0.0127	0.0397	0.0005	0.0523	0.0025	255	10.0	251.2	2.9	298	109
YZ1803-16	7.69	64.9	174	0.37	0.2668	0.0152	0.0385	0.0005	0.0502	0.0028	240	12.2	243.3	3.4	206	128
YZ1803-18	19.47	286	414	0.69	0.2654	0.0096	0.0380	0.0004	0.0505	0.0019	239	7.7	240.7	2.4	217	87.0

Table 3. Cont.

Spot No.	Contents (ppm)			Th/U	Isotope Ratios						Age (Ma)					
	Pb	Th	U		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	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ
YZ1803-19	11.27	108	252	0.43	0.2736	0.0154	0.0383	0.0004	0.0517	0.0029	246	12.3	242.5	2.8	272	125.9
YZ1803-20	11.11	130	239	0.54	0.2887	0.0127	0.0388	0.0005	0.0544	0.0025	258	10.0	245.1	2.8	387	103.7
YZ1803-21	13.67	180	297	0.61	0.2592	0.0122	0.0384	0.0004	0.0490	0.0023	234	9.8	242.6	2.7	146	111
YZ1803-22	11.12	120	249	0.48	0.2685	0.0109	0.0385	0.0004	0.0506	0.0021	242	8.7	243.5	2.7	220	101
YZ1803-23	35.6	219	446	0.49	0.5387	0.0198	0.0691	0.0014	0.0558	0.0016	438	13.0	430.8	8.5	443	58.3
YZ1803-24	7.63	61.6	171	0.36	0.2810	0.0164	0.0399	0.0006	0.0517	0.0032	251	13.0	252.3	3.6	272	141
YZ1803-25	7.63	69.3	167	0.41	0.2839	0.0165	0.0401	0.0006	0.0513	0.0029	254	13.1	253.4	3.6	254	136
YZ1803-26	8.80	94.0	191	0.49	0.2779	0.0150	0.0403	0.0006	0.0497	0.0027	249	11.9	254.7	3.4	183	124
YZ1804, Tuobake Granite Porphyry																
YZ1804-01	8.41	91.7	186	0.49	0.2848	0.0172	0.0389	0.0005	0.0534	0.0033	254	13.6	246.0	2.9	346	139
YZ1804-02	11.85	140	256	0.55	0.2915	0.0111	0.0395	0.0004	0.0535	0.0021	260	8.7	250.0	2.6	350	90.7
YZ1804-03	10.27	112	231	0.49	0.2798	0.0133	0.0382	0.0004	0.0531	0.0026	251	10.6	241.9	2.7	345	111
YZ1804-04	7.46	68.3	169	0.40	0.2644	0.0140	0.0390	0.0005	0.0496	0.0027	238	11.3	246.5	3.2	176	130
YZ1804-05	9.28	102	202	0.50	0.2907	0.0161	0.0394	0.0005	0.0540	0.0032	259	12.7	249.0	3.2	372	131
YZ1804-06	8.51	86.8	190	0.46	0.2718	0.0156	0.0386	0.0006	0.0515	0.0031	244	12.5	244.3	3.4	261	139
YZ1804-07	6.68	77.4	153	0.51	0.2687	0.0133	0.0384	0.0005	0.0514	0.0027	242	10.7	243.1	3.2	261	88
YZ1804-08	-	74.0	663	0.11	2.4732	0.0465	0.2056	0.0018	0.0866	0.0016	-	13.6	1205	9.7	1351	35.2
YZ1804-09	8.01	85.1	178	0.48	0.2639	0.0130	0.0384	0.0005	0.0497	0.0025	238	10.4	242.8	3.1	189	119
YZ1804-10	26.77	96.5	662	0.15	0.2717	0.0093	0.0381	0.0004	0.0515	0.0019	244	7.5	241.1	2.3	265	78.7
YZ1804-11	8.49	88.8	190	0.47	0.2786	0.0138	0.0384	0.0005	0.0536	0.0029	250	11.0	242.6	3.2	354	122
YZ1804-12	17.75	228	376	0.61	0.2891	0.0101	0.0391	0.0004	0.0536	0.0020	258	8.0	247.4	2.5	354	50.9
YZ1804-13	13.98	178	302	0.59	0.2776	0.0102	0.0386	0.0004	0.0527	0.0021	249	8.1	244.0	2.6	317	123.1
YZ1804-14	18.24	103	421	0.24	0.2889	0.0111	0.0394	0.0004	0.0533	0.0021	258	8.7	248.8	2.6	343	88.9
YZ1804-15	16.51	110	382	0.29	0.2719	0.0102	0.0387	0.0004	0.0509	0.0019	244	8.1	244.5	2.3	235	87.0
YZ1804-16	9.75	106	215	0.49	0.2731	0.0123	0.0385	0.0005	0.0513	0.0023	245	9.8	243.4	3.1	254	104
YZ1804-17	10.08	110	219	0.50	0.2929	0.0131	0.0394	0.0005	0.0547	0.0026	261	10.3	248.9	3.2	467	103
YZ1804-18	9.37	96.4	212	0.45	0.2823	0.0128	0.0380	0.0005	0.0542	0.0025	253	10.1	240.2	3.0	389	105.5
YZ1804-19	13.79	94.4	319	0.30	0.2735	0.0101	0.0389	0.0008	0.0521	0.0021	245	8.0	246.0	5.3	287	97.2
YZ1804-20	8.73	81.9	194	0.42	0.2801	0.0124	0.0392	0.0005	0.0520	0.0023	251	9.9	248.0	3.0	283	97.2
YZ1804-21	27.76	215	468	0.46	0.4023	0.0142	0.0520	0.0009	0.0553	0.0016	343	10.3	326.7	5.5	433	60.2
YZ1804-22	9.65	83.0	223	0.37	0.2887	0.0147	0.0389	0.0005	0.0540	0.0028	258	11.6	245.8	2.8	369	116.7
YZ1804-23	43.8	517	921	0.56	0.2851	0.0081	0.0408	0.0004	0.0506	0.0015	255	6.4	257.8	2.4	220	66.7
YZ1804-24	8.23	79.4	186	0.43	0.2971	0.0133	0.0386	0.0005	0.0563	0.0027	264	10.4	244.0	3.4	465	101
YZ1804-25	9.04	107	203	0.53	0.2644	0.0160	0.0385	0.0005	0.0496	0.0029	238	12.9	243.6	3.0	176	133

4.5. Zircon Hf Isotopic Compositions

Zircon Lu–Hf isotopic data of the above four granite samples are shown in Table 4. A total of thirty-one zircons from the Zengudi granite porphyries and thirty-one zircons from the Tuobake granite porphyries were analyzed for $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic ratios. The $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of all the analyzed zircons are less than 0.002, indicating that there is no radiogenic Hf accumulation after zircon formation [56]. Thus, the results of $^{176}\text{Hf}/^{177}\text{Hf}$ ratios can represent the Hf isotopic composition of the magmatic system.

Zircons of the Zengudi granite porphyries show variable Hf isotopic compositions with $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282256–0.282543. The calculated $\varepsilon_{\text{Hf}}(t)$ values range between -12.94 and -2.63 , which correspond to the crustal model age (T_{DM}^{C}) of 1080–2095 Ma.

Zircons of the Tuobake granite porphyries have more variable $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282222 to 0.282440. The calculated $\varepsilon_{\text{Hf}}(t)$ values vary from -14.06 to -6.55 , which correspond to the crustal model age (T_{DM}^{C}) of 1689–2164 Ma.

Table 4. LA-MC-ICPMS zircon Hf isotopic data of zircon grains from the Zengudi and Tuobake granite porphyries.

Spot	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	Age(Ma)	$(^{176}\text{Hf}/^{177}\text{Hf})_i$	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	T_{DM}	T_{DMc}	$f_{\text{Lu/Hf}}$
SC1801, Zengudi Granite Porphyry											
1	0.052434	0.001550	0.282458	0.000009	254	0.282450	−11.12	−5.81	1140	1649	−0.95
2	0.015455	0.000515	0.282427	0.000008	254	0.282425	−12.20	−6.70	1151	1706	−0.98
3	0.024921	0.000829	0.282494	0.000008	254	0.282490	−9.82	−4.40	1067	1559	−0.98
4	0.021883	0.000770	0.282533	0.000008	254	0.282530	−8.45	−2.98	1011	1471	−0.98
5	0.035953	0.001084	0.282409	0.000008	254	0.282404	−12.82	−7.44	1193	1752	−0.97
6	0.025831	0.000866	0.282493	0.000008	254	0.282489	−9.88	−4.43	1070	1563	−0.97
7	0.020342	0.000666	0.282437	0.000008	254	0.282434	−11.85	−6.38	1142	1686	−0.98
8	0.016995	0.000576	0.282483	0.000009	254	0.282480	−10.23	−4.75	1076	1583	−0.98
9	0.017185	0.000605	0.282543	0.000009	254	0.282540	−8.09	−2.63	992	1446	−0.98
10	0.034599	0.001078	0.282469	0.000008	254	0.282464	−10.71	−5.32	1109	1618	−0.97
11	0.034650	0.001123	0.282493	0.000008	254	0.282487	−9.88	−4.50	1077	1565	−0.97
12	0.022910	0.000765	0.282503	0.000007	254	0.282500	−9.50	−4.04	1052	1538	−0.98
13	0.039795	0.001268	0.282488	0.000008	254	0.282482	−10.04	−4.68	1088	1578	−0.96
14	0.022477	0.000753	0.282508	0.000007	254	0.282504	−9.34	−3.90	1045	1527	−0.98
SC1802, Zengudi Granite Porphyry											
1	0.051045	0.001464	0.282415	0.000010	246	0.282408	−12.63	−7.46	1198	1748	−0.96
2	0.041120	0.001160	0.282363	0.000008	246	0.282357	−14.48	−9.26	1261	1861	−0.97
3	0.049009	0.001353	0.282371	0.000007	246	0.282365	−14.17	−8.98	1255	1843	−0.96
4	0.034964	0.000950	0.282324	0.000008	246	0.282319	−15.85	−10.61	1309	1947	−0.97
5	0.050138	0.001380	0.282325	0.000010	246	0.282319	−15.81	−10.61	1322	1948	−0.96
6	0.042443	0.001181	0.282376	0.000008	246	0.282370	−14.02	−8.80	1244	1833	−0.96
7	0.022381	0.000578	0.282256	0.000010	246	0.282253	−18.25	−12.94	1390	2095	−0.98
8	0.043054	0.001270	0.282261	0.000009	246	0.282256	−18.06	−12.84	1407	2088	−0.96
9	0.065127	0.001787	0.282328	0.000009	246	0.282319	−15.72	−10.61	1333	1946	−0.95
10	0.043391	0.001239	0.282355	0.000009	246	0.282350	−14.73	−9.51	1274	1878	−0.96
11	0.033480	0.000914	0.282276	0.000008	246	0.282272	−17.53	−12.27	1374	2053	−0.97
12	0.041500	0.001133	0.282359	0.000007	246	0.282354	−14.59	−9.37	1265	1869	−0.97
13	0.047639	0.001299	0.282390	0.000008	246	0.282384	−13.50	−8.31	1227	1801	−0.96
14	0.051748	0.001448	0.282353	0.000008	246	0.282346	−14.83	−9.65	1285	1886	−0.96
15	0.041658	0.001197	0.282395	0.000009	246	0.282390	−13.32	−8.10	1216	1788	−0.96
16	0.039886	0.001110	0.282370	0.000008	246	0.282365	−14.21	−8.98	1249	1844	−0.97
YZ1803, Tuobake Granite Porphyry											
1	0.056035	0.001588	0.282229	0.000009	246	0.282222	−19.19	−14.06	1465	2164	−0.95
2	0.045067	0.001288	0.282418	0.000008	246	0.282412	−12.51	−7.33	1187	1738	−0.96
3	0.033968	0.000948	0.282435	0.000007	246	0.282430	−11.93	−6.70	1154	1699	−0.97
4	0.055386	0.001535	0.282325	0.000007	246	0.282318	−15.80	−10.66	1327	1949	−0.95
5	0.055885	0.001572	0.282409	0.000007	246	0.282402	−12.83	−7.69	1209	1762	−0.95
6	0.047681	0.001319	0.282295	0.000007	246	0.282289	−16.88	−11.68	1363	2016	−0.96
7	0.040449	0.001194	0.282027	0.000017	246	0.282021	−26.36	−11.17	1233	1910	−0.96
8	0.042754	0.001176	0.282398	0.000009	246	0.282393	−13.22	−8.00	1212	1783	−0.96
9	0.047543	0.001350	0.282298	0.000008	246	0.282292	−16.75	−11.58	1358	2007	−0.96
10	0.036930	0.000811	0.282442	0.000014	246	0.282138	−10.96	−11.32	1244	1756	−0.98
11	0.030327	0.000870	0.282403	0.000008	246	0.282399	−13.06	−7.79	1196	1770	−0.97
12	0.039229	0.001104	0.282429	0.000008	246	0.282424	−12.11	−6.91	1166	1712	−0.97
13	0.052511	0.001464	0.282416	0.000008	246	0.282409	−12.60	−7.44	1196	1746	−0.96
14	0.059767	0.001652	0.282440	0.000008	246	0.282432	−11.75	−6.62	1168	1694	−0.95

Table 4. Cont.

Spot	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	Age(Ma)	$(^{176}\text{Hf}/^{177}\text{Hf})_i$	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	T_{DM}	T_{DMc}	$f_{\text{Lu/Hf}}$
YZ1804, Tuobake Granite Porphyry											
1	0.056426	0.001536	0.282440	0.000009	246	0.282433	−11.75	−6.59	1164	1692	−0.95
2	0.048878	0.001315	0.282422	0.000009	246	0.282416	−12.37	−7.19	1182	1729	−0.96
3	0.060706	0.001661	0.282279	0.000008	246	0.282272	−17.43	−12.29	1397	2053	−0.95
4	0.051981	0.001418	0.282423	0.000007	246	0.282417	−12.33	−7.16	1184	1728	−0.96
5	0.046330	0.001293	0.282440	0.000014	246	0.282434	−11.73	−6.55	1156	1689	−0.96
6	0.047305	0.001318	0.282353	0.000011	246	0.282347	−14.81	−9.63	1280	1885	−0.96
7	0.047661	0.001313	0.282428	0.000009	246	0.282422	−12.17	−6.98	1174	1717	−0.96
8	0.049598	0.001395	0.282424	0.000009	246	0.282418	−12.30	−7.12	1182	1726	−0.96
9	0.045268	0.001254	0.282413	0.000008	246	0.282408	−12.69	−7.47	1193	1749	−0.96
10	0.053964	0.001442	0.282263	0.000007	246	0.282257	−17.99	−12.82	1411	2086	−0.96
11	0.051494	0.001401	0.282416	0.000007	246	0.282409	−12.60	−7.44	1194	1745	−0.96
12	0.032045	0.000872	0.282409	0.000009	246	0.282405	−12.82	−7.58	1187	1755	−0.97
14	0.050771	0.001369	0.282369	0.000008	246	0.282362	−14.27	−9.10	1260	1851	−0.96
15	0.102921	0.002808	0.282292	0.000008	246	0.282279	−16.98	−12.04	1423	2036	−0.92
16	0.068002	0.001850	0.282397	0.000010	246	0.282389	−13.26	−8.15	1235	1791	−0.94
17	0.064255	0.001732	0.282429	0.000008	246	0.282421	−12.12	−7.01	1186	1719	−0.95

5. Discussion

5.1. Genetic Type and Magma Origin of the Granite Porphyries

Granitic rocks have been commonly classified into I-, M-, S-, and A-type granites [57–60], largely based on their petrographic and geochemical characteristics, and the nature of magma sources. The studied granite porphyries are geochemically distinct from A- and M-type granites, which are both characterized by low K_2O (<1 wt.%) and high alkali index ($\text{AI} > 0.85$), respectively [61]. In this study, the Zengudi granite porphyries exhibit high contents of SiO_2 (68.04–87.61%) and Al_2O_3 (5.55–18.33%), low contents of P_2O_5 (0.043–0.16%) and HFSE, low alkali index ($\text{AI} = 0.31$ –0.69) and high A/CNK ratios of 1.07–1.86 (Table 1). In addition, these granitic rocks display typical ratios of $\text{Fe}_2\text{O}_3^{\text{T}}/\text{MgO}$ (2.24–3.29) and $10,000 \times \text{Ga}/\text{Al}$ of 2.19–2.66, Zr (12–300 ppm) and Nb (6.39–15.6 ppm) contents. Thus, these geochemical features rule out the A-type affinity for the Zengudi granite porphyries [2,62,63]. Moreover, the contents of Th and Y do not vary with increasing Rb content (Figure 7a,b), and the Sr/Ba ratios range from 0.10 to 0.24. Overall, these characteristics indicate that the Zengudi granite porphyries are S-type granites.

Figure 7. Classification diagrams of the Zengudi and Tuobake granite porphyries. (a) Rb versus Y and (b) Rb versus Th [57].

The Tuobake granite porphyries have relatively high SiO_2 (71.07–77.75%) and Al_2O_3 (9.21–13.98%), and low P_2O_5 (9.21–13.98%) contents (Table 1). Except sample YZ-H3, their A/CNK ratios are mostly higher than 1.10 (Table 1). This suggests that the Tuobake granite porphyries are peraluminous granites. These granites also display low AI values (0.51–0.68) and low contents of HFSE such as Nb (9.57–15.0 ppm) and Zr (181–289 ppm), with typical

ratios of $10,000 \times \text{Ga}/\text{Al}$ (1.97–2.81) and $\text{Fe}_2\text{O}_3^{\text{T}}/\text{MgO}$ (3.90–5.86). Moreover, the Th contents of these granites do not increase with increasing Rb content, while their Y contents exhibit a slight positive correlation with increasing Rb (Figure 7a,b). Hence, these features suggest that the Tuobake granite porphyries are S-type granites.

Most peraluminous granites are formed by partial melting of crustal rocks [64–67] or metamorphosed sediments such as (1) metamorphosed mudstones and sandstones [66], (2) metamorphosed felsic igneous rocks (orthogneiss) [68], and (3) metamorphosed basaltic igneous rocks [69,70]. Previous studies have documented that the granitic magma originated from the orthogneiss or sandstone source exhibits high $\text{CaO}/\text{Na}_2\text{O}$ ratios and low $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios [69,71]. The studied Zengudi and Tuobake granite samples show high $\text{CaO}/\text{Na}_2\text{O}$ ratios (0.08–11.97) and low $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (17.09–40.32). This indicates that partial melting of orthogneiss or sandstone in the source region may have produced the original magma for these granitic rocks. In the $\text{Na}_2\text{O}/\text{CaO}$ versus $\text{Al}_2\text{O}_3/\text{TiO}_2$ diagram (Figure 8a), most granite samples (except samples SC-H2 and SC-H3) plot in the field of psammitolite source.

Figure 8. Magma source discrimination diagrams of the Zengudi and Tuobake granite porphyries. (a) $\text{Na}_2\text{O}/\text{CaO}$ versus $\text{Al}_2\text{O}_3/\text{TiO}_2$ and (b) Rb/Sr vs. Rb/Ba [66].

The $w(\text{CaO})/w(\text{Na}_2\text{O})$ ratios are usually used as a powerful index for distinguishing the source of granitic magma [58,65]. The granites originated from a clay-rich source are characterized by $w(\text{CaO})/w(\text{Na}_2\text{O})$ ratio < 0.3 , whereas $w(\text{CaO})/w(\text{Na}_2\text{O})$ ratio > 0.3 reflects granites originated from a plagioclase-rich and clay-poor clastic source [72]. In this study, the $w(\text{CaO})/w(\text{Na}_2\text{O})$ ratios of the Zengudi and Tuobake granite porphyries are mostly > 0.3 (0.08–11.97 and 0.8–1.20, respectively), indicating that their granitic magmas were generated from a plagioclase-rich and clay-poor clastic source. In the Rb/Sr versus Rb/Ba diagram (Figure 8b), all samples plot in the field of clay-poor source and show a close affinity to pelite-derived melt. This further corroborates that the Zengudi and Tuobake granite porphyries were formed by the partial melting of psammitolite.

The Nd isotopic compositions of granitic rocks and their Hf isotopes of zircons can further reflect their magma sources [9,54,66,73]. The studied Zengudi and Tuobake granite porphyries show a narrow negative range of $\epsilon_{\text{Nd}}(t)$ values (−14.49 to −9.35) (Table 2). The corresponding Nd model ages (T_{DM}^{C}) vary from 1.78 to 2.46 Ga, suggesting that their magmas were derived from remelting of crustal source. The zircons from the Zengudi and Tuobake granite porphyries also exhibit negative $\epsilon_{\text{Hf}}(t)$ values (mostly −14 to −3) (Table 2), and have crustal model ages (T_{DM}^{C}) of 1.08–2.2 Ga. This indicates that the magma producing the studied granitic rocks originated from an old crustal source. On the $\epsilon_{\text{Nd}}(t)$ versus $\epsilon_{\text{Hf}}(t)$ diagram (Figure 9a), all the granite samples plot in the field of lower continental crust and global sediments, which reflects an old crustal source for the magmas. Moreover, on the $\epsilon_{\text{Nd}}(t)$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ diagram (Figure 9b), two samples of the Zengudi granite porphyries show a close affinity with the S-type granitoids from the Lancangjiang fault belt (LFB), while four samples of the Tuobake granite porphyries plot

in the field of Lancangjiang granitoids formed from the Indochina block (Simao Terrane). Thus, we infer that the Lancangjiang Paleo-Tethys suture zone is located at the west of this study area. The geochemical analyses of the studied granites show that these granite porphyries are strongly enriched in LILE (e.g., Rb, Th, K and U) but depleted in HFSE (e.g., Ta, Nb, and Ti) (Figure 4b), with high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and low $\epsilon_{\text{Nd}}(t)$ values. Overall, these granites were sourced from magmas of continental crust origin.

Figure 9. (a) Plots of $\epsilon_{\text{Hf}}(t)$ versus $\epsilon_{\text{Nd}}(t)$ and (b) $\epsilon_{\text{Nd}}(t)$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_i$ of the Zengudi and Tuobake granite porphyries. The initial isotopic ratios of the granite porphyries were corrected to 254 Ma and 246 Ma, respectively [16,17,22]. The Jinshajiang MORB is from [74]; Gangdese I-type granite is from [75]; I-type and S-type granites in Lancangjiang fault belt (LFB) is from [76]; and the Lancangjiang granite is from [15]. The Jinshajiang MORB represents mantle-derived magmas: $\epsilon_{\text{Nd}}(t) = 6.1$, $\text{Nd} = 7.2$ ppm, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7054$, $\text{Sr} = 260$ ppm. The rocks from the Xiongson Group [77] were considered to be formed by the melting of the upper continental crust (UCC): $\epsilon_{\text{Nd}}(t) = -12.2$, $\text{Nd} = 27.6$ ppm, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7357$, $\text{Sr} = 168$ ppm. The amphibolites of the Yangtze Craton LCC (lower continental crust) ($\epsilon_{\text{Nd}}(t) = -10$, $\text{Nd} = 12$ ppm, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.710$, $\text{Sr} = 260$ ppm) were estimated by [78].

In the $\epsilon_{\text{Hf}}(t)$ versus U–Pb age diagram (Figure 10), most granite samples plot along the crustal evolution line. Furthermore, the Nb/Ta (11.44–13.48) and Zr/Hf (37.42–38.55) ratios of the studied granite porphyries are comparable to those of the continental crust [79,80]. Combined with their significant depletion in Ba and Sr (Figure 4b), all these characteristics suggest that the granitic magmas originated from the melting of Paleoproterozoic to Mesoproterozoic crustal materials.

Figure 10. U–Pb ages versus $\epsilon_{\text{Hf}}(t)$ for zircons from the Zengudi and Tuobake granite porphyries in the Yezhi area. The values used for constructing the depleted mantle and crustal evolution reference lines were taken from [81].

5.2. Magma Evolutionary Processes of the Granite Porphyries

The Zengudi and Tuobake granite porphyries exhibit a wide range of SiO_2 concentrations (69.68–87.61%). Moreover, SiO_2 shows a clear negative correlation with major oxides (e.g., TiO_2 , P_2O_5 , CaO , Al_2O_3 , TFe_2O_3 , MgO) and trace elements (e.g., Sc, Cr, Sr, Ni, and Zr (Figure 11). This suggests a strong fractionation crystallization during magma evolution for the studied granites. On the La/Sm versus La diagram (Figure 12f), it is noticeable that the fractional crystallization is the main factor controlling the magma evolution. The conspicuous negative anomalies of Eu, low ΣHREE (8.65–30.7 ppm), and flat HREE patterns (Figure 4a) suggest that there were residual minerals (e.g., plagioclase and amphibole) in the magma source. The negative anomalies of Ba, Sr (Figure 4b) and Eu (Figure 4a) imply the fractional crystallization of amphibole and plagioclase during magmatic evolution, respectively. On the other hand, the negative correlation between Sc, Cr, Sr, Ni, and Zr versus SiO_2 (Figure 12) further confirms that the granitic magmas have undergone hornblende and plagioclase fractional crystallization during their magmatic evolutionary processes [82].

Figure 11. Harker diagrams of major elements of the Zengudi and Tuobake granite porphyries. (a) SiO_2 versus TiO_2 , (b) SiO_2 versus Al_2O_3 , (c) SiO_2 versus P_2O_5 , (d) SiO_2 versus TFe_2O_3 , (e) SiO_2 versus CaO , and (f) SiO_2 versus MgO .

Figure 12. Harker diagrams of trace elements for the Zengudi and Tuobake granite porphyries. (a) SiO_2 versus Sc, (b) SiO_2 versus Cr, (c) SiO_2 versus Sr, (d) SiO_2 versus Cr, (e) SiO_2 versus Zr, and (f) La/Sm versus La.

The Y/Yb and $(\text{Ho}/\text{Yb})_{\text{N}}$ ratios are commonly applied to distinguish the residual phases in the magma source [83]. If $\text{Y}/\text{Yb} > 10$ and $\text{Ho}_{\text{N}}/\text{Yb}_{\text{N}} > 1.2$, garnet is the main residue mineral, whereas $\text{Y}/\text{Yb} \approx 10$ and $(\text{Ho}/\text{Yb})_{\text{N}} = 1$ indicate that hornblende is the residue mineral [83]. In this study, the Y/Yb ratios range between 9.66 and 12.21 (average = 11.08), and the $(\text{Ho}/\text{Yb})_{\text{N}}$ ratios vary from 0.97 to 1.21 (average = 1.12). Thus, we infer that the hornblende is the major residue mineral in the magma source for the Zengudi and Tuobake granite porphyries.

In summary, the Zengudi and Tuobake granite porphyries have likely undergone strong fractionation crystallization processes of plagioclase and amphibole (e.g., hornblende).

5.3. Tectonic Setting of the Granite Porphyries and Its Implication for the Closure of the Paleo-Tethys Ocean

The regional tectonic evolution of the Lancangjiang area (Figure 1b) has been debated for a decade [6,14–17,36]. Two possible subduction events related to the formation of the Jiangda-Weixi volcanic arc have been proposed: (1) westward subduction of the Jinshajiang Ocean [19,20,84], and (2) eastward subduction of the Lancangjiang Ocean [17,21,24,85]. Additionally, several tectonic setting models for the Triassic granitoids and bimodal volcanic rocks in the Lancangjiang area were postulated such as: (1) the Paleo-Tethys Ocean experienced three stages of tectonic evolution including a pre-collisional (ca. 255–250 Ma),

syn-collisional (249–237 Ma), and post-collisional (236–212 Ma) setting [16]; (2) the Early Triassic and Mid Triassic magmatism were generated in volcanic arc and post-collisional extension settings, respectively [14,15]; (3) the Lincang granites (southern extension of the Baimaxueshan granodiorite [13]) were generated in late subduction to continental collision setting [23] or transitional tectonic setting from syn-to- post collision [75]. Recently, Deng et al. [18] proposed that the Lincang granites recorded three major episodes of subduction (261–252 Ma), syn-collision (250–237 Ma), and post-collision (235–203 Ma), respectively. Xin et al. [17] have suggested that the volcanic rocks of the Weixi area in north Lancangjiang were generated in a syn-subduction setting.

The Zengudi and Tuobake granite porphyries are located in the west margin of the Jiangda-Weixi arc volcanic belt (see Figure 1b), which represents an important part of the east Tethys. As mentioned above, the granite porphyries of the Zengudi and Tuobake are medium- to high-potassium, calc-alkaline, and S-type granite porphyries with intrusive ages of ca. 254–247 Ma and 246 Ma, respectively. We suggest that the Early Triassic granite porphyries of this study were probably formed in a volcanic arc setting for three reasons: (1) these rocks are characterized by high Al_2O_3 contents and LILE/HFSE and $\text{La}_\text{N}/\text{Yb}_\text{N}$ ratios, low Ni and Cr contents and $(\text{Nb}/\text{La})_\text{N}$ ratios, and conspicuous negative Nb, Ta, Ti, and P anomalies. All these features indicate a typical arc magma affinity for the studied granites (Figure 13a,b). (2) The Zengudi and Tuobake granite porphyries have similar intrusive age (254–246 Ma) to that 251–244 Ma of the bimodal volcanic rocks from the Yezhi area and other parts of the Jiangda-Weixi volcanic arc which formed under a volcanic arc setting [14–18]. (3) Previous studies proposed that the Late Permian to late Early Triassic and Middle to Late Triassic rocks were separately formed within volcanic arc setting and syn-collision to post-collision tectonic settings [14,15,18,23]. The granite porphyries of this study were synchronously generated with the Lincang S-type arc granites from the southern Lancangjiang [18].

Figure 13. Petrogenesis classification diagrams of the Zengudi and Tuobake granite porphyries. (a) Sr/Y versus Y and (b) $(\text{La}/\text{Yb})_\text{N}$ versus Yb_N [86].

Moreover, trace elements can further provide useful information to constrain the tectonic setting of granitoids [87]. In the discrimination diagrams of Rb versus Y + Nb and Nb versus Y (Figure 14a,b), most of the Zengudi and Tuobake granite porphyry samples plot in the volcanic arc field. Comparable results have been obtained using the Rb-Hf-Ta tectonic discrimination diagrams (Figure 14c,d), which confirm that the studied granite porphyries were generated in a volcanic arc setting. Therefore, a volcanic arc setting is the most plausible explanation for the generation of Late Permian to Early Triassic magmatism in the Yezhi area in the northern Lancangjiang zone.

Figure 14. Tectonic classification diagrams of the Zengudi and Tuobake granite porphyries. (a) Rb versus Y + Nb [88], (b) Nb versus Y [87], (c) Hf–Rb/10–Ta × 10 [89], and (d) Hf–Rb/30–Ta × 3 [89]. VAG = volcanic arc granites; ORG = ocean ridge granites; WPG = within-plate granites; syn-COLG = syn-collisional granites; post-COLG = post-collisional granites.

Previous research has suggested that the breakup of the Paleo-Tethys Ocean in the Lancangjiang area started in the Late Devonian and the closure of this ocean occurred in the Late Triassic [17,30,31]. In the eastern margin of the Qamdo-Simao block (Figure 1b), the age of the Jiangda-Weixi volcanism ranges from 258 to 229 Ma [16,19,20,85]. The emplacement ages of the volcanic rocks from the western margin of the Simao Basin range from 238 to 229 Ma. These rocks were considered to be formed by southwestward to northeastward subduction of the Qamdo-Changning-Menglian Paleo-Tethys oceanic basin [34].

In this study, the Zengudi and Tuobake granite porphyries have emplacement ages of Late Permian (254 Ma) to Early Triassic (246 Ma), which are comparable to the SHRIMP zircon U–Pb age (249 Ma) obtained for the adjacent Baimaxueshan pluton [19,20] and bimodal volcanic rocks [16,17]. Hence, our new geochronological data confirm that the magma emplacement in this area corresponds to the early phase of the Indosinian Orogeny. Therefore, we suggest that the S-type magmatism was synchronous to the tectonic extrusion in the Jiangda-Weixi volcanic arc [16,85], and the shortened and thickened crust in the continental arc was formed by compression. During the Late Permian to Late Triassic, the Lancangjiang and Ailaoshan Oceans subducted beneath the Baoshan and Simao blocks, respectively, while the Songma Ocean experienced a southward subduction beneath the Indochina block.

Overall, the Zengudi and Tuobake granite porphyries (254–246 Ma), the Baimaxueshan granite (249 Ma) and the Lincang granite (250 Ma) from the northern Sanjiang area were synchronously emplaced within the Jiangda-Weixi volcanic arc [17,39]. Subduction eastward of the Paleo-Tethys Ocean beneath the Indochina block began before 254 Ma (Figure 15a). From 254 to 246 Ma, the continuous subduction of the Paleo-Tethys Ocean led to a strong extrusion and slab break-off of oceanic lithosphere [90] (Figure 15b). During this late stage, partial melting of the thickened crust led to the formation of the large-scale S-type magmas, resulting in the synchronous emplacement of the Zengudi and Tuobake granite porphyries and the eruption of a large volume of volcanic rocks within the Jiangda-Weixi volcanic arc.

Figure 15. A schematic tectonic cartoon shows the Paleotethys evolution of the northern Lancangjiang tectonic zone. (a) >245 Ma (early stage subduction of the paleo-Tethys ocean) (b) 254–245 Ma (late stage subduction of the paleo-Tethys ocean).

6. Conclusions

1. The U–Pb dating of the Zengudi and Tuobake granite porphyries from the Sanjiang area reveal that these granites were emplaced between 254 and 246 Ma, indicating that their emplacement occurred at the closure of the Paleo-Tethys Ocean during Late Permian to Early Triassic.

2. Whole-rock geochemistry and zircon Hf isotopic compositions suggest that the granite porphyries are typical volcanic arc rocks formed in the continental arc setting after the subduction of oceanic crust. These rocks were originated from plagioclase-rich and clay-poor clastic source magmas which have likely undergone intensive fractional crystallization.
3. The crust of the Jiangda-Weixi volcanic arc belt was thickened by eastward subduction of the Baoshan block during the closure of the Paleo-Tethys, which resulted in partial melting of the thickened crust.

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