Petrogenesis and Tectonic Implications of Jurassic Granites in the Xingcheng Area, Northeastern North China Craton

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Abstract: New integrated geochemical studies are reported for Jurassic granites of the Xingcheng area in the northeastern North China Craton. U–Pb zircon data indicate that the Huashan and Taili monzogranites were emplaced during the Early (189 ± 2 Ma) and Late (155 ± 1 Ma) Jurassic, respectively. They are typical of high-K calc-alkaline series rocks and I-type granites, according to our whole-rock geochemical researches. Both Early and Late Jurassic monzogranites show adakitic rock characteristics because of their high Sr contents (221–347 ppm) and Sr/Y ratios (28.7–37.5), and low Y contents (7.83–14.7 ppm). The Early Jurassic monzogranite samples have an (εNd(t)) value of −11.62 to −11.51, and εHf(t) values of −13.6 to −6.4, whereas the Late Jurassic monzogranites have higher (εNd(t)) ratios of 0.7069–0.7071 and lower εHf(t) (−20.65 to −20.46) and εHf(t) (−27.6 to −20.0) values. We suggest that the Early Jurassic adakitic rocks were derived from partial melting of thickened lower crust contaminated with mantle-derived materials, related to subduction of the Paleo-Pacific Plate. The Late Jurassic adakitic rocks were derived from partial melting of thickened lower crust in an extensional tectonic setting associated with an active continental margin.

Key words: geochemistry, petrology, monzogranite, adakite, North China Craton

1 Introduction

The North China Craton (NCC) is one of the oldest Archean cratons (Liu et al., 1992) and was influenced by several surrounding tectonic systems during the Mesozoic. The Paleo-Asian Ocean (PAO) closed along the Solonker–Xra Moron–Changchun suture belt during the Late Permian–Early Triassic, forming the Central Asian Orogenic Belt (CAOB; Zhou et al., 2017; Wang et al., 2019). The Mongol–Okhotsk Ocean (MOO) closed during the Middle–Late Jurassic (Xu et al., 2013), and westward subduction of the Paleo-Pacific Ocean (PPO) Plate began in the Early Jurassic (Wang et al., 2017). Western Liaoning is located in the northeastern NCC where there was widespread magmatism associated with interactions of multiple plates during the Mesozoic, making it a key area to study the tectonic evolution of the region (Wu et al., 2008; Xu et al., 2013).

Jurassic granitic rocks and intermediate-silicic volcanic rocks in western Liaoning were formed mainly during the Early–Late Jurassic, with minor input in the Middle Jurassic (Wu et al., 2005). There is still debate concerning the petrogenesis of the Jurassic granitoids and their tectonic implications. One viewpoint is that southward subduction of the MOO Plate resulted in partial melting of the crust (Yang and Li, 2008; Xu et al., 2013). Another is that the Jurassic granites in the area, which are mostly I-type with high-Sr and low-Y adakitic characteristics, were formed through delamination of thickened lower crust or subduction of PPO crust (Gao et al., 2004; Wu et al., 2005; Yang et al., 2010, 2016). As the Jurassic has generally been defined as the period for the opening of the PPO Plate and the closure of the MOO Plate (Xu et al., 2013; Wang et al., 2017), it was considered as the critical time of transformation between the different tectonic regimes.

The Xingcheng region in western Liaoning is located in the northeastern NCC. This area has been superimposed and transformed by the tectonic evolution of the surrounding PPO and MOO plates during the Mesozoic, and thus can play a significant role in solving the above controversial issues. In view of the diverging views, the Early Jurassic Huashan monzogranites in the northern Xingcheng region and Late Jurassic Taili monzogranites from the southern Xingcheng region were selected for study. Here, we undertake new zircon U–Pb, whole-rock geochemical and Sr–Nd–Hf isotopic analyses of the Jurassic granitoids, in the cause of elucidating their petrogenesis and tectonic implications.

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[Correction added on 5 August 2021, after initial online publication. A duplicate of this article was published under the DOI 10.1111/1755-6724.14762. This duplicate has now been deleted and its DOI redirected to this version of the article.]
2 Geological Background and Sample Descriptions

The Xingcheng area is both in the northeastern NCC and the eastern Yanshan fold belt (Fig. 1a). It underwent subduction–collision of the PAO, MOO, and PPO plates during the Mesozoic with large-scale intermediate-silicic intrusive and volcanic rocks in the Late Triassic to Early Cretaceous (Wu et al., 2005; Yang et al., 2005; Cui, 2015; Ma et al., 2015). The Huashan and Taili granites are typical rock masses exposed in the area (Fig. 1b).

The Huashan pluton, in the north of the study area (Fig. 1c), is dominated by monzogranite with a granitic texture, which contains perthite (~35%), quartz (~35%), and plagioclase (~30%), with accessory zircon, magnetite, and apatite (Figs. 2a, b). The Taili pluton, in the south (Fig. 1d), contains undeformed granites, unlike the northern Taili gneissic granites. It is dominated by two-mica monzogranite with a granitic texture, which contains microcline (~30%), quartz (~30%), plagioclase (~30%), muscovite (~7%), and biotite (~3%) (Figs. 2c, d). Primary muscovite comprises automorphic to semi-automorphic flakes among the mineral grains (Fig. 2d), which differs from the altered muscovite hosted within some plagioclases.

3 Analytical Methods

Samples, thin sections and separation of zircons from samples are made at the Langfang Regional Geological Survey, Langfang, China. Zircon U–Pb dating was undertaken at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Natural Resources, Jilin University, Changchun and the Joint Laboratory of the University of Hong Kong, Hong Kong, China. Whole-rock major and trace element contents, and Sr–Nd isotopic compositions were determined at the Wuhan Sample Solution Analytical Technology Co. Ltd, Wuhan, China. Zircon Hf isotopic compositions were determined at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China. Details of analytical methods are given in the appendices.

4 Results

4.1 Zircon U–Pb dating

Zircons in the Huashan monzogranites are subhedral and display oscillatory zoning in cathodoluminescence.
(CL) images (Fig. 3a) with Th/U ratios of 0.63–1.79 (Supp. Table 1), indicating a magmatic origin. They have $^{206}\text{Pb}^{238}\text{U}$ ages of 192–187 Ma with a weighted-mean of $189 \pm 2$ Ma ($n = 15$; MSWD = 0.15; Fig. 4a), which suggests that the Huashan monzogranite was crystallized in the Early Jurassic.

Zircons from the Taili monzogranites display fine-scale oscillatory zoning in CL images (Fig. 3b) and have Th/U ratios of 0.52–1.22, indicating a magmatic origin. Their $^{206}\text{Pb}^{238}\text{U}$ ages fall into two groups with weighted means of $155 \pm 1$ Ma ($n = 8$; MSWD = 0.69) and $2469 \pm 15$ Ma ($n = 6$; MSWD = 5.5), with the former representing the timing of monzogranite crystallization (Fig. 4b), and the latter representing the age of inherited zircons entrained by the monzogranite magma (Fig. 4b). Some inherited zircons are discordant, suggesting they underwent significant Pb loss.

4.2 Geochemistry
4.2.1 Major elements

The Early Jurassic monzogranites have high SiO$_2$ (67.93–68.42 wt%), Al$_2$O$_3$ (15.69–15.76 wt%), and Na$_2$O + K$_2$O (8.34–8.39 wt%) contents, and low MgO (0.51 wt%) and CaO (1.13–1.17 wt%) contents (Supp. Table 2). As seen in the total alkali vs SiO$_2$ (TAS) diagram, data for all samples plot in the granite field (Fig. 5a), and samples are classified as peraluminous and high-K calc-alkaline rocks (Figs. 5b, c), similar to other Early Jurassic granitoids in western Liaoning (Dai et al., 2008; Cui, 2015; Xu et al., 2015).

The Late Jurassic monzogranites have higher SiO$_2$ (70.15–75.23 wt%) and lower MgO (0.06–0.15 wt%) contents than the Early Jurassic monzogranites, and also plot in the granite field in the TAS diagram (Fig. 5a). They have Al$_2$O$_3$, CaO, and Na$_2$O + K$_2$O contents of 12.43–
14.46 wt%, 0.06–0.60 wt%, and 8.72–11.43 wt%, respectively (Supp. Table 2), and are also identified as peraluminous and high-K calc-alkaline rocks (Figs. 5b, c), similar to Late Jurassic granitoids in previous studies (Li et al., 2014; Cui, 2015; Liang et al., 2015).

4.2.2 Trace elements
The Early and Late Jurassic monzogranites have similar trace element compositions, with enrichment in the light rare earth elements (LREEs) and large-ion lithophile elements (LILEs), and depletion of heavy rare earth elements (HREEs) and high-field-strength elements (HFSEs: Nb, Ta, and Ti; Figs. 6a–d). They have weakly negative Eu anomalies with Eu/Eu* = 0.94–0.96 and 0.76–0.78, respectively. The Early Jurassic monzogranites have high Sr (338–347 ppm) and low Y (11.8–12.0 ppm) and Yb (1.26–1.31 ppm) contents, and high (La/Yb)_n (15.6–15.9) and Sr/Y (28.74–28.96) ratios. The Late Jurassic forms also have high Sr (221–306 ppm), and low Y (7.83–14.7 ppm) and Yb (0.80–1.52 ppm) contents, and high Sr/Y ratios (31.84–37.52) (Supp. Table 2). All trace element characteristics are similar to those of other Early and Late Jurassic granitoids that crop out in the study area (Dai et al., 2008; Li et al., 2014; Cui, 2015; Liang et al., 2015; Xu et al., 2015).

4.3 Whole-rock Sr-Nd isotopic compositions
The Early Jurassic monzogranites have relatively low ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios (0.7046 for all three samples) and high εNd(t) values (−11.51 to −11.62), similar to those of Early Jurassic granites of eastern Liaoning (Wu et al., 2005; Fig. 7), with homogeneous Sr–Nd isotopic compositions (Supp. Table 3). The Late Jurassic monzogranites have higher ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios (0.7069–0.7071) and lower εNd(t) values (−20.46 to −20.65), similar to those of other Late Jurassic granitoids of western Liaoning (Zhang et al., 2014; Fig. 7).

4.4 Zircon Hf isotopic compositions
The Early Jurassic monzogranites have zircon $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282276–0.282478 and εHf(t) values of −6.4 to −13.6 (Supp. Table 4), similar to those of Early Jurassic granitic rocks of western and eastern Liaoning (Yang et al., 2007; Cui, 2015). As seen in the εHf(t)–age diagram (Fig. 8), sample compositions appear similar to those of the NCC, and distinct from those of the eastern CAOB. The four inherited (2502–2432 Ma) and 12 magmatic zircons from the Late Jurassic monzogranites have $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.281392–0.281757 and εHf(t) values of +3.9 to +16.2 and −27.6 to −20.0, respectively (Supp. Table 4), with the latter being similar to those of Late Jurassic granitoids of western Liaoning (Cui, 2015; Fig. 8). The lower Late Jurassic εHf(t) values are consistent with whole-rock Sr-Nd isotopic compositions.
Discussion

5.1 Jurassic magmatism in the western Liaoning and its adjacent regions

According to our geochronological studies, the Huashan monzogranites were emplaced at 189 ± 2 Ma in the Early Jurassic. In the study area, there are also many Early Jurassic granitoids exposed (Table 1), with the intrusions varying from quartz diorite, syenogranite, and monzogranite, to K-feldspar granite, as for the Yaowangmiao–Mopanshan quartz diorite (ca. 194 Ma; Cui, 2015); the Yaowangmiao–Mopanshan (ca. 186 Ma; Cui, 2015), Yangjiazhangzi (ca. 188 Ma; Wu et al., 2006), and Yangjiazhangzi (ca. 177 Ma; Cui, 2015) monzogranite plutons; the Yangjiazhangzi syenogranite pluton (ca. 174 Ma; Cui, 2015); the Lanjiangou granite (ca. 188 Ma; Dai et al., 2008); and the Yangjiazhangzi K-
feldspar granite (ca. 181 and 189 Ma; Xu et al., 2015). An Early Jurassic magmatic event is thus inferred to have occurred in western Liaoning at 194–174 Ma.

Taiji monzogranites were emplaced at 155 ± 1 Ma in the Late Jurassic, consistent with zircon U-Pb dating of the north Taiji gneissic biotite monzogranite (ca. 154 Ma; Li et al., 2014) and biotite–quartz monzogranite (ca. 159 Ma; Liang et al., 2015), suggesting the same magmatic event. Late Jurassic igneous rocks have also been recognized in the nearby study area (Table 1), as for the Jianchang monzogranite (ca. 161–156 Ma; Cui, 2015), the Yingchangkou quartz diorite (ca. 156 Ma; Cui, 2015), the Jianchang monzogranite (ca. 153 Ma; Wu et al., 2006), and the Yiwulvshan granodiorite (ca. 153 Ma; Wu et al., 2006). Therefore, a Late Jurassic magmatic event is inferred to have occurred in western Liaoning, too. The main magmatic events thus occurred in the Early (194–174 Ma) and Late (163–153 Ma) Jurassic, consistent with the eruption stage of Jurassic volcanic rocks in the study area (Song et al., 2018).

5.2 Classification of the Jurassic granites

In the (Zr + Nb + Ce + Y)–(Na2O + K2O)/CaO diagram (Fig. 9a), the Early and Late Jurassic monzogranite samples plot in the I- and S-type granite fields. They have high SiO2, Al2O3, and total alkali contents, and low MgO and HREE contents, differing from M-type granite compositions. The monzogranites are metaluminous to weakly peraluminous with A/CNK ratios of 1.0–1.1 (Fig. 5b), suggesting they may be I- rather than S-type granites. Muscovite is abundant in the Late Jurassic monzogranites but that does not confirm a S-type classification (Miller, 1985). The P2O5 content of the samples decreases with increasing SiO2 content (Supp. Table 2), consistent with I-type granites. In the Ce–SiO2 and Zr–SiO2 diagrams (Figs. 9b, c), the samples plot in the I-type granite field together with Early and Late Jurassic granitoids of western Liaoning. We therefore conclude that the Early and Late Jurassic monzogranites are both I-type granites.

5.3 Petrogenesis of the Jurassic granites

The Early Jurassic monzogranites have high SiO2 and Al2O3 contents and low MgO contents. They also show enrichment in LREEs and LILEs, depletion in HREEs and HFSEs (Fig. 7), indicating a crustal origin. They have weakly negative Eu anomalies and obvious positive K and Pb anomalies (Fig. 6), together with their relatively low ($^{87}$Sr/$^{86}$Sr) value (0.7046), high $\varepsilon_{Nd}(t)$ (−11.51 to −11.62) and $\varepsilon_{Hf}(t)$ (−6.4 to −13.6) values, suggesting that the Early Jurassic monzogranites originated from partial melting of ancient lower crust, whereas the Sr-Nd-Hf isotopic compositions indicate a contribution from mantle-derived materials.

The Early Jurassic adakite rocks are characterized by low MgO contents and relatively high K2O and SiO2 contents. Their $\varepsilon_{Nd}(t)$ (−11.51 to −11.62) and $\varepsilon_{Hf}(t)$ (−6.4 to −13.6) values also indicate that the Early Jurassic adakite rocks originated from partial melting of ancient lower crust with the influence of mantle-derived materials. Consequently, partial melting of thickened lower continental crust appears to be the most possible model for the petrogenesis of the adakitic monzogranites (Atherton and Pettford, 1993; Gao et al., 2004; Yang et al., 2016); partial melting of delaminated lower continental crust (Gao et al., 2004; Yang et al., 2012a, b), and assimilation and fractional crystallization from coeval parental basaltic magma (Castillo et al., 1999).

However, controversies about the petrogenesis of adakitic rocks never stop. Recently, there have been various proposed models, including partial melting of subducted basaltic oceanic crust (Defant and Drummond, 1990), partial melting of thickened lower continental crust (Atherton and Pettford, 1993; Yang et al., 2016); partial melting of delaminated lower continental crust (Gao et al., 2004; Yang et al., 2012a, b), and assimilation and fractional crystallization from coeval parental basaltic magma (Castillo et al., 1999).

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### Table 1 Zircon U-Pb age data for Jurassic granites in Xingcheng area

<table>
<thead>
<tr>
<th>Site</th>
<th>Lithology</th>
<th>Zircon U-Pb age (Ma)</th>
<th>References</th>
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<tr>
<td>Early Jurassic</td>
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<tr>
<td>Yaowangmiao-Mopanshan</td>
<td>Quartz diorite</td>
<td>194 ± 2 Ma</td>
<td>Cui, 2015</td>
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<tr>
<td>Yangjiashangzi-Lanjigou</td>
<td>Monzogranite</td>
<td>186 ± 2 Ma</td>
<td>Cui, 2015</td>
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<td></td>
<td>Syenogranite</td>
<td>177 ± 1 Ma</td>
<td>Cui, 2015</td>
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<tr>
<td></td>
<td>Monzogranite</td>
<td>174 ± 1 Ma</td>
<td>Cui, 2015</td>
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<tr>
<td></td>
<td>Granite</td>
<td>188 ± 2 Ma</td>
<td>Wu et al., 2006</td>
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<td></td>
<td>K-feldspar granite</td>
<td>188 ± 1 Ma</td>
<td>Dai et al., 2008</td>
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<td></td>
<td>K-feldspar granite</td>
<td>189 ± 1 Ma</td>
<td>Xu et al., 2015</td>
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<td></td>
<td>Monzogranite</td>
<td>189 ± 2 Ma</td>
<td>This study</td>
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<tr>
<td>Late Jurassic</td>
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<tr>
<td>Jianchang-Yingchangkou</td>
<td>Monzogranite</td>
<td>161 ± 2 Ma</td>
<td>Cui, 2015</td>
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<td></td>
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<td>156 ± 1 Ma</td>
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<td>156 ± 1 Ma</td>
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<td>Monzogranite</td>
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<tr>
<td>Yiwulvshan</td>
<td>Granodiorite</td>
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<td>Northern Taili</td>
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<td>Southern Taili</td>
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<td>154 ± 2 Ma</td>
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<tr>
<td></td>
<td>Two-mica monzogranite</td>
<td>155 ± 1 Ma</td>
<td>This study</td>
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during magmatic evolution.

The Late Jurassic adakitic monzogranites also have high SiO$_2$ and Al$_2$O$_3$ and low MgO contents (Supp. Table 2). Their enrichment in LREEs and LILEs and depletion in HREEs and HFSEs (Fig. 7) indicate a crustal origin. They also have small negative Eu, positive Pb, and negative P and Ti anomalies. Compared with the Early Jurassic monzogranites, they have higher ($^{87}$Sr/$^{86}$Sr)$_i$ ratios (0.7069–0.7071) and lower $\varepsilon$Nd($^t$) ($-20.46$ to $-20.65$) and $\varepsilon$Hf($^t$) ($-27.6$ to $-20.0$) values. These above characteristics indicate that the Late Jurassic monzogranites originated from partial melting of ancient lower crust without the influence of mantle-derived materials. This is also supported by the existence of the inherited zircons (ca. 2500 Ma), and low MgO contents (0.06–0.15 wt%). In addition, they have relatively high Sr (221–306 ppm), and low Y (7.83–14.7 ppm) and Yb (0.83–1.52 ppm) contents, and high Sr/Y ratios (31.84–37.52), indicative of typical adakitic rocks (Defant and Drummond, 1990). All the Late Jurassic samples plot in the adakite field in the (Sr/Y)–Y discrimination diagram (Figs. 10a, b), consistent with adakitic Late Jurassic granitoids and volcanic rocks of western Liaoning (Li et al., 2014; Cui, 2015; Liang et al., 2015). We suggest that the Late Jurassic adakitic rocks were derived from partial melting of thickened lower continental crust (Fig. 10c).

5.4 Tectonic setting

Both the Early and Late Jurassic adakitic rock assemblages in the study area display an active continental margin rock association. For instance, both of them are high-K calc-alkaline series, consistent with active continental margin rocks (Fig. 5). They plot in the volcanic arc granite field in the Nb–Y, the Rb–(Y + Nb) and the Ta–Yb diagrams (Figs. 11a–c), and in the continental arc field in the (Th/Ta)–Yb diagram (Fig. 11d), indicating an active continental margin environment. The Early and Late Jurassic adakitic rocks are chemically characterized by enrichment in LREEs and LILEs, and depletion of HREEs and HFSEs. These are typical traits of active continental margin granites.

As noted, the study area is situated on the northeastern margin of the NCC. Previous studies proposed that the gradual crustal thickening and delamination was influenced by the superposition of the PPO, MOO, and PAO systems during the Mesozoic, with the interaction of subducting plates causing intense lithospheric thinning (Xu et al., 2013; Chen et al., 2019). Therefore, tectonic movements seem complicated in the study area. The formation of Jurassic granitoids was still controversial, which is related to subduction of the PPO, MMO, or PAO plates (Gao et al., 2004; Wu et al., 2005; Yang et al., 2007).

Previous studies have confirmed that the PAO closed in the Late Permian to Early Triassic (Cao et al., 2013). Large-scale Late Triassic A-type granites and coeval bimodal volcanic rocks were exposed alongside the CAOB in the northeastern NCC, suggesting an extension environment following the collision between the NCC and the Siberian Craton (Xu et al., 2013). The Jurassic granites
the study area were no longer influenced by the PAO tectonic domain (Zhou et al., 2017). Recent studies have found evidence of southward subduction of the MOO in the Late Triassic (Sun et al., 2013), but it was defined as a passive continental margin in the south of the MOO (Wu et al., 2011). Nevertheless, the MOO Plate was subducted toward the northeastern Erguna Block during the Early Jurassic, and the western Liaoning area in the northeastern NCC was not affected (Xu et al., 2013; Wang et al., 2017; Tang et al., 2018). During the Jurassic, a mass of extrusions and intrusions occurred between the north margin of the NCC and the Erguna Block, which were previously thought to be related to the PPO Plate subduction (Liu et al., 2018; Zhang et al., 2019). Furthermore, the occurrence of Early Jurassic coeval bimodal volcanic rocks in the Xiao Hinggan Mountains–Zhangguangcailing area indicates that Early Jurassic magmatism was not related to the MOO Plate (Guo et al., 2015). The possibility that the Late Jurassic magmatism was influenced by the MOO will be excluded because of its closure in the Middle Jurassic (Kravchinsky et al., 2002). The Early Jurassic igneous rocks in the eastern margin of Eurasia are distributed as a NNE–SSW trending belt parallel to the continental margin of PPO, indicating that their formation is related to the subduction of the PPO Plate (Tang et al., 2018). Moreover, the ages of the granitoids in NE China and the northeastern NCC are trending younger westward, which are attributed to the subduction of the PPO Plate (Wu et al., 2006, 2011). As the Early Jurassic tectonic emplacement in NE China constrained the onset of subduction of the PPO Plate in the Early Jurassic (Xu et al., 2013; Tang et al., 2018), the Early–Late Jurassic granitic magmatism might also have been related to westward subduction of the PPO Plate.

Paleomagnetism and the spatial and temporal distribution of igneous rocks indicate that westward subduction of the PPO Plate began during the Early Jurassic (Xu et al., 2013; Zhang et al., 2019). Early Jurassic adakitic monzogranites in western Liaoning were formed at ca. 189 Ma, consistent with commencement of PPO Plate subduction. Geochronological studies of Mesozoic granitic magma in western Liaoning indicate that the magmatism is younger from east to west, once again consistent with PPO Plate subduction (Wu et al., 2006). Early and Late Jurassic adakitic monzogranites are high-K calc-alkaline 1-type and formed in an active continental margin. Liang et al. (2015) suggested that the formation of the Late Jurassic granitic mylonite belt in the Taili area is also related to PPO extension. Volcanic rocks of the Late Jurassic Tiaojishan Formation, in the

Fig. 11. Nb vs Y(a), Rb vs (Yb+Ta) (b), Ta vs Yb (c, after Pearce et al., 1984) and Th/Ta vs Yb (d, after Gor- ton and Schandl, 2000) discrimination diagrams.

ORG = ocean-ridge granitoids; Syn-COLG = syn-collisional granitoids; VAG = volcanic arc granitoids; WPG = within-plate granitoids; MORB = mid-ocean ridge basalts. Data sources are as in Fig. 5.
Yiwulvshan area, western Liaoning, are high-K calc-alkaline series. Furthermore, the Middle–Late Jurassic mafic-granitic dikes developed in the Yiwulvshan metamorphic core complex indicate an extensional PPO tectonic setting (Li, 2012).

With the commencement of the PPO Plate subduction in the Jurassic, the thickened lithosphere gradually delaminated with upwelling of asthenospheric material. Early Jurassic adakitic rocks were thus formed by partial melting of thickened lower crust contaminated with mantle-derived materials, whereas Late Jurassic adakitic rocks were formed directly by partial melting of thickened lower crust. In the Late Jurassic, sustained subduction of the PPO Plate resulted in an extensional tectonic setting in western Liaoning, forming the Yiwulvshan metamorphic core complex (Li, 2012). The Late Jurassic adakitic rocks were thus formed in an extensional tectonic environment following collapse of thickened continental crust (Tang et al., 2018). Upwelling of asthenospheric mantle material then caused collapse and partial melting of the thickened lower continental crust, forming the Late Jurassic adakitic rocks.

6 Conclusions

We can draw the following conclusions from this study:

(1) The Huashan and Taili monzogranites of the Xingcheng area, western Liaoning, northeastern NCC, were formed during the Early (189 Ma) and Late (155 Ma) Jurassic, respectively.

(2) The Early and Late Jurassic monzogranites have high-Sr and low-Y and Yb contents, and high-Sr/Y and high-(La/Yb)\textsubscript{n} ratios, indicating adakitic features. Early Jurassic adakitic rocks originated from partial melting of thickened lower continental crust contaminated with mantle-derived materials, whereas Late Jurassic adakitic rocks originated directly from partial melting of thickened lower continental crust.

(3) Early Jurassic adakitic rocks were formed in an active continental margin during westward subduction of the PPO Plate, whereas Late Jurassic adakitic rocks were formed in an extensional tectonic setting during subduction retreat at an active continental margin.

Acknowledgements

We appreciate the editors for handling this manuscript and two anonymous reviewers for their constructive comments and suggestions. This work was financially supported by the National Science Foundation of China (Grant No. 41722204, 42072063), and the Basic Scientific Research Foundation of Central Universities of China (Jilin University).

Supplementary data to this article can be found online at http://doi.org/10.1111/1755-6724.14698.

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Manuscript received Mar. 5, 2020
accepted Oct. 26, 2020
associate EIC: XU Jifeng
edited by Susan TURNER and FANG Xiang


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