Article

Final-Stage Magmatic Record of Paleo-Asian Oceanic Subduction? Insights from Late Permian to Early Triassic Intrusive Rocks in the Yanbian Area, Easternmost Central Asian Orogenic Belt

Chao Zhang ^{1,2,3}, Franz Neubauer ², Zheng-Hong Liu ^{3,4,*}, Fang-Hua Cui ^{1,3}
and Qing-Bin Guan ^{5,6}

¹ The School of Resources and Environmental Engineering, Shandong University of Technology, Zibo 255049, China; czhang@sdut.edu.cn (C.Z.); cuifanghua@sdut.edu.cn (F.-H.C.)

² Department of Geography and Geology, University of Salzburg, 5200 Salzburg, Austria; Franz.Neubauer@sbg.ac.at

³ Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources, Changchun 130061, China

⁴ College of Earth Science, Jilin University, Changchun 130061, China

⁵ Key Lab of Submarine Geoscience and Prospecting Techniques, MOE, Institute for Advanced Ocean Study, College of Marine Geosciences, Ocean University of China, Qingdao 266100, China; guanqingbin@ouc.edu.cn

⁶ Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266237, China

* Correspondence: zhliu@jlu.edu.cn

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Abstract: This paper reports new zircon LA-ICP-MS U-Pb and Hf isotope data, and whole-rock major and trace element data for Late Permian to Early Triassic intrusive rocks in the Yanbian area, NE China. These data provide new insights into the timing of the final subduction of the Paleo-Asian Ocean beneath the North China Craton. The zircon U-Pb age data indicate that a suite of Late Permian to Early Triassic intrusive rocks related to subduction is present within the Yanbian area. The Late Permian intrusive rocks consist of diorites while the Early Triassic granites and hornblende gabbros constitute a geochemically bimodal igneous rock association. Furthermore, the Early Triassic granites show the geochemical characteristics of shoshonitic rocks. All the rocks are characterized by enrichment in LILEs and LREEs, and depletion in HREEs and HFSEs, suggesting they formed in a subduction setting. Zircons from the Early Triassic gabbros have $\epsilon_{\text{Hf}}(t)$ values and T_{DM2} ages of +7.6 to +10.7 and 735–1022 Ma, respectively, suggesting that they formed from a primary magma generated by the partial melting of lithospheric mantle material that had been previously modified by subduction-related fluids. The Late Permian diorites have $\epsilon_{\text{Hf}}(t)$ values and T_{DM2} ages of +0.5 to +9.5 and 853 to 1669 Ma, respectively, while they have high contents of Al_2O_3 , Fe_2O_3 , and low contents of SiO_2 , Cr, and Ni, indicating Late Permian diorites should derive from the mantle and are influenced by some crustal material. Early Triassic granitic rocks have a wide range of $\epsilon_{\text{Hf}}(t)$ values and T_{DM2} ages of −4.8 to +9.4 and 852 to 2136 Ma, respectively. Their zircons imply that the Early Triassic granites could be mainly derived from partial melting of the crust, with minor contribution of the crustal material of an ancient crust. The Early Triassic bimodal intrusive rocks in Yanbian area, combined with the regional geologic information; therefore, record a final post-subduction extensional environment due to the break-off of the previously subducted slab.

Keywords: Central Asian Orogenic Belt; Paleo-Asian Ocean; NE China; Yanbian area; bimodal igneous rocks

1. Introduction

The Central Asian Orogenic Belt (CAOB) underwent a long history from the breakup of Rodinia to the convergence of Pangea and its evolution is related to the opening, subduction, and closure of the Paleo-Asian Ocean between Neoproterozoic and Late Paleozoic times [1–4]. Northeast (NE) China is located at the eastern segment of the CAOB between the Siberian Craton and the North China Craton (Figure 1) [4–7]. It was formed by long-lived subduction, continental margin accretion, and continent-arc-continent collision due to the closure of the Paleo-Asian Ocean and is a key element for understanding the evolution of the eastern CAOB [4,8–13]. Previous studies have suggested that the closure of the Paleo-Asian Ocean is a scissor-like closure process [4,11]; however, the precise timing of the final closure of the Paleo-Asian Ocean is controversial, and includes proposals for Middle to Late Devonian, Late Devonian to Early Carboniferous, Late Permian, Late Permian to Early Triassic, or even Middle to Late Triassic timing [4,5,10,11,14–17]. Moreover, the location of final closure of the Paleo-Asian Ocean in NE China is still remaining controversial [4,15,17,18]. Previous studies have focused on the evolution of the Paleo-Asian Ocean in the eastern CAOB along the Solonker–Xar Moron–Changchun suture zone [4,8,10,14,19–21], whereas few studies of the tectonic evolution have been studied the easternmost part of the CAOB. Thus, it remains debated on whether the final suture location of Paleo-Asian Ocean extends to Yanbian area at the eastern termination of CAOB. In summary, research on the Paleozoic tectonic evolution in the Yanbian area, the easternmost CAOB, is meaningful for understanding the final timing and mode of Paleo-Asian Ocean closure. In this paper, we present new petrological, geochronological and geochemical data of Late Permian–Early Triassic intrusive rocks in the Helong area, the Yanbian area, to constrain the final tectonic evolution stage of the easternmost CAOB and shed new light on the timing of the final closure of the Paleo-Asian Ocean.

Figure 1. Tectonic sketch map of Central Asian Orogenic Belt and the location of Northeast China (modified after Liu et al. [4]).

2. Geological Background and Sample Descriptions

The Yanbian area in NE China, belonging to the easternmost part of the CAOB, is located at the junction of the Jiamusi Block, the Khanka block, and the North China Craton (NCC) (Figure 2A) [4,5,21–25]. This area is bounded by the Dunhua–Mishan fault to the northwest and by the Gudonghe–Fuerhe fault to the south (Figure 2). Due to being the part of the Paleo-Asian Ocean and Paleo-Pacific tectonic domains, the Yanbian area contains numerous Phanerozoic igneous rocks, which are associated with significant deposits such as gold, copper, molybdenum, and iron [5,23,26,27]. Additionally, the sedimentary rocks, metamorphic events and tectonic deformation in Yanbian area are also related to the tectonic evolution of Paleo-Asian and Paleo-Pacific Oceans [5–7,15,25,28,29]. Despite considerable research carried out over a long time, confusion remains regarding the Permo–Triassic igneous rocks in the Yanbian area [5,12,22,24,30–35]. Many studies imply that the Permo–Triassic igneous rocks are associated with the tectonic evolution Paleo-Asian Ocean [5,15,17,28,29]. Whereas a few studies have proposed that they are related to the subduction of the Paleo-Pacific Ocean [35].

Figure 2. (A) Tectonic sketch map of Northeast China. (B) Geological map of the Yanbian area.

The study area is to the east of Helong City, in the southern Yanbian area (Figure 2B) and is located at the eastern segment of the CAOB. The basement of the study area is the Neo-Archean Guandi Formation and the outcropping strata mainly include Mesozoic sedimentary and volcanic rocks [34,36–38]. The Mesozoic sedimentary and volcanic rocks are mainly composed of Cretaceous continental volcanic clastic rocks and sandstones, and these Cretaceous rocks are deposited in the Cretaceous basins which are controlled by the faults and have no deformations. However, the Paleozoic strata are rare and difficult to analyze. In the study area, the Fuerhe–Gudonghe fault extends in the NNW-direction. Voluminous igneous rocks distribute along the fault. However, these igneous

rocks are classified as late Paleozoic based on K–Ar ages and lithostratigraphic relationships [36]. Thus, previous studies have shown that the voluminous igneous rocks include Late Permian–Cretaceous rocks [5,16,34,37,38]. Furthermore, according to their emplacement ages, the Late Permian–Triassic igneous rocks in study area could be divided into the three groups: (1) Late Permian, (2) Early Triassic, and (3) Middle Triassic [5,16,30,34,37]. However, the poor exposure of Paleozoic strata made it too difficult to analyze the tectonic evolution. Therefore, a workable way is to analyze the change in tectonic settings based on the composition and ages of igneous rocks. Then the pure geological characteristic of studied area becomes clear. In this study, we analyzed three Late Permian to Early Triassic plutons in the Helong area, with the aim to reveal their petrogenesis and tectonic setting combined with the coeval, associated rock association. The Late Permian to Early Triassic plutons have a limited distributed in the study area and are named as metamorphic Xindongcun Group in earlier studies [36]. These geological bodies are covered by Mesozoic strata and are intruded by Jurassic plutons. Unfortunately, the geological relationships of these geological bodies are unclear due to the effect of extensive vegetation cover. The representative photographs of studied plutonic rocks are shown in Figure 3. The Late Permian intrusive rocks are exposed in limited areas and are mainly composed of deformed gabbros and diorites. Sample FN25 ($129^{\circ}1'49''$ E, $42^{\circ}41'57''$ N), a diorite, was collected near Tuchengzi village, 3 km north to the Helong city. The rocks are deformed and consist mainly of quartz (15%), plagioclase (70%), biotite (10%), and hornblende (5%) (Figure 3A,B). Sample N-8 ($129^{\circ}06'27''$ E, $42^{\circ}39'24''$ N), a diorite, was collected near Bajiazi town. The rocks are slightly deformed and consist mainly of quartz (<20%), plagioclase (55%), biotite (15%), and hornblende (5%).

Figure 3. Outcrop-scale and microscopic features of the Late Permian diorites (A,B) and the Early Triassic hornblende-gabbros (C,D) in the study area. Hb—hornblende, Pl—plagioclase, Q—quartz.

The Early Triassic mafic pluton is located near the Longjing city, in the eastern part of the study area. The rocks are mainly composed of hornblende-gabbros. Sample B4117 (129°29'57" E, 42°39'35" N), a hornblende gabbro, was collected from Zhixingou, 5 km east to the Longjing City, the main minerals in the gabbroic diorite are hornblende (40%) and plagioclase (60%, An $\approx$ 65) (Figure 3C,D).

The Early granitic pluton is also located near the Longjing city. The rocks are mainly composed of mylonitic granitic rocks. Sample B4135 (129°20'24" E, 42°33'3" N) is composed of plagioclase (35%), quartz (15%), potash feldspar (35%), garnet (5%), and muscovite (5%).

3. Analytical Methods

3.1. Zircon U–Pb Dating and Situ Hf Isotope Analysis

Zircons were selected from the samples using conventional heavy liquid and magnetic techniques at the Langfang Geological Survey, Hebei province, China. Then separated grains were mounted on the resin disc under the binocular microscope and were polished to expose the grain center. The internal structures of the zircons are examined using cathodoluminescence (CL) images prior to analysis. To determine the zircon ages, LA–ICP–MS zircon U–Pb analyses are performed on a Neptune LA–MC–ICPMS made by Thermo Fisher Corporation with a 193 nm laser at Tianjin Geological Mineral Test Center, China. The spot diameter and denudation depth are 35 μ m and 20 to 40 μ m, respectively. Furthermore, a zircon GJ–1 and a standard silicate glass NIST SRM610 are the standards as optimizing the analyses [39]. We corrected for common Pb with the method of Anderson [40]. Errors on individual analyses by LA–ICP–MS were quoted at the 1 σ level, while errors on pooled ages were quoted at the 95% (2 σ) confidence level.

Zircon Hf isotopic analysis in this paper were performed using a Neptune MC–ICPMS, equipped with a 193 nm laser, at Tianjin Geological Mineral Test Center, Tianjin, China. The Hf isotopic analysis was carried out at a beam density of 10–11 J/cm² and at 8–10 Hz with a spot sizes of 50 μ m. Raw count rates for ¹⁷²Yb, ¹⁷³Yb, ¹⁷⁵Lu, ¹⁷⁶(Hf+Yb+Lu), ¹⁷⁷Hf, ¹⁷⁸Hf, ¹⁷⁹Hf, ¹⁸⁰Hf, and ¹⁸²W were collected with the technique of NEPTUNE (MC–ICPMS). The detailed procedures are described by Geng et al. [41].

3.2. Whole-Rock Elemental Analysis

Samples are selected for whole-rock geochemical data (major and trace elements) following the removal of weathered surfaces and petrographic examination in thin sections. Fresh samples are crushed and powdered to ~200 mesh in an agate mill for whole-rock analysis. Geochemical analyses were conducted at Tianjin Geological Mineral Test Centre, and X-ray fluorescence (XRF: Rigaku RIX 2100), using fused glass beads, and ICP–MS (Agilent 7500a shield torch) were used to analyze whole-rock major and trace elements, respectively. Detailed analytical procedures for major element analysis by XRF and trace element analysis using IC–MS are described by Li, 1997 [42].

3.3. Whole-Rock Sr–Nd Isotope Analysis

The situ Sr–Nd isotopic analyses are conducted using a TRITON thermal ionization mass spectrometer instrument at Tianjin Geological Mineral Test Center. During the process of test, the JNdi (Nd) and NBS SRM 987 (Sr) standard were used regularly for controlling the quality and optimizing the operation parameters with the ratios of 0.512104 ± 0.000003 (¹⁴³Nd/¹⁴⁴Nd) and 0.710264 ± 0.000004 (⁸⁷Sr/⁸⁶Sr), respectively [43].

4. Analytical Results

The LA–ICPMS zircons U–Pb data (FN25 and B4117), zircon Hf isotope data (B4117, FN25, B4135, N-8) and whole-rock major and trace elements for the intrusive rocks are listed in Tables 1 and 2, respectively.

Table 1. Zircon U–Pb data of the Late Permian(FN25) and Early Triassic(B4117) igneous rocks in the study area.

NO.	Th ($\times 10^{-6}$)	U ($\times 10^{-6}$)	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{208}\text{Pb}/^{232}\text{Th}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ
B4117.1	419	679	0.62	0.0515	0.0010	0.2827	0.0059	0.0398	0.0003	0.0084	0.0003	253	5	252	2
B4117.2	119	218	0.54	0.0595	0.0052	0.3161	0.0284	0.0385	0.0003	0.0084	0.0004	279	25	244	2
B4117.3	96	171	0.56	0.0514	0.0032	0.2784	0.0174	0.0393	0.0004	0.0092	0.0003	249	16	248	2
B4117.4	94	190	0.50	0.0524	0.0028	0.2870	0.0156	0.0397	0.0004	0.0092	0.0003	256	14	251	2
B4117.5	107	199	0.54	0.0526	0.0026	0.2857	0.0147	0.0394	0.0004	0.0092	0.0004	255	13	249	2
B4117.6	64	176	0.37	0.0527	0.0029	0.2875	0.0161	0.0396	0.0004	0.0080	0.0003	257	14	250	2
B4117.7	111	153	0.72	0.0640	0.0013	1.0229	0.0211	0.1159	0.0009	0.0260	0.0009	715	15	707	6
B4117.8	34	97	0.35	0.0520	0.0047	0.2850	0.0263	0.0398	0.0003	0.0080	0.0005	255	23	251	2
B4117.9	105	254	0.41	0.0521	0.0023	0.2818	0.0127	0.0392	0.0003	0.0105	0.0004	252	11	248	2
B4117.10	83	354	0.24	0.0514	0.0015	0.2819	0.0087	0.0397	0.0002	0.0100	0.0004	252	8	251	2
B4117.11	150	608	0.25	0.0510	0.0010	0.2839	0.0057	0.0404	0.0004	0.0115	0.0004	254	5	255	3
B4117.12	185	316	0.58	0.0513	0.0026	0.2853	0.0151	0.0403	0.0003	0.0125	0.0005	255	14	255	2
B4117.13	33	121	0.27	0.0511	0.0054	0.2836	0.0291	0.0402	0.0003	0.0130	0.0008	254	26	254	2
B4117.14	69	127	0.54	0.0515	0.0042	0.2786	0.0228	0.0393	0.0003	0.0135	0.0007	250	20	248	2
B4117.15	47	180	0.26	0.0511	0.0032	0.2823	0.0236	0.0401	0.0004	0.0152	0.0020	252	21	253	2
B4117.16	39	81	0.48	0.0511	0.0046	0.2806	0.0239	0.0398	0.0004	0.0125	0.0008	251	21	252	2
B4117.17	110	176	0.62	0.0535	0.0032	0.2894	0.0184	0.0392	0.0004	0.0140	0.0007	258	16	248	2
B4117.18	30	139	0.22	0.0548	0.0041	0.2992	0.0235	0.0396	0.0004	0.0120	0.0009	266	21	250	3
B4117.19	5	75	0.06	0.0525	0.0034	0.2885	0.0249	0.0399	0.0004	0.0480	0.0099	257	22	252	3
B4117.20	71	232	0.31	0.0493	0.0038	0.2700	0.0224	0.0398	0.0004	0.0140	0.0011	243	20	251	3
B4117.21	28	65	0.43	0.0541	0.0039	0.2982	0.0191	0.0400	0.0006	0.0190	0.0019	265	17	253	4
B4117.22	33	94	0.35	0.0534	0.0041	0.2939	0.0261	0.0399	0.0004	0.0137	0.0008	262	23	252	3
B4117.23	50	116	0.43	0.0513	0.0041	0.2841	0.0229	0.0401	0.0003	0.0102	0.0005	254	20	254	2
B4117.24	72	341	0.21	0.0542	0.0025	0.2916	0.0146	0.0390	0.0004	0.0135	0.0007	260	13	247	2
FN25.1	144	364	0.40	0.0517	0.0012	0.2981	0.0076	0.0418	0.0006	0.0124	0.0004	265	7	264	4
FN25.2	247	468	0.53	0.0526	0.0012	0.3032	0.0076	0.0418	0.0006	0.0121	0.0004	269	7	264	4
FN25.3	772	1394	0.55	0.0548	0.0014	0.3041	0.0087	0.0403	0.0005	0.0122	0.0003	270	8	254	3
FN25.4	301	709	0.42	0.0532	0.0008	0.3052	0.0050	0.0416	0.0005	0.0116	0.0003	270	4	263	3
FN25.5	705	1235	0.57	0.0539	0.0007	0.3057	0.0049	0.0411	0.0005	0.0119	0.0003	271	4	260	3
FN25.6	687	1009	0.68	0.0536	0.0007	0.3016	0.0045	0.0408	0.0005	0.0115	0.0003	268	4	258	3
FN25.7	387	678	0.57	0.0615	0.0011	0.3508	0.0084	0.0414	0.0005	0.0143	0.0005	305	7	261	3
FN25.8	381	813	0.47	0.0536	0.0007	0.3085	0.0048	0.0417	0.0005	0.0117	0.0004	273	4	263	3
FN25.9	150	297	0.51	0.0544	0.0016	0.3054	0.0092	0.0407	0.0004	0.0119	0.0004	271	8	257	3
FN25.10	601	989	0.61	0.0644	0.0009	0.3689	0.0065	0.0415	0.0005	0.0127	0.0004	319	6	262	3

Table 1. Cont.

NO.	Th ($\times 10^{-6}$)	U ($\times 10^{-6}$)	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{208}\text{Pb}/^{232}\text{Th}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ
FN25.11	214	490	0.44	0.0532	0.0010	0.3049	0.0068	0.0416	0.0005	0.0114	0.0003	270	6	263	3
FN25.12	767	1381	0.56	0.0676	0.0016	0.3820	0.0134	0.0410	0.0007	0.0142	0.0006	329	12	259	4
FN25.13	551	1010	0.55	0.0539	0.0010	0.3017	0.0064	0.0406	0.0005	0.0108	0.0003	268	6	257	3
FN25.14	564	1059	0.53	0.0970	0.0016	0.5534	0.0105	0.0414	0.0005	0.0194	0.0006	447	9	261	3
FN25.15	840	1365	0.62	0.0536	0.0008	0.2960	0.0047	0.0401	0.0004	0.0099	0.0003	263	4	253	3
FN25.16	636	1226	0.52	0.0509	0.0006	0.2570	0.0037	0.0366	0.0004	0.0094	0.0004	232	3	232	3
FN25.17	359	1134	0.32	0.0667	0.0012	0.3439	0.0067	0.0374	0.0004	0.0107	0.0004	300	6	237	3
FN25.18	347	682	0.51	0.0535	0.0007	0.3019	0.0046	0.0409	0.0005	0.0098	0.0003	268	4	259	3
FN25.19	1645	1704	0.97	0.0792	0.0011	0.4236	0.0064	0.0388	0.0004	0.0094	0.0002	359	5	245	3
FN25.20	75	1186	0.06	0.0525	0.0007	0.2953	0.0050	0.0408	0.0005	0.0092	0.0002	263	4	258	3

Table 2. Hf isotopic data of zircons extracted from the Late Permian and Early Triassic igneous rocks in the study area.

No.	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$		$^{176}\text{Lu}/^{177}\text{Hf}$		$^{176}\text{Hf}/^{177}\text{Hf}$		$^{176}\text{Hf}/^{177}\text{Hf}_i$	$e_{\text{Hf}}(0)$	$e_{\text{Hf}}(t)$	T_{DM} (Ma)	T_{DM}^{C} (Ma)	$f_{\text{Lu/Hf}}$
B4117.1	252	0.0348	0.0001	0.0014	0.0000	0.282836	0.000023	0.282830	2.3	7.6	596	1022	−0.96
B4117.2	244	0.0118	0.0001	0.0005	0.0000	0.282869	0.000021	0.282867	3.4	8.7	536	914	−0.99
B4117.3	248	0.0139	0.0001	0.0005	0.0000	0.282854	0.000016	0.282851	2.9	8.2	559	958	−0.98
B4117.4	251	0.0142	0.0001	0.0005	0.0000	0.282922	0.000017	0.282919	5.3	10.7	463	735	−0.98
B4117.5	249	0.0118	0.0001	0.0004	0.0000	0.282838	0.000016	0.282836	2.3	7.7	579	1006	−0.99
B4117.6	250	0.0112	0.0000	0.0005	0.0000	0.282849	0.000020	0.282847	2.7	8.2	564	968	−0.99
B4117.8	251	0.0070	0.0001	0.0003	0.0000	0.282839	0.000018	0.282838	2.4	7.9	575	996	−0.99
B4117.9	248	0.0148	0.0001	0.0006	0.0000	0.282916	0.000018	0.282913	5.1	10.4	472	760	−0.98
B4117.10	251	0.0116	0.0002	0.0005	0.0000	0.282882	0.000018	0.282879	3.9	9.3	519	864	−0.98
B4135.2	252	0.0177	0.0005	0.0008	0.0000	0.282639	0.000019	0.282635	−4.7	0.7	865	1644	−0.97
B4135.3	253	0.0086	0.0001	0.0004	0.0000	0.282628	0.000017	0.282626	−5.1	0.4	870	1670	−0.99
B4135.4	254	0.0230	0.0003	0.0010	0.0000	0.282630	0.000017	0.282626	−5.0	0.4	881	1671	−0.97
B4135.6	253	0.0170	0.0001	0.0008	0.0000	0.282661	0.000015	0.282658	−3.9	1.5	833	1571	−0.98
B4135.7	247	0.0116	0.0001	0.0006	0.0000	0.282618	0.000013	0.282615	−5.5	−0.1	889	1713	−0.98
B4135.8	252	0.0122	0.0003	0.0006	0.0000	0.282661	0.000012	0.282659	−3.9	1.5	828	1568	−0.98
B4135.9	253	0.0210	0.0003	0.0009	0.0000	0.282573	0.000014	0.282569	−7.0	−1.6	959	1854	−0.97
B4135.10	251	0.0087	0.0002	0.0004	0.0000	0.282885	0.000015	0.282883	4.0	9.4	513	852	−0.99
B4135.12	255	0.0525	0.0006	0.0019	0.0000	0.282488	0.000016	0.282479	−10.0	−4.8	1108	2136	−0.94
B4135.13	253	0.0060	0.0000	0.0003	0.0000	0.282668	0.000015	0.282666	−3.7	1.8	813	1543	−0.99

Table 2. Cont.

No.	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$		$^{176}\text{Lu}/^{177}\text{Hf}$		$^{176}\text{Hf}/^{177}\text{Hf}$		$^{176}\text{Hf}/^{177}\text{Hf}_i$	$e_{\text{Hf}}(0)$	$e_{\text{Hf}}(t)$	T_{DM} (Ma)	T_{DM}^{C} (Ma)	$f_{\text{Lu/Hf}}$
N8.1	257	0.0150	0.0008	0.0006	0.0000	0.282669	0.000017	0.282666	−3.6	1.9	819	1539	−0.98
N8.2	259	0.0133	0.0006	0.0006	0.0000	0.282697	0.000017	0.282694	−2.6	2.9	778	1445	−0.98
N8.3	259	0.0281	0.0009	0.0010	0.0000	0.282652	0.000021	0.282647	−4.2	1.3	851	1596	−0.97
N8.5	259	0.0167	0.0002	0.0007	0.0000	0.282656	0.000015	0.282653	−4.1	1.5	838	1578	−0.98
N8.6	257	0.0314	0.0011	0.0012	0.0000	0.282644	0.000019	0.282638	−4.5	0.9	867	1628	−0.96
N8.7	257	0.0196	0.0004	0.0007	0.0000	0.282720	0.000018	0.282716	−1.8	3.7	749	1377	−0.98
N8.8	259	0.0227	0.0002	0.0009	0.0000	0.282672	0.000016	0.282668	−3.5	2.0	819	1530	−0.97
N8.10	258	0.0228	0.0003	0.0009	0.0000	0.282669	0.000013	0.282665	−3.6	1.9	825	1541	−0.97
N8.19	259	0.0260	0.0007	0.0010	0.0000	0.282629	0.000020	0.282624	−5.1	0.5	882	1669	−0.97
N8.22	257	0.0258	0.0008	0.0010	0.0000	0.282665	0.000017	0.282660	−3.8	1.7	832	1558	−0.97
N8.23	259	0.0232	0.0003	0.0010	0.0000	0.282690	0.000020	0.282685	−2.9	2.6	796	1474	−0.97
FN25.21	258	0.0665	0.0032	0.0020	0.0001	0.282867	0.000038	0.282858	3.4	8.7	561	924	−0.94
FN25.1	264	0.0186	0.0004	0.0005	0.0000	0.282880	0.000032	0.282877	3.8	9.5	521	853	−0.99
FN25.2	264	0.0372	0.0042	0.0011	0.0001	0.282882	0.000032	0.282876	3.9	9.5	526	856	−0.97
FN25.3	254	0.0598	0.0012	0.0018	0.0000	0.282807	0.000029	0.282799	1.2	6.5	645	1118	−0.95
FN25.4	263	0.0246	0.0011	0.0008	0.0000	0.282804	0.000026	0.282801	1.1	6.8	631	1100	−0.98
FN25.8	263	0.0378	0.0003	0.0011	0.0000	0.282869	0.000024	0.282864	3.4	9.0	545	898	−0.97
FN25.9	257	0.0394	0.0010	0.0011	0.0000	0.282765	0.000027	0.282760	−0.2	5.2	691	1237	−0.97
FN25.13	257	0.0378	0.0004	0.0012	0.0000	0.282840	0.000027	0.282834	2.4	7.8	588	1002	−0.96
FN25.15	253	0.0550	0.0005	0.0016	0.0000	0.282881	0.000025	0.282873	3.9	9.1	536	881	−0.95
FN25.19	259	0.0310	0.0012	0.0009	0.0000	0.282821	0.000024	0.282816	1.7	7.3	610	1055	−0.97

4.1. LA-ICPMS Zircon U–Pb Ages

Sample FN25 and B4117 are collected for zircon LA-ICP-MS dating in the study area. CL images of the representative zircons and zircons data are presented in Figure 4.

Figure 4. CL images of the zircons and zircon U–Pb Concordia diagrams and weighted mean ages from the quartz diorite (FN25, (A,B)) and hornblende gabbro (B4117, (C,D)) in the study area. The circles that represent dating ages in red are for the weighted mean age while the circles in green are not for the weighted mean age due to the Pb loss.

4.1.1. Quartz Diorite (Sample FN25)

Twenty zircons from FN25 are generally euhedral–subhedral in shape and have the length ranging from 100 μm to 200 μm , while the length to width ratios are from 2:1 to 3:1. CL analyses reveal that most zircons have fine-scale oscillatory growth zoning, showing the features of the magmatic-like zircons (Figure 4A). In addition, they all have the high Th/U ratios (0.32–0.97) except one (spot 20) with 0.06, and most of them show magmatic-like zircon characteristics. A total of 20 spots were analyzed on 20 zircons from sample FN25, and their $^{206}\text{Pb}/^{238}\text{U}$ ages mainly range from 253 Ma to 264 Ma; however, three younger zircons with a $^{206}\text{Pb}/^{238}\text{U}$ age of 232 Ma, 237 Ma, and 245 Ma. Thirteen spots yield a weighted mean age of 259 ± 2 Ma (MSWD = 1.4, $n = 13$) (Figure 4B). This age is from zircons with oscillatory growth zoning; thus interpreted as the crystallization age of the quartz diorite. Furthermore, this age is also consistent with the age of sample N-8 (257 Ma) in Guan et al. [34].

4.1.2. Hornblende Gabbro (Sample B4117)

Twenty-four zircons from B4117 are slightly rounded and generally fractured in shape. They have the length ranging from 120 μm to 200 μm , with length/width ratios of 1:1–2:1. CL images show that most zircons have banded texture, and a few zircons have fine-scale oscillatory growth zoning (Figure 4C), in addition, the Th/U ratios are from 0.06 to 0.72. The features mentioned above are similar with the features of the basaltic magmatic-like zircons. Twenty-four analyses were made on 24 zircons and have $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 244 ± 2 Ma to 707 ± 6 Ma. Twenty-three analyses ranging from 244 ± 2 Ma to 255 ± 2 Ma have a weighted mean age of 251 ± 1 Ma (MSWD = 1.1, $n = 23$) (Figure 4D);

however, magmatic-like zircons indicate that the age of 251 ± 1 Ma represents the protolith age of the hornblende gabbros. One spot yields a Concordia age of 707 ± 6 Ma, interpreted as the crystallization age of a xenocrystic zircon inherited in the hornblende gabbro.

4.2. Zircon Hf Isotopic Compositions

A total of 40 zircon ages from four samples (FN25, B4117, B4135-2 (the sample dating age is reported by Shi et al., 2013 [44]), and N-8 (the sample dating age is reported by Guan et al., 2016 [35])) is used for Hf isotope analyses. The $\epsilon_{\text{Hf}}(t)$ for magmatic zircons with ages of 244–264 Ma are between -4.8 and $+10.7$. Their corresponding initial $^{176}\text{Hf}/^{177}\text{Hf}$ and T_{DM1} values vary from 0.282479 to 0.282922, and from 463 Ma to 1108 Ma, respectively (Table 2).

Ten zircons from sample FN25 are dated for Hf isotopic compositions, with $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282765–0.282882, $\epsilon_{\text{Hf}}(t)$ values of $+5.2$ to $+9.5$, T_{DM1} values of 521–691 Ma, and T_{DM2} values of 853–1237 Ma, respectively.

Eleven zircons from N-8 were dated for Hf isotopic compositions, with $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282624–0.282726, $\epsilon_{\text{Hf}}(t)$ values of $+0.5$ to $+3.7$, T_{DM1} values of 749–882 Ma, and T_{DM2} values of 1377–1669 Ma, respectively.

Zircon Hf spot analyses from sample B4117 were obtained. The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are from nine zircons varying from 244 to 252 Ma, with values of 0.282830–0.282919. Their $\epsilon_{\text{Hf}}(t)$ values range from $+7.6$ to $+10.7$, with T_{DM1} age between 463 Ma and 596 Ma and T_{DM2} age between 735 Ma and 1022 Ma.

Zircon Hf spot analyses from sample B4135 were obtained. The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are from ten zircons varying from 247 Ma to 255 Ma, with values of 0.282479–0.282883. Their $\epsilon_{\text{Hf}}(t)$ values range from -4.8 to $+9.4$, with T_{DM1} age between 513 Ma and 1108 Ma and T_{DM2} age between 852 Ma and 2136 Ma.

All the analyzed zircons have Hf isotopic compositions that are similar with those of Phanerozoic igneous rocks in the East CAOB (Figure 5).

Figure 5. $\epsilon_{\text{Hf}}(t)$ versus diagram of the intrusive rocks in this study. CAOB: Central Asian Orogenic Belt; YFTB: Yanshan Fold and Thrust Belt (Yang et al., 2006 [45]).

4.3. Major and Trace Elements

Four samples, listed in Table 3, are analyzed to know the geochemical features of the Early Triassic mafic plutonic rocks in the study area. The geochemical data of Late Permian diorites and Early Triassic granites are from Guan et al. [34] and Shi et al. [44]. All the data are plotted in Figures 6 and 7.

Figure 6. TAS (A), modified after Irvine and Baragar [46] and SiO_2 - K_2O (B), modified after Peccerillo and Taylor [47] diagrams of the Late Permian diorite and the Early Triassic intrusive rocks in the Yanbian area.

The diorite has the content of SiO_2 , Al_2O_3 , TiO_2 , K_2O , and Na_2O , ranging from 50.40% to 60.30%, from 17.00% to 19.60%, from 1.01% to 1.53%, from 1.09% to 2.74%, and from 3.50% to 4.20%, respectively. However, the samples are plotted in the subalkaline field in the TAS diagram (Figure 6A). In the SiO_2 - K_2O diagram, the samples are plotted in the calc alkaline to high-K calc alkaline series (Figure 6B). The samples are enriched in LREEs, depleted in HREEs and the Eu anomalies are from 0.57 to 1.35 (Figure 7A); however, the Eu anomalies of some samples are negative while the Eu anomalies of other samples are positive [34]. On the PM (primitive-mantle) normalized trace element spidergrams (Figure 7B), the rocks are enriched in large ion lithophile elements (LILEs, such as Cs, Ba, K, and Sr), but are depleted in high-field strength elements (HFSEs, such as Nb, Ta, P, and Ti) and Ba.

The mylonitic granites were divided into two groups according to the content of SiO_2 in Guan et al., 2016 [35]. However, because of the existence of ~190 Ma zircons in the Triassic sample P₄B₁₆₋₂ [34] with high SiO_2 (>70.00%), the samples with high SiO_2 (>70.00%) are not likely to represent the geochemical features of the Early Triassic mylonitic granites. Thereby, we have the opinion that the samples with low SiO_2 (<70.00%) could represent the geochemical features of the Early Triassic mylonitic granites. The mylonitic granite samples span a narrow SiO_2 range of 66.4% and 66.8%, and the content of Al_2O_3 , $\text{K}_2\text{O} + \text{Na}_2\text{O}$, and TiO_2 range from 14.5% to 16.3%, from 7.74% to 9.92%, and from 0.51% to 0.73%, respectively. The geochemical features imply that the samples have an affinity to geochemical characteristics of shoshonitic rocks [48,49]. Furthermore, the ratios of $\text{Fe}_2\text{O}_3/\text{FeO}$ (0.57–1.29) and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ (1.03–1.43) also show the geochemical characteristics of the shoshonitic rocks [48]. Most samples are plotted in the shoshonite field in the SiO_2 - K_2O diagram (Figure 6B). These samples display slightly LREE-enriched patterns with negative or no Eu anomalies (Figure 7A). On the PM (primitive-mantle) normalized trace element spidergrams (Figure 7B), the rocks are enriched in LILEs, such as Cs, Rb, and K. The depletion of Ta, Nb, and Ti (TNT) also shows the characteristics of the shoshonitic rocks.

The Early Triassic hornblende gabbros have a low content of SiO_2 ranging from 42.00% to 45.42%, intermediary contents of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ranging from 3.44% to 4.03% and high contents of Al_2O_3 ranging from 16.20% to 19.86%. The MgO , Fe_2O_3 , FeO , and TiO_2 range from 4.73% to 7.46%, from 5.41% to 14.57%, 7.26% to 9.27%, and from 1.50% to 2.24%, respectively. In the TAS diagram (Figure 6A), the gabbros show alkaline features. With increasing MgO and Ni contents SiO_2 , Al_2O_3 , and CaO decrease (Figure 8). Additionally, the concentrations of V increase with the increasing of TiO_2 (Figure 8F). All the samples display slightly LREE-enriched patterns ($(\text{La}/\text{Yb})_{\text{N}} = 4.12$ –7.61) with negligible to positive Eu anomalies ($\text{Eu} = 0.97$ –1.17) (Figure 7A). On the PM (primitive-mantle) normalized trace

element spidergrams (Figure 7B), the rocks are enriched in large ion lithophile elements (LILEs, such as Cs, Ba, K, and Sr), but are depleted in high field strength elements (HFSE, such as Nb, Ta, and Zr).

Figure 7. Chondrite-normalized REE patterns (A) and primitive mantle-normalized trace element spidergrams (B) for the Late Permian diorite and gabbro and the Early Triassic intrusive rocks in the Yanbian area. Normalizing values of chondrite and of primitive mantle are from Boynton [50] and Sun and McDonough [51].

Figure 8. Harker diagrams of the Late Permian diorite and Early Triassic gabbro samples. (A) Ni, (B) Al₂O₃, (C) Cr, (D) SiO₂, (E) CaO, versus MgO, and (F) V versus TiO₂.

4.4. Sr–Nd Isotopic Analyses

The whole-rock Sr–Nd isotopic analyses are listed in Table 4. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon\text{Nd}(t)$ isotopic compositions were calculated at $t = 251$ Ma. For the Early Triassic gabbros, $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.70376\text{--}0.70499$ and $\epsilon\text{Nd}(t) = +0.7$ to $+3.4$, and the Nd model ages (T_{DM1} and T_{DM2}) range from 1032 to 1005 Ma, and from 963 to 743 Ma, respectively. These values are consistent with those of the Phanerozoic granitoids in the CAO [52,53].

Table 3. Chemical compositions of major elements (wt%) and trace elements ($\times 10^{-6}$) of the Late Permian diorite and gabbro and the Early Triassic intrusive rocks.

Sample	B4117-1	B4117-2	Yh59-2	Yh59-3	Dh034	Dh041	1245-1	N-8	B4396-1	4119-1	YH34	4134-1
SiO ₂	42	43.6	45.42	42.36	60.3	50.4	53.3	58.0	55.7	66.8	66.4	66.6
Al ₂ O ₃	16.2	18.1	19.86	17.46	17.3	19.6	17.9	17.0	18.5	16.3	15.8	14.5
Fe ₂ O ₃	6.92	5.41	11.53	14.57	2.33	3.86	3.62	0.99	2.30	1.10	2.19	1.63
FeO	8.6	7.7	7.26	9.67	3.82	6.05	5.43	6.41	5.12	1.85	1.70	2.93
CaO	10.1	10.5	10.44	10.23	4.47	7.58	7.85	4.94	5.60	1.64	2.38	3.01
MgO	7.46	5.96	4.73	6.57	2.20	3.62	4.42	2.86	2.98	0.81	0.95	1.65
K ₂ O	0.72	0.68	0.52	0.73	2.41	1.21	1.09	2.74	1.61	5.30	4.22	4.56
Na ₂ O	2.74	3.24	3.51	2.71	4.20	4.15	3.5	4.11	4.08	4.62	4.08	3.18
TiO ₂	2.09	1.86	1.5	2.24	1.01	1.53	1.17	1.07	1.16	0.51	0.68	0.73
P ₂ O ₅	0.59	0.59	0.7	0.35	0.30	0.46	0.20	0.41	0.23	0.16	0.22	0.17
MnO	0.18	0.18	0.14	0.18	0.13	0.13	0.16	0.11	0.10	0.10	0.06	0.08
LOI	1.38	1.13	1.12	2.05	0.91	0.60	0.65	0.47	1.19	0.44	0.90	0.53
Mg [#]	47	46	45	47	50.66	51.61	59.2	44.3	50.92	43.84	49.90	50.1
A/CNK	0.685	0.719	0.784	0.732	0.98	0.89	0.84	0.91	0.99	1.00	1.01	0.93
Cr	14.6	45.9	20	20	22	7.27	23.3	24.10	20	13.1	7.7	20.5
Ni	28.9	22.9	13.5	28.1	10.0	6.47	8.56	12.5	6.8	5.23	4.21	10
Co	54.2	42.5	27.1	45.4	12.1	23.5	26.5	15.0	20.3	4.48	5.06	9.64
Rb	9.75	10.5	6.5	14.8	56.7	37.0	28.9	84.8	46.7	84.7	124	186
Cs	1.1	0.98	0.6	1.15	3.96	1.31	1.15	1.40	2.6	1.11	3.36	6.57
Sr	809	1060	1585	987	536	710	603	733	677	331	534	208
Ba	320	255	250	250	1350	621	405	789	471	1070	1240	729
V	376	306	253	412	97.1	198	218	92.7	137	35.7	42.9	81.8
Sc	29.7	24.3	12.6	24.7	15.2	19.8	22.7	8.25	6.7	6.69	3.15	11.4
Nb	3.93	3.71	3.4	3.8	8.35	5.95	4.27	8.98	4.9	9.56	10.6	10.6
Ta	0.22	0.19	0.2	0.2	0.53	0.34	0.27	0.34	0.3	0.48	0.93	0.85
Zr	62.4	46.4	48	61	300	389	59.5	318	36	499	217	307
Hf	2.37	1.9	1.6	1.9	5.93	7.21	2.37	7.97	1.5	10.2	5.22	7.57
U	0.18	0.15	0.13	0.32	0.95	0.83	0.63	0.61	0.64	0.66	3.76	4.05
Th	0.41	0.27	0.28	0.47	5.81	2.08	3.20	7.97	5.19	1.82	18.1	22.2
La	14.9	16.2	17.5	12.1	24.6	20.9	17.3	47.9	19.3	21.6	40.6	34.2

Table 3. Cont.

Sample	B4117-1	B4117-2	Yh59-2	Yh59-3	Dh034	Dh041	1245-1	N-8	B4396-1	4119-1	YH34	4134-1
Ce	35.8	37.8	42	30.3	52.3	46.0	36.7	76.0	39	39.7	80.7	74.3
Pr	5.71	5.94	6.15	4.77	7	6.39	4.87	9.54	4.9	5.5	7.58	9.63
Nd	27.6	27.9	28.2	22.8	27.6	26.9	20.2	35.3	20	21.9	26.3	35.9
Sm	6.53	6.27	5.95	5.43	5.65	5.75	4.40	6.08	4.01	4.01	4.31	7.49
Eu	1.93	1.94	2.21	2.03	2.33	1.71	1.26	1.03	1.52	1.07	1.13	1.08
Gd	5.67	5.32	5.59	5.78	4.96	4.92	3.90	5.03	4.18	3.23	3.17	6.04
Tb	0.94	0.86	0.76	0.81	0.74	0.77	0.63	0.72	0.57	0.51	0.44	0.94
Dy	5.13	4.62	4.16	4.59	3.89	4.88	3.52	3.57	2.79	2.76	2.01	5.68
Ho	0.95	0.85	0.79	0.89	0.79	0.98	0.67	0.65	0.49	0.53	0.37	1.1
Er	2.58	2.33	2.02	2.27	2.28	2.72	1.85	1.79	1.13	1.57	1	3.01
Tm	0.38	0.34	0.27	0.31	0.35	0.41	0.27	0.27	0.14	0.25	0.16	0.46
Yb	2.44	2.15	1.55	1.84	2.25	2.72	1.81	1.78	0.78	1.83	1.08	3
Lu	0.37	0.32	0.24	0.28	0.34	0.41	0.28	0.28	0.12	0.31	0.16	0.45
Y	28.6	25.3	19.7	22.1	22.5	28.3	21.3	22.6	12.4	17.5	12.6	34.7
ΣREE	110.93	112.84	117.39	94.2	135.08	125.46	97.66	189.94	98.93	104.77	169.01	183.28
Nb/Ta	17.86	19.53	17.00	19.00	15.75	17.50	15.81	26.41	16.33	19.92	11.40	12.47
Zr/Hf	26.33	24.42	30.00	32.11	50.59	53.95	25.11	39.90	24.00	48.92	41.57	40.55
Ba/Rb	32.82	24.29	38.46	16.89	23.81	16.78	14.01	9.30	10.09	12.63	10.00	3.92
(La/Yb) _N	4	5	8	4	7.37	5.18	6.44	18.14	16.68	7.96	25.34	7.69
δEu	0.97	1.03	1.17	1.11	1.35	0.98	0.93	0.57	1.14	0.91	0.93	0.49

Note: The samples of B4117-1, B4117-2, Yh59-2, and Yh59-3 are in this paper; other samples are collected from Guan et al. [35].

Table 4. Sr–Nd isotopic data for the Early Triassic gabbros in the study area.

Sample	t(Ma)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	2σ(×10 ^{−6})	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	2σ(×10 ^{−6})	I _{Sr}	ε _{Nd} (t)	T _{DM1}	T _{DM2}	f _{Sm/Nd}
B4117	251	0.0349	0.70511	3	0.1513	0.51274	4	0.70499	3.4	1005	743	−0.23
B3164-1	251	1.5093	0.70915	3	0.1265	0.512561	8	0.70376	0.7	1032	963	−0.36

5. Discussion

5.1. Petrogenesis

5.1.1. Petrogenesis of Late Permian Diorites

The Late Permian diorites are characterized by low contents of SiO_2 and high contents of Al_2O_3 , implying the characteristics of high Al-rocks. The high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios show the magma source is of crustal origin [34]. While the low contents of Cr and Ni also indicate that the parental magma of quartz diorite is not mantle-derived but represent a crustal source. In addition, the high Th/U ratios and low Cr (7.27×10^{-6} – 24.10×10^{-6}) and Ni (6.47×10^{-6} – 12.5×10^{-6}) concentrations of these diorites [34] are inconsistent with melts derived from N-MORB or delaminated lower crust ([34] and reference therein). However, the low SiO_2 , high Fe_2O_3 , FeO, and TiO_2 contents imply a mantle source for the magma because they are distinct from the magmas originated from crust derived melts or crustal materials. The zircon $\epsilon\text{Hf}(t)$ values and T_{DM2} ages of zircons from the diorites range from +0.5 to +9.5 and from 853 to 1669 Ma, respectively, suggesting that the primary magma of the diorite was from the mantle or was influenced by crustal material. Taken together with the high $^{87}\text{Sr}/^{86}\text{Sr}$ and negative $\epsilon\text{Nd}(t)$ isotopic data [34], we suggest that the primary magma for Late Permian diorites should be derived from the mantle and is influenced by crustal material during magma ascent.

5.1.2. Petrogenesis of the Early Triassic Mafic Rocks

Geochemically, the mafic rocks have high contents of Al_2O_3 and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ and have the alkali features in the TAS (Figure 6A). While the low SiO_2 and high Cr, Ni, Co, and Sc contents along with high Mg# values indicate that the mafic magma is not from crustal derived melts [54,55] or crustal materials [56], but is from a mantle source [57]. Furthermore, the ratios of Nb/Ta, Zr/Hf, and Ba/Rb are 17.00–19.53, 24.42–32.11, and 16.89–38.46, respectively, similar with the ratios of mantle magmas [56]. However, understanding the effects of crustal contamination on the mafic rocks is important because crustal contamination is almost inevitable during the ascent of mantle-derived melts through continental crust, and modifies the chemical and isotopic compositions during magma evolution [58]. The depletion of Nb and Ta implies that the parental magma of mafic rocks is related to crustal contamination or magma mixing during the ascent of magmas [59] or reflect magma generation in a subduction-related environment [60]. Due to the existence of xenocrystic zircon (~700 Ma) in sample N-8 [34], the contamination probably occurred during magma emplacement. Nevertheless, the process of magma mixing or crustal contamination could be ignored and a comprehensive consideration of the geochemical data could answer this question because of the following reasons: (1) consider to the enrichment of Zr and Hf in crustal materials, minor crustal contamination could result in positive Zr–Hf anomalies [61,62]. The mafic rocks in this study have the negative Zr–Hf anomalies (Figure 7B), suggesting that the mafic magmas are affected by little or no crustal material. (2) Lu/Yb ratios of the samples are about 0.15 and are consistent with those of mantle-derived magmas (0.14–0.15), while the continental crust has relatively high Lu/Yb ratios of 0.16–0.18 [56]. Additionally, the gabbros have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70376–0.70499) and positive $\epsilon\text{Nd}(t)$ (+0.7 to +3.4), which indicate that the magma of the Early Triassic mafic rocks is from the mantle. Furthermore, the $\epsilon\text{Hf}(t)$ values and T_{DM2} ages of zircons from the gabbros range from +7.6 to +10.7 and from 735 to 1022 Ma respectively, suggesting that the primary magma of gabbros could be derived from partial melting of a lithospheric mantle source.

Significant crustal contamination did not affect the Early Triassic mafic rocks. In contrast, fractional crystallization is commonly responsible for the petrologic and geochemical variations among the different intrusive rocks in the orogenic zone ([58] and reference therein). The absence of Eu anomalies (Figure 7A) in the REE pattern suggests that no plagioclase fractionation occurred in the mantle magmas. The negative correlations between MgO and SiO₂ and Al₂O₃, coupled with the positive correlations between MgO and CaO, as well as Cr and Ni (Figure 8), indicate that ferromagnesian minerals such as olivine and clinopyroxene are major fractionating phases. In addition, the positive correlation between V and TiO₂ imply hornblende fractionation (Figure 8F).

5.1.3. Petrogenesis of Triassic Granitic Rocks

Compared to the geochemical features of the Early Triassic gabbros, the Early Triassic granites have high SiO₂, Al₂O₃ contents, and (K₂O+Na₂O) contents and high K₂O/Na₂O ratios and Fe₂O₃/FeO ratios showing a shoshonitic affinity. In the Ta/Yb vs. Ce/Yb and Ta/Yb vs. Ce/Yb diagrams (Figure 9), the samples are plotted into the calc-alkaline to shoshonitic series. Furthermore, the samples are enriched in LREE, such as Ba and Sr, and depleted in Ta, Nb, and Ti (Figure 7B), indicating that the Early Triassic granites are shoshonitic rocks. The shoshonitic rocks with low SiO₂ (<56%) content origins have been attributed to different main types of petrogenetic scenario [63–67], but the shoshonitic rocks with high SiO₂ (>63%) are supposed to derive from the partial melting of lower crust materials ([48] and reference therein). In our study, our samples have high Th, U, Zr, and Hf contents and rocks mostly have K, Zr, and Hf positive anomaly in the spidergrams (Figure 7B), implying the magma is from the crust. Additionally, zircons from the granites in the study area have $\epsilon\text{Hf}(t)$ values of -4.8 to $+9.4$ and T_{DM2} ages of 852 to 2136 Ma, indicating that the primary magma of the Early Triassic granites could be mainly derived from partial melting of the crust, with minor contribution of the crustal material of an ancient crust (Figure 5, [33]). This interpretation is further supported by initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70429–0.70581) and $\epsilon\text{Nd}(t)$ (-2.5 to $+1.2$) of the granites [34] and the studies of the coeval granites along the Changchun–Yanji suture [33].

Figure 9. Diagrams showing the shoshonitic affinity of granitic rocks. (A) The diagram of Ta/Yb vs. Ce/Yb for granitic rocks; (B) The diagram of Ta/Yb vs. Th/Yb for granitic rocks.

5.2. Tectonic Setting of the Early Triassic Bimodal Igneous Rocks

Geochemically, the Early Triassic granites have an affinity to shoshonitic rocks. The different models for shoshonitic petrogenesis imply these rocks could be formed in various tectonic settings but are mainly formed in an extensional setting [68]. Importantly, the granites and coeval gabbros of this study represent a bimodal igneous rock association, indicating that these rocks formed in an extensional setting in the Early Triassic. Furthermore, the gabbros have high Al_2O_3 concentrations, similar with those of high-Al basalts, which are generally considered to be related to arcs or mid-ocean ridges [69–71]. Additionally, granites and hornblende gabbros in the study area also show typical arc magmatic signatures, such as enrichment in LILE, depletion in HFSE, and fractionated REE patterns. In the Th/Yb versus Nb/Yb and La/Yb versus Th/Yb diagrams (Figure 10), all the samples in the study area are in the field of continental arcs and alkaline arcs. Combined with the presence of the coeval bimodal igneous rock association in central-eastern Jilin Province [31,33], we propose that the Early Triassic rocks in the Yanbian area formed in an extensional setting related to the breakoff of the previously subducted slab [33].

Figure 10. Diagrams of Yb_N versus $(\text{La}/\text{Yb})_N$ for Early Triassic granitic rocks and La/Yb versus Nb/La for the Late Permian diorites and the Early Triassic gabbros of this study.

5.3. Late Carboniferous to Triassic Magmatic Events in the Yanbian Area

It has been suggested that the final closure of the Paleo-Asian Ocean occurred in Yanbian area [4,5,12,16,18,22,24,30,32,33,58,72]. However, knowledge of the origin of magmas along the terminal zone is important in understanding the tectonic evolutionary processes during subduction, collision, and extension [73]. Therefore, the Late Paleozoic–Early Mesozoic magmatic rocks in the Yanbian area could throw new light on the final closure of Paleo-Asian Ocean. According to a compilation of the existing Late Carboniferous to Triassic magmatic rocks data [5,12,16,22,24,30,32,33,72], five main tectono-magmatic episodes could be identified in Yanbian area, easternmost segment of CAOB: (1) Late Carboniferous–Early Permian (305–270 Ma), (2) Middle–Late Permian (270–252 Ma), (3) Early Triassic (251 Ma–245 Ma), (4) Middle Triassic (245–235 Ma), and (5) Late Triassic (230–210 Ma) (Figure 11).

Figure 11. Late Carboniferous–Late Triassic tectonic evolution in the Yanbian area, not the Latest Permian–Early Jurassic tectonic evolution in the Yanbian area. NCC—North China Craton, JMB—Jiamusi Block, and KB—Khanka Block.

5.3.1. The Late Carboniferous–Early Permian Magmatic Event in Yanbian Area

The Late Carboniferous–Early Permian igneous rocks in the Yanbian area, including tonalites, gabbros and basalt-andesites, are mainly outcropping in the Hunchun and Bailiping areas [16,22]. Geochemically, the tonalites belong to the calc-alkaline series with I-type igneous features and have an affinity to adakitic magmas, indicating that the magma could have been derived from the partial melting of subducting oceanic slab material in an active continental margin setting [16]. Meanwhile, the gabbros and basalt-andesites belong to the low-K tholeiitic series and have similar geochemical features to high-aluminum basalts that formed in an island arc setting [22,31]. Furthermore, the coeval volcanic rocks, interpreted as the product of subduction, are also reported in the Huadian area, central Jilin Province [72]. Taken together, the petrogenesis and tectonic setting of Late Carboniferous–Early Permian rocks reveal that the subduction of the Paleo-Asian Ocean in the Yanbian area occurred in the Late Carboniferous–Early Permian (Figure 11A).

5.3.2. The Middle–Late Permian Magmatic Event in the Yanbian Area

Importantly, along with the Middle–Late Permian magmatic rocks in the Yanbian area, coeval calc-alkaline to high-K calc-alkaline I-type magmatic rocks were reported from the western segments of the Changchun–Yanji belt, such as from the Huadian region, and the southern Changchun, Bailiping and Helong areas [12,16,22,24,30,31,33,34,58,72], and form an E–W-trending magmatic belt of continental arc magmatic rocks. The Middle–Late Permian magmatic rocks in the Yanbian area, including basalts, monzogranites, diorites, gabbros, and granodiorites, are enriched in LILEs, depleted in HFSEs and have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and positive $\epsilon_{\text{Nd}}(t)$ values, suggesting their magma source regions have

undergone metasomatism by subduction-related fluids [12,58]. Furthermore, the Late Permian high-Mg andesites occur along the Changchun–Yanji belt in the eastern CAOB segment and are interpreted as the products of partial melting of enriched mantle induced by dehydration of a subducted slab [74]. However, the Middle–Late Permian intrusive rocks in the Yanbian area formed in a continental arc setting (Figure 11B; [16,34]).

5.3.3. The Early Triassic Magmatic Event in the Yanbian Area

The Early Triassic intrusive rocks form a similar bimodal igneous association to the Late Permian bimodal igneous rocks in the central Jilin Province [31,33,75], indicating that they formed in an extensional setting. Furthermore, the geochemical features imply a shoshonitic affinity of the Early Triassic rocks; also, suggesting the existence of an extensional setting. Combined with the Late Permian continental arc setting, the Early Triassic bimodal igneous rocks are likely to have formed in an extensional setting due to the break-off of the previously subducted slab in the Yanbian area (Figure 11C).

5.3.4. The Middle Triassic Magmatic Events in Yanbian Area

The Middle Triassic intrusive rocks are composed of quartz monzonite, monzogranite, and syenogranite, characterized by high Sr, low Y, and Yb contents classifying these as adakitic rocks [16,20,31,33]. This implies that these rocks formed in a compressional tectonic setting (Figure 11D). Additionally, a few Middle Triassic metamorphic zircons are distinguished, indicating the Middle Triassic metamorphic ages were recorded from the Huangyingtun Formation (233 Ma; [28]), Kedao Group (241 Ma and 231 Ma; [15,29]), and Jiefangcun (234 Ma; [29]) and Sidonggou Formations (233 Ma; [29]) in the Yanbian area. In summary, the Middle Triassic adakitic rocks formed in a compressional tectonic setting, indicating the final closure of the Paleo-Asian Ocean.

5.3.5. The Late Triassic Magmatic Event in Yanbian Area

Based on the E–W trending spatial distribution of Late Triassic igneous rocks along the final suture, the Late Triassic magmatic events are linked to the tectonic evolution of the Paleo-Asian Ocean, rather than the subduction of the Paleo-Pacific Plate [32]. The Late Triassic igneous rocks in the Yanbian area include mafic–ultramafic intrusions, I–A-type granitoids and A-type rhyolites and are interpreted to have formed in an extensional environment [16,76,77]. Additionally, the extensional events are also recorded by the Late Triassic Dajianggang Formation (molasse) [28] and structural analysis in the Hulan group [78]. Furthermore, metamorphic ages were also recorded in the Hulan (Ar–Ar, biotite, ~220 Ma; [78]) and Kedao Groups (metamorphic zircon, ~210 Ma; [15]). Thereby, we suggest that the Late Triassic rocks in Yanbian area formed in an extensional setting related to the tectonic evolution of the Paleo-Asian Ocean (Figure 11E).

5.4. Tectonic Implications

5.4.1. Eastward Extent of the Solonker–Xar Moron–Changchun Suture

The study area is located in the Yanbian area of the easternmost CAOB. However, it is well known that the CAOB underwent ocean basin closure, terrane amalgamation, crustal thickening, accretion, and lithospheric delamination during Permian–Triassic times [5,12,15,16,18,22,24,29,33]. Additionally, it is widely accepted that the Paleo-Asian Ocean finally closed during the Late Permian–Middle Triassic [5,12,15,16,18,22,24,29,33]. Thus, due to lack of ophiolite outcrops in the central-eastern Jilin Province (the eastern CAOB), fierce debate continues over whether the Yanbian area is the eastward extension of the Solonker suture belt or not [5,18,19]. Some scholars have suggested that the Yanbian area is a suture zone related to the subduction of the Paleo-Pacific Ocean instead of the Paleo-Asian Ocean during the Permo–Triassic period [19]. On the contrary, the other popular

proposal suggests that the Yanbian area is the site of the closure of the Paleo-Asian Ocean, and therefore constitutes the eastern part of the CAOB [5,12,15,16,18,22,24,29,33].

Based on increasing evidences during the past decades [5,12,15,16,18,22,24,28,29,33], we suggest that the Changchun–Yanji belt is the easternmost part to the Solonker–Xar Moron–Changchun Suture zone, which records the final closure of the Paleo-Asian Ocean. The evidences include as follows: (1) Paleozoic–Early Mesozoic magmatic events occurred in the Changchun and Yanbian areas along the Solonker–Xar Moron–Changchun–Yanji [5,12,16,18,22,24,33]. These magmatisms represent independent regional tectonic events and are similar with the products of the five Late Paleozoic evolution stages of the western Solonker–Xar Moron–Changchun–Yanji Suture zone proposed by Jian et al., 2010 [14]. Furthermore, due to the detachment and sinking of subducted slabs of the Paleo-Asian Oceanic plate after closure, the Changchun and Yanbian areas (eastern Solonker–Xar Moron–Changchun–Yanji Suture zone) is within an extensional setting during 255–242 Ma. This view is also supported by the existence of the bimodal magmatism and molasse in the study and adjacent areas [15,28,29]. Additionally, the Early–Middle Triassic adakitic rocks outcrop along the Changchun–Yanji belt with the coeval metamorphic events recorded in the Hulan and Kedao Groups, and Huangyingtun and Sidaogou Formations [16,31,33]. (2) The Permian strata in the northern part of the Yanbian area are composed of Hesheng, Dasuangou, and Kaishantun Formations and contain mainly detritus from NCC sources while the source of Wudaogou Group in the northern part of the Yanbian area is mainly from the Jiamusi block ([29] and references therein). Therefore, the distribution and composition of Permian formations in Yanbian area indicate that the Yanbian area is the suture belt between the northern NCC and the Jiamusi block and Khanka block. (3) The Kaishantun and Hesheng flora are mainly Cathaysia flora, while the Jiefangcun flora is a mixture of the Cathaysian and the Angaran flora elements ([29] and reference therein). Anyway, the coeval mixture of cool-and warm-water faunas are also reported in central Jilin Province and Inner Mongolia and coexists along the Solonker–Xar Moron–Changchun–Yanji Suture zone in E–W direction ([29] and references therein). Considering the magmatic, sedimentary, metamorphic, and sedimentary evidences, we suggest that the Late Permian–Early Triassic magmatism in the study area is linked with the final subduction of Paleo-Asian Ocean.

5.4.2. The Final Scissor-Like Closure Model of the Paleo-Asian Ocean in Easternmost Central Asian Ocean Belt

Many studies have suggested that the final closure of the Paleo-Asian Ocean occurred from west to east along the Solonker–Xar Moron–Changchun–Yanji suture zone in a scissor-like closure model [4,8–13]. However, the precise timing of final closure is debated [15,16,18,28,30,31,33]. According to a compilation of existing data, three main tectonic episodes could be identified that are linked to the closure of the Paleo-Asian Ocean in the Yanbian area, the easternmost of Central Asian Ocean Belt. (1) The Late Carboniferous to Early Triassic development of subduction–collision–extension systems are related to the subduction of Paleo-Asian Ocean. (2) The Middle Triassic tectonic development relates to compression and thickening of the continental crust. (3) A Late Triassic post-collision extensional stage followed. However, the Early Triassic bimodal igneous rocks are likely to record the final subduction of the Paleo-Asian Ocean, while the Middle Triassic adakitic rocks record collision between the North China Craton and combined Jiamusi and Khanka blocks. Furthermore, a similar rocks association occurs in the central Jilin Province, which relates to the Yanbian area [31,33,75].

Considering the emplacement ages of bimodal and adakitic rocks in the central Jilin Province and Yanbian area, we suggest that the final closure of Paleo-Asian Ocean in central Jilin Province is during Early Triassic while it occurred in the Yanbian area during Middle Triassic times (Wang et al., 2015). Furthermore, the Angaran and Cathaysian floras mixed during the Late Permian–Middle Triassic in the Yanbian area and delineate the final closure of Paleo-Asian Ocean in the eastern segment of CAOB [29].

In brief, based on the magmatic, metamorphic and sedimentary events along Changchun–Yanbian belt, we suggest that the final closure of Paleo-Asian Ocean occurred in a scissor-like manner in the Yanbian area, the easternmost segment of CAOB, during the Middle Triassic times (Figure 12).

Figure 12. Simplified model showing the Middle Permian–Middle Triassic tectonic evolution of the northern margin of the North China Craton (NCC) and the combined Khanka (KB) and Jiamusi Blocks (JMB). PAO—Paleo-Asian Ocean.

6. Conclusions

1. LA–ICP–MS zircon U–Pb dating indicates that mafic and granitic intrusions in the Helong area of NE China formed in Late Permian (~257 Ma) and Early Triassic (~251 Ma) times.
2. The Late Permian diorites show the petrologic and geochemical characteristics of arc type igneous rocks enriched in LILE and depleted in HFSE. The geochemical and isotopic features suggest that the primary magma for Late Permian quartz diorite should be derived from partial melting of a juvenile lower continental crust.
3. The Early Triassic intrusions including granites and gabbros represent a bimodal igneous rock association. The granites have an affinity to the shoshonitic rocks with enrichment of LILE and LREEs and depletion of TNT (Ta, Nb, and Ti). The Sr–Nd isotopic and zircon Hf isotopic data show that the primary magma of gabbros could be derived from partial melting of a juvenile lithospheric depleted mantle source whereas the primary magma of the Early Triassic granites could be mainly derived from partial melting of juvenile lower crust, with minor contributions of the crustal material of the NCC.
4. The Early Triassic intrusions formed in an extensional setting due to the breakoff of the previously subducted slab.

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