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Abstract: This paper presents age and geochemical data of a recently identified Late Paleoozoic volcanic sequence in central Jilin Province, with aims to discuss the petrogenesis and to constrain the tectonic evolution of the Central Asian Orogenic Belt in this area. Firstly, the volcanic rocks have zircon U–Pb ages of 290–270 Ma. Secondly, they are characterized by (a) ranging in composition from the low-K tholeiite series to high-K calc-alkaline series; (b) enrichment in light rare earth elements and depletion of heavy rare earth elements, with negative Eu anomalies; and (c) negative Nb, Ta, and Ti anomalies. Finally, the volcanic rocks yield εHf(t) values of +7.1 to +17. These data suggest that the central Jilin volcanic rocks were possibly derived from predominant partial melting of a depleted lithospheric mantle that might have been modified by subducted slab–derived fluids. Combined with previous studies, the Late Paleoozoic–Early Mesozoic magmatism in Central Jilin can be divided into two stages: (a) a volcanic arc stage (290–270 Ma) represented by low-K to high-K, tholeiite to calc–alkaline plutons and (b) a syn-collisional stage (260–240 Ma) represented by high-K calc–alkaline I-type granites. Furthermore, the timing and the tectonic setting of the above magmatic rocks show that the arc was probably produced by the northward subduction of the Paleo-Asian Ocean and that the final closure of the Paleo-Asian Ocean occurred prior to the Early Triassic.

Key words: volcanic rocks, zircon U–Pb age, tectonic evolution, Paleo–Asian Ocean


1 Introduction

Northeastern (NE) China and its adjacent areas, including the Russian Far East and North Korea, are situated between the North China North China Craton (NCC) and Siberia Craton (SC) and have traditionally been regarded as the eastern segment of the Central Asian Orogenic Belt (CAOB)(Bei et al., 2014; Cheng et al., 2014; Kröner et al., 2014; Xu and Zhao, 2014; Pei et al., 2016a; Guo et al., 2017; Isozaki et al., 2017; Liu et al., 2017; Xu et al., 2018; Li et al., 2019; Wang et al., 2019). The CAOB is the largest accretion orogenic belt on our planet and has undergone more than 800 million–years of tectonic evolution, ranging from Mesoproterozoic to Paleoozoic eras (Jahn, 2004; Kovalenko et al., 2004; Xiao et al., 2004). NE China contains several microcontinental blocks/terranes, including the Erguna and Xing’an blocks and the Songliao, Jiamusi–Khanka, and Ndanindara terranes (Fig. 1). They are cut by several main faults, including the Xar Moron–Changchun, Mudanjiang, Heilongjiang, Hegenshan–Heihe, Xinlin–Xiguitu, Yilan–Yitong, Dunhua–Mishan, and Primoria Faults (Xiao et al., 2004; Wang et al., 2016a; Wang et al., 2016b; Ge et al., 2017; Guo et al., 2017) (Fig. 1). The tectonic evolutionary history between these amalgamated blocks and the NCC is the key to understanding the timing of the final closure of the Paleo-Asian Ocean and shedding new light on the Paleo-Asian evolution of the northern margins of the NCC (Isozaki et al., 2017; Liu et al., 2017; Xu et al., 2018; Shi et al., 2019; Shi et al., 2020).

The timing of the final closure of the Paleo-Asian Ocean is a highly controversial topic. Number of researchers have suggested that the terminal closure of the Paleo-Asian Ocean occurred during the Middle Devonian (Xu et al., 2015), which sandwiched the Late Devonian and Early Carboniferous epochs (Ren et al., 1999; Sun et al., 2004; Zhu and Ren, 2017). Meanwhile, others have proposed that it occurred during either the Late Permian (Li, 2006; Li et al., 2007a), or Early Triassic period (Zhou et al., 2012b; Yang et al., 2013; Zhang et al., 2013; Zhou et al., 2013; Zhou and Wilde, 2013). In this context, several researchers have simply focused on the aspect of magmatism and sedimentation (Sun et al., 2004; Xiao et al., 2004; Kim et al., 2012; Zhang et al., 2013; Zhou et al., 2013; Zhu and Ren, 2017; Xu et al., 2018). These conflicting views indicate that there remains some uncertainty regarding both the timing of the final closure...
of the Paleo-Asian Ocean and Late Paleozoic tectonic evolution in the eastern segment of the CAOB. The Changchun area that forms the eastern part of the Xar Moron–Changchun suture can be used to help us better understand this problem. However, since most scholars have tended to focus on the study of intrusive and sedimentary rocks, little attention has been paid to the role of the associated volcanic rocks in this area.

In this study, we review the research on zircon uranium–lead (U–Pb) geochronology and hafnium (Hf) isotopes related to rhyolite–dacitic–andesitic sequence samples from central Jilin Province, NE China. The research results can not only provide useful information on the tectonic evolution of the eastern CAOB, but also provide a comprehensive interpretation of the timing of the closure of the Paleo-Asian Ocean in the eastern segment.

2 Geological Settings

The research area (in central Jilin Province) is situated at the Songliao Block and not far from Jiamusi terrane and Khanka terrane (Fig. 1).

The Songliao Block possesses a tremendous region in NE China (Fig. 1), bounded by the Hegenshan–Heihe tectonic suture zone in the northwest, the Jilin–Heilongjiang Ultrahigh Pressure Belt in the east, and the Xar Moron–Changchun–Yanjir tectonic suture zone in the south (Zhou et al., 2012b; Zhou et al., 2013; Zhou and Wilde, 2013; Shi et al., 2019; Shi et al., 2020). It comprises the the Lesser Xing'an Range in the northeast, Zhangguangcui Range in the east, the southern Great Xing'an Range in the west, and the Songliao Basin in the central part, associated with the existence of basement rocks beneath the Songliao Basin.

The Songliao Basin is characterized by deformed and weakly metamorphosed Paleozoic strata and Phanerozoic granites. And the Zhangguangcui Range developed a large number of Mesozoic–Cenozoic igneous–sedimentary rocks, as well as Phanerozoic granitoids, presenting as remnants within a granitoids ‘sea’ and a small number of
Proterozoic metamorphic rocks, and Paleozoic strata (Wu et al., 2001; Wang et al., 2006; Ying et al., 2006; Gao et al., 2007; Pei et al., 2007; Zhou et al., 2012a).

Jiamusi Terrane considered to be composed of three rock assemblages: (i) Paleozoic magmatic rocks that distribute chiefly along with the southeastern and eastern edges of the Jiamusi Terrane. (ii) the blueschist–facies Heilongjiang accretionary complex, which was considered as the tectonic suture zone between the Songliao Block and Jiamusi terrane, that distribute along with the western edge of the Jiamusi Terrane and (iii) Mashan metamorphosed complex, which was a granulite–facies terrane formed during the Early Paleozoic (~ 500 Ma) (Yang et al., 2014; Yang et al., 2015).

The Khanka Terrane is composed of carbonate, elastic sediments and volcanic rocks, and is largely situated in Far East Russia, with only a small segment cropping out in NE China (Fig. 1). The Mashan Complex is also present in the Khanka Block, with a westward decrease in metamorphic grade from granulite to amphibolite facies (Wilde et al., 2010; Zhou et al., 2010). Recently, the Khanka Block has been confirmed as forming a single crustal entity with the Jiamusi Block since the Early Paleozoic (Wilde et al., 2010; Zhou et al., 2010; Yang et al., 2014; Guo et al., 2017).

The central Jilin Province is located between the Jamusi–Khanka Terrane to the north and the NCC to the south. It consists of a series of subduction–accretion complexes along the eastern part of the Xra Moron–Changchun suture zone, including the Hulan, Seluohu, Qinglongcun metamorphic complexes, and Kaishantun ophiolitic melange (Hua et al., 2003; Li et al., 2007a; Wu et al., 2007; Zhang et al., 2007). The northern margin of the NCC is known as the “granite ocean”, and contains a lot of Late Palaeozoic to Mesozoic granitoids and sedimentary rocks (Fig. 2a). (Wu et al., 2000; Jahn et al., 2001; Salnikova et al., 2001; Wu, 2001; Li et al., 2007b; Liu et al., 2008a; Liu et al., 2008b; Xie et al., 2008). Our research area is located in the Shitoukoumen area of central Jilin province, which is mainly dominated by Paleozoic strata (Fig. 2b).

3 Samples and Methods

3.1 Samples

The volcanic–sequence that crops out in the Permian Fanjiatun Formation in the Shitoukoumen reservoir near Changchun city.

The collected rhyolitic tuffs are characterized by a welded tuff texture. The rocks are composed of crystal fragments (30–35%), rock fragments (10%), and plastic glass fragments (50%) (Fig. 3a). The size of the rock is mainly the tuff < 2.0 mm, and a small amount of volcanic breccias over 2 mm. The crystal chips are composed of plagioclase, potassium feldspar, quartz and dark minerals. The plagioclase is more common, mainly showing the direction, with a diameter generally < 0.005 mm. Directional distribution, with a diameter < 0.3 mm.

The normal sediment consists of terrigenous sand, clayey material, mixed with tuff. Terrigenous sand is composed of feldspar, quartz and rock debris, mainly feldspar and rock debris, less quartz, mainly angular, subangular, showing directional distribution, the size of the main < 0.05 mm of silt, 0.05–0.1 mm of fine sand. Clayey is composed of cryptocrystalline–microscopical scaly clay minerals, which are mixed with silty sand in a slightly directional distribution, with a diameter generally < 0.005 mm.

The opaque mineral is distributed in linear striation and has been changed into white titanite.

3.2 Methods

3.2.1 LA-ICP-MS U-Pb dating

A Franz magnetic separator and heavy liquid are used to separate zircon at the Hebei Regional Geological Survey, China. Cathodoluminescence (CL) images were got at Beijing GeoAnalysis by using JSM6510 scanning electron microscope. The Inner Mongolia Autonomous Region Institute of Geological Survey Analysis and Test Center used the Neptune Plus multi–receive inductively coupled plasma mass spectrometer (LA-MC-ICP-MS) and Geolas HD 193 nm laser ablation system to date the zircon U-Pb isotope. The Geolas HD laser ablation system produced by the German Coherent Company includes excimer laser devices, optical and mechanical devices, observation devices, computer control and packaging devices, and gas system accessories for two–way trigger control with mass spectrometers. Plešovice, GJ-1 and GJ91500 standard were worked for zircon standard samples. The ICPSMS DataCal program was be worked for data processing; the Isoplott 4.0 program was used for analysis and mapping (Ludwig, 2012), and 206Pb was made for correcting normal lead. Using NIST 610 as an external standard, the content of U, Th, and Pb in zircon samples was calculated (Liu et al., 2008c). Finally, common Pb corrections were made
3.2.2 Major- and trace-element analyses

Major and trace elements (including REE) data were obtained at the National geological experiment testing center, Chinese Academy of Geological Sciences (CAGS). The major elements were analyzed on fused-glass discs using inductively coupled plasma optical emission spectrometry (ICP-OES) equipped with Thermo Scientific™ iCAP™ 7000 Plus Prodigy. The trace elements were analyzed using ICP-MS (Agilent 7500a) fitted with a 193 nm laser sampler. The details of the analysis procedures and techniques are described by (Wu et al., 2006). 32 μm spot size, energy density 10^4/cm^2 and laser repetition frequency 6 Hz, and original count rate. \( \text{^{176}Hf} / \text{^{177}Hf} \) ratio of standard zircon GJ–1, 91500, Mud tank, and Plešovice were used for collection. 176 Hf /\(^{177}\)Hf ratio of standard zircon GJ–1, 91500, Mud tank, and Plešovice were used for collection.

3.2.3 In situ zircon Hf isotope analysis

The LA-MC-ICP-MS instrument and Geolas HD 193 nm instrument were used to determine the in situ zircon Hf isotope at the Inner Mongolia Autonomous Region Institute of Geological Survey Analysis and Test Center. The details of the analysis procedures and techniques are described by (Wu et al., 2006). 32 μm spot size, energy density 10^4/cm^2 and laser repetition frequency 6 Hz, and original count rate. \( \text{^{172}Yb} , \text{^{173}Yb} , \text{^{174}Lu} , \text{^{176}(Hf + Yb + Lu)} , \text{^{177}Hf} , \text{^{178}Hf} , \text{^{179}Hf} , \text{^{180}Hf} , \text{ and } \text{^{182}W} \) were used for collection. 176 Hf /\(^{177}\)Hf ratio of standard zircon GJ–1, 91500, Mud tank, and Plešovice were used for collection.
0.000023(2σ), 0.282299 ± 0.000038(2σ), 0.282501 ± 0.000011 (2σ), and 0.282476 ± 0.000024 (2σ), respectively. The initial 176\text{Hf} / 177\text{Hf} ratio was calculated by measuring the 176\text{Hf}/177\text{Hf} and 176\text{Lu}/177\text{Hf} ratio. The decay constant of 176\text{Lu} is 1.865 × 10^{-11} years (Scherer E. et al., 2001). Now the ratio of chondrites such as 176\text{Lu}/177\text{Hf} = 0.0332 and 176\text{Hf}/177\text{Hf} = 0.282772 as used to calculate the \( \varepsilon_{\text{Hf}}(t) \) value (Blichert-Toft and Albarède, 1997). The age of the Hf model was calculated from the average crust (Amelin et al., 2000).

4 Results

4.1 Zircon U-Pb dating

The results of LA-ICP-MS zircon U-Pb analyses are listed in Table 1 and are plotted in Fig. 5. All the data points were located on or close to the concordia, indicating minimal Pb-loss after zircon crystallization. The zircon grains were transparent to semi-transparent, colorless or light brown, and euhedral. They were generally 100–150 μm long with 2:1–3:1 length to width ratios. The CL images indicated that most of the zircons contained no inherited cores and that they exhibited good oscillatory zoning (Fig. 4).

Twenty-four spots on 24 zircon grains were analyzed in the 170804–2 sample. 19 of them were concordant (Fig. 5). The weighted mean 206\text{Pb}/238\text{U} age of these 19 analyses was 1 = 276.7 ± 3.2 Ma (mean square of weighted deviates [MSWD] = 3.5, 95% confidence). Data–point error symbols are 1σ (Fig. 5). The high Th/U ratios (ranging from 0.2 to 1.19), oscillatory zoning, and euhedral–shaped prisms indicated that they were magmatic zircons.

Twenty-seven spots on 20 zircons were analyzed for sample170804–5; 14 of these were reasonably concordant (Fig. 5). The high Th/U ratios (ranging from 0.56 to 1.98),
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oscillatory zoning, and euhedral shape indicated a magmatic origin. The 14 spots generated a weighted mean of 288 ± 2.7 Ma (MSWD = 2.3, 95% confidence) (Fig. 6).

4.2.2 Major and trace elements

The major and trace element geochemistry of Early–Middle Permian volcanic rocks of the Jilin Province is shown in Table 2.

The Early–Middle Permian volcanic rocks in the study area are rhyolitic–dacitic–andesitic sequence (Fig. 7a). They have SiO$_2$ = 56.28–68.16%, Al$_2$O$_3$ = 11.62–14.78%, TiO$_2$ = 0.29–1.18%, MgO = 2.42–6.23%, Na$_2$O = 4.47–4.95%, K$_2$O = 3.59–4.18% (Table 2), they range from the low-K tholeiite series to high-K calc–alkaline series (Fig.

Fig. 6. Concordia and probability density plots of detrital zircon ages from the sample 170804-5.

Fig. 7. Classification diagrams for the studied volcanic rocks and the Early Paleozoic granitoids in southern Sonid Zuoqi of (a) Total alkali vs. silica, (b) Na$_2$O+K$_2$O–CaO vs. SiO$_2$ (Frost et al., 2001), (c) K$_2$O vs. SiO$_2$ (Peccerillo and Taylor, 1976) and (d) A/NK vs. A/ CNK (A= Al$_2$O$_3$, C= CaO, N= Na$_2$O, K= K$_2$O)(Maniar and Piccoli, 1989).
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### Table 2: Major (%) and trace element (ppm) data from the Early-Late Permian volcanic rocks in central Jilin, NE China

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<th>MgO (%)</th>
<th>Na₂O (%)</th>
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<th>P₂O₅ (%)</th>
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**Note:** The data represent major and trace element compositions from the Early-Late Permian volcanic rocks in central Jilin, NE China. The values are given as percentages for major oxides and parts per million for trace elements.
A molecule $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ (A/NK) versus a molecular $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ (A/CNK) diagram indicated that all of the samples were from metaluminous to peraluminous ($A$/CNK $= 0.62–1.33$ and $A$/NK $= 1.19–1.89$) (Fig. 7d) (Maniar and Piccoli, 1989).

The geochemical data of the representative related Early Triassic granites we collected from (Sun et al., 2004), were used for a detailed comparison with these volcanic rocks. Moreover, an ascending tendency in $K_2O$ from the low-$K$ to high-$K$ series was also observed (Fig. 7c). Finally, the tendency of $A$/CNK increases and the tendency of $A$/NK decreases, showing the transition from metaluminous to peraluminous (Fig. 7d).

The total REE content of these volcanic rocks is around 67.71–143.7 with light REE (LREE)/heavy REE (HREE) values of 3.67–9.51. Chondrite–normalized REE patterns show moderate enrichment in LREE and depletion of HREE (flat patterns; Fig. 8a), with (La/Yb)$_n$ values of 4.94–22.96, (La/Sm)$_n$ values of 2.80–4.89, and (Gd/Yb)$_n$ values of 1.60–3.74. The negative Eu anomalies are clear (Eu/Eu* values of 0.20–0.37), indicating the fractional crystallization of plagioclase. The REE patterns are similar to those found in arc magmatism. In comparison, the Early Triassic (248 Ma) have relatively lower REE abundances (Fig. 8c) than those of the Early–Middle Permian (290 Ma–270 Ma) volcanic rocks (this study). In addition, they do not have negative, but instead slightly positive, Eu anomalies, indicating little accumulation of plagioclase (Sun and Mcdonough, 1989).

4.2.3 Zircon Hf isotopes

The results of in situ Hf isotopic analysis of zircons from 40 samples are given in Table 3. The Hf isotopic compositions of 20 zircons from dacitic rock were analysed in this paper (276.7 ± 3.2 Ma, sample 170804-2) have $^{176}\text{Hf}/^{177}\text{Hf}$ values of 0.030338–0.073306, with $\varepsilon_{\text{Hf}}(t)$ values of +7.1 to +16.2, $T_{\text{DM1}}$ values of 284–652 Ma, and $T_{\text{DM2}}$ values of 274–948 Ma.

The Hf isotopic compositions of 20 zircons from rhyolitic rock were analysed in this paper (288.1 ± 2.7, sample 170804-5) have $^{176}\text{Hf}/^{177}\text{Hf}$ values of 0.032578–0.103758, with $\varepsilon_{\text{Hf}}(t)$ values of +7.7 to +17, $T_{\text{DM1}}$ values of 245–623 Ma, and $T_{\text{DM2}}$ values of 210–890 Ma.

5 Discussions

5.1 Late Paleozoic–Early Mesozoic magmatism in the eastern segment of CAOB

The magmatism within central Jilin Province discussed
here were previously thought to be Silurian, Devonian–Early Carboniferous, Early–Middle Permian, and Triassic in age, with these ages based on lithostratigraphic relationships with sedimentary or granitoid country rocks of various ages (JBGMR, 1988; JBGMR, 1997). Late Paleozoic–Early Mesozoic is considered as the critical time about the final closure of the Paleo–Asian Ocean (JBGMR, 1988; JBGMR, 1997; Xiao et al., 2009; Xu et al., 2009; Pei et al., 2016b; Pei et al., 2016a; Wang et al., 2016a; Wang et al., 2016b; Ge et al., 2017; Guo et al., 2017; Isozaki et al., 2017; Liu et al., 2017; Xu et al., 2018).

Only a small number of magmatism happened in the Early–Middle Permian in the eastern segment of the CAOB, and has to date only been documented in the southeastern margin of the Jiamusi Terrane (Yang et al., 2013; Yang et al., 2014; Bi et al., 2015; Hao et al., 2015; Yang et al., 2015; Dong et al., 2017).

Late Permian–Early Triassic magmatism is widespread throughout central Jilin Province and adjacent regions including intrusions such as Dahangshan quartz syenite (264 Ma), the Yumuchuan sillite (264–262 Ma), the Permian granodiorite (263 Ma) and gabbro (262 Ma), the Dahongshilazi alkali feldspar granite (260 Ma), Qingyang syenogranite (259 Ma), the Anyi monzogranite (252 Ma), and Dayushan granite (248 Ma) (Sun et al., 2004; Feng et al., 2010; Liu et al., 2010; Wu et al., 2011; Cao et al., 2013; Pei et al., 2016b; Wang et al., 2016b). However, Scientists pay more attention on the granitoids, there is a lack of precise geochronological data about volcanic rocks.

In the present study, we identified a rhyolitic–dacitic–andesitic sequence from Fanjiatun Formation that yielded two zircon U–Pb ages of 288 ± 2.7 Ma, and 276 ± 3.2 Ma from the two volcanic rock samples. Apparently, this volcanism is synchronous with one arc–related tectonic–thermal event in Early–Middle Permian. The reasons will be discussed in detail below.

5.2 Petrogenesis

The Early–Middle Permian rhyolitic–andesitic sequence exhibits a changing trend in geochemical characteristics from a low-K tholeiite series to a high-K calc–alkaline series, and from a metaluminous to a peraluminous concentration. This indicates that the large-ion lithophile element (LILE)-enriched, high-field-strength element (HFSE)-depleted, and negative europium (Eu) anomalies are very similar to those of the arc-derived magmatic rocks (Dare et al., 2014), which implies that the magma source is modified by subducted slab-derived fluids (Pearce et al., 1984; Donnelly et al., 2004; Dare et al., 2014; Yang, 2015). The collected samples have negative tantalum (Ta), niobium (Nb), and titanium (Ti) (TNT) anomalies, which are typical characteristics of subduction-related magma. (Ryerson and Watson, 1987; Castro et al., 2010; Castro, 2013). This data indicates that the primary magma that formed these rhyolitic–andesitic sequences was likely derived from the partial melting of a depleted lithospheric mantle that had been modified by subducted slab-derived fluids. Moreover, these sequences have a tendency to change from low to high alkali concentrations and small to large compositional variations of potassium (K), suggesting that they are derived from different primary magmas and have differing fractionation histories.

Previous researchers have focused on the petrography and geochemistry of the Late Permian–Early Triassic period to reveal the petrogenesis during these periods (Yang et al., 2015; Pei et al., 2016a; Wang et al., 2016a; Liu et al., 2017). In this study, the Early–Middle Permian andesites, low-to-moderate K, calcic-to-calcic–alkaline trend, and metaluminous plutons, combined with the coherent granites, were likely generated from a juvenile mid-low crust in an arc setting. (Roberts and Clemens, 1993; Donnelly et al., 2004; Dare et al., 2014). Meanwhile, the Early Triassic high-silica, high-K, calcic–alkaline, and peraluminous granites have the combined characteristics of deformed mantle and continental materials, which were likely formed in a syn-collisional setting (Roberts and Clemens, 1993; Donnelly et al., 2004; Dare et al., 2014).

The geochemical data obtained from the representative magmatic rocks from the Early–Middle Permian and Early Triassic periods (Sun et al., 2004) were used for comparing the tectonic setting in detail. Herein, the tectonic setting discrimination diagrams shown in Fig. 9 were used for replotting, along with the geochemical data, of the volcanic rocks (this study) and previous granitoids. Herein, the tectonic setting discrimination diagrams shown in Fig. 9 were used for replotting, along with the geochemical data, of the volcanic rocks (this study) and previous granitoids. First, they shifted from volcanic arc granite (VAG) at earlier times to syn-collisional granite (Syn-COLG) at more recent times in the Ta vs. yttrium (Y) diagram (Fig. 9a) and at all the plots in the VAG + Syn-COLG field in the Nb vs. Y diagram (Fig. 9b) (Pearce et al., 1984). Second, as indicated by the R1 vs. R2 tectonic setting discrimination diagram shown in Fig. 9c (Batchelor and Bowden, 1985), here was a variation tendency from preplate collision to syn-collision, which followed a chronological order. Finally, in the discrimination diagram of Rb/Zr vs. Nb for arc maturity (Fig. 9d) (Brown et al., 1984), the arc evolved from a primitive arc at 288–275 Ma to a normal continental arc at 248 Ma, which corresponds with an Early–Middle Permian andesitic sequence and the Early Triassic high-silica, high-K, calcic–alkaline, peraluminous granites. Thus, the Early Permian–Early Triassic tectonic activity evolved from an arc stage to a collisional stage, which indicates a subduction–accretion event in the eastern CAOB.

In the La/Sm vs. La diagram (Fig. 10) (Bougault et al., 1979), the Early–Middle Permian rhyolitic–andesitic volcanic rocks (this study) and Early Triassic granites are plotted in terms of an increasing tendency for partial melting and fractional crystallization. The Early–Middle Permian rhyolitic–andesitic volcanic rocks with a negative Eu anomaly were mostly generated from the partial melting of the basaltic magma, while some emerged from a depleted lithospheric mantle modified by fluids. Meanwhile, the Early Triassic high-K granites indicate a complicated petrogenesis in the partial melting of the arc and continental materials, which was caused by a subduction–accretion event (Sun and Mcdonough, 1989;
Dare et al., 2014; Yang, 2015).

Hf isotope methods are a responsible approach for the crustal evolutional research (Wu et al., 2007). Zircon Hf isotope compositions can be used for constraining the sourcing of the primary magma, for example, with zircons from Phanerozoic igneous rocks within the NCC have negative $\varepsilon_{Hf}(t)$ values (Yang et al., 2006; Liu et al., 2017), whereas those within igneous rocks of the CAOB having positive $\varepsilon_{Hf}(t)$ values (Liu et al., 2010; Cao et al., 2013; Shi et al., 2019; Shi et al., 2020). The positive $\varepsilon_{Hf}(t)$ values (7.1 to 17), and Hf two–stage model ages (284–652 Ma and 210–890 Ma) of zircons from the Early–Midlle Permian rhyolitic–andesitic sequence, suggest that the primary magma for these volcanic rocks, was probably derived from partial melting of a depleted lithospheric mantle of the CAOB (Fig. 11).

5.3 Implications for the tectonic evolution of the eastern CAOB

The variation tendency in the geochemical composition of the associated magmatism presents an effective approach for researching the tectonic evolution of orogenic belts (Pearce et al., 1984; Holland and Powell, 2003; Dare et al., 2014). Herein, we can reconstruct the tectonic evolutional history of the central Jilin Province by using the volcanic rock sequence and intrusive rocks as
discussed above. As noted above, the Late Paleozoic–Early Mesozoic magmatism in the central Jilin Province can be divided into two stages: a volcanic arc setting due to subduction, and a syn-collisional stage following continent–continent collision (Fig. 12.).

5.3.1 Early–Middle Permian subduction stage

The Early–Middle Permian magmatism that is relevant to our study area is composed of rhyolitic–andesitic volcanic rocks ranging in chemical composition from metaluminous to peraluminous. Peraluminous magmatic rocks are generally thought to be formed in compressional tectonic settings associated with the crustal thickening that occurs during collisional orogenic events (Pearce et al., 1984; Ryerson and Watson, 1987; Roberts and Clemens, 1993; Hofmann, 2003; Donnelly et al., 2004; Castro, 2013). Herein, the primary mafic lower crust is metamorphosed and undergoes tectonic thickening (Pearce et al., 1984; Ryerson and Watson, 1987; Dare et al., 2014). The thickening of the lower crust subsequently causes the partial melting of the lithospheric mantle, which triggers magma with highly intense TNT anomalies during the compressional stage (Pearce et al., 1984; Ryerson and Watson, 1987; Dare et al., 2014). These data indicate that the Early–Middle Permian rhyolitic–andesitic volcanic rocks formed in a crustal-thickening-related, compressional, tectonic setting during one such collisional orogenic event (Pearce et al., 1984; Hofmann, 2003; Donnelly et al., 2004). This view corresponds with the regional tectonic background of the area in question. In fact, the area underwent Early Permian subduction of the Paleo-Asian oceanic plate beneath the northern margin of the NCC (Fig. 10a) (Shi et al., 2020), and the subsequent regional sedimentation indicates that the Paleo-Asian Ocean evolved into an intercontinental remnant marine basin at the end of the Early Permian period due to the continuous subduction of the Paleo-Asian oceanic plate (Shi et al., 2019; Shi et al., 2020), which represents the initial collision between the microcontinents of NE China and northern margin of the NCC (Li, 2006). This strongly suggests that the formation of the Early–Middle Permian rhyolitic–dacitic volcanic rocks was associated with a subduction in the central Jilin Province (Fig. 12a).

5.3.2 Late Permian–Early Triassic final closure of the Paleo–Asian Ocean

The Late Permian–Early Triassic magmatism in the central Jilin Province is dominated by granitoids and very little associated volcanic rocks (Pei et al., 2016a; Ge et al., 2017; Liu et al., 2017). Li et al. (2007a) reported that the Seluohe Complex with andesite zircon U–Pb ages of 252 ± 5 Ma may have formed during the Late Permian period. These andesites have high Mg geochemical characteristics (MgO = 3.68%–5.30%; Sr = 258 ppm), indicating that they formed owing to the partial melting of an enriched mantle wedge, which would have been modified by the injection of aqueous fluids from sediments along the subduction zone, followed by fractional crystallization during the ascent of the magma (Pearce et al., 1984; Hofmann, 2003; Donnelly et al., 2004; Sun et al., 2004) reported an age of 248 ± 4 Ma for the Dayushan syn-collisional high-K, I-type granites. In general, I-type granites can be formed through the mixing of mantle-derived basaltic magmas and crustal melts or partial melting of mafic magma (Roberts and Clemens, 1993; Wu et al., 2003). However, the experimental data suggest that
high-K, I-type granitoid magmas can be derived only from the partial melting of hydrous, high-K calc-alkaline series, which is intermediate to the mafic, metamorphic rocks in the crust (Roberts and Clemens, 1993; Wu et al., 2003). From the regional tectonic setting, we know that the Early Triassic high-K, I-type granitoids in this area reflect magma generation in the partial melting of mafic magma, which is enriched through some interaction with the fluids evolved from downgoing, dehydrating slabs. (Sun and Mcdonough, 1989; Donnelly et al., 2004; Dare et al., 2014). The thickness of the continental crust due to the hybrid magma that had ascended to the upper crust resulted in weak to no TNT anomalies and an enrichment of incompatible elements (Pearce et al., 1984; Roberts and Clemens, 1993; Holland and Powell, 2003) (Fig. 12b).

Thus, it can be concluded that the NCC and SC collided during the Late Permian period as the slab subducted, and that the closure of the Paleo-Asian Ocean occurred before the Early Triassic period.

6 Conclusions

Based on zircon U-Pb ages and Hf isotopic data, as well as geochemical data presented above, and comparison with other research, we draw the following conclusions:

(1) These volcanic rocks were probably arc derived from partial melting of a depleted lithospheric mantle that was modified by subducted slab–derived fluids.

(2) Late Paleozoic–Early Mesozoic magmatism in the eastern segment of the northern margin of the NCB can be subdivided into two stages: Early–Middle Permian (290–270 Ma) and Late Permian–Early Triassic (260–240 Ma)

(3) The subduction of the Paleo–Asian Ocean probably terminated before Early Triassic.

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