Geochronology and geochemistry of Late Triassic bimodal igneous rocks at the eastern margin of the Songnen–Zhangguangcai Range Massif, Northeast China: petrogenesis and tectonic implications

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\textbf{ABSTRACT}

New zircon laser ablation inductively coupled plasma mass spectrometry and secondary ion mass spectrometry U–Pb ages, and Hf isotope and whole-rock geochemical data are reported for Mesozoic igneous rocks from the eastern margin of the Songnen–Zhangguangcai Range Massif, Northeast China, in order to document the petrogenesis of the igneous rocks and reconstruct the early Mesozoic tectonic setting of the region. Zircons from five representative igneous rocks are euhedral–subhedral and display oscillatory growth zoning or striped absorption in cathodoluminescence images, suggesting a magmatic origin. The dating results indicate that granite, gabbro, and rhyolite from the eastern Songnen–Zhangguangcai Range Massif formed during Late Triassic (204–211 Ma). The Late Triassic granitoids and rhyolites have an affinity to A-type granites or rhyolites. Their zircon $\varepsilon_{Hf}(t)$ values and Hf two-stage model ages range from $-3.8$ to $+3.8$ and from 999 to 1485 Ma, respectively, indicating that their primary melts were derived from the partial melting of the Meso-Proterozoic crust. The geochemistry of coeval gabbros, which reflects primary magma composition, shows a significant large ion lithophile element (e.g. Ba and Sr) enrichment and high field strength element (i.e. Zr, Hf, Nb, Ta, and Ti) depletion. Based on zircon $\varepsilon_{Hf}(t)$ values ($-4.2$ to $+2.8$) and Hf single-stage model ages (746–1031 Ma), we conclude that the mafic magma is the product of partial melting of lithospheric mantle that was metasomatically enriched by fluids derived from the subducted oceanic crust. The Late Triassic magmatism along the eastern margin of the Eurasian continent has bimodal magmatic mantle, indicating an extensional setting after the final closure of the Palaeo-Asian Ocean rather than being related to subduction of the Palaeo-Pacific Plate beneath the Eurasian continent. The occurrence of Late Triassic igneous rocks on the eastern side of the Mudanjiang Fault suggests that this fault does not represent the suture zone between the Songnen–Zhangguangcai Range and Jiamusi massifs.

1. Introduction

Tectonically, Northeast China has been considered to be the eastern segment of the Central Asian Orogenic Belt (CAOB), located between the Siberian and the North China Cratons (NCCs) (Figure 1a; Şengör \textit{et al}. 1993; \textit{Jahn et al}. 2000\textit{a, b}, 2000\textit{c}, 2004; \textit{Xiao et al}. 2004; \textit{Li} 2006; \textit{Windley et al}. 2007). The Palaeozoic tectonic evolution of Northeast China is dominated by amalgamation of multiple microcontinental massifs (including, from west to east, the Erguna, Xing’an, Songnen–Zhangguangcai Range, Jiamusi, and Khanka massifs; Şengör \textit{et al}. 1993; \textit{Li et al}. 1999; \textit{Zhang et al}. 2006; \textit{Liu et al}. 2010\textit{a}) and the closure of the Palaeo-Asian Ocean. The Mesozoic tectonic evolution of the area is characterized by structural overprinting of the circum-Pacific system in the east and the Mongol–Okhotsk system in the northwest (\textit{Wu et al}. 2007\textit{a}; \textit{Xu et al}. 2009, 2013; \textit{Meng et al}. 2010, 2011; \textit{Wang et al}. 2012; \textit{Tang et al}. 2014, 2015). Most researchers accept that the final closure of the Palaeozoic Asian Ocean occurred along the Solonker–Xar Moron–Changchun–Yanji suture zone during the late Permian to Early Triassic (\textit{Li} and \textit{Ou} 1998, \textit{Sun et al}. 2004; \textit{Xiao et al}. 2004; \textit{Zhang et al}. 2004, 2009; \textit{Li} 2006, 2007; \textit{Wu et al}. 2007\textit{a}, 2011; \textit{Zhao et al}. 2010; \textit{Peng et al}. 2012; \textit{Cao et al}. 2013). However, it is still debated whether the transformation of the Palaeo-Asian tectonic regime into the circum-Pacific regime occurred during the Late Triassic (\textit{Jilin Bureau of Geology and Mineral Resources (JBGMR)} 1988; \textit{Heilongjiang Bureau of Geology Mineral Resources (HBGMR)} 1993; \textit{Zhao et al}. 1996; \textit{Zhou et al}. 2009) or Early–Middle Jurassic (\textit{Zhao et al}. 1994; \textit{Sun et al}. 2005; \textit{Wu et al}. 2007\textit{b}; \textit{Pei et al}. 2008; \textit{Yu et al}. 2012; \textit{Xu et al}. 2013). \textit{Wu et al}. (2011)
proposed that the circum-Pacific tectonic regime began in at least the Late Triassic (~210 Ma) based on Palaeozoic and Mesozoic magmatic events in Northeast China (Figure 1b). Yang et al. (2014) considered that the late Permian and Late Triassic igneous rocks in the eastern Jiamusi–Khanka massifs formed under subduction of the Palaeo-Pacific Plate. However, Xu et al. (2009) considered that the Late Triassic A-type of rhyolites occurred in the western margin of the Khanka Massif and formed under an extensional environment related to the final closure of the Palaeo-Asian Ocean (Figure 1b). Moreover, the EW-trending Middle–Late Triassic mafic–ultramafic igneous rocks, together with the coeval granitoids, occurring in the northern continental accretionary belt of the NCC, also reflect an extensional environment related to the post-closure of the Palaeo-Asian Ocean (Figure 1b). In contrast, the Late Triassic intrusive igneous rocks in the Erguna Massif to the west of the Songliao Basin are composed of a suite of calc-alkaline gabbro, gabbro–diorite, and granitoids, recording the southward subduction of the Mongol–Okhotsk oceanic plate during the Early Mesozoic (Figure 1b; Tang et al. 2014, 2015). Therefore, the tectonic setting of the Late Triassic igneous rocks in Northeast China remains unrefined.
debated (Wu et al. 2007b, 2011; Xu et al. 2013; Cao et al. 2013; Yang et al. 2014; Wang et al. 2015a). This study examines whether the igneous rocks formed in an extensional setting after the closure of the Palaeo-Asian Ocean (Sun et al. 2004; Han et al. 2009; Xu et al. 2013; Wang et al. 2015a) or whether they relate to the subduction of the Palaeo-Pacific Plate beneath the Eurasian continent, as proposed by Wu et al. (2011) and Yang et al. (2014).

Debate regarding the tectonic setting of the Late Triassic igneous rocks arises from the fact that there is currently only a limited understanding of early Mesozoic tectonism along the eastern margin of the Eurasian continent. However, study of early Mesozoic igneous rocks from the eastern margin of the Songneng–Zhangguangcai Range Massif, especially the Late Triassic igneous suite, provides new insights into the early Mesozoic tectonic evolution of the eastern margin of Eurasia.

In this study, we first report the occurrence of Late Triassic igneous rocks to the east of the present-day Mudanjiang Fault. We then report new laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and secondary ion mass spectrometry (SIMS) U–Pb zircon ages, as well as Hf isotopic compositions and whole-rock geochemical data for the Late Triassic igneous suite from the eastern Songneng–Zhangguangcai Range Massif, Northeast China. These new data provide clues to the tectonic evolution of the eastern Songneng–Zhangguangcai Range Massif during the Late Triassic, and afford new insights into the processes and timing that overprinted both tectonic regimes (i.e. the Palaeo-Asian Ocean and the circum-Pacific regimes).

Additionally, one of the aims of this study is to identify the boundary between the Songneng–Zhangguangcai Range and Jiamusi massifs. Traditionally, the present-day Mudanjiang Fault is considered to represent the boundary between the Songneng–Zhangguangcai Range and the Jiamusi massifs, based on the distribution of the rocks of the Heilongjiang Complex and the lack of Late Triassic igneous rocks within the Jiamusi Massif. However, the Late Triassic igneous rocks examined in the present study occur to the east of the present-day Mudanjiang Fault (i.e. within the so-called Jiamusi Massif), which merits re-evaluation of the location of the boundary between the Songneng–Zhangguangcai Range and Jiamusi massifs.

2. Geological background
Northeast China, located in the eastern part (usually termed the Xing–Meng Orogenic Belt (XMOB); Figure 1a) of the CAOB, is interpreted as a collage of microcontinents that are separated by major suture zones (Şengör et al. 1993; Li et al. 1999; Jahn et al. 2000a; Li 2006; Figure 1b). The study areas are situated at the eastern part of the Songneng–Zhangguangcai Range Massif and at two sides of the present-day Mudanjiang Fault (Figure 1b). The Songneng–Zhangguangcai Range Massif is composed of voluminous Phanerozoic granitoids and rare Palaeozoic and late Mesozoic volcanics (Wilde et al. 2000, 2003; Wu et al. 2001, 2007b; Meng et al. 2008; Xu et al. 2013). The Heilongjiang Complex occurs discontinuously along the western margin of the Jiamusi Massif (Figure 2a). Rocks outcropping in the study area include the Precambrian Dongfengshan Group, the Devonian Baoquan Formation, the Permian Tumenling and Wudaoling Formations, the Jurassic Jielihe Formation, and the Cretaceous Songmuhe and Taqihe Formations (HBGMR 1993; Wang et al. 2014; Figure 2a and b). In addition, the study area contains voluminous Mesozoic granitoids and rare Palaeozoic granites (Wu et al. 2011; Wang et al. 2012; Yu et al. 2012, 2013).

Along the Northeast Asian continental margin, Middle–Late Triassic igneous rocks are widespread. These include (1) Middle–Late Triassic post-orogenic alkaline and granitic rocks that are parallel to the Sulu orogenic belt, which formed in the Korean Peninsula, and similar units that crop out along eastern Shandong and southern Liaoning–southern Jilin provinces (Lu et al. 2003; Wu et al. 2007d; Yang and Wu 2009; Chen and Jiang 2011; Kim et al. 2011; Pei et al. 2011); (2) Middle–Late Triassic post-orogenic alkaline and bimodal igneous rocks that are parallel to the Solonker–Xar Moron–Changchun–Yanjí suture zone, which formed in the northern margin of the NCC (Yan et al. 2000; Yang et al. 2012; Cao et al. 2013); (3) Middle–Late Triassic calc-alkaline igneous rocks in the Erguna Massif formed under an active continental margin setting related to southward subduction of the Mongol–Okhotsk oceanic plate (Tang et al. 2014, 2015); and (4) Late Triassic bimodal igneous rocks in the eastern Heilongjiang–Jilin provinces formed in an extensional environment (Xu et al. 2013; Wang et al. 2015a). Here, we focus on (1) the petrogenesis of Late Triassic igneous rocks of the lesser Xing’an–Zhangguangcai Ranges to reveal the tectonic nature of the Northeast Asian continental margin during the Late Triassic and (2) constraining the timing of inception of the Palaeo-Pacific Plate beneath the Eurasian continent.
3. Sample descriptions

For this study, three samples (13HYL8, 13HYL9, and 13HYC23) were collected from the eastern part of the Songnen–Zhangguangcai Range Massif (i.e. to the west of the present-day Mudanjiang Fault) and two samples (13HYL1 and 13HYL3) were collected from the east of the present-day Mudanjiang Fault (Figure 2a and b). The aim of this sampling strategy is to identify whether the present-day Mudanjiang Fault is the boundary or the suture zone between the Songnen–Zhangguangcai Range and Jiamusi massifs.

Olivine gabbro sample 13HYL1 was collected from a site ~3 km south of the Dadingshan village in Yilan county (Figure 2a). Field observation indicates that the gabbro intrusion is intruded by a late-stage granitic dike (Figure 2a). The photomicrograph of olivine gabbro exhibits a diabasic texture and massive structure. Plagioclase is euhedral and subhedral in shape; pyroxene and olivine occur as intergrains between plagioclases (Figure 2a and b). The gabbro consists of plagioclase (~54 vol%), clinopyroxene (~33 vol%), and olivine (~10 vol%) with minor hornblende and hypersthene as well as accessory magnetite, apatite, and zircon (Figure 3a and b; Table 1).

Samples 13HYL3, 13HYL8, and 13HYL9 (all syenogranites) were, respectively, collected ~200 m east of the Dadingshan forest farm in Yilan county (Figure 2a), ~300 m west of the Xiangshan village in Tangyuan county (Figure 2a), and from a site located ~200 m south of the Yaoying forest farm in Tangyuan county (Figure 2a). Based on field observation and a 1:200,000 geological map of the study area, we suggest that the syenogranite intrudes not only the Palaeozoic granitoids, but also the olivine gabbro (Figure 2c). All three samples are fresh and have a medium- to coarse-grained massive texture. They are composed of quartz (25–45 vol%), perthite (35–50 vol%), plagioclase (15–20 vol%), and biotite (5–10 vol%) as well as accessory zircon, apatite, and magnetite (Figure 3c–e; Table 1).
Rhyolite sample 13HYC23 was collected at the Wengcui forest farm in Qingshan country (Figure 2b). This area is marked as part of the Jurassic Jieliehe Formation on the 1:200,000 regional geology map (HBGMR 1993). The sample is fresh and porphyritic and comprises phenocrysts (~25 vol%) of plagioclase and quartz in a fine-grained groundmass of felsic minerals (Figure 3f; Table 1).
The classification and nomenclature of these igneous rocks are shown in Figure 4.

4. Analytical methods

4.1. Zircon U–Pb dating

Zircons were separated from samples using conventional heavy liquid and magnetic techniques before being purified by hand-picking under a binocular microscope at the Langfang Geophysical Survey, Hebei Province, China. The hand-picked zircons were examined using transmitted and reflected light, and their internal structures were examined by cathodoluminescence (CL) imaging using a JEOL scanning electron microscope at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. The CL images were used to identify distinct domains within zircons for analysis. Zircon U–Pb ages were obtained using an Agilent 7500a ICP-MS equipped with a 193 nm laser at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. The 91,500 zircon standard was used as an external standard for age calibration and a National Institute of Standards and Technology Glass Standard Reference Material 610 silicate glass was used for instrument optimization during analysis. A 30 μm spot size was used during analysis and all other instrument parameters and procedures used are given in Liu et al. (2008). The ICPMSDataCal (Ver. 6.7; Liu et al. 2008, 2010b) and Isoplot (Ver. 3.0; Ludwig 2003) programs were used for data reduction, and common Pb corrections were undertaken using the approach of Andersen (2002). Uncertainties on individual LA-ICP-MS analyses are reported at the 1σ level, and errors on weighted mean ages are given at the 95% (2σ) confidence level.

The sample 13HYL1 (olivine gabbro) was analysed using a Cameca 1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, using operating and data-processing procedures similar to those described by Li et al. (2009). Dating results are presented in Supplemental Table 1 (see http://dx.doi.org/10.1080/00206814.2015.1059295 for supplemental tables).

4.2. Major and trace element analysis

Samples for whole-rock analysis were cleaned and the altered material was removed prior to crushing in an agate mill to pass ~200 mesh. The geochemical data (whole-rock major and trace elements) were obtained at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. Major elements were analysed by X-ray fluorescence using a Rigaku RIX 2100 spectrometer. Trace elements were determined by ICP-MS after acid digestion of samples in Teflon bombs using an Agilent
7500a equipped with a shield torch. Analytical uncertainties are between 1% and 3%, and analyses of BHVO-1 (basalt), BCR-2 (basalt), and AGV-1 (andesite) standards indicate that the major element analytical precision is better than 5%, and that trace element analytical precision is generally better than 10% (Rudnick et al. 2004). Supplemental Table 2 presents major and trace element compositions of the Late Triassic igneous rocks analysed in this study.

### 4.3. Zircon Hf isotope analyses

In situ zircon Hf isotope analysis was undertaken using MC-ICP-MS and a Neptune equipped with a 193 nm ArF excimer laser ablation system at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. A simple Y junction downstream from the sample cell was used to add small amounts of nitrogen (4 ml min⁻¹) to the argon gas (Hu et al. 2008); this addition of nitrogen in combination with the use of newly designed X skimmer and Jet sample cones within the Neptune Plus instrument improved the signal intensities of Hf, Yb, and Lu compared to standard arrangements by factors of 5.3, 4.0, and 2.4, respectively. All data were acquired using single-spot ablation mode and a 44 μm spot size. Each measurement consisted of 20 s of background signal acquisition followed by 50 s of ablation signal acquisition. Detailed operating conditions for the laser ablation system, the MC-ICP-MS instrument, and the analytical methods used during this study are given in Hu et al. (2012a, 2012b) and the analytical results of the zircon Hf isotopes are presented in Supplemental Table 3.

### 5. Analytical results

#### 5.1. Zircon U–Pb dating

The zircons selected for analysis are euhedral to subhedral and display striped absorption or fine-scale oscillatory growth zoning in CL images (Figure 5). These properties, together with Th/U ratios of 0.14–1.17 (Supplemental Table 1), indicate a magmatic origin (Pupin 1980; Koschek 1993). Compared with the zircons with the ages of 204–211 Ma, the captured zircons with older ages exhibit larger grains and a cleaner core–rim structure as well as subhedral or anhedral shapes (Figure 5).

Sample 13HLYL1-1 is an olivine gabbro. The $^{206}\text{Pb}/^{238}\text{U}$ ages from 10 analytical spots on the zircons range from 207 to 214 Ma, yielding a weighted mean age of 211 ± 2 Ma (mean square weighted deviation (MSWD) = 0.73, n = 10) (Figure 6a). Other concordant ages are 350 ± 5 Ma (n = 2), 306 ± 5 Ma (n = 1), 290 ± 5 Ma (n = 1), and 253 ± 4 Ma (n = 1). The age of 211 Ma is interpreted as the formation age of the gabbro, i.e. Late Triassic rather than Variscan as previously suggested (HBGMR 1993). The older ages are interpreted to represent the crystallization times of captured zircons incorporated during emplacement of the gabbro.

The $^{206}\text{Pb}/^{238}\text{U}$ ages from 16 analytical spots on zircons separated from sample 13HLYL3-1, a syenogranite, are 203–220 Ma, yielding two age populations at 204 ± 2 Ma (MSWD = 0.19, n = 7) and 219 ± 2 Ma (MSWD = 0.19, n = 9) (Figure 6b)). The 204 Ma age is considered to represent the crystallization age of the syenogranite, i.e. Late Triassic rather than early Yanshanian as previously reported by HBGMR (1993). The 219 Ma age population is interpreted to represent the crystallization time of captured zircons incorporated during intrusion of the syenogranite.

For sample 13HLYL8-1, another syenogranite, the $^{206}\text{Pb}/^{238}\text{U}$ ages from 11 analytical spots on zircon grains are 201–208 Ma, yielding a weighted mean age of 205 ± 2 Ma (MSWD = 0.44, n = 11) (Figure 6c). This Late Triassic age contrasts that of a Variscan age as previously proposed by HBGMR (1993). The concordant age of 452 ± 4 Ma (n = 1) is interpreted to represent the crystallization age of a captured zircon entained by the syenogranite.

For sample 13HLYL9-1, another syenogranite, the $^{206}\text{Pb}/^{238}\text{U}$ ages from 13 analytical spots on zircon grains are 202–222 Ma including two age populations of 204 ± 2 Ma (MSWD = 0.40, n = 4) and 219 ± 2 Ma (MSWD = 0.16, n = 9) (Figure 6d). The former age population (204 Ma) is interpreted as the crystallization age of the syenogranite (i.e. Late Triassic rather than Variscan as previously suggested by HBGMR (1993)), while the latter age is interpreted to represent the crystallization time of captured zircons incorporated during intrusion of the syenogranite.

Rhyolite sample 13HYC23-1 was collected from the Jielihe Formation, previously mapped as Jurassic (HBGMR 1993). The $^{206}\text{Pb}/^{238}\text{U}$ ages from 16 analytical zircon spots are 202–221 Ma, including two groups of concordia ages of 206 ± 2 Ma (MSWD = 0.72, n = 14) and 221 ± 3 Ma (n = 2) (Figure 6e). The former represents the crystallization age of the rhyolite, while the latter is interpreted as the crystallization age of the captured zircons entained by the rhyolite.

Based on the new age data, the Late Triassic magmatic activity in the study area can be subdivided into two main events at ~219 Ma and 211–204 Ma.
(Figure 6f). The former represents the crystallization age of captured zircons and the latter is discussed below.

5.2. Geochemistry

5.2.1. Major elements

Whole-rock compositions of the Late Triassic felsic rocks, including syenogranites and rhyolites, are shown in Figure 7a and b. The rocks have SiO₂ = 71.69–76.91 wt.%, Al₂O₃ = 12.60–14.10 wt.%, CaO = 0.48–1.51 wt.%, Mg# (Mg# = 100 Mg²⁺/(Mg²⁺ + TFe²⁺)) = 5.70–32.0, and (K₂O + Na₂O) = 7.69–8.97 wt.%. On a total alkali versus SiO₂ (TAS) diagram (Figure 7a; Irvine and Baragar 1971), the rocks fall into the subalkaline series. Their A/CNK [molar Al₂O₃/(CaO + K₂O + Na₂O)] values are 1.04–1.06, indicating a metaluminous composition (Figure 7b).

The Late Triassic mafic rocks have SiO₂ = 44.97–47.35 wt.%, TiO₂ = 0.18–0.30 wt.%, (K₂O + Na₂O) = 7.69–8.44 wt.%, Al₂O₃ = 17.75–23.92 wt.%, and Mg# = 63.4–75.7. On the TAS plot of the total alkali versus SiO₂ (Figure 7a; Irvine and Baragar 1971), the rocks fall into the subalkaline series.
Figure 6. Zircon U–Pb concordia diagrams (a–e) and relative probability (f) for the Late Triassic igneous rocks at the eastern margin of the Songnen–Zhangguangcai Range Massif.

Figure 7. Plots of total alkali versus SiO₂ (TAS) (a) and K₂O versus SiO₂ (b). The field boundaries are from Irvine and Baragar (1971) and Peccerillo and Taylor (1976), respectively. The shaded areas are the other Late Triassic igneous rocks from the regions (Wang et al. 2015a).
The Late Triassic igneous suite has a distinct compositional gap between 47.35 and 71.69 wt.% SiO$_2$, which is typical for bimodal igneous suites.

### 5.2.2. Trace elements

The Late Triassic felsic rocks are characterized by light rare earth element (LREE) fractionation ([La/Yb]$_N$ ratios of 4.94–9.39), large ion lithophile element (LILE) enrichment (e.g. Rb and K), Pb, Th, and U, but depletion in heavy rare earth element (HREE), P, and high field strength elements (HFSEs) such as Nb, Ta, and Ti. The highly mobile elements Ba and Sr are also depleted. The strong negative Eu anomalies ($\delta$Eu = 0.09–0.56) are characteristic of their evolved compositions (Figure 8a and b).

In contrast, the Late Triassic mafic rocks are defined by the low total rare earth element (REE) abundances ($\Sigma$REE = 10.10–14.52 ppm), positive Eu anomalies ($\delta$Eu = 1.22–1.90), and flat REE patterns with [La/Yb]$_N$ ratios of 1.14–3.13 (Figure 8a). The mafic rocks contain up to 29.3 ppm Sc, 258 ppm Cr, 39.4 ppm Ni, and 54.5 ppm Co. The mafic rocks are also enriched in LILEs (e.g. Ba, K, and Sr) and Pb, but depleted in HFSEs (Nb, Ta, Zr, Hf, and Ti) (Figure 8a and b).

### 5.2.3. In situ zircon Hf isotope compositions

Some of the U–Pb dating spots on zircons from samples 13HYL1-1, 13HYL3-1, 13HYL8-1, 13HYL9-1, and 13HYC23-1 were selected for in situ Hf isotope analyses (Supplemental Table 3). The initial $^{176}$Hf/$^{177}$Hf ratios of zircons from the gabbro (sample 13HYL1-1, 211 Ma) range from 0.282526 to 0.282724, and their $\varepsilon_{\text{Hf}}(t)$ values and single-stage modal ages ($T_{\text{DM1}}$) range from –4.2 to +2.8 and from 746 to 1031 Ma, respectively. The initial $^{176}$Hf/$^{177}$Hf ratios of zircons from granites and rhyolites (samples 13HYL3-1, 204 Ma; 13HYL8-1, 205 Ma; 13HYL9-1, 204 Ma; 13HYC23-1, 206 Ma) range from 0.282544 to 0.282784, and the corresponding $\varepsilon_{\text{Hf}}(t)$ values and two-stage modal ages ($T_{\text{DM2}}$) vary from –3.8 to +3.8 and from 999 to 1485 Ma, respectively. The Hf isotopic compositions of the selected zircon grains are similar to those of zircons derived from Phanerozoic igneous rocks from the CAOB (Figure 9; Xiao et al. 2004; Yang et al. 2006; Chen et al. 2009), but are different from those of captured Neo-Archaean and Palaeo-Proterozoic zircons in Palaeozoic–Mesozoic strata of the Yanshan Fold-and-Thrust Belt (YFTB; Yang et al. 2006).

### 6. Discussion

#### 6.1. Late Triassic magmatism in the Songneng–Zhangguangcai Range Massif

The analysed rocks were previously mapped as early Yanshanian, or late Variscan on the basis of K–Ar dating and lithostratigraphic relationships (HBGMR 1993). The
K–Ar ages are unreliable due to the occurrence of late-stage tectono-magmatic events (such as Early Jurassic, Early Cretaceous, and Late Cretaceous magmatic events; Ji et al. 2007; Yu et al. 2012; Zhang et al. 2012; Xu et al. 2013) that affected the study area, which may result in Ar loss. New zircon ages, supported by field relationships including cross-cutting intrusions, indicate that the inferred Palaeozoic ages of these units should be reviewed (Meng et al. 2011). Zircon U–Pb dating provides the most accurate tool to date the magmatic rocks in the study area, given the high closure temperature and stability of zircons (Lee et al. 1997; Kosler and Sylvester 2003).

The separated zircon grains are euhedral–subhedral and show striped absorption or oscillatory growth zoning in CL images, suggesting a magmatic origin (Pupin 1980; Koschek 1993). This supports the interpretation that the U–Pb zircon ages represent the timing of crystallization of these rocks. All zircons from this study yield Late Triassic weighted mean 206Pb/238U ages of 211–204 Ma (13HYL1-1, 211 Ma; 13HYC23-1, 206 Ma; 13HYLB-1, 205 Ma; 13HYL3-1; and 13HYL9-1, 204 Ma; Figure 6), indicating a Late Triassic magmatic event in the Songnen–Zhangguangcai Range Massif. Recent work has shown that Late Triassic igneous rocks are major constituents of the Songnen–Zhangguangcai Range Massif (Wu et al. 2011; Figure 1b). Examples are the Sanyadohe syenogranite pluton (216 Ma) in the central Jilin Province (Sun et al. 2005); the Maojiatun (212 Ma), Tuanjie (201 Ma), Langxiang (200 Ma), Dafeng (201 Ma), Xiaoxilin (200 Ma), and Taiqing granitic plutons (210 Ma) in the lesser Xing'an–Zhangguangcai Range Massif (Wu et al. 2002, 2011); and Late Triassic igneous rocks (202–228 Ma) in the eastern Heilongjiang Province (Xu et al. 2009; Wang et al. 2015a) and the Erguna Massif (Tang et al. 2014, 2015). Taken together, these igneous suites provide evidence for a significant Late Triassic igneous event in NE China.

6.2. Petrogenesis of the Late Triassic igneous rocks

6.2.1. Petrogenetic relationships between mafic and felsic rocks

Zircon U–Pb ages and geochemical results indicate that the formation ages of olivine gabbros, granitoids, and rhyolites represent a bimodal igneous succession. Here, we consider the petrological evolution of the bimodal suite and examine whether the felsic rocks were generated by fractional crystallization of the mafic magma or whether the two end members have independent origins.

The presence of a distinct compositional gap in SiO₂ concentrations (Figure 7a) between the mafic and felsic end members, and the lack of coeval intermediate rocks in the study area suggests that the felsic rocks were not generated by fractional crystallization of the parental mafic melt. Given the typical mineral–melt distribution coefficients for basaltic melts (Dostal et al. 1983; Yang et al. 2000; Sun and Liang 2012), we can exclude the possibility that the felsic rocks are the products of fractional crystallization of a mafic parental magma, because in such a case they would have high LREE and low HREE concentrations (i.e. steep REE patterns) compared with the mafic igneous rocks. In fact, the felsic rocks have higher HREE abundances than the coeval mafic rocks (Figure 8a). Therefore, we conclude that the mafic and felsic end members of the igneous suite were derived from independent magma sources.

6.2.2. Origin of the mafic igneous rocks

6.2.2.1. Magmatic evolution and contamination.

Reaction rims of orthopyroxene and clinopyroxene surround the olivine phenocrysts and we observed cumulative textures of plagioclase in the olivine gabbro (Figure 3a and b), indicating fractional crystallization of olivine and plagioclase during their magmatic evolution. Accumulation of plagioclase was responsible for the positive Sr and Eu anomalies in spidergram patterns as well as the high Al₂O₃ contents (up to 23.92 wt.%%) in these rocks (Figure 8a and b). The relatively high whole-rock Cr abundances of the olivine gabbros also suggest fractional crystallization of clinopyroxene during magmatic evolution, consistent with the diabasic texture and hornblende reaction rims around clinopyroxene phenocrysts (Figure 3a and b). Hence, we conclude that fractionation of olivine, clinopyroxene, and plagioclase was an important process during the magmatic evolution of the mafic rocks.

The low SiO₂ (44.97–47.35 wt.% contents, high Mg# (63.4–75.7), and relatively high Sc (up to 29.3 ppm), Cr (up to 258 ppm), Ni (up to 39.4 ppm), and Co (up to 54.5 ppm) concentrations of the mafic rocks (Supplemental Table 2) indicate that crustal contamination was a minor factor during magmatic evolution. However, rare inherited zircons with older ages are also recorded in these rocks.

6.2.2.2. Source characteristics. Petrographic observations and geochemical characteristics of the investigated mafic rocks indicate that they represent early-stage cumulates. However, their low SiO₂ contents (<47.35 wt.% and relatively high Mg# (63.4–75.7) suggest that they are products of fractional crystallization of a basaltic primary magma that formed during partial melting of the upper mantle (Frey and Prinz 1978;
Hofmann 1988; Xu et al. 2004). Given the minor influence of crustal contamination, the geochemistry of the mafic rocks still reflects the nature of its upper mantle source. The LILE (e.g. Ba and Sr) enrichment and HFSE (Zr, Hf, Nb, Ta, and Ti) depletion (Figure 8b) suggest that the parental magma was derived from the partial melting of lithospheric mantle modified by the input of fluids or melts that resulted from the partial melting of subducted sediments (Gill 1981; Grove et al. 1986; Ayers 1998; Eiler et al. 2000, 2003). The Ba, Th, Nb, and REE contents can be used to distinguish between the relative roles of fluid and melt fractions in overprinting the upper mantle source. These elements show a different geochemical behaviour in hydrous fluids compared with melt fractions that are derived from partial melting of a subducted slab (Kogiso et al. 1997; Ayers 1998; Woodhead et al. 2001). The investigated mafic igneous rocks have high Ba/Nb (183–333), Th/Nb (0.40–0.56), and Ba/La (32–46) ratios (Figure 10), showing variation trends that are typical of sediment-derived fluids (Guo et al. 2015). In addition, the $\varepsilon_{Hf}(t)$ values of zircons separated from the mafic rocks range from −4.2 to +2.8 and their corresponding single-stage modal ages ($T_{DM1}$) vary from 746 to 1031 Ma, indicating that the primary mafic magma was derived from partial melting of a relatively enriched lithospheric mantle (Wu et al. 2007c). In summary, we conclude that the mafic magma was formed by the partial melting of lithospheric mantle previously enriched by fluids derived from subducted sediments. The simultaneous enrichment of the mafic rocks in incompatible trace elements (e.g. Ba and Sr) and Hf isotopic compositions indicate that the enrichment process of the lithospheric mantle could be much older than the Late Triassic mafic rocks.

We propose that the mafic magma formed from partial melting of the lithospheric mantle wedge over a palaeo-subduction zone (Yu et al. 2012; Xu et al. 2013) rather than the southward subduction of the Mongol–Okhotsk oceanic plate. The evidence is as follows: (1) the Late Triassic igneous rocks in the lesser Xing’an–Zhangguangcai Ranges are far away from the Mongol–Okhotsk suture zone (ca. 1500 km), not supporting back-arc magmatism related to this subduction process during ca. 200 Ma; (2) if the formation of the gabbros is related to the southward subduction of the Mongol–Okhotsk oceanic plate, the gabbros should only exhibit enrichments in LILEs and LREEs rather than Hf isotopic enrichments, because Hf isotopic equilibrium could be reached during this process (Yu et al. 2012); (3) these Late Triassic gabbros occur over a palaeo-subduction zone; i.e. the presence of a Caledonian calcalkaline igneous suite at the eastern margin of the Songnen–Zhangguangcai Range Massif indicates that the westward subduction and subsequent closure of a palaeo-ocean that once separated the Songnen–Zhangguangcai Range Massif from the Jiamusi Massif took place during the Late Ordovician and Silurian (450–425 Ma) (Wang et al. 2012). Collectively, we conclude that the arc-style geochemical signatures of the gabbros in this study are attributable to the influence of a palaeo-subduction zone rather than the southward subduction of the Mongol–Okhotsk oceanic plate. Additionally, owing to the lack of intensive Late Palaeozoic magmatisms in the lesser Xing’an–Zhangguangcai Ranges (except for the ~320 Ma minor rhyolites; Li et al. 2014), this enriched mantle wedge was not removed or destructed prior to the interval of the Late Triassic magmatism in the study area.

Figure 10. Ba/Nb and Ba/La versus $\varepsilon_{Hf}(t)$ diagrams illustrating the possible roles of partial melting of sediments and/or slab-derived fluids in modifying the upper mantle source of the Late Triassic mafic rocks (after Guo et al. 2015). DM, depleted mantle. Some data are the other Late Triassic and Early Jurassic igneous rocks from the regions (Yu et al. 2012; Wang et al. 2015a).
6.2.3. Origin of the felsic igneous rocks

Late Triassic felsic rocks exposed along the eastern margin of the Songneng–Zhangguangcai Range Massif include syenogranites (samples 13HYL3, 13HYL8, and 13HYL9) and rhyolite (sample 13HYC23), all of which have similar geochemical and Hf isotope compositions (Figures 7, 8a and b), suggesting that these rocks are genetically related. Their major element compositions are characterized by high SiO$_2$ (71.69–76.91 wt.%) and total alkali contents (7.69–8.97 wt.%, especially K$_2$O = 4.46–5.10 wt.%), and low MgO concentrations (<0.56 wt.%), indicating that their primary parental magmas were likely derived from partial melting of lower crust material (Hofmann 1988; Xu et al. 2009). The felsic rocks have relatively high HREE abundances (Figure 8a), indicating that the garnet is absent in their magma sources and consistent with a lower crustal anatexis origin. Their depletions in Nb, Ta, Ti, Ba, Sr, P, and Eu suggest that rutile, Fe–Ti oxides, and apatite were rare or absent in the magma sources (Xu et al. 2009). The $\varepsilon_{Hf}$ (t) values of zircons separate from the felsic rock range from −3.8 to +3.8 and the corresponding $T_{DM2}$ varies from 999 to 1485 Ma (Figure 9), suggesting that the primary magma was the product of partial melting of the Meso-Proterozoic crust. This interpretation is also supported by the presence of a Precambrian terrane in the eastern Songneng–Zhangguangcai Range Massif (Wang et al. 2014). Therefore, we conclude that the parental melts of the Late Triassic igneous rocks formed by partial melting of the lower crust that was accreted during the Meso-Proterozoic.

6.3. The suture zone between the Songnen–Zhangguangcai Range and Jiamusi massifs

The present-day Mudanjiang Fault and the Heilongjiang Complex exposed along the fault are considered to represent the suture zone between the Songneng–Zhangguangcai Range and the Jiamusi massifs (Zhang 1991; Cao et al. 1994; Zhao et al. 1996; Li et al. 1999; Wu et al. 2000, 2007b; Zhou et al. 2009). Based on the absence of Late Triassic and Early Jurassic igneous rocks in the Jiamusi Massif, Wu et al. (2007b) and Xu et al. (2012) proposed that the Songnen–Zhangguangcai Range Massif was separated from the Jiamusi Massif during the Middle–Late Triassic along the Mudanjiang Fault, and that the fault represents the suture zone between the two massifs. However, the Late Triassic igneous rocks recovered in this study occur at the eastern side of the fault and within the Jiamusi Massif according to previous interpretations. Importantly, if the boundary between the two massifs is determined based on the concept that no Middle to Late Triassic igneous rocks occur within the Jiamusi Massif, the current Mudanjiang Fault cannot represent the suture zone between the Songnen–Zhangguangcai Range and Jiamusi massifs. Based on the fact that the ultramafic complex, attributed to the Heilongjiang Complex, occurs to the east of the Late Triassic igneous suite of this study (Figure 2a), we conclude that the suture zone separating the two massifs must be located either within the ultramafic complex or along its eastern boundary. Additional research is needed to define the location of the suture between the Songnen–Zhangguangcai Range and the Jiamusi massifs.

6.4. Tectonic implications

The Late Triassic tectonic evolution of Northeast China has been debated for some time. Most researchers propose that Late Triassic tectono-magmatism was controlled mainly by the inception of subduction of the Palaeo-Pacific Plate beneath the Eurasian continent (Wu et al. 2011; Peng et al. 2012; Zhou and Wilde 2013; Yang et al. 2014). Others argued that the tectono-magmatism occurred in an extensional tectonic setting after the final closure of the Palaeo-Asian Ocean, based on the occurrence of Late Triassic bimodal volcanism and rhyolites with A-type characteristics in the eastern Heilongjiang Province (Xu et al. 2009, 2013; Wang et al. 2015a). Additionally, Tang et al. (2014, 2015) and Wang et al. (2015b) proposed that the Early Triassic to Early Jurassic magmatisms in the Erguna Massif formed under an active continental margin setting related to southward subduction of the Mongol–Okhotsk oceanic plate. Therefore, we believe that the Late Triassic igneous rocks in the study area, and their spatial variations in geochemistry from the continental margin to the continental interior, are the key to resolving this debate.

6.4.1. Late Triassic igneous rocks to the east of the Songliao Basin

The bimodal nature of the Late Triassic magmatism along the eastern margin of the Songneng–Zhangguangcai Range Massif (Figure 7a) suggests an extensional rather than a compressional tectonic setting related to subduction of the Palaeo-Pacific Plate beneath the Eurasian continent. In addition, the Late Triassic felsic igneous rocks in the study area have geochemical affinities to A-type granites (Figure11; Whalen et al. 1987; Wu et al. 2002; Sun et al. 2005; Han et al. 2009) that are typical of extensional environments. Additionally, coeval igneous rocks in the Eurasian continental margin (Figure 1b) display A-type
rhyolite affinities and bimodal intrusive rocks, also revealing an extensional environment (Xu et al. 2009; Wang et al. 2015a). Therefore, both the Late Triassic igneous rocks of the eastern Heilongjiang Province and the Songnen–Zhangguangcai Range Massif include bimodal volcanism, and rhyolites and granites with A-type characteristics (Xu et al. 2009, 2013; Yang et al. 2014; Wang et al. 2015a), which are typical features of an extensional tectonic setting. This spatial variation in coeval igneous rocks is different from calc-alkaline igneous successions that are related to subduction in general (Gill 1981), and the Palaeo-Pacific Plate beneath the Eurasian continent especially (Xu et al. 2013). Taken together, we conclude that the Late Triassic magmatism in eastern Northeast China is unrelated to subduction of the Palaeo-Pacific Plate beneath the Eurasian continent but instead related to the extension as suggested by Xu et al. (2013).

6.4.2. Late Triassic igneous rocks in the Erguna Massif
The Late Triassic magmatic rocks in the Erguna Massif consist of a suite of calc-alkaline gabbro, gabbro–diorite, and granitoids, revealing an active continental margin setting related to the southward subduction of the Mongol–Okhotsk oceanic plate (Tang et al. 2014, 2015; Wang et al. 2015b), and different from the Late Triassic extensional environment revealed by the coeval A-type and bimodal igneous rock association to the east of the Songliao Basin (Xu et al. 2009, 2013; Wang et al. 2015a).

6.4.3. Late Triassic igneous rocks at the northern margin of the NCC
The Late Triassic igneous rocks at the northern margin of the NCC consist of alkaline igneous rocks that are formed in an extensional tectonic setting (Yan et al. 2001; Pei et al. 2008; Yang et al. 2012), whereas the coeval igneous rocks within the northern continental margin accretionary belt of the NCC are composed of a suite of mafic–ultramafic intrusive rocks and granitoids with bimodal successions (Wu et al. 2004; Cao et al. 2013) and A-type affinity (Shi et al. 2007). These Late Triassic igneous rocks all formed in an extensional environment.

6.4.4. Tectonic implications
In summary, we conclude that the Late Triassic igneous rocks to the east of the Songliao Basin, together with coeval igneous rocks from the northern margin of the NCC, all formed in an extensional environment. Considering their E–W distribution, we conclude that the Late Triassic igneous rocks in eastern Northeast China formed in a post-orogenic extensional setting related to, but post-dating, the final closure of the Palaeo-Asian Ocean (Figure 12), and that initial subduction of the

Figure 11. Granitoid discrimination diagrams (after Whalen et al. 1987). A, A-type granites; FG, fractionated felsic granites; OGT, unfractonated M-, I-, S-type granites.

Figure 12. Geodynamical model of the Late Triassic igneous rocks in Northeast China. (a) Plane map (modified after Yin and Nie 1996); (b) A–B cross section. NCC, North China Craton; XMOB, Xing–Meng Orogenic Belt.
Palaeo-Pacific Plate beneath the Eurasian continent did not occur during the Late Triassic (Xu et al. 2009, 2013; Wang et al. 2015a). The final closure of the Palaeo-Asian Ocean occurred along the Solonker–Xar Moron–Changchun–Yanjii zone during the late Permian to Early Triassic (Figure 12a; Sun et al. 2004; Li 2006; Wu et al. 2007a; Li et al. 2009; Cao et al. 2013) resulting in lithospheric thickening. The thickened lithosphere, in gravity, is unstable, which resulted in delamination and subsequent upwelling of the asthenosphere as well as underplating of mafic magma near the mantle–crust boundary. The underplated magma would not only cause the partial melting of the overlying lower crust, i.e. producing granitic magma which intrudes or erupts as a result of granitoids or rhyolites, but also rise and intrude as gabbros. Therefore, a bimodal igneous succession formed in eastern Northeast China (Figure 12b). In contrast, early Mesozoic magmatic activity within the Erguna Massif occurred in an active continental margin setting related to the southward subduction of the Mongol–Okhotsk oceanic plate (Figure 12b; Tang et al. 2014, 2015; Wang et al. 2015b).

7. Conclusions

Based on new zircon U–Pb ages and geochemical data, we draw the following conclusions.

1) A Late Triassic (204–211 Ma) bimodal igneous suite ranging from olivine gabbros to syenogranites and rhyolites occurs along the eastern margin of the Songnen–Zhangguangcai Range Massif.

2) The primary parental melts of the mafic rocks were derived from partial melting of the lithospheric mantle material enriched by slab sediment-derived fluids in a palaeo-subduction zone, while the coeval felsic rocks mainly originated from partial melting of the Mesoproterozoic lower crust.

3) The present-day Mudanjiang Fault does not represent the suture zone between the Songnen–Zhangguangcai Range and Jiamusi massifs. The suture zone must be to the east of the Late Triassic igneous rocks.

4) The Late Triassic bimodal igneous succession of the eastern Songnen–Zhangguangcai Range Massif formed in an extensional tectonic setting after the closure of the Palaeo-Asian Ocean. Subduction of the Palaeo-Pacific Plate beneath the Eurasian continent took place in the Early Jurassic as opposed to as previously suggested in the Late Triassic.

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Supplemental data

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