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ARTICLE

Large-scale early cretaceous lower-crust melting derived adakitic rocks in NE China: implications for convergent bidirectional subduction and slab rollback

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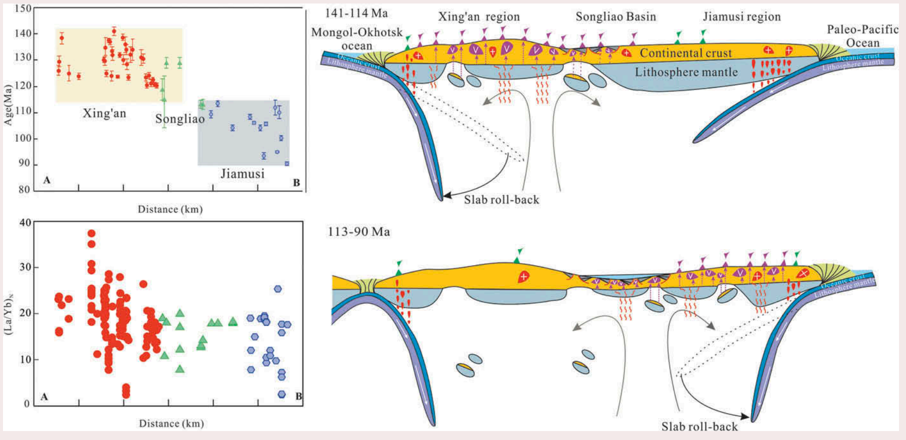
ABSTRACT

Large volumes of Early Cretaceous adakitic rocks crop out in northeast China. In this paper, we summarize their spatial-temporal distribution and geochemical characteristics. These adakitic rocks exhibit variable MgO, Cr and Ni contents, as well as potassium enrichments, in contrasting with those of the slab melting derived adakites. Positive $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values and low $^{87}Sr/^{86}Sr(i)$ indicate significant Phanerozoic crust growth in NE China. Based on their geochemistry, these adakitic rocks are mainly derived from partial melting of juvenile lower crust. We interpret the melting to have resulted from extension and associated delamination. The ages of adakitic rocks are 141–120 Ma in the Xing'an region, 129–113 Ma in the Songliao basin, and 113–90 Ma in the Jiamusi region. Based on the lower-crustal-melting geochemical characteristics and spatial distribution of ages, we propose a new two-stage convergent bidirectional subduction model: Mongol-Okhotsk oceanic plate subduction and associated slab rollback in the west from 141–114 Ma and the Paleo-Pacific oceanic plate subduction and associated slab rollback in the east from 113–90 Ma.



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Adakitic rocks; crust reworking; convergent bidirectional subduction; slab rollback; Northeast China

1. Introduction

Adakitic rocks, characterized by high fractionation of rare earth elements, relatively high silica content (≥56 wt.% SiO_2) and high Sr/Y and La/Yb ratios (Castillo 2008, 2012; Xu *et al*. 2014, 2015; Zheng *et al*. 2014; Zhu *et al*. 2016; Wang *et al*. 2017a), are widely distributed in NE China. Previous studies proposed that the adakitic rocks can form by: (1) subducted slab melting in a convergent margin followed by some degree of continental crust contamination and mantle wedge alteration (Wang *et al*. 2007a, 2007b, 2008; Castillo 2012; Zhang 2014; Zhu *et al*. 2015); (2) lower-crustal melting associated with delamination of the mantle lithosphere (Wang *et al*. 2001, 2008, 2012; Zhu *et al*. 2009; Wu *et al*. 2011b; Zhang 2014); (3) fractional crystallization of basaltic magmas at high pressure (Macpherson *et al*. 2006); (4) assimilation and fractional crystallization (AFC) of basaltic magmas at low pressure (Castillo *et al*. 1999); and (5) the mixture of siliceous and basaltic magmas (Castillo 2012; Chen *et al*. 2013). In NE

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Supplemental data for this article can be accessed here.

China (Figure 1), Cretaceous adakitic rocks are widespread (Chai *et al*. 2015; Fan *et al*. 2003; Ge *et al*. 2005; He *et al*. 2017; Ji *et al*. 2007; Jin *et al*. 2011; Li *et al*. 2007, 2012a, 2014b, 2015; Liu 2016; Liu *et al*. 2017; Ma *et al*. 2009; Niu *et al*. 2016; Pei *et al*. 2008; Ren *et al*. 2012; Shu *et al*. 2014; Sun *et al*. 2013a, 2016; Wang 2017; Wu *et al*. 2011b, 2014; Xu *et al*. 2011; Xu 2017; Ying *et al*. 2010; Yu *et al*. 2013; Zhang *et al*. 2007a, 2008c, 2010. Their petrogenesis are controversial. Although the majority of the researchers have interpreted them to have formed by slab melting, some have suggested that they are the result of lower-crustal melting. In this paper, we reappraise the spatial-temporal distribution and geochemical characteristics of adakitic rocks in NE China to address this discrepancy in interpretations and propose a new model for the Mesozoic tectonic evolution of the region.

Non-adakitic Late Mesozoic igneous rocks also cropped out in NE China (Zou *et al*. 2011; Wu *et al*. 2011a; Shu *et al*. 2014; Li *et al*. 2015, 2018a, 2018b; Wang *et al*. 2017b) and provide context for the interpretation of the adakitic rocks. (1) Early Cretaceous alkaline basalts with intraplate geochemical features are characterized by high K_2O contents, high K_2O/Na_2O, Th/Ta, Ce/Nb and Ta/Nb ratios and highly enriched large ion lithophile elements and light rare earth elements (Fan *et al*. 2003; Zhao *et al*. 2004; Yin *et al*. 2005; Ji *et al*. 2007; Cao and Hou 2009; Sun *et al*. 2013a; Zhang 2014; Li *et al*. 2014b; Ma *et al*. 2015). (2) Felsic rocks with geochemical similarity to A-type granite have high $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values, reflecting significant crustal growth in NE China during this time period (Ge *et al*. 2005; Ji *et al*. 2007; Cong and Li 2008; Ying *et al*. 2010; Xie *et al*. 2012; Sun 2013; Yang *et al*. 2014; Li *et al*. 2014a; Wang *et al*. 2017a). Different tectonic models have proposed for these Mesozoic igneous rocks, including: (1) Asthenospheric upwelling following delamination of thickened lithosphere in a post-orogenic environment (Wu *et al*. 2008, 2011a); (2) Subduction of the Paleo-Pacific oceanic plate

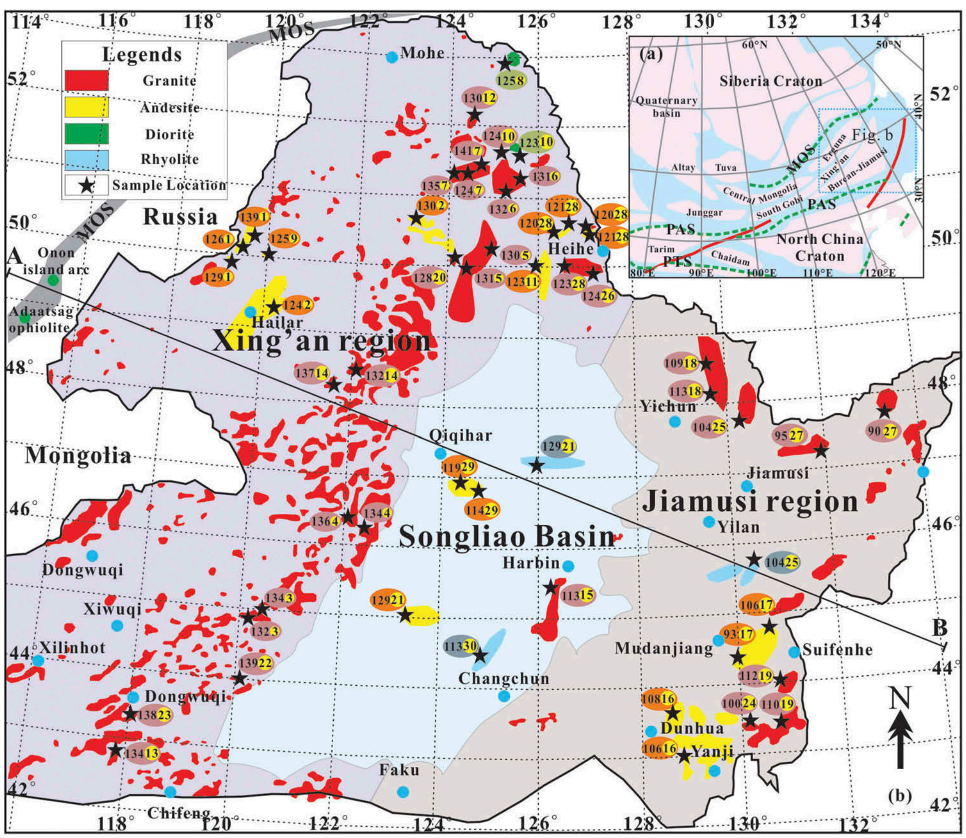

Figure 1. (a) Tectonic setting of Northeast Asia (modified after Tang *et al*. 2016), and (b) simplified geological map of NE China (Wu *et al*. 2003; Zhou *et al*. 2015). MOS = Mongol-Okhotsk suture; PAS = Paleo-Asian suture; PTS = Paleo-Tethys suture. The numbers in the yellow circle correspond to the data source number in Table 1. Numbers on the age data refer to the following sources: 1. (Fan *et al*. 2003), 2. (Ying *et al*. 2010), 3. (Ma *et al*. 2009), 4. (Ge *et al*. 2005), 5. (Wu *et al*. 2014), 6. (Zhang *et al*. 2008c), 7. (Sun *et al*. 2016), 8. (Li *et al*. 2012a), 9. (Xu *et al*. 2011), 10. (Xu 2017), 11. (Liu *et al*. 2017), 12. (Niu *et al*. 2016), 13. (Zhang *et al*. 2010), 14. (He *et al*. 2017), 15. (Li *et al*. 2015), 16. (Li *et al*. 2007), 17. (Ji *et al*. 2007), 18. (Sun *et al*. 2013a), 19. (Chai *et al*. 2015), 20. (Li *et al*. 2014b), 21. (Pei *et al*. 2008), 22. (Wu *et al*. 2011b), 23. (Shu *et al*. 2014), 24. (Ren *et al*. 2012), 25. (Sun 2013), 26. (Liu 2016), 27. (Yu *et al*. 2013), 28. (Wang 2017), 29. (Jin *et al*. 2011), 30. (Zhang *et al*. 2007a). The number in the ellipse represent the age of the rock, while the number inside the yellow circle correspond to the reference number in Table 1.

and associated slab rollback (Sun 2013); (3) Subduction of the Mongol-Okhotsk oceanic plate and subsequent post-collision extension (Zhao *et al*. 2004); (4) Back-arc extension with Paleo-Asian or Mongol-Okhotsk Ocean subduction (Fan *et al*. 2003; Ma *et al*. 2009; Ying *et al*. 2010; Zou *et al*. 2011); (5) A mantle plume (Ge *et al*. 2005).

To settle the aforementioned disputes, we subdivided NE China into three main regions based on their geographical locations and age variations, namely, the Xing'an region, Songliao Basin and Jiamusi regions (Figure 1(b)). The petrological, geochemical and geochronological characteristics of the Early Cretaceous adakitic rocks in the three parts have been summarized to reassess their genesis and Early Cretaceous tectonic evolution of NE China.

2. Regional geological background

Located between the North China and Siberia cratons (Figure 1(a)), NE China is comprised of the Erguna, Xing'an, Songliao, Bureya-Jiamusi-Khanka massifs and the Sikhote-Alin accretionary complex. From northwest to southeast, these terranes are separated from each other by the Xinlin–Xiguitu-Toudaoqiao, Hegenshan–Heihe, Mudanjiang and Ondor Sum–Yongji suture zones, respectively (Wu *et al*. 2011a; Li *et al*. 2014a; Liu *et al*. 2018b). Northeastern China is separated from the North China Craton by the Solonker-Xar Moron-Changchun-Yanji suture and separated from the Siberian Craton by the Mongol-Okhotsk suture (Wu *et al*. 2011a; Wang *et al*. 2017a). After the Cambrian, NE China experienced a series of microcontinental collisions, of which the timing and geodynamics are still controversial (Şengör *et al*. 1993; Wu *et al*. 2011a). The collision between the Erguna and Xing'an blocks occurred in the early Palaeozoic, while the collision between the Xing'an and Songliao blocks is thought to have happened in the late Palaeozoic (Li *et al*. 2015, 2018b). The circum-Pacific accreted terranes – the Bureya–Jiamusi–Khanka massif and the Sikhote–Alin accretionary complex – were amalgamated later, in the early Mesozoic (Sun *et al*. 2013b). In the Palaeozoic, NE China was dominated by the closure of the Paleo-Asian Ocean, resulting in one of the largest and best preserved accretionary orogens on the earth (Li *et al*. 2013, 2017a). In the Mesozoic, subduction of Paleo-Pacific ocean from the east and the closure of the Mongol-Okhotsk plate from the west strongly influenced NE China (Ying *et al*. 2010; Wu *et al*. 2014).

The geological evolution of the Erguna massif has been rarely studied because of its abundant forests (Wu *et al*. 2011a). Although there is no reliable geochronological data, it is interpreted to contain Proterozoic to Palaeozoic strata and some granites (Miao *et al*. 2007). As for the Xing'an massif, it is still controversial whether its crystalline basement is Precambrian or possibly Palaeozoic (Miao *et al*. 2004, 2007). Large-scale Mesozoic volcanics are also widely distributed in the Erguna and Xing'an massifs, including the Wanbao (J_2w), Tamulangou (J_2tm), Manketouebo (J_3mk), Manitu (J_3mn), Baiyingaolao (K_1b), and Meiletu (K_1m) formations (Li *et al*. 2017b; Liu *et al*. 2018b).

The Songliao basin is one of the most essential petroleum basins in China (Jin *et al*. 2011; Meng *et al*. 2013). It is located between the Xing'an and Zhangguangcai mountain ranges (Wang *et al*. 2006b). The basement includes Palaeozoic marine meta-sediments, intermediate-acid extrusive rocks, regional Precambrian or Palaeozoic metamorphic rocks; how the metamorphic rocks formed is still unknown (Wang and Wang 2007; Zhang *et al*. 2008a). Based on sequence stratigraphy, the evolution of the Songliao Basin can be subdivided into three main stages, including rifting, sagging, and inversion (Zhang *et al*. 2007a, 2011; Yu *et al*. 2012).

The basement of the Bureya-Jiamusi-Khanka Massif is mainly composed of the amphibolite–granulite-facies Mashan Group metamorphic rocks in the interior of the massif and the greenschist–amphibolite-facies Heilongjiang Group metamorphic rocks along the western and southern margins (Wilde *et al*. 1999, 2000; Wilde and Wu 2001). Geochronology shows that the oldest protolith of the Mashan Group is Mesoproterozoic and metamorphism occurred c. 500 Ma (Wilde *et al*. 2003). The Heilongjiang Group may be a remnant of ancient oceanic crust (Wu *et al*. 2010).

3. Temporal and spatial distribution of adakitic rocks

Mesozoic igneous rocks of NE China, include adakites, within-plate basalts, granites, and a variety of calc-alkaline rocks (Meng *et al*. 2013; Zhang 2014; Chai *et al*. 2015; Wang 2017). The adakitic magmatism occurred c. 141–90 Ma (Figure 1 and Table 1). We subdivided the adakitic rocks in NE China into three geographic groups, as we mentioned before, to discuss their temporal and spatial distribution and geochemical characteristics.

3.1 Xing'an region

Ninety-four adakitic samples have been reported in the Xing'an region, which contains basaltic trachyandesite, basaltic andesite, trachyandesite, andesite, tranchydacite, dacite and rhyolite, diorite, granite, monzogranite and granodiorite, from Genhe (Fan *et al*. 2003; Ying *et al*. 2010; Xu *et al*. 2011), the Mohe and Tahe areas (Lin *et al*. 2004;

Table 1. Geochronological data for adakitic rocks of Early Cretaceous from the Northeast China.

No.	Location	Rock type	Age (Ma)	Error	Dating method	$\varepsilon_{Hf}(t)$	$\varepsilon_{Nd}(t)$	SiO_2 (wt %)	Refs.
1	Murui Farm	Andesite	126.1	±2.0	K-Ar whole rock		0.5	56.12	Fan *et al.* (2003)
1	Murui Farm	Andesite	138.5	±2.2	K-Ar whole rock		0.9	57.60	Fan *et al.* (2003)
1	Qiyi Prairie	Andesite	129.5	±2.0	K-Ar wholerock		0.6–0.9	55.74–56.82	Fan *et al.* (2003)
2	Tahe	Andesite	129.7	±1.6	SHRIMP U-Pb zircon		−1.4–0.1	56.6–58	Ying *et al.* (2010)
2	Genhe	Andesite	123.8	±1.3	SHRIMP U-Pb zircon				Ying *et al.* (2010)
3	Aolunhua	Granite-porphyry	134.0	±4.0	SHRIMP U-Pb zircon				Ma *et al.* (2009)
3	Aolunhua	Granite-porphyry	132.0	±1.0	Re-Os isochron molybdenite				Ma *et al.* (2009)
4	Wulanhaote	Granite	134.0	±2.0	LA-ICPMS U-Pb zircon	6.5–9.4	2.7–2.9	71.22–71.23	Ge *et al.* (2005)
4	Wulanhaote	Granite	136.0	±3.0	LA-ICPMS U-Pb zircon	6.2–10.2	2.7–2.9	71.22–71.23	Ge *et al.* (2005)
5	Yili Mo	Granite-porphyry	130.5	±1.8	Re-Os isochron molybdenite			68.49–72.77	Wu *et al.* (2014)
5	Yili Mo	Granite-porphyry	130.1	±1.9	Re-Os isochron molybdenite			68.49–72.77	Wu *et al.* (2014)
6	Xinlin Town	Granodiorite	132.0	±3.0	LA-ICPMS U-Pb zircon	1.3–5.9	0–0.8		Zhang *et al.* (2008c)
6	Xinlin Town	Granodiorite	131.0	±3.0	LA-ICPMS U-Pb zircon	2.0–8.2	−0.2		Zhang *et al.* (2008c)
7	Xinlin Town	Quartz monzonite	135.2	±3.4	LA-ICPMS U-Pb zircon	1.9–5.9		61.78–70.17	Sun *et al.* (2016)
7	Xinlin Town	Quartz monzonite	141.1	±1.7	LA-ICPMS U-Pb zircon			61.78–70.17	Sun *et al.* (2016)
7	Xinlin Town	Quartz monzonite	123.8	±1.9	LA-ICPMS U-Pb zircon	2.4–6.1		61.78–70.17	Sun *et al.* (2016)
8	Baoxinggou Gold Mine	Diorite	124.92	±1.3	LA-ICPMS U-Pb zircon			56.34–63.69	Li *et al.* (2012b)
9	Genheqiao	Andesite	125.0	±3.0	LA-ICPMS U-Pb zircon			55.33–58.18	Xu *et al.* (2011)
10	South of Tahe	Diorite	123.4	±1.0	LA-ICPMS U-Pb zircon	0.8–4.3		57.40	Xu (2017)
10	South of Tahe	Monzonite	123.6	±0.6	LA-ICPMS U-Pb zircon	−0.3–8.6		68.18	Xu (2017)
11	Xiaomoerke	Andesite	123.3	±1.3	LA-ICPMS U-Pb zircon	1.7–9.7		55.97–60.78	Liu *et al.* (2017)
12	Shiwuliqiao	Granodiorite	130.0	±1.0	LA-ICPMS U-Pb zircon			61. 32–69.1	Niu *et al.* (2016)
13	Lazishan	Granodiorite-porphyry	133.5	±1.7	LA-ICPMS U-Pb zircon	−0.8–4.7		62.86–65.44	Zhang *et al.* (2010)
14	Chuoer	Monzogranite	137.0	±1.0	LA-ICPMS U-Pb zircon	3.9–7.9		72.24–73.18	He *et al.* (2017)
14	Chuoer	Monzogranite	132.0	±2.0	LA-ICPMS U-Pb zircon	2.9–8.0		72.24–73.18	He *et al.* (2017)
15	Changchun	Monzogranite	113.0	±2.0	LA-ICPMS U-Pb zircon			74.05	Li *et al.* (2015)
16	Yanji	Dacitic	108.2	±0.9	$^{40}Ar/^{39}Ar$			63.43–63.87	Li *et al.* (2007)
16	Yanji	Dacitic	105.9	±0.6	$^{40}Ar/^{39}Ar$			63.43–63.87	Li *et al.* (2007)
17	Suifenhe	Dacitic	93.2	±1.3	LA-ICPMS U-Pb zircon		0.4–0.9	65–65.47	Ji *et al.* (2007)
17	Suifenhe	Andesite	105.5	±0.8	LA-ICPMS U-Pb zircon		0.8–1.3	61.96–62.29	Ji *et al.* (2007)
18	Pingdingshan	Granodiorite porphyry	109.1	±1.4	LA-ICPMS U-Pb zircon	4.8–8.0		70.14	Sun et al. (2013a)
18	Pingdingshan	Granodiorite porphyry	113.2	±1.1	LA-ICPMS U-Pb zircon	4.8–8.0		70.14	Sun et al. (2013a)
19	Xinancha	Granodiorite porphyry	109.9	±2.5	LA-ICPMS U-Pb zircon	6.9–10.0		67.22–67.58	Chai *et al.* (2015)
19	Xinancha	Granodiorite porphyry	111.7	±2.8	LA-ICPMS U-Pb zircon	6.9–10.0		67.22–67.58	Chai *et al.* (2015)
20	Chalukou	Quartz monzonite porphyry	128.4	±2.1	LA-ICPMS U-Pb zircon	5.6–8.2	0.5	66.38–68.54	Li *et al.* (2014b)
21	Daqing	Trachyte	129.0	±2.0	LA-ICPMS U-Pb zircon		1–2	61.78–66.08	Pei *et al.* (2008)
21	Daqing	Andesite	129.0	±2.0	LA-ICPMS U-Pb zircon		1–5.3	58.24–61.9	Pei *et al.* (2008)
22	Chifeng	Monzogranite-porphyry	138.7	±1.2	LA-ICPMS U-Pb zircon	3.6–9.2		70.51–71.72	Wu *et al.* (2011b)
23	Haisugou	Granite	137.6	±0.9	LA-ICPMS U-Pb zircon	4.5–10.0	0.2–1.1	68.6–72.57	Shu *et al.* (2014)
24	Nongping	Granodiorite porphyry	100.0	±0.9	LA-ICPMS U-Pb zircon			68.58–70.69	Ren *et al.* (2012)
25	Yilin	Rhyolite	104	±1.0	SHRIMP U-Pb zircon	6.0–12.6	0.7	71.27	Sun (2013)
25	Wulaga goldmine	Granite porphyry	104	±1.0	SHRIMP U-Pb zircon	7.2–12.1	0.7–0.8	69.04–69.21	Sun (2013)
26	Sandaowanzi	Granodiorite	124	±1.3	LA-ICPMS U-Pb zircon	4.8–8.8		65.05	Liu (2016)
27	Qindeli	Granodiorite	94.7	±0.4	LA-ICPMS U-Pb zircon	4.5–9.0		70.4	Yu *et al.* (2013)
27	Fuyuan Town	Granodiorite	90.2	±0.7	LA-ICPMS U-Pb zircon	4.7–8.1		66.6	Yu *et al.* (2013)

(*Continued*)

Table 1. (Continued).

No.	Location	Rock type	Age (Ma)	Error	Dating method	$\varepsilon_{Hf}(t)$	$\varepsilon_{Nd}(t)$	SiO_2 (wt %)	Refs.
28	Sandaowanzi	Andesite	122.9	±2.5	LA-ICPMS U-Pb zircon	5.8–12.0	0.9–1.8	56.38–63.66	Wang (2017)
28	Sandaowanzi	Andesite	121.1	±1.4	LA-ICPMS U-Pb zircon	5.8–12.0	0.9–1.8	56.38–63.66	Wang (2017)
28	Sandaowanzi	Andesite	120.4	±1.1	LA-ICPMS U-Pb zircon	5.8–12.0	0.9–1.8	56.38–63.66	Wang (2017)
28	Sandaowanzi	Andesite	124.0	±1.8	LA-ICPMS U-Pb zircon	5.8–12.0	0.9–1.8	56.38–63.66	Wang (2017)
28	Beidagou	Andesite	120.7	±0.8	LA-ICPMS U-Pb zircon	3.3–9.8	0.3	61.82	Wang (2017)
28	Beidagou	Andesite	120.3	±0.9	LA-ICPMS U-Pb zircon	3.3–9.8	0.8	59.98	Wang (2017)
28	Sandaowanzi	Altered andesite	122.4	±2.2	LA-ICPMS U-Pb zircon	7.6–9.8		79.71	Wang (2017)
28	Sandaowanzi	Altered dacite	122.4	±2.2	LA-ICPMS U-Pb zircon	7.6–9.8		64.27–81.57	Wang (2017)
28	Sandaowanzi	Granite porphyry	122.4	±1.0	LA-ICPMS U-Pb zircon	6.5–11.3		76.84	Wang (2017)
29	Lindian	Andesite	118.7	±4.2	LA-ICPMS U-Pb zircon	1.4–8.7		62.74–63.37	Jin *et al.* (2011)
29	Lindian	Andesite	114.0	±10	LA-ICPMS U-Pb zircon	4.6–7.2		62.74–63.37	Jin *et al.* (2011)
30	Dehui	Rhyolite	112.7	±1.6	SHRIMP U-Pb zircon		−1.2–−1.1	65.94–68.79	Zhang *et al.* (2007a)

Zhao *et al.* 2004; Yin *et al.* 2005; Zhang *et al.* 2005, 2007b, 2008c; Wu *et al.* 2008; Cao and Hou 2009; Li *et al.* 2012a; Niu *et al.* 2016; Sun *et al.* 2016; Xu 2017), Heihe (Wu *et al.* 2014; Li *et al.* 2014b; Liu 2016; Liu *et al.* 2017; Wang 2017; Wang *et al.* 2017b), Chuoer (He *et al.* 2017), Wulanhaote (Ge *et al.* 2005; Zhou *et al.* 2011), Taohaiyingzi (Ma *et al.* 2009; Wu *et al.* 2011b) and Chifeng (Zhang *et al.* 2010; Shu *et al.* 2014). Their ages are 141–120 Ma.

Adakitic rocks in Xing'an region have Na_2O of 0.09–7.25 wt. % and K_2O of 0.01–8.44 wt. %, and belong to High-K calc-alkaline series, with minor tholeiite and shoshonite (Figure 2(b,d)). They are characterized by variable SiO_2 (55.33–81.57 wt. %), Al_2O_3 (11.66–20.67 wt. %), and Sr (276–2146 ppm, minor<225 ppm) contents, as well as relatively low MgO (0.010–3.89 wt. %, one sample of 6.39 wt. %), low total Fe_2O_3 (0.84–6.95 wt. %), Y (4.32–19.1 ppm), and Yb (0.300–1.90 ppm) contents (Figure 3). Most samples have $Mg^\#$ values ranging from 21 to 63, strongly fractionated REE patterns [$(La/Yb)_N$ of 10–87, a few less than 10] and variable Eu anomalies (Eu/Eu* = 0.40–1.52, but only ~8% show positive anomalies) (Figure 4(a)). The enrichment of incompatible elements is also a significant feature of these samples, with large negative Nb–Ta anomalies (Figure 4(b) and Supplemental Table 1). The samples show $\varepsilon_{Nd}(t)$ values varying from −1.4 to +2.9 (one sample is −6.4) with $^{87}Sr/^{86}Sr(i)$ values of 0.7030–0.7074 (Figures 5 and 6) and Supplemental Table 1). Variable *in-situ* zircon $\varepsilon_{Hf}(t)$ values (−0.8 to +12.0), with the T_{DM2} of ~1701–388 Ma (Figure 6) and Supplemental table 2).

3.2 Songliao basin

The adakitic rocks of the Songliao Basin are 129–113 Ma. They include trachyandesite, andesite, tranchydacite, dacite, rhyolite and granite and are mainly concentrated in Dehui (Zhang *et al.* 2007a; Meng *et al.* 2013), Lindian and Lamadian (Pei *et al.* 2008; Jin *et al.* 2011), east of Qiqihar (Wang *et al.* 2006b; Pei *et al.* 2008) and south of Harbin (Li *et al.* 2015). These rocks have Na_2O of 0.22–5.00 wt. % and K_2O of 0.77–4.92 wt. %, plotting into the high-K calc-alkaline series. They exhibit high SiO_2 (58.24–74.05 wt. %), Al_2O_3 (13.43–15.71 wt. %), and Sr (257–1053 ppm) and low total Fe_2O_3 (1.44–5.90 wt. %), Y (8.30–16.20 ppm), and Yb (0.740–1.33 ppm) (Figure 3). Values of MgO are 0.08–4.07 wt. % and most samples' $Mg^\#$ are higher than 50. The strongly fractioned [$(La/Yb)_N$ = 8–21] REE patterns show weak to moderate negative Eu anomalies (Eu/Eu* = 0.63–0.90; Figure 4(c)). The $\varepsilon_{Nd}(t)$ values are −1.2 to +5.3 and $^{87}Sr/^{86}Sr(i)$ values are 0.7034–0.7060 (Figure 5 and 6), Supplemental Table 1). Values of *in-situ* zircon $\varepsilon_{Hf}(t)$

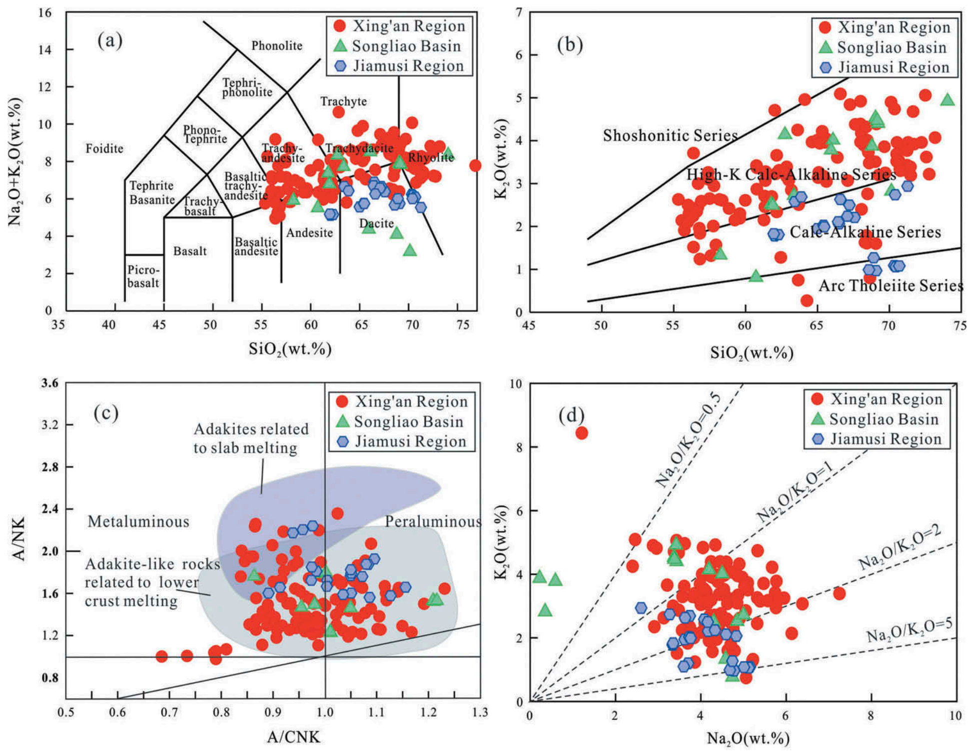

Figure 2. (a) SiO_2 versus (K_2O + Na_2O) plot (Le Bas *et al*. 1986), (b) K_2O versus SiO_2 diagram (Le Maitre *et al*. 2005), (c) A/CNK (Al_2O_3/(CaO + Na_2O + K_2O)) versus A/NK (Al_2O_3/(Na_2O + K_2O)) diagram, and (d) Na_2O versus K_2O plot. The field of adakites related to slab melting and lower crustal melting are from Condie (2005) and Zhu *et al*. (2009).

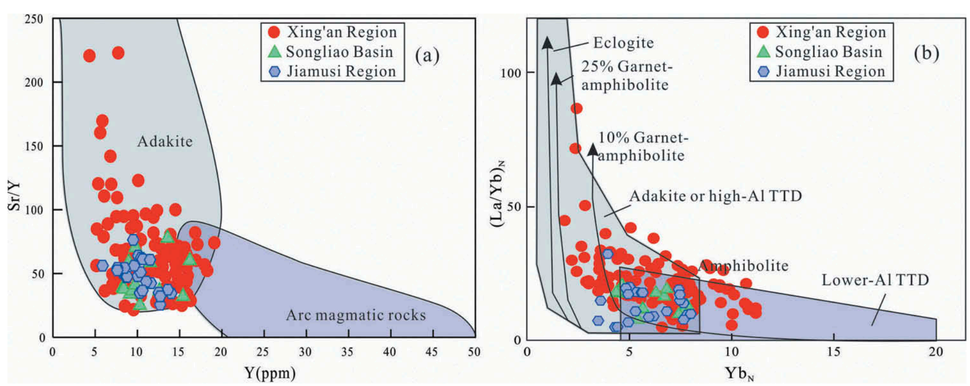

Figure 3. (a) Sr/Y versus Y discrimination diagram used to define the adakitic rocks used for this study and (b) (La/Yb)N versus YbN discrimination diagrams showing data for adakites and normal calc–alkaline rocks (Defant and Drummond 1990).

range from +1.4 to +12.6 and show T_{DM2} ages of ~1494–408 Ma (Figure 6), Supplemental table 2).

3.3 Jiamusi region

The adakitic rocks in the Jiamusi region are calc-alkaline basaltic andesite, andesite, dacite, rhyolite diorite, granite, monzogranite and granodiorite. Six concentrated areas of adakitic rocks have been identified in Jiamusi region, including northeast of the Yichun (Sun 2013; Sun *et al*. 2013a), Northeast of Jiamusi (Yu *et al*. 2013), Dunhua and Yanji (Li *et al*. 2007), Suifenghe (Chai *et al*. 2015), east of the Mudanjiang (Ji *et al*. 2007) and south of the Yilan (Sun 2013). Their ages are 113 Ma–90 Ma. They are enriched in Na_2O (2.60–5.15 wt. %) and K_2O (0.97–2.94 wt. %), They have variable total Fe_2O_3 (0.880–7.11 wt. %), MgO (0.050–4.90 wt. %), and $Mg^{\#}$ values (26–58, most > 40). They show high LREE/HREE ratios [$(La/Yb)_N$ of 5–32] (Figure 4(e)), variable Eu anomalies (0.36–1.63), and negative Nb–Ta anomalies (Figure 4(f) and Supplemental Table 1). Adakitic rocks in this area have relatively homogeneous Sr–Nd isotopic ratios

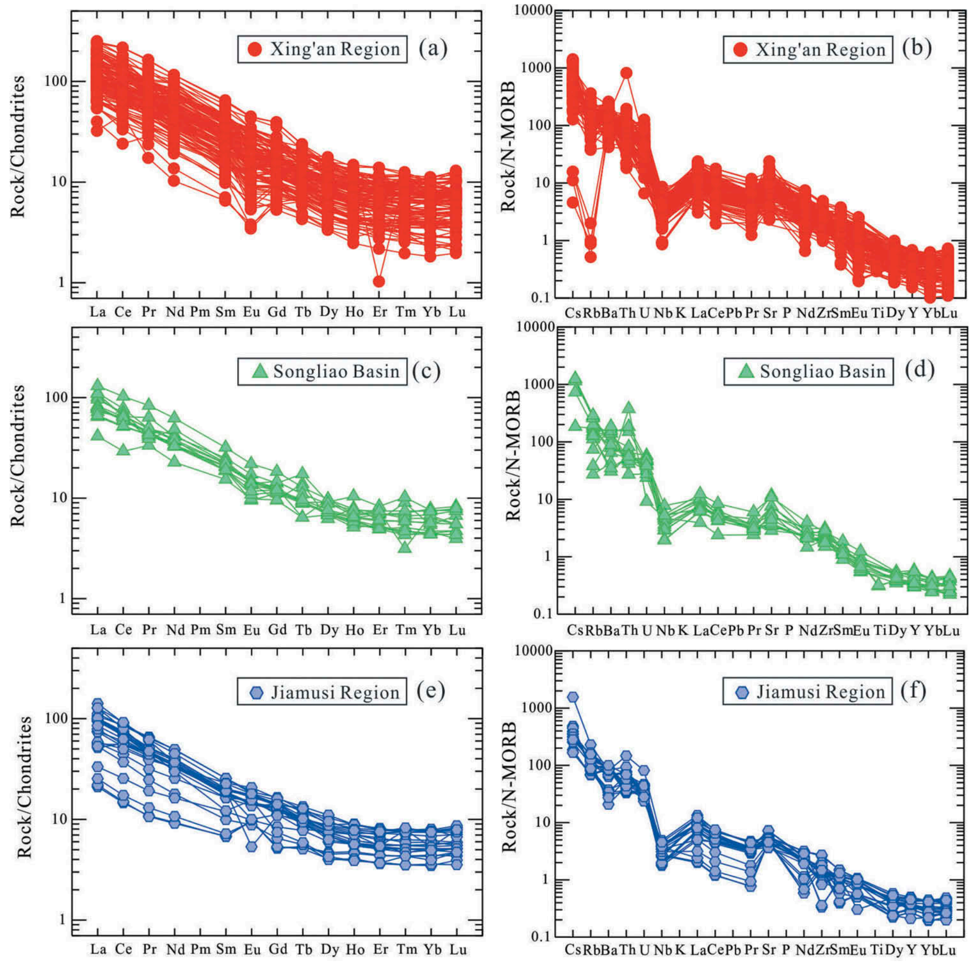

Figure 4. (a, b) Chondrite-normalized REE patterns and Primitive-mantle-normalized trace element patterns for adakitic rocks from the Xing'an region, (c, d) Chondrite-normalized REE patterns and Primitive-mantle-normalized trace element patterns for adakitic rocks from the Songliao Basin, (e, f) Chondrite-normalized REE patterns and Primitive-mantle-normalized trace element patterns for adakitic rocks from the Jiamusi region. Data for chondrite-normalized and primitive-mantle-normalized values and plotting order are from Sun and McDonough (1989).

compared to the rocks of the Xing'an region and Songliao basin: $\varepsilon_{Nd}(t)$ = +0.4 to +1.3,$^{87}Sr/^{86}Sr(i)$ = 0.7047–0.7057 (Figure 5), Supplemental Table 1), and *in-situ* zircon $\varepsilon_{Hf}(t)$ = +4.5 to +10.0 corresponding to T_{DM2} of ~997–583 Ma (Figure 6), Supplemental table 2).

No garnet has been reported in any of the adakitic rocks of NE China. In general, the andesitic adakitic rocks contain phenocrysts of pyroxene, clinopyroxene and plagioclase; dacites contain phenocrysts of quartz, plagioclase, K-feldspar, and biotite; and rhyolites contain phenocrysts of quartz, plagioclase, and K-feldspar. Adakitic diorites are comprised of plagioclase, quartz, clinopyroxene, hornblende and biotite; granites are composed mainly of plagioclase, K-feldspar, quartz and biotite.

The average age of adakitic rocks in the Xing'an region and the western portion of the Songliao Basin is older, and the number of reported adakitic rocks larger, than in the Jiamusi region and eastern portion of the Songliao Basin (Figure 7(a)).

4. Reappraisal of the petrogenesis of the early cretaceous adakitic rocks in NE China

The term adaktite was first defined by Defant and Drummond (1990) to describe the intermediate-felsic volcanic and intrusive rocks with slab-melting geochemical characteristics in the Aleutian Islands (Kay 1978). According to their Na_2O/K_2O ratios, Sr–Nd isotope characteristics and formation environments, adakites can be subdivided into five genetic types: (1) melting of young and hot oceanic plate during subduction (O-type, original definition type; Castillo 2012; Xu *et al*. 2014; Zhu *et al*. 2009), (2) melting of basaltic lower crust and delamination of lower crust (C-type; Atherton and Petford 1993; Wang *et al*. 2001). (3) fractional crystallization of basaltic

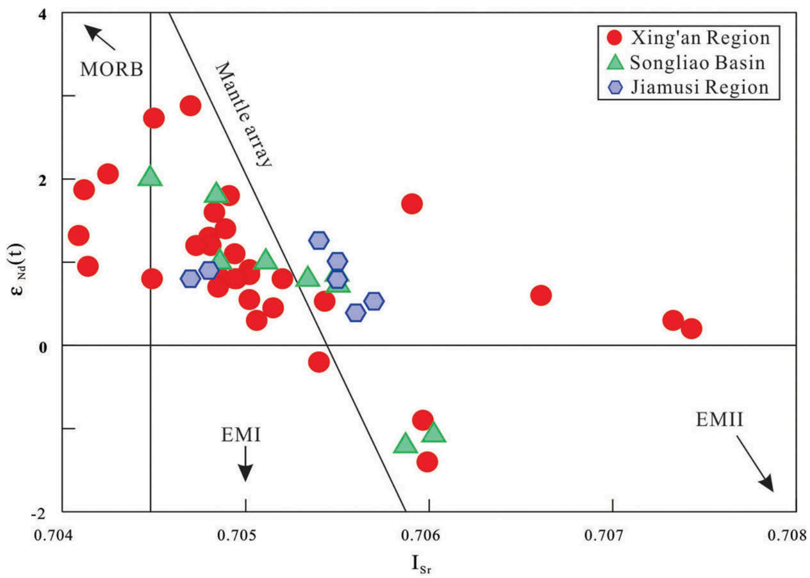

Figure 5. Whole-rock $\varepsilon_{Nd}(t)$ and initial $^{87}Sr/^{86}Sr$ isotopic compositions of the adakitic rocks in NE China.

magmas at high pressure (Macpherson *et al.* 2006); (4) assimilation and fractional crystallization (AFC) of basaltic magmas at low pressure (Castillo *et al.* 1999); and (5) the mixture of siliceous magmas and basaltic magma (Castillo 2012; Chen *et al.* 2013).

Firstly, adakitic rocks in NE China do not show an obvious characteristics of magma mixing and crustal assimilation (Castillo *et al.* 1999; Streck *et al.* 2007; Castillo 2012; Wang *et al.* 2012), as by the increasing of SiO_2, K_2O/P_2O_5 and K_2O/TiO_2 have no obvious change of some rocks (Zhang *et al.* 2007b). Same trend also exists between the SiO_2 and Sr-Nd isotopic data, with SiO_2 showing neither negatively correlated with and $\varepsilon_{Nd}(t)$ values nor positively correlated with initial $^{87}Sr/^{86}Sr$ ratios (Gao *et al.* 2005; Ying *et al.* 2010; Zhou *et al.* 2011; Xu 2017). Some samples show relatively low Rb/Sr (Wu *et al.* 2008; Li *et al.* 2018a) and constant Th/La and U/Nb ratios with increasing SiO_2 content (Ma *et al.* 2015). Their Th and U contents are depleted in comparation with the LREE (Ma *et al.* 2015), indicating crustal components are absent in the formation of these adakitic rocks (Taylor and McLennan 1985).

Factional crystallization (FC) of basaltic magmas also cannot dominate the petrogenesis of adakitic rocks in NE China, because the correlations are insignificant in the La–Sm, La–La/Sm, La–La/Yb, Yb–La/Yb and Ce/Yb–K_2O diagrams (Zhao *et al.* 2004; Sun *et al.* 2009, 2016; Zhou *et al.* 2011; Sun 2013; Wu *et al.* 2014; Li *et al.* 2018a). In addition, if the adakitic rocks were derived by FC processes, one would predict to find a continuous range of compositions, from mafic to felsic (Castillo

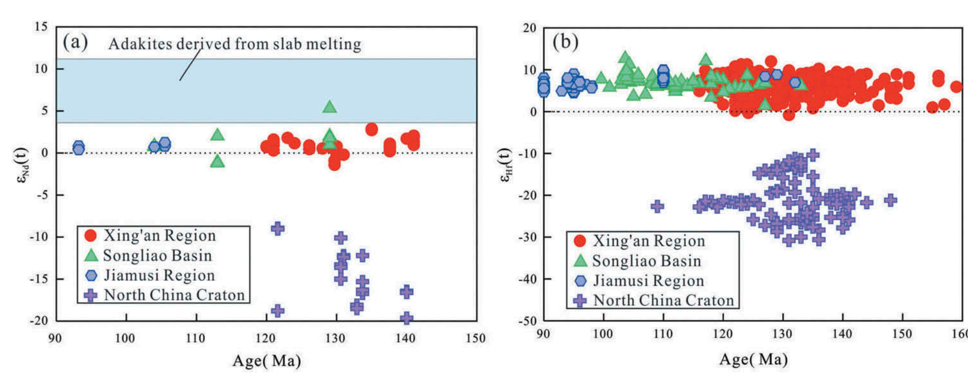

Figure 6. (a) zircon U-Pb weighted mean ages (Ma) versus $\varepsilon_{Nd}(t)$ values and (b) zircon U-Pb apparent $^{206}Pb/^{238}U$ ages (Ma) versus $\varepsilon_{Hf}(t)$ values for the adakitic rocks in NE China and North China Craton. The data from NE China sources are shown in Table 1 and supplemental Table 2. The rocks in North China Craton are from Jiang *et al.* (2007), Ma *et al.* (2016), Wang *et al.* (2016), Wang *et al.* (2013), Zhao *et al.* (2012). The area of adakites derived from slab melting is from Castillo (2012

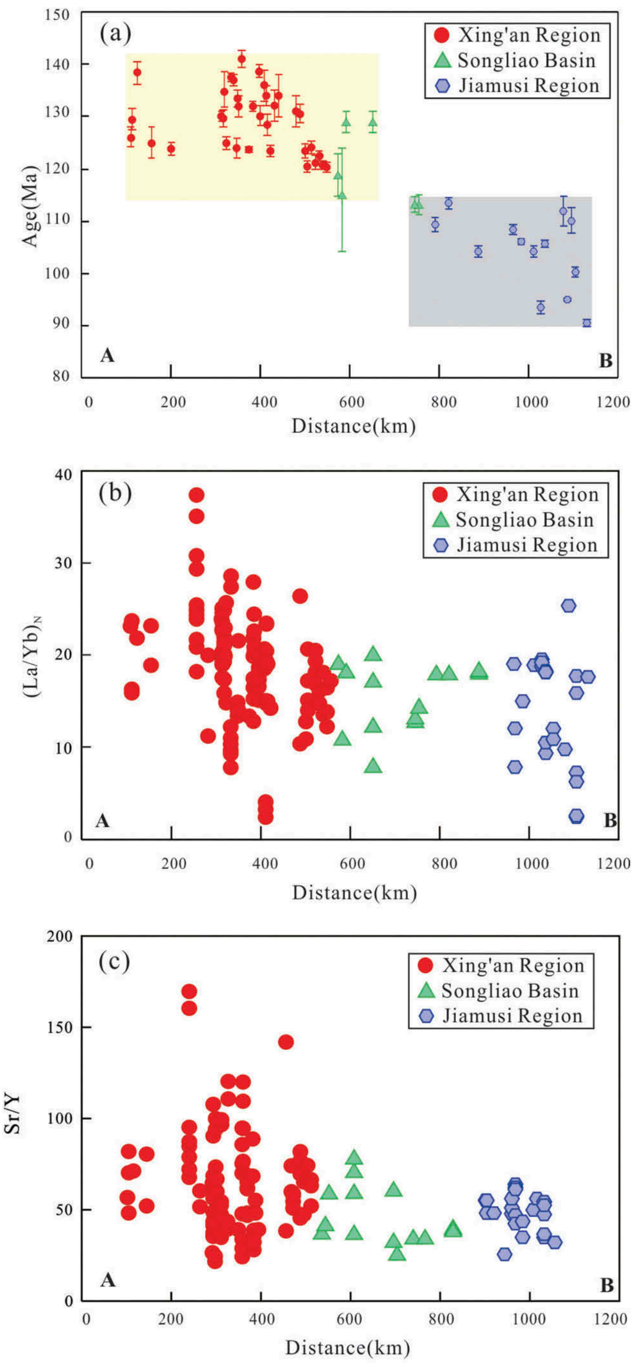

Figure 7. (a) Time-scale plots as projected on cross section A–B from Figure 1 (The source data are listed in Table 1). (b) $(La/Yb)_N$ plots as projected on the cross section (The data sources are shown in supplemental Table 1). (c) Sr/Y plots as projected on the cross section (The data sources are shown in supplemental Table 1).

et al. 1999; Macpherson *et al.* 2006). However, there is a notable lack of mafic rocks temporally and spatially associated with the Early Cretaceous adakitic rocks (Chai *et al.* 2015; He *et al.* 2017; Huang *et al.* 2014; Li *et al.* 2015, 2014b; Liu 2016; Sun *et al.* 2009; Sun 2013; Zhang *et al.* 2010, 2008c). The few mafic rocks that do exist in association with the adakitic rocks do not define a continuous chemical and/or mineral compositional trend with the adakitic rocks (Zhao *et al.* 2004; Gao *et al.* 2005; Ji *et al.* 2007; Chai *et al.* 2015). The few plutons that fit the characteristics of FC (Fan *et al.* 2003; Lin *et al.* 2004; Shu *et al.* 2014; Xu 2017) are highly localized and not representative of the range of Early Cretaceous adakitic rocks in NE China.

What remains most controversial is whether the adakitic rocks were derived from slab melting or lower-crustal melting. Adakitic rocks derived from slab melting usually show relatively high $Mg^{\#}$ values and compatible element contents, such as Cr and Ni, from having interacted with peridotite as they ascend through the upper mantle wedge (Wang *et al*. 2007b; Zhu *et al*. 2009; Zheng *et al*. 2014; Yang *et al*. 2015). Furthermore, most slab-melting adakites belong to the calc-alkaline series and typically have $Na_2O/K_2O>2$ (Wang *et al*. 2007b; Zhang *et al*. 2008b). Although some previous research has suggested that the adakitic rocks in NE China were derived from slab melting (Ren *et al*. 2012; Sun 2013; Zhang 2014; Chai *et al*. 2015; Ma *et al*. 2015) and some samples do show geochemical affinity to slab-melting adakites, the majority of adakitic rocks from NE China show relationships between SiO_2 and compatible elements that are more similar to lower-crustal magmas (Figure 8). Many of them also show $Na_2O/K_2O < 2$ (Figure 2(d)) and are characterized by higher K_2O content than the typical calc-alkaline series (Figure 2(b); Li *et al*. 2014b; Martin *et al*. 2005), further supporting the interpretation that they were primarily derived from lower-crustal melting.

Based on these observations, other researchers have also proposed that the formation of adakitic rocks in NE China may be attributed to the lower crust (Wu *et al*. 2011b, 2014; Sun *et al*. 2013b; Wang 2017). Importantly, these rocks show relatively positive whole-rock $\varepsilon_{Nd}(t)$ and *in-situ* zircon $\varepsilon_{Hf}(t)$ values and low whole-rock $^{87}Sr/^{86}Sr(i)$ (Supplemental Tables 1 and 2; Figure 5 and 6)). We also collected some Early Cretaceous adakitic rocks in North China Craton,which is considered by previous researchers that they originated from the lower crust (Jiang *et al*. 2007; Zhao *et al*. 2012; Wang *et al*. 2013, 2016; Ma *et al*. 2016) and compared their $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ with the samples in our manuscript. If these adakitic rocks are derived from Paleo-Pacific oceanic slab melting, they should show similar $\varepsilon_{Hf}(t)$, $\varepsilon_{Nd}(t)$ as well as T_{DM2}, but the samples from North China Craton show highly different isotope characteristics (Figure 6) and much older T_{DM2}, which coincides with the difference of crustal properties between the two regions, suggesting the origin is from lower crust melting.

As the residue of these rocks, because the rare earth pattern is relatively flat, especially the HREEs (Figure 4(a,c,e)), combined the $(La/Yb)_N$ and Sr/Y of most adakitic rocks is not so high (Figure 7), suggesting the residues may be a garnet-bearing hornblende source (Li *et al*. 2016). Similar conclusion can be drawn by MMEs of these rocks. Most of them are dioritic (Lin *et al*. 2004; Zhang *et al*. 2008c; Li *et al*. 2013; Shu *et al*. 2014; Sun *et al*. 2016) and we can see a residue characteristic but not cumulate rocks from these MMEs, and the main mineral of them is mainly hornblende, thus we can see an obvious trend that the residues mainly consist of hornblende.

Some samples have relatively much high Mg#, V (>70 ppm), Cr (>36ppm), Ni (>13 ppm) and Co (>10 ppm) contents, similar to the adakitic rocks associate with lower crust delamination (Ren *et al*. 2017). Eu anomaly is also of significance to trace the crustal evolution and exchange between crust and mantle (Taylor and McLennan 1985). Mantle-derived rocks and juvenile crust usually have no or negative Eu anomalies (Gao and Wedepohl 1995). The reworking lower crust shows obvious positive Eu anomalies (Li *et al*. 2018a). The negative Eu anomalies in the Songliao Basin (Eu* = 0.63–0.90), Xing'an (most samples with Eu*<1) and Jiamusi regions (more than half of the samples with negative Eu anomalies) indicate that their crust origin and lower crust detachment. Furthermore, in Figure 8(d,e), most samples fall into the fields of the delaminated lower crust-derived adakitic rocks, indicating that adakitic magma passed through the lithospheric mantle and react with mantle peridotite as they rise (Stern and Kilian 1996; Zhu *et al*. 2009; Zheng *et al*. 2014; Li *et al*. 2018a). Besides, according to the previous research, only when the melt suffers more than 1.2 GPa (about 40 km deep in the crust) can it balance with the residual garnet and form adakitic solute (Rapp and Watson 1995; Rapp *et al*. 1999, 2003). Nevertheless, tele-seismic P-wave detection results indicate that the thickness of continental crust in the Xing'an and Jiamusi regions is about 40 km, thicker than the 28–35 km thick crust in the Songliao Basin (Gao and Li 2014), so that the thickness of crust in the Songliao Basin is not enough to produce adakitic melt (≥~40 km: Rapp and Watson 1995; Rapp *et al*. 1999, 2003) unless the lower crust delaminated into the mantle. Similar conclusions can be drawn by the $(La/Yb)_N$ and Sr/Y ratios. In fact, the global arc-averaged La/Yb and Sr/Y ratios is positively correlated with the formation depth of adakitic magmas (Profeta *et al*. 2015; Zhu *et al*. 2015, 2016). On this premise, along the scan line A-B in Figure 1, we can estimate the relative depths of adakitic magmas in the Xing'an region, Songliao Basin and Jiamusi region, and interpret the approximate crustal thickness required to produce the adakitic magmas (Figure 7(b,c)). By this measure, the Cretaceous crust in the Songliao Basin and Jiamusi region was notably thinner than some parts of Xing'an region (Stracke and Bourdon 2009; Gao and Li 2014; Bao *et al*. 2014). Therefore, some of the Early Cretaceous adakitic rocks in NE China maybe also related to lower crust delamination.

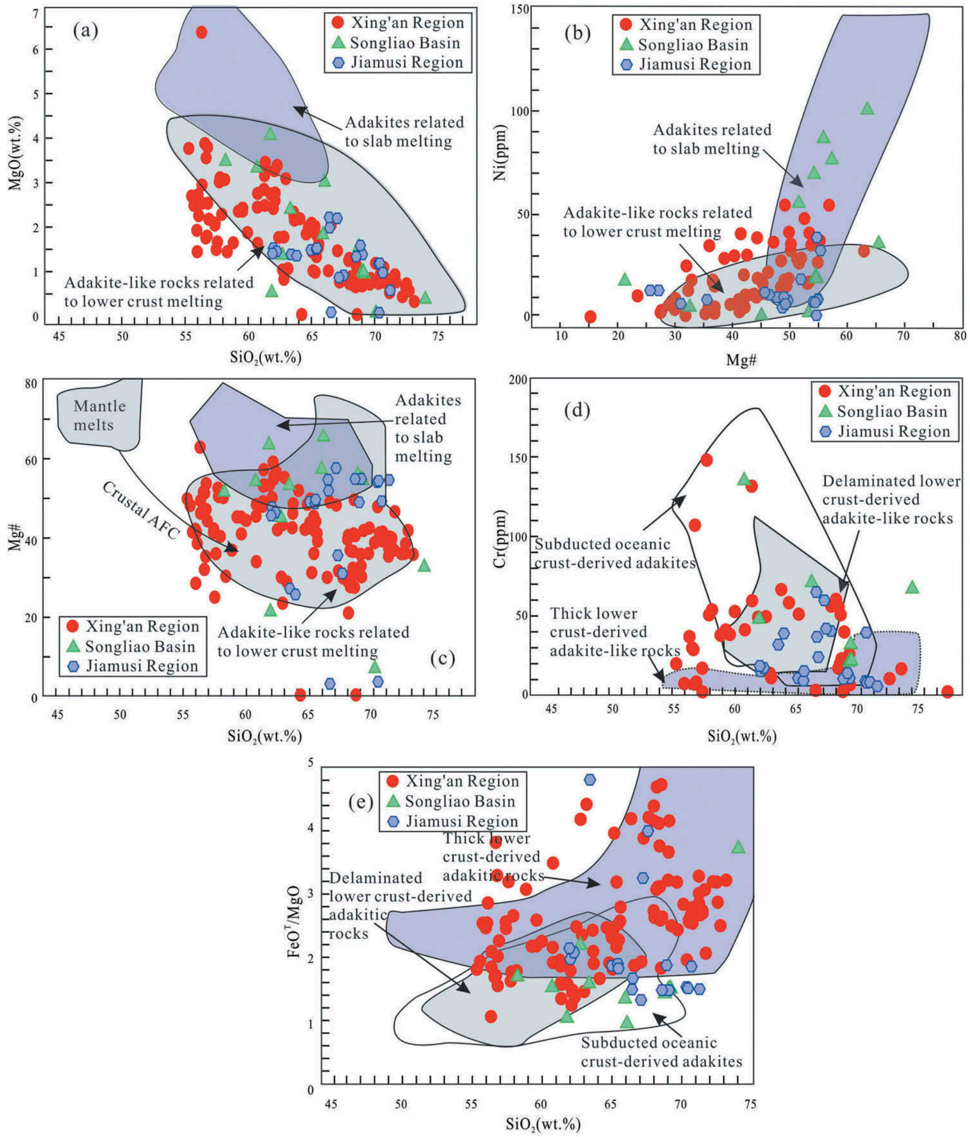

Figure 8. (a) MgO contents and (b)Mg# values versus SiO_2 contents, (c) Ni contents versus Mg#. The field of adakites related to slab melting and lower crustal melting are from Condie (2005). (d) Cr versus SiO_2. Fields of subducted oceanic crust-derived adakites, thick lower crust-derived adakite-like rocks and delaminated lower crust-derived adakite-like rocks are after Wang *et al*. (2005). (e) FeO^T/MgO contents versus SiO_2 contents. Fields of subducted oceanic crust-derived adakites, thick lower crust-derived adakite-like rocks and delaminated lower crust-derived adakite-like rocks are after Wang *et al*. (2006c).

5. Tectonic implications

5.1 Convergent bidirectional subduction and associated slab rollback

As mentioned in the introduction, several models for the Cretaceous tectonic evolution of NE China have been proposed. Palaeomagnetic data suggests that the direction of Paleo-Pacific Plate subduction was north–north-west-ward (Northrup *et al*. 1995) and began westward subduction c. 125–110 Ma (Zhang 2013). Adakitic rocks in the Xing'an region are generally older than this and as much as 1300 km from the Paleo-Pacific trench, so are unlikely to be related to that evolution of that margin (Liu *et al*. 2018a). There is evidence that, in the late Mesozoic, the subduction of the Mongol-Okhotsk plate was still active (Zhang 2014; Li *et al*. 2018a), so the effect from the west cannot be ignored for the Xing'an adakitic rocks. The closure of the Mongol-Okhotsk Ocean and associated continent collision are not likely the case, either. There is no evidence of crustal thickening caused by continental collision, such as S-type granite, renders the orogenic collapse model untenably (Zhang 2014). The Paleo-Asian Ocean was completely closed at the latest in the Middle Triassic, and the associated collision ended in the Late Triassic (Yang *et al*. 2017; Zhou *et al*. 2017; Li *et al*. 2018c) so cannot explain the Cretaceous adakitic rocks ofthis study. The spatial and temporal distributions of the adakitic rocks over a wide region of

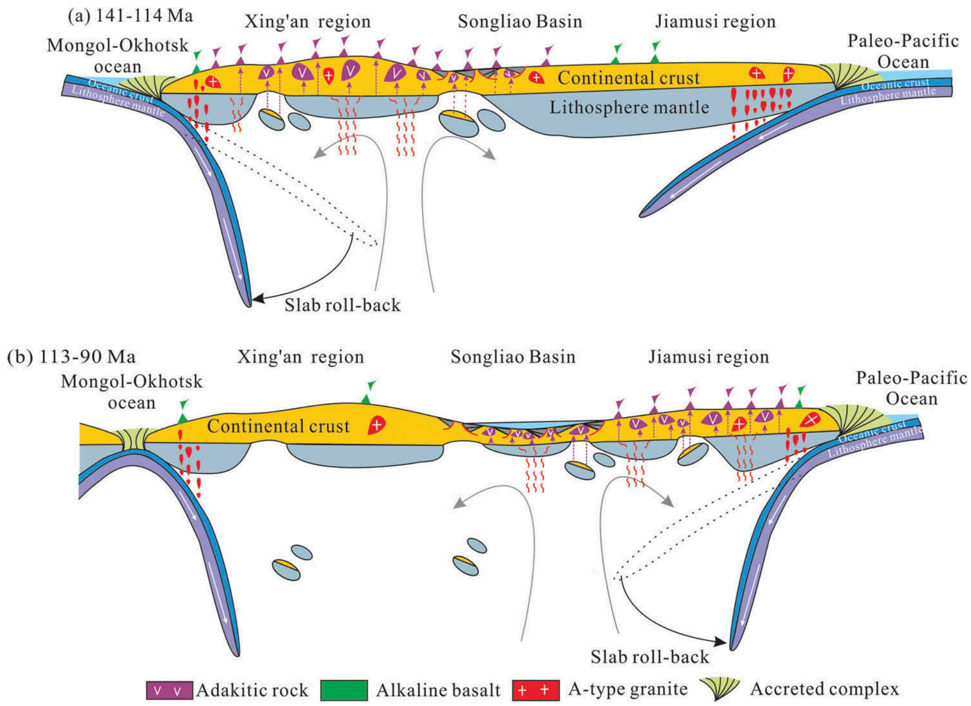

Figure 9. A schematic cartoon showing the Mongo-Okhotsk oceanic plate subduction and associated slab rollback in the west from 141 to 120 Ma and the Paleo-Pacific oceanic plate subduction rollback and associated slab rollback in the east from 113 to 90 Ma. Both stages are accompanied by lithosphere delamination and asthenosphere upwelling.

NE China are also inconsistent with a mantle plumes being responsible for formation of the adakitic rocks.

Our compiled age data show that Early Cretaceous adakitic rocks in NE China formed in one of two stages: 141–114 Ma and 113–90 Ma. As shown in Figure 7(a), all the 141–114 Ma rocks are located in the western part of the NE China (the whole Xing'an region and the western Songliao Basin), and the 113–90 Ma rocks are located in the eastern part of NE China (the whole Jiamusi region and the eastern Songliao Basin). Those observations suggest that the adakitic rocks in eastern and western NE China maybe have formed in two different tectonic settings. Thus, we proposed a convergent bidirectional subduction model of Mongol-Okhotsk Ocean closure and associated slab rollback in the west from 141 to 114 Ma and subduction of Paleo-Pacific oceanic slab and associated rollback in the east from 113 to 90 Ma, both of which induced asthenosphere upwelling and melting of the lower crust (Figure 9).

5.2 *Early cretaceous tectonic evolution of NE China*

When the Mongol-Okhotsk oceanic slab was subducting, before the Early Cretaceous, resulting in lithospheric thickening in NE China. Lithospheric delamination and partial melting of the subduction slab during this stage were limited (Wu *et al.* 2005b, 2011a). But from 141 to 114 Ma, the subducted Mongol-Okhotsk oceanic plate rolled back, resulting in a transition from compression to extension possibly with significant delamination in the Xing'an region and the western part of the Songliao basin.

The delamination hypothesis is further supported by the following lines of evidence. Volume wave imaging of the Songliao Basin shows that high-speed anomalies dominate its interior, suggesting that lithospheric delamination might have influenced the Songliao Basin (Zhang *et al.* 2013). Anisotropy with smaller delay time (~0.4s) is also observed in some areas of the Songliao Basin and Jiamusi Block. It may be the result of delamination and associated mantle upwelling, and thus destroy the differences in physical and chemical properties of the remaining rocks in different directions (Qiang and Wu 2015). Furthermore, artificial seismic sounding across the Songliao Basin shows that the Poisson ratios of the crust beneath some parts of the Songliao Basin and neighbouring regions are relatively high (Liu *et al.* 2007). Some researchers have suggested that the this might be the result of delamination of an eclogitic lower crust in the Songliao Basin (Ji *et al.* 2009; Gao and Li 2014). Moreover, some geophysicists noticed that the lithospheric mantle in the east-central part of the NE China had formed a mushroom-cloud structure during the Mesozoic, resulting in a significant decrease in the seismic wave velocity (Yuan 2007; Ye *et al.* 2012). These particular structures in the Songliao Basin and its adjacent basin groups may be caused by crustal thinning, delamination and associated asthenosphere upwelling (Gao and Li 2014).

Widespread Early Cretaceous A-type granites and alkaline basalts in NE China also suggest an extensional environment (Fan *et al*. 2003; Zhao *et al*. 2004; Yin *et al*. 2005; Ge *et al*. 2005; Ji *et al*. 2007; Cao and Hou 2009; Sun *et al*. 2013a; Zhang 2014; Li *et al*. 2014b; Ma *et al*. 2015), which is further supported by the presence of metamorphic core complexes (Yang *et al*. 2007; Donskaya *et al*. 2008). To illustrate, some A-type granites cropout in the Dongshanwan of the Xing'an region, and show strong alkalinity, high Fe/Mg ratio, high content of Zr, Nb, Y and low content of Al_2O_3, CaO and Sr. Relatively high positive anomalies of $\varepsilon_{Hf}(t)$ (+5.5 to +9.2) and young crust model ages (820–615 Ma) indicate derivation from juvenile lower crust (Zeng *et al*. 2016). In addition, some Late Mesozoic lamprophyre dyke swarms have been found in the Liaodong Peninsula (Jiamusi region) could be subdivided into two types according to their geochemical characteristics. The first one has higher $Mg^{\#}$, SiO_2 and compatible element contents, and lower $\varepsilon_{Nd}(t)$ (−12.1 to −9.6) and higher $^{87}Sr/^{86}Sr(i)$, similar to subcontinental lithospheric mantle while the other has lower $Mg^{\#}$, SiO_2 and compatible element contents, and higher $\varepsilon_{Nd}(t)$ (−6.1 to −1.4) and lower $^{87}Sr/^{86}Sr(i)$ values, suggesting the occurrence of delamination (Jiang and Jiang 2006). Also, Late Mesozoic I-type granites, including granodiorites and highly fractionated monzogranites, have been found in the Dandong area of the Jiamusi region, and show variable $^{87}Sr/^{86}Sr(i)$ and $\varepsilon_{Nd}(t)$ values. For their petrogenesis, Wu *et al*. (2005b) proposed that local lithospheric delamination associated with subduction of the Pacific Plate triggered partial melting of both ancient and juvenile crust. A certain amount of Cretaceous alkaline basalts also emerged in NE China; they have depleted isotopic compositions and ultra-ferromagnesian xenoliths (Xu *et al*. 1999), indicating the existence of earlier mantle magma cumulates near the crust-mantle boundary. This also suggests that NE China may have been subjected to an important magmatic underplating event induced by local lithospheric delamination (Wang *et al*. 2006d). Previous studies have also revealed that metamorphic core complexes occur extensively in NE China, suggesting that a Late Mesozoic low-angle C′-foliation turned into some extensional detachment faults that propagating upwards into the lower crust in an extensive setting (Wang *et al*. 2011; Xu *et al*. 2013). According to all of the lines of evidence mentioned above, in the Late Mesozoic delamination likely occurred in NE China, which is manifest in the geochemistry of some of the reported adakitic rocks.

For the slab-melting derived adakites, their ages may decrease gradually from the front of the slab to the trench zone during slab-rollback. However, the Early Cretaceous adakites in NE China are formed by lithosphere-delamination induced lower crust partial melting. The NE China is made up of several diverse micro massifs (Şengör *et al*. 1993), and the lithospheric mantle and lower crust in NE China are heterogeneous (Stracke and Bourdon 2009; Bao *et al*. 2014). Thus, the delamination and lower crust melting could be localized and do not show an obvious distribution rule (Stracke and Bourdon 2009; Ueda *et al*. 2012). This phenomenon is further tested by the Figure 7(b,c), as all the Xing'an region suffered the upwelling of asthenosphere but the crust thickness is heterogeneous.

To summarize, we believe that 141–114 Ma lithospheric delamination, asthenosphere upwelling, large-scale lower crust melting and insignificant slab melting occurred in the Xing'an region and western part of the Songliao basin, producing adakitic rocks. This process may have been triggered by rollback of the Mongol-Okhotsk oceanic slab to the west. As the slab began to sink, extension and associated upwelling of the asthenosphere broke apart the mantle lithosphere and lower crust beneath the Songliao Basin and Xing'an region Figure 9(a).

As for the Jiamusi region and eastern part of the Songliao basin, the adakitic rocks older than 113 Ma are sparse, thus delamination did not significantly influence these areas at that time Figure 9(a). We suggest that low-angle subduction of the Paleo-Pacific Ocean lasted until 113 Ma, after which slab rollback commenced. As had previously occurred in the Xing'an region, the upwelling asthenosphere caused lower-crustal delamination and melting leading to the formation of adakitic rocks (Wu *et al*. 2005a; Wang *et al*. 2006a) Figure 9(b).

6. Conclusions

(1) The adakitic rocks in NE China show high K_2O contents and variable $Mg^{\#}$, MgO, Cr, and Ni contents. These geochemical characteristics, along with positive whole-rock $\varepsilon_{Nd}(t)$, positive *in-situ* zircon $\varepsilon_{Hf}(t)$, low whole-rock $^{87}Sr/^{86}Sr(i)$ values, and young model ages support the interpretation that these rocks are mainly derived from melting of juvenile lower crust.

(2) The adakitic rocks in NE China could be subdivided into two stages: 141–114 Ma in the west and the 113–90 Ma in the east, suggesting two different tectonic settings.

(3) A two-stage convergent bidirectional subduction model was proposed, involving subduction and

rollback of the Mongol-Okhotsk oceanic plate in the west from 141 to 114 Ma followed by subduction and rollback of the Paleo-Pacific oceanic plate in the east from 113 to 90 Ma. Both stages were accompanied by lithosphere delamination and asthenosphere upwelling.

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