Geochronology and provenance of detrital zircons from late Palaeozoic strata of central Jilin Province, Northeast China: implications for the tectonic evolution of the eastern Central Asian Orogenic Belt

Zi-Jin Wang\textsuperscript{a}, Wen-Liang Xu\textsuperscript{a,b,*}, Fu-Ping Pei\textsuperscript{a}, Zhi-Wei Wang\textsuperscript{a} and Yu Li\textsuperscript{a}

\textsuperscript{a}College of Earth Sciences, Jilin University, Changchun, PR China; \textsuperscript{b}State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, PR China

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Here we present new U–Pb and Hf isotopic data for detrital zircons obtained from six samples of late Palaeozoic units from central Jilin Province, Northeast China, and use these data and sedimentary formations to constrain the late Palaeozoic tectonic evolution of the eastern segment of the southern margin of the Central Asian Orogenic Belt. The majority of the detrital zircons from the six samples are euhedral–subhedral and exhibit oscillatory zoning, indicating a magmatic origin. Zircons from sandstones in the Devonian Wangjiajie and Xiaoauhui formations yield seven main age populations (399, 440, 921, 1648, 1864, 1911, and 2066 Ma) and two minor age populations (384 and 432 Ma), respectively. Zircons from a quartz sandstone in the Carboniferous Luquantun Formation yield four age populations (~332, 363, 402, and 428 Ma), and zircons from quartz sandstones of the Permian Shoushangou, Fanjiatun, and Yangjiagou formations yield age populations of 265, 369, 463, 503, and 963 Ma; 264, 310, 337, 486, and 529 Ma; and 262, 282, 312, 338, 380, 465, and 492 Ma, respectively. These data, together with the ages of magmatic zircons from interbedded volcanics and biostratigraphic evidence, as well as analysis of formations, give rise to the following conclusions. (1) The Wangjiajie and Xiaoauhui formations were deposited in an extensional environment during Middle and Middle–Late Devonian time, respectively. The former was sourced mainly from ancient continental material of the North China Craton with minor contributions from newly accreted crust, while the latter was sourced mainly from newly accreted crust. (2) The Luquantun Formation formed in an extensional environment during early–late Carboniferous time from material sourced mainly from newly accreted crust. (3) The Shoushangou, Fanjiatun, and Yangjiagou formations formed during a period of rapid uplift in the late Permian, from material sourced mainly from newly accreted crust.

Keywords: Northeast China; Central Asian Orogenic Belt; detrital zircon U–Pb geochronology; late Palaeozoic; provenance; tectonic evolution

1. Introduction

The Central Asian Orogenic Belt (CAOB) is located between the North China Craton (NCC) and the Siberian Craton (SC; Figure 1(a)). The eastern segment of the CAOB includes the Xing’an–Mongolia Orogenic Belt (XMOB), a collage of multiple microcontinental massifs that include, from east to west, the Khanka, Jiamusi, Songnen–Zhangguancai Range, Xing’an, and Erguna massifs, all of which are separated by major faults (Şengör et al. 1993; Ye et al. 1994; Li et al. 1999; Jahn et al. 2000, 2004; Xie 2000; Li 2006; Figure 1(b)). The XMOB formed in the Palaeozoic and is characterized by the amalgamation of multiple microcontinental massifs and the occurrence of newly accreted crust (positive εHf(t) values) (Yang et al. 2006; Meng et al. 2010). The NCC is characterized by widespread occurrence of Palaeoproterozoic (~1.8 Ga) and Neoarchaeen (~2.5 Ga) tectonic-magmatic thermal events and ancient crust (negative εHf(t) values) (Gao et al. 2004; Yang et al. 2012). Determining the Palaeozoic relationships between these microcontinental massifs and the NCC is important for furthering our understanding of the tectonic evolution and timing of the final closure of the Palaeo-Asian Ocean. It was originally thought that formation of continental margin-related accretionary belts within the northern margin of the NCC migrated from south to north during Palaeozoic time (JBGMR 1988); however, new zircon U–Pb dates of granitoids within the so-called Palaeozoic accretionary belts that were originally thought to have formed during early Palaeozoic time actually indicate that these intrusions formed during late Palaeozoic and Mesozoic time (285–116 Ma) (Zhang et al. 2004). In addition, the late Palaeozoic tectonic evolution of the southern margin of the XMOB and the northern margin of the NCC remain controversial. Some palaeontological evidence and the presence of late Palaeozoic sediments suggests that the northern margin of the NCC was a passive continental margin (Hsu et al. 1991; Li 1998; Jia et al. 2004; Zhang et al. 2008); alternatively, the northern margin of the NCC may have been an active continental
margin that formed during the southward subduction of the Palaeo-Asian oceanic plate beneath the NCC (Xiao et al. 2003; Li 2006; Zhang et al. 2009c; Cao et al. 2012, 2013). These differing models indicate the uncertainty in our current knowledge of the late Palaeozoic tectonic evolution of the Palaeo-Asian Ocean within the eastern segment of the northern NCC.

Detrital zircon geochronology and provenance analysis, as powerful tools, have been widely used to constrain palaeogeography, tectonic reconstruction, and crustal evolution (e.g. Ross and Bowring 1990; Meng et al. 2010; Yang et al. 2013). In Northeast China, previous studies on detrital zircon geochronology focus mainly on the Devonian sedimentary rocks within the Songnen–Zhangguangcai Range and Jiamusi massifs and discuss their depositional ages, provenance, and amalgamation history (Figure 1(b); Meng et al. 2010). However, up to now there have been no studies on detrital zircons from the late Palaeozoic strata in the eastern segment of the southern margin of the XMOB. Geochronological data and formation analysis from the late Palaeozoic sedimentary units between the NCC and the XMOB is the key for us to understand the late Palaeozoic tectonic evolution of the southern margin of the XMOB and the northern margin of the NCC. Here, we present new detrital zircon U–Pb and Hf isotope data for the late Palaeozoic sedimentary rocks from central Jilin Province, Northeast China, and use these data and sedimentary formations to constrain the depositional ages and provenances of these late Palaeozoic sediments and the tectonic evolution of the southern margin of the XMOB. Thus, these new data provide new insights to understanding the late Palaeozoic tectonic

Figure 1. (a) Tectonic sketch map of the CAOB; (b) tectonic sketch map of Northeast China, modified after Wu et al. (2007). (1) In the inset, CAOB, Central Asian Orogenic Belt; XMOB, Xing’an–Mongolia Orogenic Belt; (I) Hegenshan–Heihe suture zone; (II) Mongolia–Okhotsk suture zone; (III) Solonker–Xa Moron–Changchun suture zone; (IV) Middle Sikhote suture zone; (2) Ages in legends of Figure 1(b) are age estimates for different massifs.
evolution of the southern margin of the XMOB and the timing of the final closure of the Palaeo-Asian Ocean (Cao et al. 2012, 2013).

2. Geological setting and sample descriptions

The central part of Jilin Province is located in the southern margin of the XMOB adjacent to the Xar Moron–Changchun–Yanzi suture zone and the northern margin of the NCC in the south. The southeast and northwest of this area also contains the Dunhua–Mishan Fault and the Songliao Basin, respectively (Figure 1(b)).

The Songnen–Zhangguangcai Range Massif is dominated by the Songliao Basin and the Zhangguangcai Range (Figure 1(b)). The Songliao Basin is a late Mesozoic basin that formed over a basement of weakly deformed and metamorphosed Phanerozoic granites and Palaeozoic units (Wu et al. 2001; Gao et al. 2007; Pei et al. 2007), whereas the Zhangguangcai Range is characterized by voluminous Phanerozoic granitoids with rare Proterozoic metamorphic rocks (Wang et al. 2014), Palaeozoic sediments, and late Mesozoic–Cenozoic volcanic–sedimentary sequences that form isolated islands within a ‘granite ocean’ (Wu et al. 2002; Figure 2).

The central part of Jilin Province contains minor late Palaeozoic sediments that include the Middle Devonian Wangjiajie, the Middle–Late Devonian Xiaosuihe, the early–late Carboniferous Luquantun, Mopanshan, Shizuizi, and Woguadi, the early Permian Daheshen, and the late Permian Shoushangou, Fanjiatun, and Yangjiagou formations (Figure 3). The Wangjiajie Formation occurs within the northern accretion margin of the NCC and contains grey feldspathic sandstone, limestone, tuffaceous sandstone, and coral fossil-bearing grey limestone units. The Xiaosuihe Formation occurs within the Xar Moron–Changchun–Yanzi suture zone and is dominated by siltstone, grey greywacke, and limestone units, whereas the Luquantun Formation occurs within the northern accretionary margin of the NCC and consists of grey sandstone and limestone units. The Shoushangou Formation occurs within the northern accretionary margin of the NCC and contains sandy slate, siltstone, and grey siltstone units, and the Fanjiatun Formation occurs in the north of the Xar Moron–Changchun–Yanzi suture zone and consists of a series of grey–black sandstone, siltstone, slate, and tuffaceous sandstone units. Finally, the Yangjiagou Formation occurs in the north of the Xar Moron–Changchun–Yanzi suture zone and contains grey siltstone, sandy slate, limestone, and tuffaceous sandstone units (Figures 2 and 3). The lithology, locations, textures, structures, and mineral compositions of the studied samples are summarized in Table 1. Their petrographical features are shown in Figure 4(a–f).

3. Analytical methods

3.1. Zircon U–Pb dating and trace element analysis

Zircons were separated from samples using the conventional heavy liquid and magnetic techniques and purified by handpicking under a binocular microscope at the
Langfang Geophysical Survey, Hebei Province, China. The handpicked zircons were examined under transmitted and reflected light with an optical microscope, and in order to reveal their internal structures, cathodoluminescence (CL) images were obtained using a JEOL scanning electron microscope housed at the State Key Laboratory of Continental Dynamics, Northwest University, China. Distinct domains within the zircons were selected for analysis, based on their CL images. Zircon U–Pb isotopes and trace elements were analysed using the same LA–ICP–MS system at the State Key Laboratory of Geological Processes and Mineral Resources, China.

| System             | FM  | Section | Ages       | Description                                      |
|--------------------|-----|---------|------------|--------------------------------------------------|
| Yangjiagou         | JK21-1 | 262 Ma |            | siltstone and sandstone black slate conglomerate |
| Yilaxi             | JS1-1 | 264 Ma |            | slate, limestone, tuff, sandstone, sandy conglomerate, rhyolite, rhyolitic tuff and slate andesite |
| Fanjiatun          | JS1-1 | 264 Ma |            | gritstone and tuffaceous gritstone, grey green tuff and tuffaceous sandstones limestone, grey green siltstone and sandy slate |
| Shoushangou        | JKG-1 | 285 Ma |            | silver phyllitic siltstone limestone and arglaceous limestone and flint nodule |
| Daoshen            | JH4-1 | 279 Ma |            | limestone, rhyolite tuff and calcareous siltstone, carbonaceous andesitic tuff, rhyolitic tuff and rhyolite |
| Woguadi            | JK8-1 | 301 Ma |            | rhyolite phyllitic siltstone, metamorphic sandstones dacite and tuffaceous sandstone, metamorphic dacite |
| Shizuizi           |      |         |            | phyllitic shale and tuffaceous sandstone, argilaceous limestone, tuffaceous sandstones, metamorphic sandstones and phyllitic shale, white marble |
| Mopanshan          |      |         |            | white grey limestone and flint nodule limestone |
| Luquantun          | LK39-1 | 332 Ma |            | limestone, feldspar-quartz sandstone and acidic volcanic rock, tuffaceous siltstone and grey black siltstone, slate, marble, spilite keratophyre tuff and tuffaceous siltstone |
| Xiaosuihe          | 11JXS1-1 | 384 Ma |            | grey white limestone and siltstone, charcoal grey graywacke, sandstone, siltstone |
| Wangjiagie         | LK41-1 | 398 Ma |            | grey black limestone shale, intermediate-acid silty tuffaceous fine sandstone, quartz sandstone, siltstone |

Figure 3. Stratigraphic column for late Palaeozoic units in the study area, indicating variations in lithology, sampling sites, and the results of the dating undertaken during this study. The zircon U–Pb ages for the volcanic rocks from the Daheshen (JH4-1) and Woguadi formations (JK8-1) are from Cao et al. (2012) and our unpublished data, respectively.
University of Geosciences (Wuhan). The LA–ICP–MS system is composed of an Agilent 7500a ICP–MS coupled with a Resonetic RESOLUTION M-50 ArF-Excimer laser source \((k = 193\ \text{nm})\). Laser energy was 80 mJ, with repetition rate of 10 Hz, a spot size of 30 \(\mu\text{m}\) diameter, and a total of 40 s ablation time. Helium was used as the carrier gas to enhance the transport efficiency of the ablated material. Zircon 91,500 was used as the external standard for age calibration, and the NIST SRM 610 silicate glass was applied for the instrument optimization. The calculations of zircon isotope ratios and zircon trace elements were performed by ICPMSDataCal 7.0 \(\text{(Liu et al. 2010)}\). Zircon age was calculated using ISOPLOT 3.23 \(\text{(Ludwig 2003)}\). Correction for common Pb was made following Andersen \(\text{(2002)}\). Errors on individual analyses by LA–ICP–MS are quoted at the 1\(\sigma\) level, while errors on pooled ages are quoted at the 95% confidence level.

### 3.2. Hf isotope analyses

Experiments were conducted using a Neptune Plus MC-ICP-MS \(\text{(Thermo Fisher Scientific, Germany)}\) in combination with a Geolas 2005 excimer ArF laser ablation system \(\text{(Lambda Physik, Göttingen, Germany)}\) that was hosted at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, in Wuhan. The energy density of laser ablation that was used in this study was 5.3 J cm\(^{-2}\). Helium was used as the carrier gas within the ablation cell and was merged with argon \(\text{(makeup gas)}\) after the ablation cell. As demonstrated by our previous study, for the 193 nm laser a consistent twofold signal enhancement was achieved in helium over argon gas \(\text{(Hu et al. 2008a)}\). We used a simple Y junction downstream from the sample cell to add small amounts of nitrogen \(\text{(4 ml min}^{-1}\text{)}\) to the argon makeup gas \(\text{(Hu et al. 2008b)}\). Compared to the standard arrangement, the addition of nitrogen in combination with the use of the newly designed X skimmer cone and Jet sample cone in Neptune Plus improved the signal intensity of Hf, Yb, and Lu by factors of 5.3, 4.0, and 2.4, respectively. All data were acquired on zircon in single-spot ablation mode at a spot size of 44 \(\mu\text{m}\) in this study. Each measurement consisted of 20 s of acquisition of the background signal followed by 50 s of ablation signal acquisition. Detailed operating conditions for the laser ablation system and the MC-ICP-MS instrument and analytical method are the same as the description by Hu \text{et al. (2012)}.

### 4. Results

#### 4.1. Zircon U–Pb dating

In total, 326 detrital zircon grains have been subjected to U–Pb age dating, and the results are listed in
Supplementary Table 1 (see http://dx.doi.org/10.1080/00206814.2014.1002118). Uncertainties in individual analyses in the data table and concordia plots are presented with an error of 1σ. The Hf isotopic data for 153 detrital zircon grains are listed in Supplementary Table 2. All the Lu–Hf isotope results are reported with a 2σ error. Representative zircon CL images are shown in Figure 5. The results are presented in a series of concordia diagrams (Figure 6). For statistical purposes, \(^{206}\text{Pb}/^{238}\text{U}\) ages are used for grains <1000 Ma, and \(^{207}\text{Pb}/^{206}\text{Pb}\) ages are used for grains >1000 Ma. We rely only on analytical data that are less than ±10% discordant.

4.1.1. Wangjiajie Formation (sample LK41-1)
The majority of zircons from this sample are rounded to subrounded and have core–rim textures visible during CL imaging, although other zircons from this sample are euhedral–subhedral and contain fine-scale oscillatory growth zoning visible during CL imaging (Figure 5(a)). Barring a single analysis (Th/U = 0.05), the majority of detrital zircons from this sample have Th/U ratios of 0.10–3.10. Only 2 of the 54 analyses were discordant. These analyses yielded a wide range of ages (2520–397 Ma) (Supplementary Table 1), the majority of which can be split into seven distinct age populations (Table 2, Figure 6(a–c)). The seven youngest detrital zircons have \(^{206}\text{Pb}/^{238}\text{U}\) ages of 400–397 Ma, with a weighted mean age of 399 ± 2 Ma.

4.1.2. Xiaosuihe Formation (sample 11JXS1-1)
Zircons from this sample are euhedral–subhedral and have striped absorption zoning visible during CL imaging (Figure 5(b)) that, when combined with the Th/U ratios (0.41–2.26) of these zircons, is indicative of a magmatic origin. A total of 42 analyses from this sample yielded \(^{206}\text{Pb}/^{238}\text{U}\) ages of 437–371 Ma (Supplementary Table 1).
that are split into two main age populations (Table 2, Figure 6(d)). The 17 youngest detrital zircons have $^{206}\text{Pb}/^{238}\text{U}$ ages of 393–371 Ma that yield a weighted mean age of 384 ± 3 Ma.

4.1.3. Luquantun Formation (sample LK39-1)

Zircons from this sample are subhedral and the majority contain inherited cores that are overgrown by rims with fine-scale oscillatory zoning, although some zircons have striped absorption zones visible during CL imaging (Figure 5(c)). These zircons have Th/U ratios of 0.32–1.74. Two of the 54 analyses are discordant, with the concordant analyses yielding ages of 430–330 Ma (Supplementary Table 1) that can be split into four main age populations (Table 2, Figure 6(e)). The 12 youngest detrital zircons have $^{206}\text{Pb}/^{238}\text{U}$ ages of 334–330 Ma that yield a weighted mean age of 332 ± 3 Ma.
4.1.4. Shoushangou Formation (sample JK6-1)

The majority of the zircons from this sample are euhedral–subhedral and have fine-scale oscillatory growth zoning visible during CL imaging (Figure 5(d)). However, one zircon from this sample is rounded to subrounded and has a core–rim texture. With the exception of one analysis (JK6-1-12, Th/U of 0.09; Supplementary Table 1), these zircons have Th/U ratios of 0.12–0.94. Four out of the 60 analyses of 60 zircons from this sample were discordant. The concordant analyses have $^{206}\text{Pb}^{238}\text{U}$ ages of 1893–261 Ma that can be split into six main age populations (Table 2, Figure 6(f)). The 27 youngest zircons yielded a weighted mean $^{206}\text{Pb}^{238}\text{U}$ age of 265 ± 1 Ma.

4.1.5. Fanjiatun Formation (sample JS1-1)

The zircons from this sample are euhedral–subhedral, contain fine-scale oscillatory growth zoning visible during CL imaging and have Th/U ratios of 0.31–1.13, indicative of a magmatic origin (Figure 5(e)). A total of 68 analyses yielded concordant ages from 798 to 262 Ma.
Table 2. Weighted mean age for detrital zircons from late Palaeozoic sediments of central Jilin Province, Northeast China.

| Group        | Grains | Weighted mean age (Ma) | 207Pb/206Pb | 1σ | 206Pb/238U | 1σ |
|--------------|--------|------------------------|-------------|----|------------|----|
| LK41-1 Wangjiajie Formation | 1 5 2066 | 206 | 21 | 0.27 | 0.17 | 0.02 |
|              | 2 6 1911 | 17 | 11 | 0.19 | 0.11 | 0.01 |
|              | 3 9 1864 | 11 | 11 | 0.17 | 0.11 | 0.01 |
|              | 4 2 1648 | 25 | 17 | 0.24 | 0.15 | 0.02 |
|              | 5 3 921 | 9 | 2 | 0.15 | 0.1 | 0.01 |
|              | 6 10 440 | 2 | 2 | 0.13 | 0.1 | 0.01 |
|              | 7 7 399 | 2 | 2 | 0.13 | 0.1 | 0.01 |
| 11JXS1-1 Xiaosuihe Formation | 1 25 432 | 3 | 3 | 0.17 | 0.11 | 0.01 |
|              | 2 17 384 | 3 | 3 | 0.17 | 0.11 | 0.01 |
| LK39-1 Luquantun Formation | 1 2 428 | 5 | 5 | 0.22 | 0.14 | 0.02 |
|              | 2 9 402 | 3 | 3 | 0.18 | 0.11 | 0.01 |
|              | 3 29 363 | 1 | 1 | 0.13 | 0.1 | 0.01 |
|              | 4 12 332 | 3 | 3 | 0.17 | 0.11 | 0.01 |
| JK6-1 Shoushangou Formation | 1 1 1893 | 47 | 47 | 0.27 | 0.17 | 0.02 |
|              | 2 3 963 | 11 | 11 | 0.18 | 0.11 | 0.01 |
|              | 3 9 503 | 4 | 4 | 0.13 | 0.1 | 0.01 |
|              | 4 8 463 | 4 | 4 | 0.13 | 0.1 | 0.01 |
|              | 5 6 369 | 5 | 5 | 0.17 | 0.11 | 0.01 |
|              | 6 27 265 | 1 | 1 | 0.13 | 0.1 | 0.01 |
| JS1-1 Fanjiatun Formation | 1 2 529 | 6 | 6 | 0.22 | 0.14 | 0.02 |
|              | 2 10 486 | 3 | 3 | 0.18 | 0.11 | 0.01 |
|              | 3 2 441 | 4 | 4 | 0.13 | 0.1 | 0.01 |
|              | 4 4 337 | 4 | 4 | 0.13 | 0.1 | 0.01 |
|              | 5 5 310 | 3 | 3 | 0.17 | 0.11 | 0.01 |
|              | 6 43 264 | 1 | 1 | 0.13 | 0.1 | 0.01 |
| JK21-1 Yangjiagou Formation | 1 1 1820 | 59 | 59 | 0.27 | 0.17 | 0.02 |
|              | 2 4 492 | 5 | 5 | 0.18 | 0.11 | 0.01 |
|              | 3 3 465 | 5 | 5 | 0.13 | 0.1 | 0.01 |
|              | 4 6 380 | 3 | 3 | 0.17 | 0.11 | 0.01 |
|              | 5 8 337 | 3 | 3 | 0.17 | 0.11 | 0.01 |
|              | 6 8 312 | 3 | 3 | 0.17 | 0.11 | 0.01 |
|              | 7 4 282 | 3 | 3 | 0.17 | 0.11 | 0.01 |
|              | 8 13 262 | 3 | 3 | 0.17 | 0.11 | 0.01 |

( Supplementary Table 1) that can be split into six main age populations (Table 2, Figure 6(g)). The 43 youngest grains have 206Pb/238U ages of 267–262 Ma that yielded a weighted mean age of 264 ± 1 Ma.

4.1.6. Yangjiagou Formation (sample JK21-1)

The majority of the zircons in this sample are euhedral–subhedral and have fine-scale oscillatory growth zoning visible during CL imaging, although a single zircon is rounded to subrounded and has a core–rim texture (Figure 5(f)). All of these zircons have Th/U ratios of 0.39–1.74, indicative of a magmatic origin. Only one of the 48 analyses was discordant, with the concordant analyses yielding 206Pb/238U ages of 1820–258 Ma (Supplementary Table 1) that can be split into eight main age populations (Table 2, Figure 6(h)). The 13 youngest detrital zircons have 206Pb/238U ages of 264–258 Ma that yield a weighted mean age of 262 ± 3 Ma.

5. Zircon Hf isotopes

5.1. Wangjiajie and Xiaosuihe Formations

In the Wangjiajie Formation, Neorchaean to Palaeoproterozoic grains have εHf(t) values of −2.0 to +17.7, Neoproterozoic zircons have εHf(t) values of −16.9 to −1.5, and the majority of Phanerozoic zircons have negative εHf(t) values (−21.4 to −1.9), although two Phanerozoic zircons have positive εHf(t) values (+2.3 and +4.9; Supplementary Table 2 and Figure 7(a)).

The Hf isotopic compositions of 16 detrital zircons from the Xiaosuihe Formation were determined during this study. These detrital zircons have ages of 432–383 Ma and all have positive εHf(t) values ranging of +5.5 to +11.0 (Supplementary Table 2; Figure 7(b)).

5.2. Luquantun Formation

The Hf isotopic compositions of 25 detrital zircons from the Luquantun Formation were determined during this study. These zircons have ages of 428–332 Ma and the majority have positive εHf(t) values (+7.2 to +16.3), although some of these zircons yielded negative εHf(t) values (−17.9 to −5.5; Supplementary Table 2; Figure 7(c)).

5.3. Shoushangou, Fanjiatun, and Yangjiagou Formations

The Hf isotopic compositions of 23 detrital zircons from the Shoushangou Formation were determined during this study. Neoproterozoic zircons from this formation have εHf(t) values of −6.9 to −2.2, whereas the majority of Phanerozoic zircons have positive εHf(t) values (+0.4 to +8.4), although a few other Phanerozoic zircons from this formation have negative εHf(t) values (−7.2 to −0.2) (Supplementary Table 2; Figure 7(d)).

The Hf isotopic compositions of 36 detrital zircons from the Fanjiatun Formation were determined during this study. The majority of the Phanerozoic zircons from this formation have positive εHf(t) values (+1.1 to +16.6), although a few Phanerozoic zircons have negative εHf(t) values (−5.5 to −1.2). In addition, a single Neoproterozoic zircon from this formation yielded an εHf(t) value of +1.9 (Supplementary Table 1; Figure 7(e)).

The Hf isotopic compositions of 29 detrital zircons from the Yangjiagou Formation were determined during
this study. The majority of Phanerozoic zircons from this sample have positive $\varepsilon_{Hf}(t)$ values (+1.3 to +13.7), although other Phanerozoic zircons from this sample have negative $\varepsilon_{Hf}(t)$ values (−16.0 to −0.3). In addition, a Palaeoproterozoic zircon from this sample yielded a $\varepsilon_{Hf}(t)$ value of −2.5 (Supplementary Table 2; Figure 7(f)).

6. Discussion

6.1. Depositional ages

Generally, the youngest concordant detrital zircon age is thought to represent the maximum depositional age of a sediment if the U–Pb system of the analysed zircons was not disturbed during post-depositional tectono-metamorphic or hydrothermal events (Zeh and Gerdes 2012). In this study, we use the youngest weighted mean age mode as maximum depositional age based on analytical uncertainty. Additionally, the youngest ages of overlying sediments, age-diagnostic fossils, and the age of igneous rocks that intrude the unit can also provide additional limits on the timing of deposition of a given sedimentary unit.

6.1.1. Wangjiajie Formation

The Wangjiajie Formation (sample LK41-1) has a youngest cluster of zircons at ca. 399 Ma (Figure 6(a)), indicating that this unit has a maximum Early Devonian depositional age. In addition, the youngest ages of detrital zircons from overlying sediments provide further constraints on the minimum age of this unit, with the youngest age (332 Ma) of zircons in the overlying Luquantun Formation (Figure 3). Therefore, we conclude that the Wangjiajie Formation was deposited between 399 and 332 Ma. However, the fossil assemblage within the Wangjiajie Formation is indicative of deposition during Middle Devonian time (Zheng 1989). All of these
data indicate that the Wangjiajie Formation formed between Late–Early Devonian (399 Ma) and Middle Devonian time.

### 6.1.2. Xiaosuihe Formation

The Xiaosuihe Formation has a youngest cluster of zircons at ca. 384 Ma that indicate a maximum Middle Devonian depositional age. This, combined with presence of the overlying early Carboniferous Luquantun formation, suggests that the Xiaosuihe Formation formed between the Middle Devonian and the early Carboniferous. In addition, the absence of Late Devonian (364–369 Ma) age detrital zircons suggests that the Xiaosuihe Formation was deposited in the Middle–Late Devonian, rather than the Early Devonian as was previously proposed (JBGMR 1988).

### 6.1.3. Luquantun Formation

The Luquantun Formation (LK39-1) contains zircons that have a cluster of youngest ages at ca. 332 Ma (Figure 6(e)) that indicate an early Carboniferous maximum depositional age. This, combined with the presence of late Carboniferous fossils in limestones of the Mopanshan Formation that conformably overlies this formation (Zhang and Sun 1987; Li et al. 2012), suggests that the Luquantun Formation was deposited between the early and late Carboniferous.

### 6.1.4. Shoushangou, Fanjiatun, and Yangjiagou Formations

The Shoushangou Formation (sample JK6-1) contains zircons that have a cluster of youngest ages of ca. 265 Ma (Figure 6(f)), indicative of a middle Permian maximum depositional age. The Daheshen Formation was thought to overlie the Shoushangou Formation but contains rhyolites that have zircon $^{206}$Pb/$^{238}$U ages of 279 Ma (Cao et al. 2012). This dating indicates that the Shoushangou Formation formed after the deposition of the Daheshen Formation and therefore the two most likely have a faulted contact. In addition, a widespread ca. 250 Ma magmatic event is known to have occurred along the northern margin of the NCC (Cao et al. 2013), although there are no ca. 250 Ma magmatic zircons within the Shoushangou Formation, suggesting that these sediments were deposited before ca. 250 Ma. In addition, the fossil assemblage within this formation is indicative of deposition during late–early Permian time (Wang et al. 2013a). These data suggest that the Shoushangou Formation was deposited during late Permian time rather than the early Permian as was previously suggested (JBGMR 1988).

The presence of a youngest cluster of zircons with an age of ca. 264 Ma within a sample from the Fanjiatun Formation is indicative of a middle Permian maximum depositional age, similar to the Shoushangou Formation. This, combined with the presence of a middle–late Permian fossil assemblage (Wang et al. 2000) and the absence of ca. 250 Ma zircons, suggests that the Fanjiatun Formation was deposited during late Permian time rather than during early Permian time as was previously suggested (JBGMR 1988).

Finally, the presence of a youngest cluster of zircons with an age of ca. 262 Ma within a sample from the Yangjiagou Formation is indicative of a middle Permian maximum depositional age, similar to the Shoushangou and Fanjiatun formations. In addition, this formation was intruded by a hornblende gabbro at ca. 256 Ma (Wang et al. 2013b), suggesting that the Yangjiagou Formation was deposited between 262 and 256 Ma, an age that is identical to the previously published biostratigraphic age of this unit (JBGMR 1988).

In summary, the data presented here indicate that the Wangjiajie and Xiaosuihe formations were deposited during Middle–Late Devonian time, the Luquantun Formation was deposited during early–late Carboniferous time, and the Shoushangou, Fanjiatun, and Yangjiagou formations were deposited during late Permian time.

### 6.2. Provenance of late Palaeozoic sedimentary units

The generally accepted method of identifying the source of sedimentary units is by comparing zircon U–Pb ages and Hf isotopic data with potential provenance areas or units (Dickinson and Gehrels 2008). The 317 detrital zircon U–Pb analyses (less than ±10% discordant) undertaken during this study allow three age populations to be identified, namely Neoarchaean to Palaeoproterozoic, Neoproterozoic, and Phanerozoic zircon populations. Igneous zircons from metaigneous and intrusive rocks within the northern margin of the NCC generally yield two Neoarchaean to Palaeoproterozoic and late Palaeozoic age populations (Yang et al. 2006; Zhang et al. 2010), whereas igneous rocks and Palaeozoic sediments from the southern margin of the XMOB predominantly contain Phanerozoic and minor Neoproterozoic as well as rare Archaean or Palaeoproterozoic zircons (Meng et al. 2010; Wang et al. 2012, 2014).

In addition, Phanerozoic zircons from the NCC generally have negative $\varepsilon_{Hf}(t)$ values, whereas Phanerozoic zircons from the southern margin of the XMOB have positive $\varepsilon_{Hf}(t)$ values (Yang et al. 2006; Cao et al. 2013).

#### 6.2.1. Provenance of the Middle–Late Devonian Wangjiajie and Xiaosuihe Formations

The material deposited within the Middle Devonian Wangjiajie Formation was predominantly derived from a Phanerozoic geological source (440 and 399 Ma), with contributions from Neoarchaean (2500 Ma) and
Palaeoproterozoic (2066, 1911, 1864, and 1648 Ma) sources, and with minor amounts of material sourced from a Neoproterozoic terrane (Figure 8). The Archaean to Palaeoproterozoic zircon grains have $\epsilon_{Hf}(t)$ values of $-2.0$ to $+17.7$, similar to Precambrian magmatic and detrital zircons from the NCC (Yang et al. 2008a, 2012; Sun et al. 2012; Figure 7(a)). This suggests that Neoarchaean to Palaeoproterozoic zircons in this unit were sourced from Precambrian basement rocks of the NCC. In addition, previous research has suggested the presence of Neoarchaean and Palaeoproterozoic magmatic-thermal events in the NCC (Ma and Wu 1981; Zhao et al. 2001; Guo et al. 2005) and the SC (Zonenshain et al. 1990; Jahn et al. 2004; Rojas-Agramonte et al. 2006; Kelty et al. 2008), indicating that the ancient detrital zircons within this unit may have been sourced from both NCC and SC. However, our study area is located within the continental margin accretionary belts near the northern margin of the NCC, although the NCC and SC have similar age associations such as Neoarchaean (~2500 Ma) and Palaeoproterozoic (~1800–1900 Ma) (Zhao et al. 2001; Rojas-Agramonte et al. 2006; Kelty et al. 2008), meaning that these ancient zircons most likely were not sourced from the SC. In addition, these zircons are rounded to sub-rounded in shape, indicating that they underwent long distance transportation prior to

![Figure 8. Relative probability diagram for detrital zircons from late Palaeozoic sedimentary units within central Jilin Province, Northeast China.](image-url)
deposition; this differs significantly from the subhedral Neoarchaean and Palaeoproterozoic detrital zircons within the Heilonggong Complex in eastern Heilongjiang Province, Northeast China (Meng et al. 2010). These data indicate that the majority of Neoarchaean and Palaeoproterozoic detrital zircons within the Wangjiajie Formation were sourced from the NCC. All of the Neoproterozoic (920 Ma) detrital zircons within our sample have εHf(t) values of −16.9 to −1.5 and are subhedral–euhedral, indicating that they underwent minimal transportation before deposition, suggesting that these zircons were derived from the northern margin of the NCC (Yang et al. 2006). The majority of the Phanerozoic zircons within this unit have negative εHf(t) values (−21.4 to −1.9) and could have been sourced from igneous rocks in the northern part of the NCC (Zhang et al. 2007a, 2007b, 2009a, 2009b, 2009c; Yang et al. 2012), whereas Phanerozoic zircons in this unit with positive εHf(t) values (+2.3 to +4.9; Figure 7(a)) were most likely sourced from newly accreted crust within the XMOB (Yang et al. 2006). This indicates that detrital zircons within the Middle Devonian Wangjiajie Formation were sourced predominantly from the northern part of the NCC with a relatively minor contribution from the XMOB.

D detrital zircons from the Xiaosuihe Formation are subhedral–euhedral, suggesting that they were transported only a short distance prior to deposition. There are no Neoarchaean, Palaeoproterozoic, or Neoproterozoic detrital zircons within the Xiaosuihe Formation (Figure 8), and all of the Phanerozoic zircons within this formation have positive εHf(t) values (+5.5 to +11.0; Figure 7(b)), suggesting that they were all sourced from newly accreted crustal material within the XMOB. This is consistent with the position of the Xiaosuihe Formation adjacent to the Xar Moron–Changchun–Yanji suture zone and contrasting with the position of the Wangjiajie Formation that outcrops adjacent to the NCC.

6.2.2. Provenance of the early–late Carboniferous Luquantun Formation

No Neoarchaean, Palaeoproterozoic, or Neoproterozoic detrital zircons are present in the Luquantun Formation. The detrital zircons within this formation are subhedral–euhedral in shape, indicating that they underwent minimal transportation. The majority of the Phanerozoic zircons from this formation have positive εHf(t) values (+7.2 to +16.3; Figure 7(c)), suggesting that they were sourced from newly accreted crustal material within the XMOB, whereas others with negative εHf(t) values (−17.9 to −5.5; Supplementary Table 1) were most likely sourced from the northern margin of the NCC (Yang et al. 2006; Cao et al. 2013; Zhang et al. 2014). This suggests that the material deposited within the Luquantun Formation was predominantly sourced from the XMOB with a relatively minor contribution from the northern part of the NCC.

6.2.3. Provenance of the late Permian Shoushangou, Fanjiatun, and Yangjiagou Formations

The Shoushangou Formation contains Neoproterozoic (ca. 963 Ma) zircons in addition to a single round Palaeoproterozoic detrital zircon. The Neoproterozoic detrital zircons have εHf(t) values of −6.9 to −2.2. This, combined with the subhedral–euhedral shapes of these zircons, suggests that they were dominantly sourced from the northern margin of the NCC. In addition, the majority of the Phanerozoic zircons in this unit have positive εHf(t) values (+0.4 to +8.4; Figure 7(d)) that suggest they were sourced from newly accreted crust within the XMOB, whereas other Phanerozoic zircons in this area have negative εHf(t) values (−7.2 to −0.2; Supplementary Table 2) that, together with the Neoproterozoic detrital zircons with negative εHf(t) values, were probably sourced from the northern part of the NCC (Yang et al. 2006; Cao et al. 2013; Zhang et al. 2014).

D detrital zircons from the Fanjiatun Formation are subhedral and euhedral, suggesting that they underwent short distance transportation. The majority of the Phanerozoic zircons in this unit have positive εHf(t) values (+1.1 to +16.6) that suggest they were sourced from the XMOB, whereas the other Phanerozoic zircons in this unit have negative εHf(t) values (−5.5 to −1.2; Supplementary Table 2) that are indicative of derivation from the northern margin of the NCC (Yang et al. 2006; Cao et al. 2013; Zhang et al. 2014). This suggests that the material deposited within the Fanjiatun Formation was primarily sourced from the XMOB, with a relatively minor contribution from the northern part of the NCC.

The majority of the Phanerozoic zircons from the Yangjiagou Formation have positive εHf(t) values (+1.3 to +13.7), whereas other Phanerozoic zircons in this unit have negative εHf(t) values (−16.0 to −0.3), with a single Palaeoproterozoic zircon yielding a εHf(t) value of −2.5 (Supplementary Table 2). The Phanerozoic detrital zircons are subhedral–euhedral, indicating that they were transported over only short distances, whereas the single Palaeoproterozoic zircon is rounded, indicative of transportation over long distances. This indicates that the sediments within the Yangjiagou Formation were sourced mainly from the XMOB with only minor amounts of material derived from the northern part of the NCC (Yang et al. 2006; Cao et al. 2013; Zhang et al. 2014).
In summary, the U–Pb ages and Hf isotopic compositions of detrital zircons within the study area indicate that Middle Devonian sandstones within the Wangjiajie Formation were mainly sourced from the basement of the NCC with minor material derived from newly accreted continental crust of the XMOB. In addition, the Middle–Late Devonian sandstones of the Xiaosuihe Formation were sourced from material derived from the XMOB, whereas early–late Carboniferous sandstones in the Luquantun Formation were mainly sourced from the XMOB, but also contain minor amounts of material from the northern margin of the NCC. Finally, the late Permian sandstones of the Shoushangou, Fanjiatun, and Yangjiagou formations were derived from material sourced from the XMOB with minor contributions from the northern margin of the NCC. Additionally, based on the sampling locations, it is suggested that the samples (such as LK41-1 and JK6-1) collected from the northern accretionary margin of the NCC have more NCC components (Zhang et al. 2014). In contrast, the samples (such as 11JXS1-1, JS1-1, and JK21-1) collected from areas north of the Solonker–Xra Moron–Changchun–Yanji suture zone or within the suture zone are characterized by minor or no NCC components.

6.3. Late Palaeozoic tectonic evolution of the southern margin of the XMOB

6.3.1. Early Palaeozoic arc–continent collision in the eastern segment of the northern margin of the NCC

The presence of early Palaeozoic igneous rocks meant that the northern margin of the NCC was traditionally considered to be an active continental margin (JBGMR 1988). Recent zircon U–Pb dating indicates that these early Palaeozoic igneous rocks actually formed during late Palaeozoic and early Mesozoic time (Zhang et al. 2004). However, with the improving of investigation for these Palaeozoic igneous rocks in the eastern segment of the southern margin of the XMOB, early Palaeozoic igneous rocks within the eastern segment of the southern margin of the XMOB have led to the identification of increasing numbers of early Palaeozoic igneous units (~443 Ma) in this area (Pei et al. 2014). For example, the Zhangjiatun tonalite within central Jilin Province formed under the forearc setting of an island arc background and was most likely derived from partial melting of oceanic cumulate gabbro material. In addition, the geochemistry of 420–440 Ma igneous rocks within the central part of Jilin Province also suggests that they formed in an island arc setting (Pei et al. 2014). Combined with the unconformity relationship with the overlying late Silurian–Early Devonian Zhangjiatun Formation (molasses formation), we concluded that the early Palaeozoic accretionary belt existed along the eastern segment of the northern margin of the NCC and an arc (here called the Zhangjiatun island arc)–continent collision occurred within the eastern segment of northern margin of the NCC during the later stages of the early Palaeozoic or the earliest late Palaeozoic (Figure 9(a) and (b)).

6.3.2. Late Palaeozoic tectonic evolution of the southern margin of the XMOB and the northern margin of the NCC

Middle Devonian sedimentation in the study area involved the sourcing of sediments within the Wangjiajie Formation from the northern part of the NCC, with only minor amounts of sediment derived from the southern margin of the XMOB. In comparison, Middle–Late Devonian deposition of the Xiaosuihe Formation involved material derived from the southern margin of the XMOB. In addition, the Middle Devonian Wangjiajie Formation and Middle–Late Devonian Xiaosuihe Formation are composed mainly of carbonate and marine clastic units such as quartz sandstone (JBGMR 1988). These sedimentary formations formed under a stable environment, which is likely related to a post-collisional extensional environment that occurred within a Middle–Late Devonian continental marginal setting along the southern margin of the XMOB (Figure 9(c)).

The early–late Carboniferous deposition of sediments of the Luquantun Formation involved material sourced primarily from the southern margin of the XMOB with only minor amounts of material sourced from the northern part of the NCC. In addition, the Luquantun Formation contains neritic terrigenous clastic, carbonate, and siltite–keratophyre units (JBGMR 1988) that are indicative of formation in a passive continental margin extensional setting (Figure 9(d)). This is consistent with the presence of early Carboniferous bimodal igneous rocks and an alkali granite in the central part of Jilin Province (Wang et al. 2015).

The late Permian deposition of sandstones within the Shoushangou, Fanjiatun, and Yangjiagou formations involved material predominantly sourced from the southern margin of the XMOB with minor amounts of material from the northern part of the NCC. The Shoushangou Formation contains neritic terrigenous clastic and carbonate sediments (JBGMR 1988), whereas the Fanjiatun Formation contains neritic terrigenous clastic and volcanic clastic sediments, and the Yangjiagou Formation contains marine–terrigenous molasse and carbonate sediments. In addition, the detrital zircons within these units are euhehedral–subhedral, indicating that they were only transported short distances before deposition. This suggests that these late Permian sediments formed during rapid uplift after the late Permian continent–continent collision between the SZM and the NCC (Figure 9(e)), which is consistent with the presence of a significant amount of late Permian (260 Ma) molasse sediments within the southern margin of the XMOB (Peng et al. 2012; Zhao et al. 2012).
In summary, the provenance and formation analyses of the late Palaeozoic sedimentary rocks from the eastern segment of the southern margin of the XMOB have revealed that a passive continental setting occurred in the eastern segment of the northern margin of the NCC during the Devonian–early Carboniferous, and that the final closure of the Palaeo-Asian Ocean likely happened during the late Permian owing to the presence of molasse formation.

7. Conclusions
The U–Pb ages and Hf isotopic compositions of detrital zircons from late Palaeozoic sediments in the central part of Jilin Province, Northeast China, support the following conclusions.

1. The Wangjiajie and Xiaosuihe formations formed in the Middle and Middle–Late Devonian, respectively, whereas the Luquantun Formation was deposited during early–late Carboniferous time, and the Shoushangou, Fanjiatun, and Yangjiagou formations were deposited during the late Permian rather than the early Permian as has been suggested previously.
2. Middle–Late Devonian sandstones in the study area were mainly sourced from the northern
margin of the NCC, with minor amounts of material sourced from newly accreted crust within the XMOB, whereas the early–late Carboniferous and late Permian sandstones in this area were mainly sourced from the XMOB with only minor amounts from the NCC.

(3) The carbonate and marine clastic sedimentary formations in the Wangjiajie and Xiaosuihe formations reveal that an extensional environment occurred in the southern margin of the XMOB during Middle–Late Devonian time; the carbonate and marine clastic sedimentary rock association from the Luquantun Formation, together with coeval bimodal igneous rocks and alkali granites, indicate that an extensional tectonism occurred in this area during early–late Carboniferous time, whereas the molasse formation from late Permian Shoushangou, Fanjiatun, and Yangjiagou formations suggests that they formed during rapid uplift.

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Disclosure statement

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Supplemental data

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