U-Pb ages and Hf isotopic composition of zircons and whole rock geochemistry of volcanic rocks from the Fangniugou area: Implications for early-middle Paleozoic tectonic evolution in Jilin Province, NE China

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The Changchun-Yanji suture in Jilin Province, NE China is generally interpreted to mark the closure position of the Paleo-Asian Ocean along the north margin of the North China Craton. However, the issue about the early-middle Paleozoic tectonic evolution in this region has long been debated. In order to provide evidence for resolving this issue, we carried out a geochemical and zircon U-Pb-Hf study on the Fangniugou and Taoshan volcanic rocks from the Fangniugou area of Jilin Province, in the Changchun-Yanji suture zone. Laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) zircon U-Pb dating indicates that the Fangniugou volcanic rocks are products of at least two volcanic events (~ 425 and 390 Ma) and that episodes of magmatism existed in Jilin Province during the early-middle Paleozoic period. These rocks, in conjunction with relevant data from the literature, indicate that early-middle Paleozoic magmatism occurred along the Changchun-Yanji suture. The volcanic rocks belong to medium- to high-K calc-alkaline series and display features of I-type granites of subduction-related igneous rocks. During the late Silurian-middle Devonian, the Y and Yb concentrations progressively decreased with time, accompanied by an increase in K₂O concentrations and (La/Yb)_N values, indicating a process of crustal thickening. This interpretation is supported by the presence of early Paleozoic arc igneous rocks and the formation of early Devonian molasse in central Jilin Province. Zircon grains separated from the rocks have high $\epsilon_{\text{Hf}}(t)$ values and two-stage Hf model (T_{DM2}) ages varying from +4.92–8.76 and 0.84–1.09 Ga, respectively. All these characteristics, in conjunction with trace element features, suggest that the late Silurian rocks were generated by partial melting of a depleted mafic lower crust in a subduction zone setting, whereas the middle Devonian rocks were derived from partial melting of a thickened lower crust the most probably related to a collisional event.

Keywords: Early-middle Paleozoic, Geochronology, Geochemistry, Volcanic rocks, NE China

INTRODUCTION

Northeastern (NE) China, which has been tectonically referred to as the Xing'an-Mongolia (or Xing-Meng) Orogenic Belt (XMOB) in the past, forms part of the eastern segment of the Central Asian Orogenic Belt, a region that

experienced the amalgamation of multiple microcontinental blocks (Fig. 1a: the Erguna, Xing'an, Songliao-Xilinhot, Jiamusi, and Khanka blocks) (Şengör et al., 1993; Wu et al., 2007; Tang et al., 2013; Bi et al., 2014; Liu et al., 2017). Li (1998, 2006) described this amalgamated continent as the Burean-Jiamusi block or paleoplate. During the long tectonic history, the region between this amalgamated block and the North China Craton (NCC) had close relationships with the Paleozoic evolution of the eastern

Figure 1. (a) Tectonic sketch map of NE China, modified after Liu et al. (2017). (b) Detailed geological map of study region and the sampling localities for the studied volcanic rocks.

segment of the Paleo-Asian Ocean (PAO), the Mesozoic-Cenozoic subduction of the Paleo-Pacific oceanic plate and the long-distance effect of the collisional orogeny of the Mongol-Okhotsk domain, which is considered as being a possible dynamic mechanism for Mesozoic magmatic activity and crustal shortening in NE China (Davis et al., 1998; Meng, 2003; Li 2006; Windley et al., 2007; Wu et al., 2007; Wilde and Zhou, 2015; Liu et al., 2017). Therefore, it is critical to understand the tectonic history of this area, which will shed light on the Paleozoic evolution of the eastern segment of the PAO.

The eastern segment of the northern margin of the NCC is adjacent to the south margin of the XMOB bounded by the Changchun-Yanji suture (Fig. 1a). The Changchun-Yanji suture is considered to mark the closure position of the PAO (Xiao et al., 2003; Li, 2006; Xiao et al., 2009; Liu et al., 2010; Cao et al., 2013; Xiao et al., 2015;

Liu et al., 2017). This area is dominated by the Phanerozoic granitoids with minor mafic-ultramafic intrusives, and limited outcrops of Neoproterozoic-Cenozoic volcanics and sediments [Jilin Bureau of Geology and Mineral Resources (JBGMR), 1988; Wu et al., 2007, 2011]. Subjected by intensive alteration and destruction which were induced by late Paleozoic orogeny and the middle-late Cenozoic circum Pacific orogeny, as well as the inundation of large amount of granite, the early Paleozoic geologic masses occur as roof pendant. With the continuous improvement of zircon U-Pb dating technique, more and more strata (e.g., Hulan Group and Xiaertai Group) and plutons (e.g., Dayushan pluton and Huangnihe pluton), previously thought to be the products of Caledonian movement, have proven to be formed during the late Paleozoic or early Mesozoic (Jia et al., 2004; Zhang et al., 2004; Wu et al., 2007, 2011; Wang et al., 2015b). There-

fore, the existence of early Paleozoic accretionary tectonic belt is being called into question (Wu et al., 2004). This issue restrains our recognition to the early Paleozoic tectonic evolution of the PAO.

In this contribution, we focus on the Fangniugou volcanic rocks and the Taoshan Formation, which were previously thought to be late Ordovician–Silurian (Fig. 1b), since these rocks are located along the Changchun–Yanji suture and tectonically experienced the evolution of the PAO during the Paleozoic. Here, we present results of U–Pb dating and Hf isotopic composition of zircons, and whole-rock geochemical analyses of these volcanic rocks. These data provide new evidence for the existence of early–middle Paleozoic magmatism and enable us to further constrain the early–middle Paleozoic tectonic evolution of the eastern segment of the PAO.

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

The Fangniugou area is located in the Daheishan Horst, which connects the Solonker–Xar Moron–Changchun suture and Changchun–Yanji suture (Fig. 1a). The previously established view was that several groups of early Paleozoic strata crop out in this area, including the Jingtai marbles, Fangniugou volcanic rocks, Taoshan Formation and Daheishan volcanic rocks (Fig. 1b). The Taoshan Formation is dominated by black graptolite-bearing slate, siltstone, tuffaceous siltstone and minor interbedded intermediate–acid volcanic rocks. It was previously identified as early Silurian in age on the basis of the recognition of graptolites from the slate (Peng et al., 1979). Zircon SHRIMP U–Pb data of volcanic rocks from the Taoshan Formation (collected from Daheishan and Duanjiadian) demonstrated that these volcanic rocks formed during the late Silurian (Jiang et al., 2014a). The U–Pb ages of inherited zircons from these volcanic rocks reflect multiple volcanic activities occurred during the middle Ordovician, late Ordovician, early Silurian and middle Silurian. The Jingtai marbles, Fangniugou volcanic rocks and Daheishan volcanic rocks are dominated by marble, calcareous sandstone, quartz schist and foliated volcanic rocks. The ages of these rocks were previously assigned to late Ordovician based on lithostratigraphic relationships and regional correlations (Jia, 1994; Wu, 1994; Jiang et al., 2014b). However, laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) zircon U–Pb dating of calcareous sandstone, quartz schist and volcanic rocks (Han et al., 2017; Han Z.Z et al., unpublished data, 2017) show that the ages of the Jingtai marbles and Daheishan volcanic rocks are Permian–Triassic. The above–mentioned geochronological data indicate that

the previous age estimates of the Paleozoic strata in the study area are unreliable. To constrain the age of the Fangniugou volcanic rocks, which lack geochronological data, we collected magmatic zircons for U–Pb dating from two samples from the Fangniugou volcanic rocks. The samples are described below.

Sample HXT1 is a rhyodacite that was collected from Hongxitang village (Fig. 1b: 43°28′04″N, 125°08′51″E). The rock is greyish–green, displays a porphyritic texture and a massive structure (Figs. 2a and 2b). The phenocrysts are mainly K–feldspar, while the groundmass is composed of felsic minerals with sericitic alteration.

Sample LS1 is a rhyolite that was collected from ~ 0.4 km northeast of Liuyang village (Fig. 1b: 43°28′27″N, 124°59′39″E). This sample is dark grey in colour, with a porphyritic texture and a massive structure (Figs. 2c and 2d). The phenocrysts consist of quartz and sanidine, and the groundmass is composed of felsic minerals with spherulitic texture.

Three samples from the HXT rhyodacite and three samples from the LS rhyolite were chosen for geochemical analyses. In addition, four volcanic samples from the Taoshan Formation outcropping in Daheishan (DH1 and DH2: ~ 413 Ma) and Duanjiadian (DJ1 and DJ2: ~ 392 Ma), the ages of which were obtained using SHRIMP U–Pb dating (Jiang et al., 2014a), were also collected for geochemical study. The DH samples were named as ignimbrite, while the DJ samples were described as foliated dacite from field observation (Figs. 2e and 2f). Their locations are shown in Figure 1b and their petrographic descriptions can be found in Jiang et al. (2014a).

ANALYTICAL METHODS

Zircon U–Pb analysis

Zircon grains were separated from whole-rock samples by conventional magnetic and heavy liquid techniques before hand-picked under a binocular microscope at Langfang Regional Geological Survey, Hebei Province, China. They were embedded in epoxy and polished down to half size and cleaned in an acid bath before analysis. Cathodoluminescence (CL) images were taken using JEOL JXA–8900RL scanning electron microscope at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China.

Zircon trace elements and U–Th–Pb isotopes were simultaneously determined using an Agilent 7500a ICP–MS equipped with a 193 nm laser ablation system GeoLas 2005 at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China. The instrument parameter and detail procedures were described by Yuan

Figure 2. Field photographs and photomicrographs of the volcanic rocks from the Fangniugou area in Jilin Province, NE China. (a) Outcrop of the HXT rhyodacite, (b) photomicrograph of the HXT rhyodacite, crossed polarized light, (c) outcrop of the LS rhyolite, and (d) photomicrograph of the LS rhyolite, crossed polarized light. Abbreviations: Q, quartz; Kfs, K-feldspar; Srt, sericitic alteration; Pl, plagioclase. Color version is available online from <https://doi.org/10.2465/jmps.170708>.

et al. (2004). The laser spot size was 32 μm with a repetition rate of 6 Hz during the analyses. The zircon 91500 was used as an external standard for age calibration, and the NIST SRM 610 silicate glass was applied for instrument optimization. In addition, GJ-1 (Jackson et al., 2004) was treated as a secondary standard as an unknown. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for GJ-1 was 598.6 ± 5.2 Ma ($n = 12$), consistent within uncertainty with the recommended values (GJ-1: 599.81 ± 1.7 Ma, Jackson et al., 2004). The relative standard deviations of the refer-

ence values for 91500 were set at 2%, and the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios were calculated using GLITTER 4.0 (Van Achterbergh et al., 2001). Common Pb corrections were made following the method of Andersen (2002). Weighted mean ages and concordia diagrams were created using Isoplot 3.0 (Ludwig, 2003). The analytical data are presented with 1σ error boxes on the concordia plots and uncertainties in weighted mean ages are quoted at 95% confidence level (2σ). The zircon U-Pb age data and trace element data for two volcanic samples are presented in

Supplementary Tables S1 and S2, respectively (Tables S1 and S2 are available online from <https://doi.org/10.2465/jmps.170708>).

Zircon Hf isotopic analysis

Zircon Hf isotope analyses were conducted in the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China, using a Nu Plasma HR multiple collector (MC)-ICP-MS coupled with Geolas 2005 laser-ablation system. The Hf analyses were made on the same spots previously used for U-Pb isotope dating with a spot size of 44 μm and a repetition rate of 10 Hz. Helium was used as the carrier gas to transport the ablated sample from the laser-ablation cell to the MC-ICP-MS torch and was mixed with argon. The analytical procedures are similar to those described by Xu et al. (2004). Interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of an interference-free ^{175}Lu isotope and also a recommended $^{176}\text{Lu}/^{175}\text{Lu}$ ratio of 0.02655 to calculate $^{176}\text{Lu}/^{177}\text{Hf}$ ratios (Chu et al., 2002). Similarly, interference of ^{176}Yb on ^{176}Hf was corrected by measuring an interference-free ^{172}Yb isotope and using a $^{176}\text{Yb}/^{172}\text{Yb}$ ratio of 0.5886 to calculate $^{176}\text{Yb}/^{177}\text{Hf}$ ratios (Chu et al., 2002). Zircon 91500 was used as the reference standard, with weighted mean $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282314 ± 0.000011 ($n = 34$, 2σ). The decay constant for ^{176}Lu of $1.867 \times 10^{-11} \text{ year}^{-1}$ (Albarède et al., 2006) and the present-day chondritic ratios of $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$ (Bouvier et al., 2008) were adopted to calculate $\varepsilon_{\text{Hf}}(t)$ values. Single-stage model ages (T_{DM1}) were calculated using a depleted mantle with a present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.28325 and $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0384 (Griffin et al., 2000). Two-stage model ages (T_{DM2}) were calculated using an assumed $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.015 (Rudnick and Gao, 2003) for the average continental crust.

Whole-rock geochemical analysis

The major and trace element concentrations of the whole-rock samples were determined at the Supervision and Inspection Center of Mineral Resources, the Ministry of Land and Resources of Jinan, China. The concentrations of SiO_2 and Al_2O_3 were analyzed using the gelatin coagulation gravimetric method and the xylenol orange method, respectively. The other major oxides and some trace elements, (Ba, Sr, V, and Cr) were determined by IRIS-Intrepid ICP atomic emission spectrometer (AES) using the standard analytical protocol of GB/T14506-2010 for the oxides. Detailed analytical procedures are similar to those described by Rudnick et al. (2004). Analytical uncertainties range from 1 to 5%. The other trace element

concentrations were determined using an X-Series 2 ICP-MS, and the analytical procedures are similar to those described by Li (1997). All samples were crushed and powdered in an agate mortar. Precisely weighed sample powders (50 mg) were dissolved in Teflon bombs in $\text{HF} + \text{HNO}_3$. An internal standard solution containing the single element Rh was used to monitor signal drift during counting. The USGS rock standards AGV-1, G-2, and W-2 and the Chinese national rock standards GSR-1 and GSR-3 were chosen for calibrating element concentrations of measured samples. Analytical uncertainties were generally less than 5%. The data are listed in Supplementary Tables S3 and S4 (Tables S3 and S4 are available online from <https://doi.org/10.2465/jmps.170708>).

ANALYTICAL RESULTS

Zircon U-Pb geochronology

Zircons from the samples in this study occur as euhedral to subhedral crystals (80–200 μm in length), with aspect ratios of ~ 1 –2. CL imaging and LA-ICP-MS analysis revealed that these zircons show fine-scale oscillatory growth zoning (Fig. 3), high Th/U ratios (Table S1; available online from <https://doi.org/10.2465/jmps.170708>), and magmatic rare earth element (REE) patterns with steeply increasing from La to Lu, positive Ce and negative Eu anomalies (Fig. 4), indicating a magmatic origin (Hoskin and Ireland, 2000; Corfu et al., 2003; Hoskin and Schaltegger, 2003).

Fifty-eight zircon grains from sample HXT1 were analyzed, 57 of which are concordant with concordance within 90–110 percent (Table S1). Fifty-eight analyses yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 421–489 Ma (Figs. 4a and 4c). Considering that the measuring points were on oscillatory zonings, the U-Pb ages should represent the crystalline age of zircons, and that the asymmetric distribution is caused by the captured zircons (Zhang et al., 2015; Du et al., 2017). The youngest group age of late Silurian gives a weighted mean age of $425 \pm 4 \text{ Ma}$ ($\text{MSWD} = 0.04$, $n = 16$), which is interpreted as the timing of the rhyodacite eruption, whereas the remaining older ages reflect that continuous and multiple magmatic activities occurred in the study area from the early Ordovician to middle Silurian.

Twenty-seven spots were analyzed on 27 zircon grains from sample LS1, and the obtained $^{206}\text{Pb}/^{238}\text{U}$ ages are concordant or near concordant and range from 385 to 446 Ma (Figs. 4b and 4d). Similar to sample HXT1, the youngest group age of middle Devonian gives a weighted mean age of $390 \pm 4 \text{ Ma}$ ($\text{MSWD} = 0.15$, $n = 12$), which is interpreted as the timing of the rhyolite eruption. The re-

Figure 3. Representative CL images of zircons from Fangniugou area, Jilin Province, China. (a) Zircons from sample HXT1 and (b) zircons from sample LS1. Numbers below the images show zircon ages and $\epsilon_{\text{Hf}}(t)$ values. The solid-line and dash-line circles represent locations for U-Pb dating and Lu-Hf isotope analysis, respectively.

maining older ages reflect that continuous and multiple magmatic activities occurred in the study area from the late Ordovician to early Devonian.

Whole rock major and trace elements

Geochemically, the volcanic rocks in this study consist of dacite, rhyodacite and rhyolite as shown in the total alkalis versus SiO_2 (TAS) and Zr/Ti versus Nb/Y diagrams (Figs. 5a and 5b). The rocks contain $\text{SiO}_2 = 69.06\text{--}74.90$ wt%, $\text{K}_2\text{O} + \text{Na}_2\text{O}$ (total alkaline) = $5.98\text{--}7.66$ wt%, $\text{Al}_2\text{O}_3 = 10.81\text{--}14.58$ wt%, and $\text{Mg\#} = 37.51\text{--}47.24$. In the K_2O versus SiO_2 diagram, these samples plot within the medium- and high-K calc-alkaline series (Fig. 5c). The A/NK and A/CNK values of all samples range from 1.03–1.65 and 0.93–1.34, respectively, and plot in the

metaluminous and peraluminous fields in the A/NK versus A/CNK diagram (Fig. 5d).

All samples are characterized by enrichment of light rare elements (LREEs) and depletion of heavy rare earth elements (HREEs) $[(\text{La/Yb})_N = 4.24\text{--}21.65]$, where the subscript N indicates normalized to chondrite] in the chondrite-normalized rare earth element diagram (Fig. 6a). They show weak negative Eu ($\delta\text{Eu} = 0.55\text{--}0.86$) and Sr anomalies, which are thought to be caused by plagioclase fractionation, either in the solid residuum left by partial melting or via fractional crystallization (Green, 1994). In the primitive mantle normalized trace element spidergram, all samples show characteristics of enrichment of large ion lithophile elements (LILEs: e.g., Rb, Ba, Th, and U) and depletion of high field strength elements (HFSEs: e.g., Nb, Ta, P, and Ti) (Fig. 6b).

Figure 4. LA-ICP-MS U-Pb concordia diagrams (a) and (b), age data histograms with probability curves (c) and (d), and chondrite-normalized REE patterns of zircons (e) and (f) for the volcanic rocks from the Fangniugou area in Jilin Province, NE China.

Hf isotopic composition

Hafnium isotope concentrations were collected for 17 zircon grains from sample HXT1 and 14 zircons from sample LS1 (Supplementary Table S5; available online from <https://doi.org/10.2465/jmps.170708>). The magmatic zircons from these samples have relatively homogeneous Hf isotopic compositions with initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282674–0.282776, $\varepsilon_{\text{Hf}}(t)$ values of +4.92 to +8.76 and corresponding single-stage model ages (T_{DM1}) of 0.67–0.86 Ga and two-stage Hf model ages (T_{DM2}) of

0.84–1.09 Ga.

DISCUSSION

Ages of volcanic eruptions

Zircon crystals separated from the Fangniugou volcanic rocks are characterized by oscillatory growth zoning, high Th/U ratios (0.38–1.20), and magmatic REE patterns with positive Ce and negative Eu anomalies (Fig. 4), indicative of a magmatic origin. This indicates that the U–

Figure 5. Classification of the volcanic rocks from the Fangniugou area in Jilin Province, NE China. (a) Total alkali versus SiO_2 diagram (Irvine and Baragar, 1971), (b) Zr/Ti versus Nb/Y diagram (Winchester and Floyd, 1977), (c) K_2O versus SiO_2 diagram (Peccerillo and Taylor, 1976), and (d) A/NK versus A/CNK diagram (Maniar and Piccoli, 1989). The literature data of late Silurian to middle Devonian igneous rocks are from Pei et al. (2016).

Pb ages most likely represent the crystallization ages of the zircon grains. The zircon U-Pb dating undertaken during this study, together with the U-Pb ages of typical magmatic zircons from Taoshan meta-volcanic rocks (biotite schist and acidic ignimbrite) reported by Jiang et al. (2014a), indicates that the volcanic rocks in the Fangniugou area are products of at least two volcanic events, with one occurred during the late Silurian (~ 425 Ma), while the other one occurred during the middle Devonian (~ 390 Ma), rather than the late Ordovician or early Silurian as reported previously (Peng et al., 1979; JBGMR, 1988; Jia, 1994; Wu, 1994; Jiang et al., 2014b). Additionally, abundant zircon xenocrysts in these samples have ages of early Ordovician to middle Silurian, comparable to ages of recently recognized magmatic rocks (e.g., Zhangjiatun tonalite and Xiaosuihe pyroxene andesite) in the adjacent area (Pei et al., 2016), although magmatic rocks forming at these phases are not exposed or have been destroyed at the present erosion level in the Fangniugou area.

Geochemical and isotopic constraints on petrogenesis of the volcanic rocks

The Fangniugou and Taoshan volcanic rocks are characterized by relatively high SiO_2 (68.45–74.90 wt%), Al_2O_3 (10.81–14.58 wt%) and low TiO_2 (0.13–0.55 wt%), MgO (1.38–2.23 wt%), and CaO (0.31–2.56 wt%). These rocks are metaluminous and peraluminous, with $\text{A/NK} > 1.0$ and $\text{A/CNK} < 1.1$ or close to 1.1 (except one 1.34). It is shown that Y and Th of these rocks positively correlate with Rb (Figs. 7a and 7b), P_2O_5 positively correlate with SiO_2 , whereas Pb has a negative correlation with increasing SiO_2 (Figs. 7c and 7d). These features show affinity to I-type or A-type granites (Chappell and White, 1992; Li et al., 2007). In addition, the absence of mafic alkaline minerals (Fig. 3), together with relatively low contents of Zr, Nb, Y, La, Ce, Zn, and Ga, suggests that these rocks belong to I-type rather than A-type (Wu et al., 2003). These rocks are further characterized by low $\text{Mg\#}$ of 37.51–47.24 and T_{DM2} model ages range from 1.09 to 0.84 Ga suggesting generation by partial melting of juve-

Figure 6. (a) Chondrite-normalized rare earth element patterns, (b) primitive mantle-normalized trace element spider diagram, (c) Sr/Y versus Y diagram (Defant and Drummond, 1990), and (d) $(La/Yb)_N$ versus Yb_N diagram (Martin et al., 2005). Chondrite and primitive mantle values are from Boynton (1984) and Sun and McDonough (1989), respectively. Symbols are as in Figure 5.

Figure 7. (a)–(b) Y versus Rb diagram, Th versus Rb diagram (Li et al., 2007) and (c)–(d) P_2O_5 versus SiO_2 diagram and Pb versus SiO_2 diagram (Chappell and White, 1992) showing that the rhyolitic rocks follow the trend of I-type. Symbols are as in Figure 5.

nile mafic crustal source rocks. This is supported by high $\epsilon_{\text{Hf}}(t)$ values varying from +4.92 to +8.76.

The Fangniugou and Taoshan volcanic rocks are medium- to high-K calc-alkaline rocks and enriched in LILEs such as Cs, Rb, Th, and K with respect to the HFSEs, especially Nb, Ta, and Ti (Fig. 6b). Magmas with these chemical features are generally regarded to be generated in subduction-related environment or their protolith was produced in a subduction context (Rogers and Hawkesworth, 1989; Sajona et al., 1996; Hieu et al., 2016). In Sr/Y-Y and (La/Yb)_N-Yb_N diagrams, the late Silurian samples plot within the arc magmatic rocks field, whereas the middle Devonian samples plot within the adakite field (Figs. 6c and 6d). During the late Silurian-middle Devonian, the Y and Yb concentrations progressively decrease through time, accompanied by a commensurate increase in K₂O concentrations and (La/Yb)_N values (Figs. 5c, 6c, and 6d), indicating a process of crustal thickening, leaving a residue of garnet (Defant and Drummond, 1990; Castillo, 2006; Bao et al., 2017). This interpretation is also supported by the following lines of evidence. First, the regional unconformity between the late Silurian Xibiehe Formation, a molasse deposition of shallow marine facies, and the underlying early Paleozoic ophiolites and arc-island volcanic rocks and Caledonian granite implies that the continental crust accretion occurred during Caledonian in central Inner Mongolia (Zhang et al., 2010b). Second, the presence of early Paleozoic arc igneous rocks (Pei et al., 2016; Figs. 5-7) and the formation of early Devonian molasse in central Jilin Province suggest that early Paleozoic subduction and early Devonian collision occurred in this region (JBGMR, 1997). Third, the early Devonian Sandaogou alkaline complex of south Inner Mongolia and the late Devonian I-A-type rhyolites from Jifanggou Group of central Jilin Province formed in a post-collisional extensional environment associated with collisional events along the northern margin of the NCC during the latest early Paleozoic (Zhang et al., 2010a; Wang et al., 2015b). Fourth, the middle-late Devonian Wangjiajie Formation and Xiaosuihe Formation of central Jilin Province are composed mainly of marine clastic units and carbonate, which formed under a stable environment that related to a post-collisional extensional environment (JBGMR, 1988; Wang et al., 2015a). Fifth, the varied detrital zircon Hf isotopic compositions from the Devonian clastic rocks (e.g., Wangjiajie sandstone and Zhangjiatun rhyolitic breccias) of central Jilin Province imply two sources with ancient and juvenile features respectively (Fig. 8; Wang et al., 2015a; Pei et al., 2016). Therefore, we conclude that the Fangniugou area underwent a period of transition from subduction to collisional setting, and that the late

Figure 8. Correlations between the Hf isotopic compositions and the ages of zircons from the early to middle Paleozoic igneous and sedimentary rocks in central Jilin Province. The data for Zhangjiatun rhyolitic breccias and Wangjiajie sandstone are from Pei et al. (2016) and Wang et al. (2015a), respectively.

Silurian rhyodacites were derived from partial melting of a depleted mafic lower crust in a subduction zone setting, whereas the middle Devonian rhyolites were derived from partial melting of a thickened lower crust, which was related to a collisional event.

Reworking of the crustal rocks to form the Fangniugou and Taoshan volcanic rocks perhaps took place during the Cambrian-Silurian as revealed by the large number of Cambrian-Silurian magmatic zircons from the samples. The crustal source rocks are probably dominant Meso-Neoproterozoic in age as revealed by T_{DM2} model ages (1.09-0.84 Ga). This is totally compatible with the suggestion of Liu et al. (2010) that the Meso-Neoproterozoic event is the magmatism for the formation of the protoliths of Phanerozoic igneous rocks in NE China.

Implications for early-middle Paleozoic tectonic evolution in Jilin Province

Zircon U-Pb ages for the Fangniugou volcanic rocks in this study, in combination with the previously published geochronological data, point to early-middle Paleozoic magmatism in the study area which produced the ~ 425 and ~ 390 Ma Fangniugou and Taoshan volcanic rocks. Such ages are comparable to the inferred ages of many igneous rocks along the Solonker-Xar Moron-Changchun-Yanji suture. Several papers have reported the occurrence of the early-middle Paleozoic magmatism along the Solonker suture in Inner Mongolia (Chen et al., 2000; Liu et al., 2003; Shi et al., 2005; Jian et al., 2008; Zhang

Figure 9. Simplified geological map of central-eastern Jilin, which shows the localities of the early-middle Paleozoic igneous rocks along the Changchun-Yanji suture.

and Jian, 2008; Xu et al., 2013; Qin et al., 2013). Early-middle Paleozoic magmatism that related to the subduction of the Paleo-Asian oceanic plate also was identified by SHRIMP/LA-ICP-MS U-Pb zircon concordia ages and whole-rock geochemistry of igneous rocks along the Changchun-Yanji suture in central Jilin Province and the Yanbian area (Fig. 9: Jiang et al., 2014a; Pei et al., 2016; Wang et al., 2016). In addition, the depleted mantle model ages (T_{DM2}) obtained from zircon Hf isotopes indicate a crustal formation event during the Meso-Neoproterozoic in the study area. Zircon U-Pb age and geochemical characteristics of the Fangniugou and Taoshan volcanic rocks from our study suggest the presence of subduction-related magmatism during the late Silurian, followed by a collisional event during the middle Devonian in the region. This coincides with conclusion of Xiao et al. (2003), Pei et al. (2016) and Wang et al. (2016) that during the Cambrian-Silurian, the region along the Solonker-Xar Moron-Changchun-Yanji suture was characterized by active continental margin tectonics, followed by an arc-continental collision during the middle Paleozoic (Xiao et al., 2009; Jian et al., 2008; Li et al., 2014).

CONCLUSION

The LA-ICP-MS zircon U-Pb dating indicates that the Fangniugou volcanic rocks in Jilin Province, NE China are products of at least two volcanic events (~ 425 and 390 Ma). These ages, together with previously reported U-Pb ages in the region, point to the existence of early-

middle Paleozoic magmatism in Jilin Province along the Changchun-Yanji suture.

The Fangniugou and Taoshan volcanic rocks belong to medium- to high-K calc-alkaline series and display features of I-type granites of subduction-related igneous rocks. Geochemical and Hafnium isotope characteristics suggest that the late Silurian rocks were generated by partial melting of a depleted mafic lower crust in a subduction zone setting, whereas the middle Devonian rocks were derived from partial melting of a thickened lower crust, which was related to a collisional event. The lower crusts are probably Meso-Neoproterozoic in age as identified by depleted mantle model (T_{DM2}) ages.

ACKNOWLEDGMENTS

We are indebted to two anonymous reviewers, whose insightful and constructive reviews have greatly improved the paper. We thank the staff of the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China, for their advice and assistance during zircon U-Pb and Hf-isotopic dating. We appreciate the Supervision and Inspection Center of Mineral Resources, the Ministry of Land and Resources of Jinan, China, for their assistance in the major and trace element analysis. This study was financially supported by the National Natural Science Foundation of China (Grants no. 41372108 and 41602110), Taishan Scholar Talent Team Support Plan for Advanced & Unique Discipline Areas, Major Scientific and Technological Innovation Projects of Shandong Prov-

ince (Grants no. 2017CXGC1602 and 2017CXGC1603), and SDUST Research Fund (Grant no. 2015TDJH101).

SUPPLEMENTARY MATERIALS

Color version of Figure 2 and Supplementary Tables S1-S5 are available online from <https://doi.org/10.2465/jmps.170708>.

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Manuscript received July 8, 2017

Manuscript accepted November 20, 2017

Published online February 6, 2018

Manuscript handled by Jun-Ichi Kimura