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Intra-oceanic arc accretion along Northeast Asia during Early Cretaceous provides a plate tectonic context for North China craton destruction

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Kiselevka-Manoma
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Okuniikappu
Adakite

ABSTRACT

North China craton destruction (i.e., NCC destruction) during the Early Cretaceous is typically considered within the context of continuous, westward subduction of the Izanagi /paleo-Pacific plate beneath eastern Eurasia (i.e., Andean-style subduction). However, geological evidence indicates intra-oceanic arc accretions along east Eurasia during the Early Cretaceous that are incompatible with Andean-style plate tectonics. Here we review oceanic terrane accretions along NE Asia during Cretaceous times from published magmatism, stratigraphy, and paleomagnetism. We synthesize an alternative 'intra-oceanic subduction'-style NE Asian plate tectonic model between ~15–40° N latitudes during the Early Cretaceous (130–100 Ma) and discuss implications for NCC destruction.

Well-known NE Asian magmatism migrated >1000 km inboard to NE China during the Jurassic, and then >1000 km outboard during early Cretaceous (140–110 Ma). Early Cretaceous NE Asian igneous rocks include: (1) arc-related igneous rocks, (2) 132–99 Ma adakites in Japan and Sikhote-Alin, and (3) 145–120 Ma K-rich adakites in NE China. Roughly co-eval to these periods (130 to 100 Ma), intra-oceanic arcs accreted diachronously along the Sambagawa belts, SW Japan, Oku-Niikappu belts, NE Japan, and Kema and Kiselevka-Manoma, Russian Far East. Based on the adakite geochemistry and spatiotemporal overlap between the arc accretions and adakites, we link the NE China adakites to lower NCC crustal melting, whereas the Japan-Sikhote Alin adakites originated from oceanic slab melting. We show that eastern Eurasia-NW Panthalassan plate tectonics during the Early Cretaceous was more complex than generally recognized, involving intra-oceanic subduction zones and multiple oceanic plates. The Early Cretaceous-aged NE Asian adakites were generated within elevated mantle geotherms during 140–110 Ma slab rollback and 130–100 Ma intra-oceanic arc accretions. Oceanic mantle emplaced during these events replaced the NCC subcontinental lithospheric mantle with more juvenile mantle during final NCC destruction at 115 Ma. The more complete plate tectonic picture provided here suggests that NCC destruction models that rely on straightforward Andean-style subduction are likely oversimplified. Instead, future NCC destruction studies should include more complex geodynamics with intra-oceanic subduction and additional plates that will alter boundary conditions for geodynamic modeling, petrogenesis, and magmatic mixing models.

1. Introduction

The eastern Eurasian continental margin along northeast Asia shows abundant evidence for subduction-related igneous activity during Cretaceous times (Fig. 1) (Grebennikov et al., 2016; Isozaki et al., 2010; Khanchuk et al., 2016; Wakita, 2013). Consequently, studies of the eastern Eurasian margin typically reconstruct long-lived plate convergence that involves the subduction of the modern and Paleo-Pacific plates through time (Isozaki et al., 2010; Li et al., 2017; Wilde, 2015). However, many first-order details of NW Paleo-Pacific (Panthalassa) plate tectonic reconstructions remain controversial, including the possibility of intra-oceanic accretion along the continental margin (Fig. 2). Some models consider that during the Early Cretaceous times, an oceanic plate continuously subducted under the Eurasian continental margin to form an 'Andean-type' margin, and a continental arc-trench system was developed (Fig. 2a) (Engebretson, 1985; Li et al., 2019; Matthews et al., 2016; Torsvik et al., 2019). In contrast, others suggest that intra-oceanic arcs formed outboard of the continental margin due to

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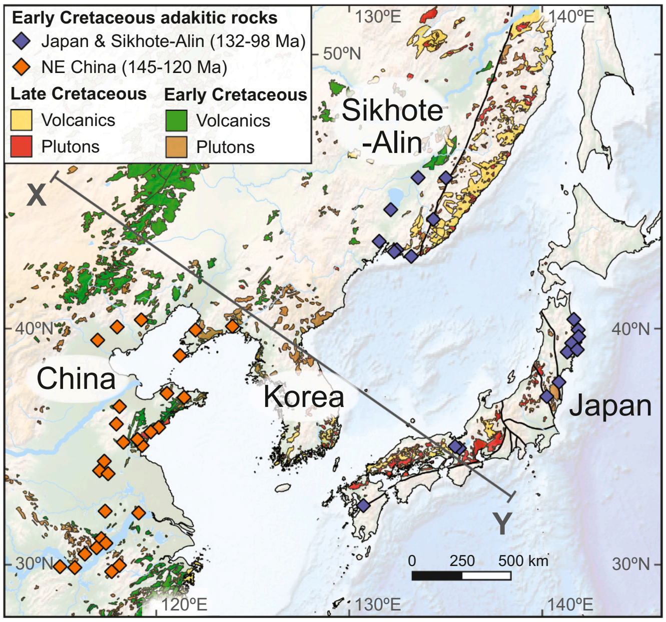


Fig. 1. Location map showing Cretaceous igneous rocks in NE Asia. Transect X-Y shows a line of projection for the spatiotemporal distribution of igneous rocks shown in Fig. 3a.

intra-oceanic subduction, and these arcs accreted along the East Asian margin; we call these 'intra-oceanic arc' models (Fig. 2b) (Arkhipov et al., 2019; Malinovsky and Markevich, 2007; Ueda and Miyashita, 2005). The plate tectonic context for northeast Asia during Early Cretaceous times has important implications for the following events: biogeographic realms of the Jehol biota, one of the best-preserved terrestrial fossil assemblages in Earth history (Pan et al., 2013); the origin of economic mineral deposits in the region (Li et al., 2019); voluminous magmatism (Figs. 1, 3) (Li et al., 2022; Li, 2022); an abrupt change from contractional to extensional stresses that induced sedimentary basin formation and metamorphic core complexes within continental NE China (Li et al., 2019); and, thinning and loss of a significant (~120 km) thickness of mantle lithosphere from the North China craton (i.e. North China craton destruction) (Dai et al., 2016; Liu et al., 2019; Ma et al., 2016a; Zheng et al., 2018), which is the focus of this paper.

Most studies explain North China craton destruction within the context of an Andean-type margin during the Early Cretaceous, specifically, continuous Izanagi /paleo-Pacific plate subduction under Eurasia (e.g. Fig. 2a) (Liu et al., 2019; Wu et al., 2019; Zheng et al., 2018). However, the alternative possibility that North China craton destruction occurred during intra-oceanic arc accretion (Fig. 2b) has been proposed (e.g. Ueda and Miyashita, 2005) but not fully examined. In this study, we review NE Asian margin geology during Cretaceous times from published igneous activity, stratigraphy, and paleomagnetism of accreted Cretaceous oceanic terranes in Japan, Korea, North China, and the southern Russian Far East (Sikhote-Alin and Sakhalin). We give particular attention to Early Cretaceous-aged adakitic rock suites within NE Asia because the adakites occur between now-separated parts of the continental arc (Wu et al., 2017) and may have tectonic significance (Castillo, 2012). We synthesize an alternative view of NW Pacific basin plate tectonic boundary conditions during Early Cretaceous that includes accretion of intra-oceanic arcs along the NE Asian margin, and discuss their implications for North China craton destruction models.

2. A brief review of Eurasian margin geology along NE Asia during Cretaceous times

2.1. Published plate tectonic reconstructions of the NW Pacific basin

The geology of the NE Asian margin is typically interpreted in the context of westward subduction of Pacific and paleo-Pacific plates beneath the Eurasian margin since at least ~200 Ma (Guan et al., 2020; Kusky et al., 2007; Li et al., 2017; Wilde, 2015; Zhou et al., 2009). In reality, plate reconstruction constraints are extremely sparse due to consumption of >8000 km of oceanic lithosphere since the Cretaceous by subduction (e.g. Matthews et al., 2016). Consequently, numerous plate tectonic reconstruction models for the NW Pacific basin during Cretaceous times have been proposed. The most popular class of proposed plate models are Andean-type models (Fig. 2a) that show a continental arc-trench system and continuous subduction of oceanic plate(s) along the NE Asian margin. Recent global plate reconstructions and other plate models constrained by NE China geology consider Andean-type subduction of a large Izanagi /paleo-Pacific plate that occupied the NW Pacific basin from the late Triassic to Cretaceous (Li et al., 2019; Matthews et al., 2016; Torsvik et al., 2019). Other Andean-type models show mid-oceanic ridges between the Izanagi and Pacific plates that intersected the Eurasian margin and swept northwards during the Cretaceous (Engebretson, 1985; Isozaki et al., 2010; Maruyama et al., 1997). A variant suggests that during the Early Cretaceous, a northward-sweeping Izanagi-Farallon ridge-trench intersection produced the adakitic Kitakami granitic plutons, NE Japan (Osozawa et al., 2019).

An alternative, less-considered class of models involves the accretion of intra-oceanic arc(s) and multiple plates (Fig. 2b). These models suggest one or more intra-oceanic arc system(s) formed outboard of Eurasia along an intra-oceanic subduction zone between the Izanagi plate and other oceanic plate(s), and these arcs were later accreted during the Early Cretaceous to mid-Cretaceous (Arkhipov et al., 2019; Boschman et al., 2021; Malinovsky et al., 2008; Ueda and Miyashita, 2005; Utsunomiya et al., 2011). Models in this category imply that at least one additional oceanic arc-trench existed outboard and co-eval to the NE Asian continental arc-trench system. One model that included global seismic tomographic constraints implied a long-lived and very wide (>3000 km width in the early Jurassic) oceanic plate named Pontus existed between Eurasia and the Izanagi plate since at least early Triassic to the Early Cretaceous (Van der Meer et al., 2012). Other models propose intra-oceanic arcs formed along the eastern boundary of narrower (3000–1000 km during Early Cretaceous) marginal seas that were located near the East Asia continental margin during the late Jurassic to Early Cretaceous (Arkhipov et al., 2019; Malinovsky and Markevich, 2007; Ueda and Miyashita, 2005). These models suggest that the intra-oceanic arcs were located sufficiently close to the Eurasian continental margin to receive continent-derived sediments based on geological constraints from Early Cretaceous accretionary terranes in Japan and Sikhote-Alin (Russian Far East).

2.2. North China Craton destruction

Cratons are old and stable regions of stable continental lithosphere that often have thick lithospheric roots to ~200 km (Boyd, 1989; Lee et al., 2011; Pearson, 1999; Pearson et al., 2021). However, xenoliths show that lithospheric thicknesses along the eastern part of the North China Craton decreased from ~200 km in the Paleozoic to less than 80 km in the Cenozoic, implying lithospheric thinning and destruction of the lowermost NCC between these periods (Griffin et al., 1998; Menzies et al., 1993). Some suggest the initiation of NCC destruction occurred ~145 Ma based on a 145–120 Ma episode of adakitic magmatism that was likely generated from partial melting of the eastern NCC lower crust (Gu et al., 2013; Ma et al., 2016b; Wang et al., 2007). The ancient NCC sub-continental lithospheric mantle (SCLM) was then replaced by a juvenile one at 120–110 Ma, based on an abrupt change in mafic

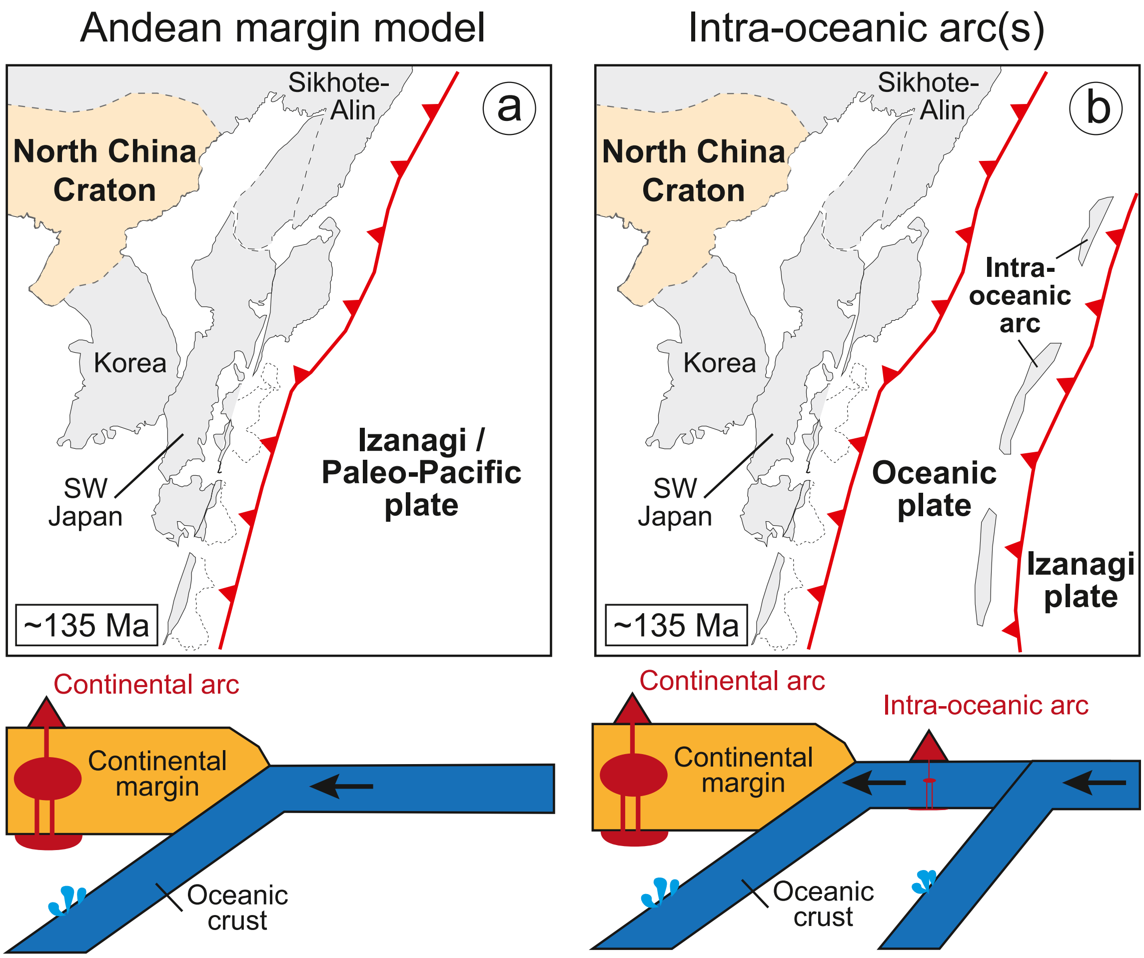


Fig. 2. Proposed NW Pacific basin plate tectonic reconstructions during the Early Cretaceous and associated schematic cross-sections. a) Andean margin type models show continuous westward subduction of a large Izanagi /paleo-Pacific plate under NE Asia (e.g. Matthews et al., 2016). b) Intra-oceanic arc models show intra-oceanic subduction zone(s) developed outboard of NE Asia, which results in multiple subduction zones (e.g. Ueda and Miyashita, 2005). In b), the Izanagi /paleo-Pacific plate subducts offshore along the intra-oceanic subduction zone and is precluded from subducting under the NE Asian continental margin. The subduction polarity of the intra-oceanic subduction zone in b) is uncertain but drawn as landward-dipping.

magmatism from isotopically-enriched and arc-like to an isotopically-depleted (i.e. juvenile) and intraplate-like signature (Dai et al., 2016; Liu et al., 2019; Ma et al., 2016a; Zheng et al., 2018).

Continuous westward subduction of the Izanagi /paleo-Pacific plate (i.e Andean-type models in Fig. 2a) has been considered as the first-order geodynamic mechanism for NCC thinning, destruction, and development of juvenile lithospheric mantle (Liu et al., 2019; Wu et al., 2019; Zheng et al., 2018). A subduction origin for NCC thinning is supported by very high water contents (>1000 ppm) within lithospheric mantle-sourced basalts of Early Cretaceous age within the NCC (Xia et al., 2019; Xia et al., 2013). Within the context of Andean-style models (Fig. 2a), the following mechanisms have been proposed: (1) Back-arc extension in NE China corresponding to the roll-back of the Izanagi plate during Early Cretaceous (Zheng and Dai, 2018; Zhu et al., 2012a; Zhu and Xu, 2019; Zhu et al., 2012b); (2) mantle wedge suction forces induced by the subduction of the paleo-Pacific plate (Niu, 2005); (3) convective erosion or asthenosphere upwelling within a big mantle wedge that sat between a stagnant slab and the overriding NCC lithosphere (He, 2014; Li and Wang, 2018; Liu et al., 2019); or, (4) a spreading ridge on the paleo-Pacific plate subducted beneath the NCC, triggered the destruction of the cratonic lithosphere (Ling et al., 2013). We do not find many models that relate possible intra-oceanic arc accretion along the NE Asian margin (Fig. 2b) to NCC destruction, which has motivated this paper, since the accretion of an intra-oceanic arc along East Asia would change the first-order plate tectonic boundary conditions and possibly introduce slab breakoff, subduction polarity changes, or other complexities. Furthermore, if an intra-oceanic subduction zone existed, it would preclude Izanagi subduction under the Eurasian continental margin (Fig. 2b). This would mean that NW Pacific basin plate tectonic models are much less insightful for interpreting eastern Eurasian continental magmatism.

3. Cretaceous igneous activity along the Eurasian margin, northeast Asia

3.1. General observations

We provide a broader picture of Eurasian continental margin magmatism during the Mesozoic by newly synthesizing the spatial-temporal distribution of igneous rocks from Wu et al. (2019) with newly compiled data ($N = 616$) from Japan, Korean and Sikhote-Alin (see Appendix 1 for references; Appendix 2 for data). The compiled igneous ages are primarily U—Pb zircon ages, with smaller numbers of U—Pb monazite ages ($N = 59$), U—Pb sphene ages ($N = 9$), and Rb—Sr whole-rock ages ($N = 14$). The igneous rock ages and distributions are projected along a transect across NE Asia (Fig. 3a). Precise positioning of Japanese igneous rocks (labeled 'paleo-Japan' in Fig. 3a) is not critical to our analysis, but for added realism, these rocks were palinspastically-restored to the first-order by applying a ~ 500 km westward shift from their present location following the previous Japan Sea plate reconstructions (e.g. van Horne

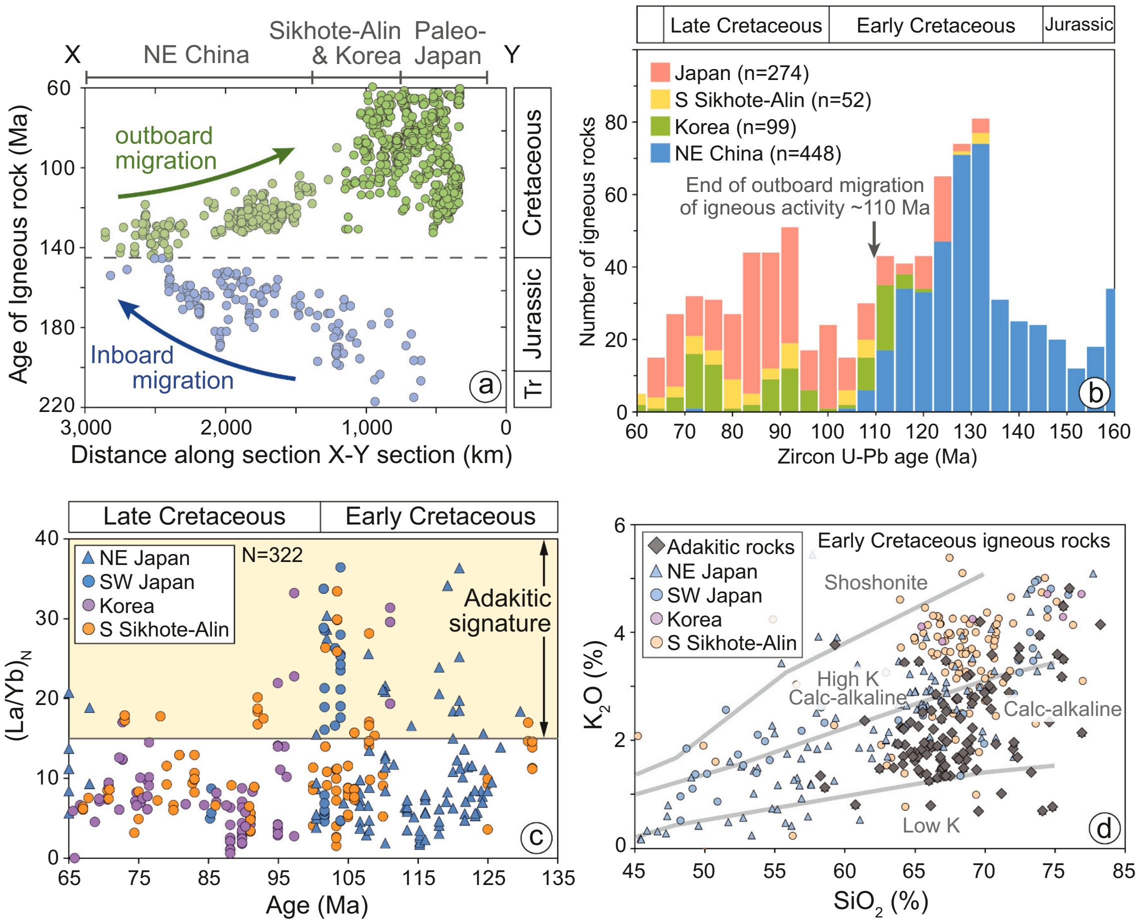


Fig. 3. a) Spatiotemporal distribution of igneous rocks in NE Asia projected along the X-Y section in Fig. 1, modified from Wu et al. (2019) with newly compiled data for Japan, Korea, and Sikhote-Alin (See Appendix 1 for references). The location of igneous rocks in "Paleo-Japan" are shifted ~500 km west from their present location along the X-Y section to provide a first-order restoration of Japan Sea opening (~500 km is the average opening distance of the Japan islands during Japan Sea opening in the Miocene). We note the easternmost NE Asian area (Japan, Korea, and Sikhote-Alin) shows a 160–140 Ma magmatic quiescence that is supported by the detrital zircon age spectrum of sedimentary rocks within Japan and Korea (Lee et al., 2018; Pastor-Galán et al., 2021). b) Histogram of zircon U—Pb ages of late Jurassic to Cretaceous igneous rocks in NE Asia. At ~110 Ma, igneous activity moved eastwards from NE China towards easternmost NE Asia. c) Age vs CI chondrite value normalized La/Yb ratios plot highlighting adakitic signatures of some Cretaceous igneous rocks. d) K_2O vs SiO_2 plot of Early Cretaceous igneous rocks within easternmost NE Asia. Points are color-coded to show rocks with and without adakitic signatures.

et al., 2017; Wu and Wu, 2019). We also created a statistics histogram with the complied U—Pb zircon ages of igneous rocks from NE China, Japan, Korea, and Sikhote-Alin separately, to reveal the spatiotemporal evolution and intensity of the late Jurassic to Cretaceous magmatic activity in NE Asia (Fig. 3b). We herein call the areas of Sikhote-Alin, Japan, and Korea as 'easternmost NE Asia'. We will contrast these areas to 'NE China', which includes the areas within the North China craton.

Mesozoic igneous activity along NE China migrated >1000 km inboard (i.e. westwards) during the Jurassic followed by a > 1000 km migration outboard (i.e. eastward) during the Early Cretaceous (Fig. 3a) (Liu et al., 2019; Wang et al., 2006; Wu et al., 2019). This was followed by a 132–120 Ma magmatic flare-up (Fig. 3b) (Li et al., 2017; Liu et al., 2019; Wu et al., 2005; Zhang et al., 2014). We newly show that the NE China outboard migration of magmatism during the Early Cretaceous occurred co-eval to extensive magmatism along easternmost NE Asia (i.e. Sikhote-Alin, Japan, and Korea) (Fig. 3a, b and Appendix1). The outboard migration ended ~110 Ma when the majority of igneous activity moved eastward from NE China to easternmost NE Asia (Fig. 3b). Before the 160–140 Ma outboard migration, NE China magmatism was continuous, whereas the easternmost NE Asian margin shows a clear 160–140 Ma gap in igneous activity (Fig. 3a). The 160 to 140 Ma magmatic quiescence has been noted in previous studies (Zhai et al., 2016), and is further supported by a hiatus in U—Pb detrital zircon ages in Japan and Korea sedimentary basins that confirm very limited igneous activity during this time (Lee et al., 2018; Pastor-Galán et al., 2021). After the 160–140 Ma magmatic quiescence, Early Cretaceous magmatism within easternmost NE Asia shows dominant high-K calc-alkaline and calc-alkaline signatures (Fig. 3d). Some of the Early Cretaceous-aged magmatism in NE Asia show typical arc-related chemical signatures (i.e. derived from slab-fluid saturated mantle source with crustal contamination) (Chen et al., 2004; Jahn et al., 2015; Osozawa et al., 2019). In contrast, other igneous rocks with adakitic signatures formed within both NE China and easternmost NE Asia (Figs. 3c, 4a). These adakites can be sub-divided into two adakite suites that show contrasting isotopic signatures (e.g. Fig. 4d, e), and are discussed in more detail in the following section.

3.2. *Adakitic magmatism*

Adakitic rocks are intermediate to felsic igneous rocks that are geochemically defined by high Sr/Y and La/Yb ratios, low Y and Yb (Defant and Drummond, 1990) and thought to be generated by partial melting of garnet-bearing basaltic rock or garnet-involved fractional crystallization. Previous studies have interpreted adakite petrogenesis to be meta-basic rock melting in a subduction zone (i.e. partial melting of a

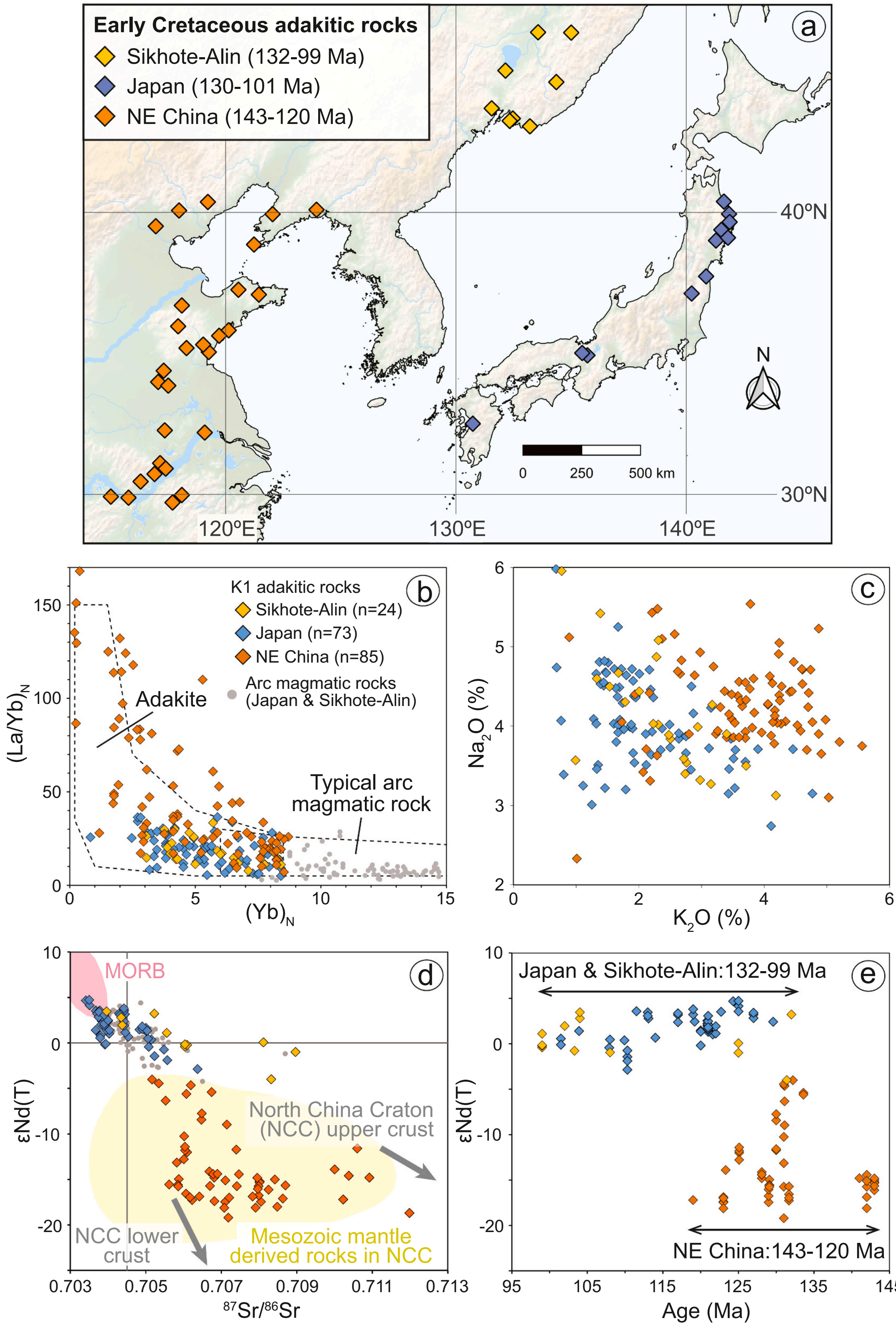


Fig. 4. Early Cretaceous adakitic rocks in NE Asia (See Appendix 2 for the database). a) Locations of adakitic rocks in Sikhote-Alin, Japan and NE China. b) CI chondrite value normalized La vs La/Yb diagram that distinguishes adakites and typical arc magmatic rock. c) K_2O vs Na_2O plot showing adakitic rocks in NE China are more enriched in K_2O than those in Japan and Sikhote-Alin. d) Nd—Sr isotope diagram for Early Cretaceous-aged adakitic rocks in NE China, Japan, and Sikhote-Alin. The plot differentiates two contrasting adakitic suites within NE Asia that are located within NE China, and within Japan and Sikhote-Alin. e) Igneous rock age vs whole-rock Nd isotope diagram. The 132–99 Ma adakites in Japan and Sikhote-Alin are more depleted in Nd isotopic composition compared to 143–120 Ma adakites in NE China.

subducted oceanic lithosphere), melting of thickened, mafic-composition lower crust at depths greater than 10–12 kbar, or fractional crystallization of amphibole/garnet from a basaltic magma at about 5–6 kbar (Castillo, 2012; Moyen, 2009). Since this is the case, the interpretation that adakites signify melted oceanic crust (i.e. slabs) has been viewed with increasing caution (e.g. (Castillo, 2012; Moyen, 2009; Ribeiro et al., 2016). Nonetheless, some adakites could be generated during specific tectonic events, including arc collision, ridge subduction, and slab break-off, if the ocean crust is melting within the garnet stability field (Castillo, 2012). Here we discuss the petrogenesis of adakitic rocks along the Eurasian margin in detail, since at least two adakitic suites have been previously identified and shown to have possible plate tectonic significance (e.g. Gu et al., 2013; Wu et al., 2017).

A group of easternmost NE Asian igneous rocks (i.e. Japan and Sikhote-Alin, Russian Far East) with ages 132–99 Ma show adakitic signatures (purple and yellow diamonds in Fig. 4 and Appendix 2) (Imaoka et al., 2014; Kamei, 2004; Kamei and Takagi, 2003; Osozawa et al., 2019; Tsuchiya and Kanisawa, 1994; Tsuchiya et al., 2007; Tsuchiya et al., 2012; Wu et al., 2017). A second suite of 143–120 Ma adakitic rocks are widespread in NE China, far to the west of the 132–99 Ma easternmost NE Asian adakites (orange diamonds in Fig. 4; Appendix 2) (Gu et al., 2013; Liu et al., 2010; Ma et al., 2016b; Wang et al., 2007; Xu et al., 2006). The two Early Cretaceous adakitic magmatism episodes show contrasting geochemistry (Fig. 4): the 132–99 Ma adakitic rocks in Japan and Sikhote-Alin show lower potassium concentrations and more depleted Nd—Sr isotopic compositions (Average $K_2O = 2.9$ wt%; εNd(t) $= -4.0$ to 4.7; $(^{87}Sr/^{86}Sr)_0 = 0.7034$ to 0.7090), compared to the 145–120 Ma adakitic rocks in NE China, which have high potassium and enriched isotopic composition (Average $K_2O = 3.8$ wt%; εNd(t) $= -20$ to -4; $(^{87}Sr/^{86}Sr)_0 = 0.7052$ to 0.7120) (Fig. 4c–e).

The K-rich adakitic rocks in NE China with ages 143–120 Ma are generally thought to be derived from the partial melting of the lower crust of the NCC during the destruction of the craton lithosphere (Gu et al., 2013; Liu et al., 2012; Ma et al., 2016b). In contrast, the origin of the 132–99 Ma adakites in easternmost NE Asia (Japan and Sikhote-Alin) is less clear. Some adakites can be explained by differentiation within the garnet stability field (Macpherson et al., 2006) where rocks with typical adakitic signatures (high La/Yb, Sr/Y) evolve from a basaltic precursor generated from a fluid-modified mantle. In such a case, the adakites would have a strong positive correlation between SiO_2 and the adakitic signatures, and lower Na_2O, higher K_2O, and similar or more enriched Nd isotopic composition than the basaltic precursor. The easternmost NE Asia 132–99 Ma adakitic rocks, however, have more depleted Nd isotopic compositions and higher Na_2O than the contemporaneous mafic rocks (Tsuchiya and Kanisawa, 1994; Wu et al., 2017). Moreover, there is no significant correlation between the SiO_2 and adakitic signature of the rocks (Wu et al., 2017). Thus, it seems that the 132–99 Ma adakitic rocks were probably not differentiated from mantle-derived mafic magmas.

The easternmost NE Asia overriding plate had an insufficient crustal thickness to produce depths and pressures to stabilize a significant amount of garnet in the lower crust; therefore, lower crustal melting is also an unlikely mechanism to explain the adakites. The present Moho depth in NE Asian margin is 30–35 km in north Japan and 30–40 km in Sikhote-Alin, (Matsubara et al., 2017; Nevstruyev and Kozlova, 2018). During the Early Cretaceous times, the accretionary complex would have been younger and thinner than the present (30 to 40 km). This thin, juvenile crust would be inadequate to generate adakitic magma through its garnet stability field, even if the lower crust was partially melted (Tsuchiya et al., 2007). As well, previous studies have noted the trace element composition of the adakitic rocks shows a fit when modeled as a mixed source by MORB and minor subduction sediments with mantle contamination (Tsuchiya et al., 2007; Tsuchiya et al., 2005). Thus, we prefer to interpret the source region of the adakites to be a subducting oceanic slab. This interpretation also fits with their spatial extent along a former subduction zone at the outer Eurasian continental margin (Fig. 4a). We will further discuss the thermal mechanism that induced oceanic slab melting resulting in the 132–99 Ma adakitic magmatism in easternmost NE Asia (see Section 4.4).

4. Evidence for Early Cretaceous intra-oceanic arc accretion along the NE Asian continental margin from sedimentary records and paleomagnetism

4.1. SW Japan

In SW Japan, subduction-accretion processes during the Cretaceous are mainly recorded within the Sambagawa metamorphic belt and the Northern Shimanto belt (Fig. 4) (Aoki et al., 2019; Taira, 1988). The Sambagawa belt is an early to middle Cretaceous accretionary complex that experienced metamorphic conditions up to eclogite facies (Aoki et al., 2009; Okamoto et al., 2000). According to Aoki et al. (2019), three eclogite-facies units with different accretion ages have been identified in the Sambagawa belt (Fig. 4): The Besshi unit with accretion ages of ~130 Ma (Okamoto et al., 2000; Okamoto et al., 2004), the Asemi-gawa unit with accretion ages 100–90 Ma (Aoki et al., 2019), and the Oboke unit that has protolith accreted after 95–90 Ma (Endo et al., 2018).

Strong deformation of mafic metamorphic rocks like those in the Sambagawa belt can obliterate the original mineralogy and texture of the rocks, creating challenges for determining their petrogenesis. To resolve the difficulty, previous studies have looked into the age and geochemistry of the core and rim domains of zircons in the Besshi unit. Aoki and others considered the 120–90 Ma zircon rim domain with metamorphic origin as a record of strong metamorphism, and the 200–180 Ma zircon core domain were from an igneous rock-origin protolith that showed oceanic arc-like zircon geochemistry (Aoki et al., 2020a; Aoki et al., 2020b). The protolith of the Besshi unit accreted to the margin around 130–120 Ma, constrained by 120–110 Ma peak metamorphic U—Pb ages in the zircon rim domain, and by late Jurassic to Early Cretaceous protolith ages determined by fossil ages and 148–134 Ma U-Pb ages from the core domain of zircons in quartz-rich rocks (Isozaki and Itaya, 1990; Okamoto et al., 2004).

The eclogites and garnet amphibolites of the Besshi unit may be the lower crustal portion of an oceanic island arc, based on evidence for crystallization under oxygen-enriched and hydrous conditions (Utsunomiya et al., 2011). In contrast, the Asemi-gawa and Oboke units show MORB-origin chemical compositions (Fig. 7) (Endo et al., 2018; Nozaki et al., 2006) and have been interpreted to be fragments of typical subducted oceanic crust that accreted at ~100 to 80 Ma (Fig. 6b). Therefore, the geology of the Sambagawa belt in SW Japan shows an ocean island arc accretion along SW Japan at ~130 Ma, followed by accretion of typical oceanic crustal fragments at 100–90 Ma.

4.2. NE Japan

The Cretaceous accretionary complex of the Japan arc-trench system extends northwards into western Hokkaido, and includes the Idonnappu, Sorachi-Yenzo, and Rebun-Kabato belts (Fig. 8) (Ueda, 2016). The Oku-Niikappu complex within the Idonnappu belt is a mid-Cretaceous accretionary complex (Fig. 8) (Kiyokawa, 1992). Here, late Jurassic volcanic rocks show island arc geochemical characteristics (Fig. 7b) (Ueda and Miyashita, 2005). These are interpreted to be a fragment of an island arc that accreted during the mid-Cretaceous (Ueda and Miyashita, 2005). Contemporaneous volcanic breccia of Hachimoriyama Tuff Member in the adjacent Sorachi-Yenzo belt also shows arc-related geochemical signatures (Takashima et al., 2002, 2006), further supporting an island arc origin. The mid-Cretaceous (~100 Ma) accretion time of the island arc was constrained by ages of the siliciclastic trench-filled turbidites that sit stratigraphically above the island-arc volcanic unit (Ueda and Miyashita, 2005). The subduction polarity of the island arc system was probably west-dipping, since the accretionary complexes in the Idonnappu belt display an overall eastwards-

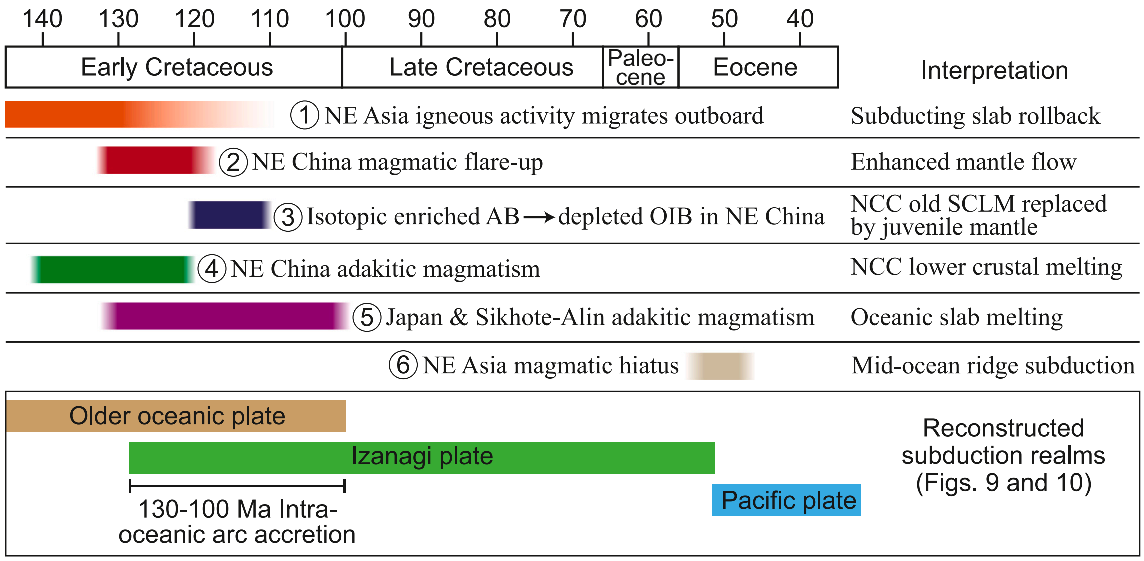


Fig. 5. Cretaceous to early Cenozoic igneous activity and tectonics within the NE Asian active margin and reconstructed subduction realms from our reconstruction model (See Figs. 9 and 10 for details). AB – arc basalt, OIB – ocean island basalt (intra-plate basalt), NCC – North China craton, SCLM – sub-continental lithospheric mantle. References for the igneous events and tectonic interpretation: Event 1 (Jing et al., 2021; Wu et al., 2019; Zhang et al., 2014); see also Figs. 3a, b); Event 2 (Liu et al., 2019; Wu et al., 2005; Zhang et al., 2014)); Event 3 (Dai et al., 2016; Liu et al., 2019; Zheng et al., 2018)); Event 4 (Gu et al., 2013; Liu et al., 2010; Ma et al., 2016b; Wang et al., 2007; Xu et al., 2006); see also Fig. 4); Event 5 (Kamei, 2004; Kamei and Takagi, 2003; Osozawa et al., 2019; Tsuchiya and Kanisawa, 1994; Tsuchiya et al., 2007; Tsuchiya et al., 2012; Wu et al., 2017); see also Fig. 4); Event 6 (Kimura et al., 2019; Wu and Wu, 2019).

younging arrangement (Fig. 8) (Ueda, 2001). In summary, NE Japan ophiolite sequences are incompatible with Andean-style subduction models (Fig. 2a), and instead, show a record of island arc accretion during mid-Cretaceous times around ~100 Ma that is more consistent with intra-oceanic subduction models (Fig. 2b).

4.3. Sikhote-Alin (Russian Far East)

In the southernmost of the Russian Far East, the Sikhote-Alin orogenic belt consists of several Mesozoic-aged, accreted oceanic terranes, with the last stage of amalgamation involving accretion of an Early Cretaceous island arc during the mid-Cretaceous (i.e. late Albian) (Khanchuk et al., 2016). The island arc system, sometimes known as the Moneron–Samarga island arc, includes the Early Cretaceous Kema and Kesilevka-Manoma terranes in the Sikhote-Alin (Fig. 6); these are considered to be the back-arc basin and accretionary prism, respectively (Malinovsky, 2010; Malinovsky et al., 2006; Simanenko et al., 2011). Some also considered the Rebun-Kabato belt as the volcanic arc of the Moneron–Samarga island arc (Simanenko et al., 2011), while others suggested that the belt was the arc volcanics erupted on the accretionary complex of continental margin (Kiminami, 1986; Taira et al., 2016). Other models suggest that the Kiselevka-Manoma and Kema terranes represent different oceanic arc systems (Arkhipov et al., 2019). Regardless, the island arc origin of these terranes is supported by Early Cretaceous volcanic rock chemical compositions that show arc-related signatures (Fig. 7a) (Arkhipov et al., 2019; Malinovsky et al., 2008; Simanenko et al., 2011). It is considered that the Kiselevka-Manoma terranes accreted during the late Aptian to middle Albian (~110 Ma) based on the age of trench fill sediments within the terrane (Fig. 8) (Zyabrev, 2011). Clastic rocks in the Kema terrane have heterogeneous sources including volcanic island arc and minor continental crust material, which suggest that a back-arc basin setting for the terrane (Malinovsky and Markevich, 2007). Importantly, this implies the Kema island arc was not very far offshore from the continental margin, perhaps within 1000 km of the continent, consistent with typical turbidite fan transport distances (Shanmugam, 2016). In summary, Sikhote-Alin geology is incompatible with straightforward Andean-style subduction (Fig. 2b) and instead requires accretion of active island arcs (Kiselevka-Manoma and Kema terranes) to eastern Eurasia around the mid-Cretaceous ~100 Ma or slightly earlier. There is some evidence that the island arcs were not far removed from the eastern Eurasian margin (e.g. intra-oceanic model shown in Fig. 2b) based on continent-derived clastics within the Kema terrane.

4.4. Timing of intra-oceanic arc accretions and potential link to adakitic magmatism

The Kiselevka-Manoma and Oku-Niikappu island arcs likely accreted at ~110 Ma and ~ 100 Ma, respectively, based on the ages of continental-derived clastics identified as trench fill sediments that overlie pelagic sediments within the accretionary units (Matsuda and Isozaki, 1991) (Arkhipov et al., 2019; Ueda and Miyashita, 2005). The accretion time for island arc-origin Besshi unit in the Sambagawa belt is 130–120 Ma, constrained by peak metamorphic U—Pb ages and protolith U—Pb ages from zircon rims and cores, respectively (Okamoto et al., 2004). Thus, Early Cretaceous geological records in Japan and Sikhote-Alin area reveal a relatively widespread accretion of late Jurassic to Early Cretaceous-aged intra-oceanic arcs to the East Asian continental margin within the period 130–100 Ma (Figs. 5, 7).

As previously mentioned, there are multiple sources of Early Cretaceous igneous activity along the NE Asian margin including 132–99 Ma adakitic magmatism derived from subducting oceanic slab (Fig. 3c–d and Fig. 4). This adakitic magmatism has been formerly linked to the ridge-trench intersection of a mid-ocean with the continental margin (Tsuchiya and Kanisawa, 1994), or slab rollback after flat subduction (Yan et al., 2015). Indeed, oceanic slab-derived adakitic melt can be generated during subduction rollback (Kincaid and Griffiths, 2003). However, considering that the 140–110 Ma period of slab rollback does not precisely overlap with the 132–99 Ma adakitic magmatism at easternmost NE Asia (event 1and 5in Fig. 5), some of the younger adakites (<110 Ma) are unlikely to be generated by slab rollback. We also do not prefer a scenario where the 132–99 Ma adakites were generated from the ridge-trench intersection (Osozawa et al., 2019; Tsuchiya and Kanisawa, 1994). A previous study indicated that the subducting oceanic crustal ages in the Hokkaido area during the Jurassic to Early Cretaceous was 150–200 Myrs old (Ueda and Miyashita, 2005). These

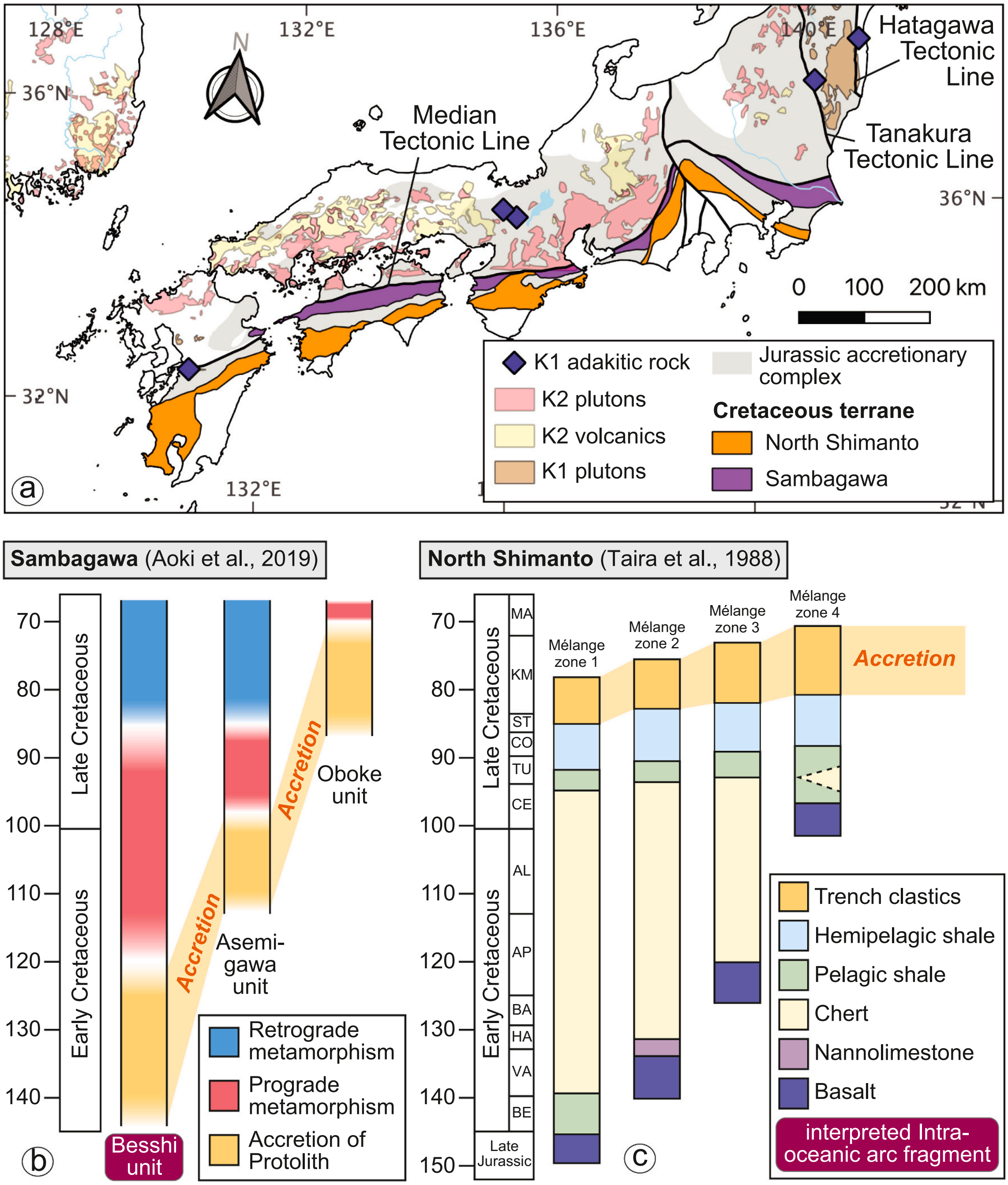


Fig. 6. Cretaceous geological framework of SW Japan. a) Surface geological map of SW Japan. b) Geological units in the Sambagawa metamorphic belt. c) Geological units in the North Shimanto belt. The Besshi unit in the Sambagawa belt is interpreted as an ocean island arc that accreted to the continental margin at ~130 Ma.

very old ages seem to exclude the possibility of an active mid-ocean ridge offshore of the East Asian margin during the Early Cretaceous, since an active ridge near the trench would generate a much younger oceanic crust.

Instead, we observe that the 132–99 Ma adakitic magmatism was relatively coeval with the 130–100 Ma intra-oceanic arc accretion (Fig. 7). We therefore link the 132–99 Ma adakites to slab melting that was induced by enhanced mantle flow within the wedge, under a tectonic setting that includes both intra-oceanic arc accretion and slab rollback in the Early Cretaceous. Adakites have been found in other arc accretion/collision settings in Tibet, Philippine, and the Solomon Islands (Gao et al., 2007; König et al., 2007; Sajona et al., 1996) and have been linked to sinking oceanic slabs after they were fully consumed following arc accretion. Although the detailed mantle thermal evolution under an arc accretion setting has not been fully explored, some suggest that the detachment of a sinking slab may lead to partial melting of the slab surface (Gao et al., 2007).

5. Discussion

We synthesize an alternative, intra-oceanic subduction-style plate tectonic setting of the NE Asian margin that spans NE China, Japan, Korea, and southern Sikhote-Alin. We do not attempt to build a fully-kinematic plate tectonic reconstruction due to the considerable challenge of spatiotemporally restoring Eurasian continental deformation; thousands of kilometers of subducted oceanic plates; ancient intra-oceanic subduction zone positionings; and, plate kinematics without seafloor or paleomagnetic constraints. Instead, we reconstruct the NE

Table 1
Published paleolatitudes of Early Cretaceous terranes within NE Asia (Arkhipov et al., 2019; Abrajevitch et al., 2012; Uno et al., 2011).

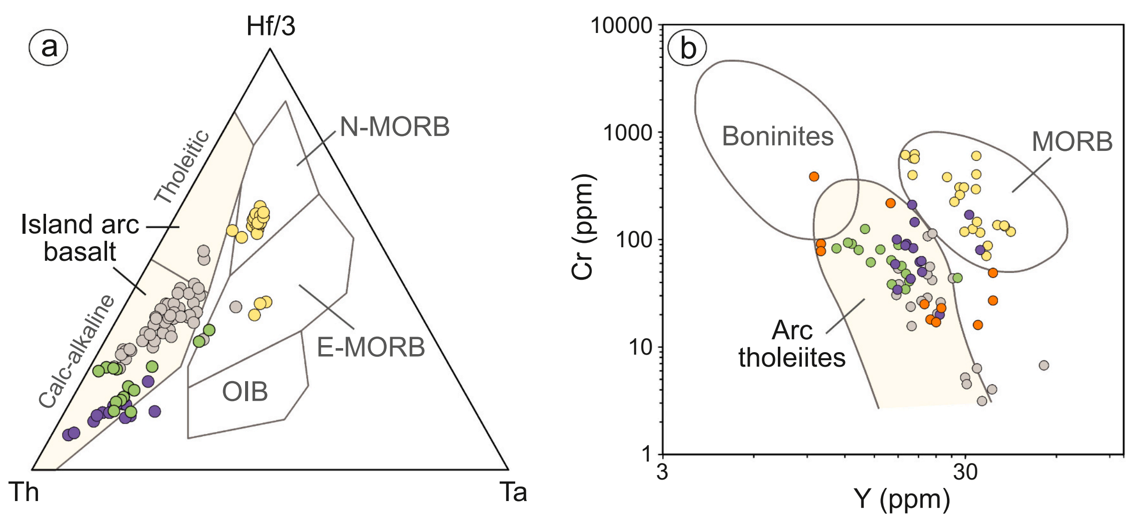
Geological unit	Present latitude	Paleolatitude	Sample age
Kiselevka-Manoma	52.1 °N	33 ± 5°N	Albian-Cenomanian (113–94 Ma)
Kema	45.7°N	36 ± 6°N	Albian (113–100 Ma)
West Sakhalin	47.3°N	28 ± 5°N	Early Albian (~110 Ma)
SW Kyushu	32.3°N	18 ± 3°N	Aptian-Albian (125–100 Ma)

Asian margin during three key time windows in the mid-Cretaceous (Figs. 9, 10), building from a composite of published models (described next). We then reconstruct the timing of possible intra-oceanic arc accretion events and their associated plate tectonics, taking an approach of implementing the most straightforward solution (i.e. Occam's razor). Finally, we discuss the implications of our newly synthesized plate tectonic setting against current models of North China craton destruction.

5.1. Plate tectonic reconstruction of the NE Asian margin during the Early Cretaceous: A synthesis

5.1.1. Restoring the Eurasian continental margin

Reconstructions of the NE Asia Eurasian continental margin are controversial, especially before the Japan Sea opening (Jolivet et al., 1994; Kim et al., 2007; Otofuji, 1996; Otsuki, 1990; Van Horne et al., 2017; Yamakita and Otoh, 2000). We close the Japan Sea and reconstruct left-lateral strike-slip faulting along the Eurasian margin by creating a composite of two published models (Fig. 9b): a model for Sikhote-Alin (Kemkin, 2008), and the Yamakita and Otoh (2000) model for Japan. Our reconstruction of Cretaceous geology in NE China follows Wu et al. (2019) and Zhu et al. (2012a). During the Cretaceous, NE China was under crustal extension (Zhu et al., 2012a), as shown by the blue faults in Fig. 9a and b. Our synthesized plate model reconstructs a throughgoing, left-lateral strike-slip fault system along the East Asian margin that connects the Median Tectonic Line in Japan (Fig. 6) with the Central Sikhote-Alin fault to the north (Fig. 8). In our model, left-lateral strike-slip motions produce a limited northward translation of some geological units along the outboard Eurasian margin during the Cretaceous, including the Sambagawa belt (SW Japan), the north and south Kitakami terrane (NE Japan), and the Zhuravlevka terrane (Sikhote-Alin). These limited northward motions may explain some of the paleolatitudes of SW Kyushu, Kiselevka-Manoma, Kema, and West Sakhalin terranes, which were between 9° to 19° further south in the latest Early Cretaceous relative to present (Table 1) (Abrajevitch et al., 2012; Arkhipov et al., 2019; Uno et al., 2011). Evidence from radiolarians also suggests that Hokkaido was located at the sub-tropical or tropical area in the late Jurassic, with a paleolatitude lower than 25° N (Matsuoka, 1996). The Sambagawa belt in Japan restores as an accretionary prism along the Eurasian margin in the mid-Cretaceous (Fig. 9b).



ⓒ **Mafic rocks within Early Cretaceous terranes**

	Geological unit	Accretion time	Geochemistry	Reference
(green)	Kiselevka-Manoma	~110 Ma	Island arc	Arkhipov et al. (2019)
(purple)	Kema	~110 Ma	Island arc	Malinovsky et al. (2008)
(grey)	Rebun-Kabato	~110 Ma	Island arc	Simanenko et al. (2011)
(orange)	Oku-Niikappu complex / Idonnappu	~100 Ma	Island arc	Ueda et al. (2005)
	Besshi unit / Sambagawa	~130 Ma	Island arc (zircon chem.)	Aoki et al. (2019, 2020)
(yellow)	Asemi-gawa unit / Sambagawa	~90 Ma	MORB	Nozaki et al. (2006)

Fig. 7. Mafic rocks with arc affinities in Early Cretaceous-aged accretionary terranes along NE Asia, and their accretion times. a) Whole-rock Hf-Th-Ta ternary diagram (Wood, 1980). b) Whole-rock Y vs Cr diagram (Pearce et al., 1981). c) shows a legend for the color-coded data points in a), b) and timing of intra-oceanic arc accretion. The island arc origin of the eclogites from the Besshi unit in the Sambagawa belt was determined by zircon geochemistry (Aoki et al., 2020a; Aoki et al., 2020b). Accretion time for the Besshi unit is constrained by peak metamorphic U—Pb ages and protolith U—Pb ages from zircon rim and core domains, respectively. For the rest of the geological units, the accretion time was constrained using the age of continental-derived clastics that were identified as trench-filled sediments overlying the pelagic sediments (Arkhipov et al., 2019; Ueda and Miyashita, 2005). In general, the ocean island arc terranes accreted to the Eurasian continental margin along NE Asia during the Early Cretaceous 130 to 100 Ma.

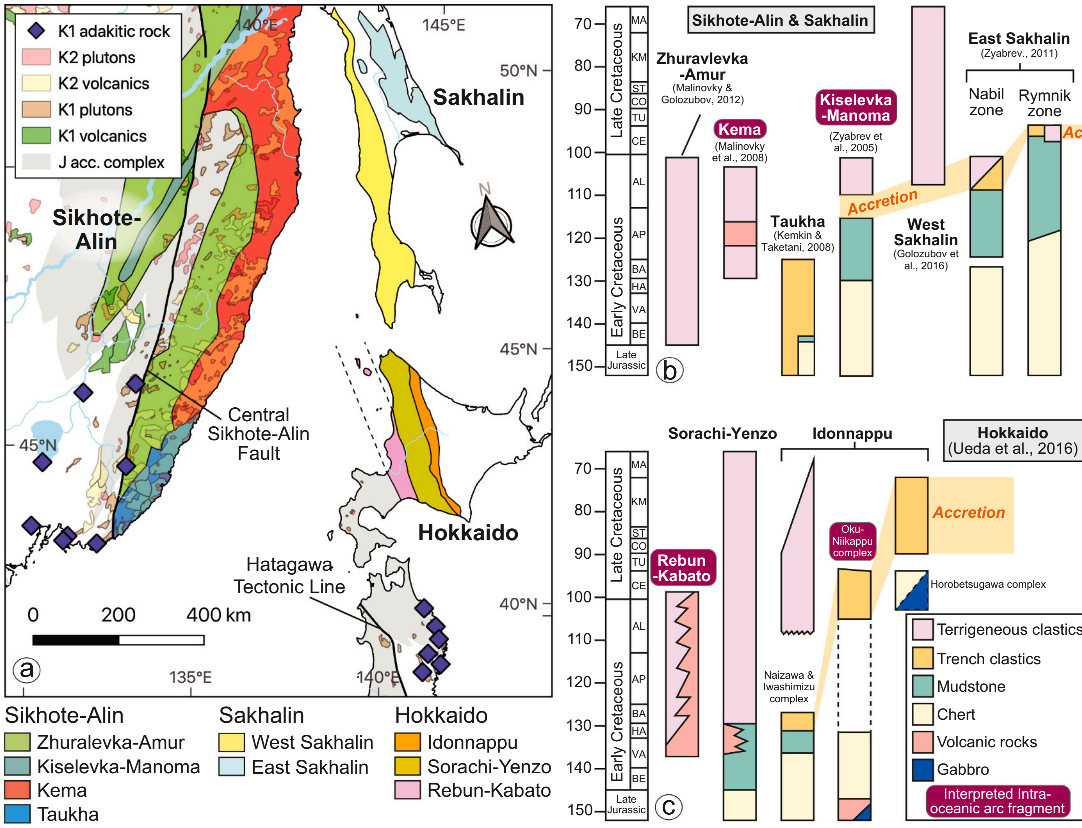


Fig. 8. Cretaceous geological framework of NE Japan, Sakhalin, and Sikhote-Alin, Russian Far East. a) Surface geological map; b) Geological units in Sikhote-Alin & Sakhalin; (c) Geological units in Hokkaido, NE Japan. In general, the geology of these areas shows accretion of oceanic arcs between ~115 to 100 Ma.

5.1.2. *Reconstructed NW Pacific basin plate tectonics during the early cretaceous*

According to the compiled igneous activity, stratigraphy, and paleomagnetism evidence in NE Asia, and following an approach to implement the least-complex solution, we reconstruct the most likely plate tectonic boundary conditions within the oceanic realms (Figs.9, 10). We make the following choices:

(1) We follow the Hokkaido accreted ocean plate stratigraphy of Ueda and Miyashita (2005) and reconstruct Izanagi plate subduction from the mid-Cretaceous (~100 Ma) to early Cenozoic based on the accreted oceanic crust of progressively younger ages Ueda and Miyashita (2005) and evidence for Izanagi-Pacific ridge subduction between 56 and 46 Ma (Wu and Wu, 2019).

(2) We reconstruct our intra-oceanic arc accretions during the Early Cretaceous (see Section 4.4) by invoking a 'marginal sea plate' (e. g. Fig. 9b) within the NW Pacific basin, outboard of the Eurasian margin. Hokkaido ocean plate stratigraphy supports our inferred marginal sea along NE Asia during the Early Cretaceous and indicates that the marginal sea was probably formed of older oceanic crust (>100 Myr ages) (cf. Ueda and Miyashita, 2005). Such intra-oceanic subduction within the NW Pacific basin has been suggested by previous studies (e.g. Ueda and Miyashita, 2005; van der Meer et al., 2012).

(3) We reconstruct the intra-oceanic arcs that were later accreted to the Eurasian margin by invoking a convergent plate boundary between the 'marginal sea plate' and the Izanagi plate as a convergent plate boundary. We choose a westward subduction polarity (Fig. 10b) with the acknowledgment that reconstructing subduction polarities of intra-oceanic arcs is challenging.

(4) We reconstruct the intra-oceanic arc-trench system of (2) and (3) above within a minimum latitude range of 15°N to 42° N based on published paleolatitudes (Table 1). This places our restored intra-oceanic arcs between the latitudes of South China and southern Sikhote-Alin, which effectively spans the entire range of our plate reconstructions (Figs. 9, 10).

(5) The intra-oceanic subduction zone plate boundary between the marginal sea plate and the Izanagi plate in (2) and (3) was reconstructed as a single, curved subduction zone to accommodate a diachronous 130–100 intra-oceanic arc accretion time-frame (see Section 4.4, Fig. 7c). Other more complex solutions are certainly possible, but we choose this scenario in line with our approach to reconstruct the most straightforward solution.

Following the assumptions above, we interpret a late Jurassic to middle Cretaceous plate tectonic evolution model for the NW Pacific basin and NE Asia, as follows (Figs. 9 and 10): (1) From 160 to 140 Ma (Fig. 8a), a marginal sea plate subducted beneath the Eurasian continent. We follow Wu et al. (2019) and interpret the inboard and outboard migration of magmatism (Fig. 3a) to be a result of flat subduction followed by slab rollback; our model indicates that the subducting slab was not Izanagi, but would has been a marginal sea; (2) From 140 to 125 Ma (Fig. 10b), two co-eval arc-trench systems existed along East Asia; these included the Eurasian continental arc system and an intra-oceanic arc formed by Izanagi plate subduction beneath the marginal sea plate that kept rolling backward. We move the intra-oceanic arc system westward in order to reconstruct its accretion to the Eurasia continent, which results in the closure of the marginal sea (Fig. 10b). Destruction of the lower NCC lithosphere occurred during this period (Fig. 10b). The 145–120 Ma K-rich adakitic rocks in NE China were generated by partial melting of North China craton lower crust (orange diamonds in Fig. 4); (3) From 130 to 100 Ma, the marginal sea fully closed and the intra-oceanic arc system(s) accreted to the Eurasian continental margin (Figs. 7, 9b, 10b, and c). The outboard migration of NE Asia igneous

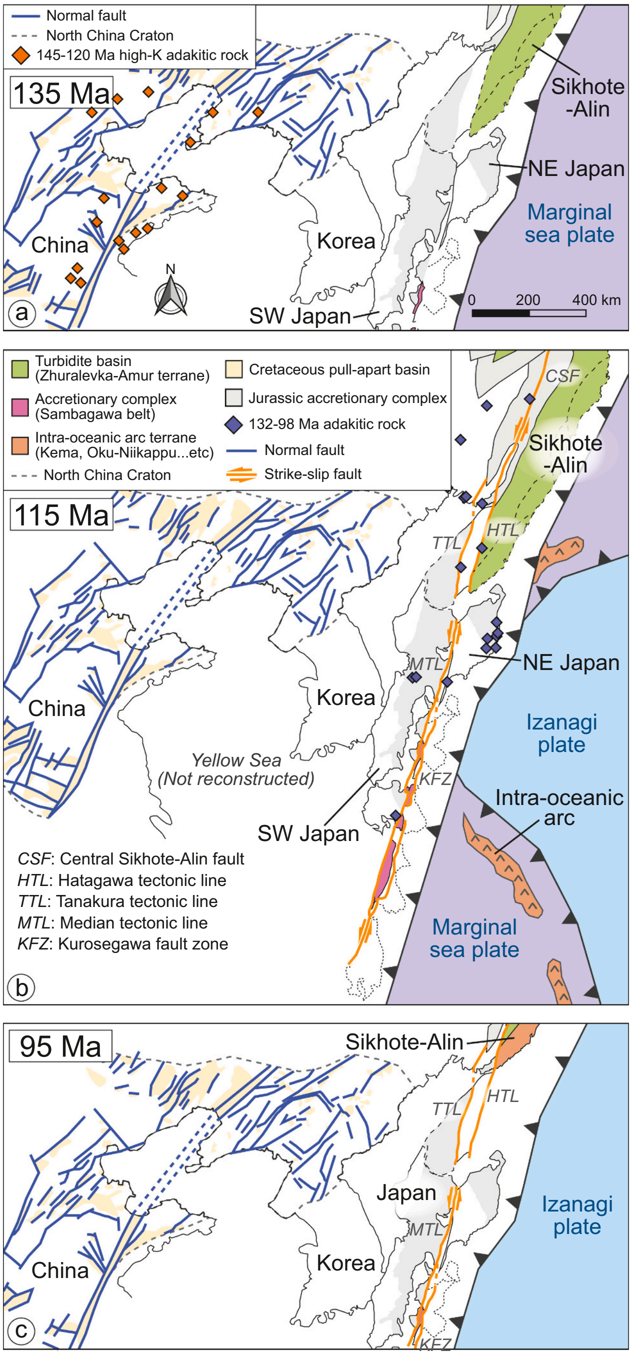


Fig. 9. Plate tectonic reconstructions of NE Asia during the Cretaceous synthesized from this study for the time periods: a) 135 Ma, b) 115 Ma, and c) 95 Ma. The Eurasian margin was reconstructed by building a composite from various published studies (Kemkin, 2008; Wu et al., 2018; Yamakita and Otoh, 2000; Zhu et al., 2012a, 2012b). We follow an approach to produce the most straightforward reconstruction for the oceanic realm and synthesize a single, curved intra-oceanic arc-trench system between a marginal sea plate and the Izanagi plate that diachronously accretes to Eurasia between 130 and 100 Ma. More complex reconstructions are possible that could include multiple intra-oceanic arcs and other oceanic plates. It may also be possible to reconstruct the intra-oceanic subduction zone with an opposite polarity (i.e. seaward-dipping). Regardless, it is important to note the 130 to 100 Ma arc accretion timings along NE Asia overlap with the timing of the outboard adakites (purple and yellow diamonds), which we suggest were formed from oceanic slab melting. CSF – Central Sikhote-Alin fault; HTL – Hatagawa tectonic line; KFZ – Kurosegawa fault zone; MTL – Median tectonic line; TTL – Tanakura tectonic line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

activity ended ~110 Ma (Figs. 3a, b) during this period. The adakitic magmatism in Japan and Sikhote-Alin with 132–99 Ma ages (purple and yellow diamonds in Fig. 4) were generated by oceanic slab melting following their temporal correlation to intra-oceanic arc accretion (and possible subduction) (see 4.4).

Although the schematic plate tectonic model (Figs. 9, 10) shows only the most straightforward solution, a single intra-oceanic arc-trench along East Asia during the Early Cretaceous, we acknowledge that constraints for the latest accretion time of the intra-oceanic arc fragments show a wide range, from 130 to 100 Ma (Table 1). Within these constraints, alternative scenarios involving accretion of multiple arc-trench systems and marginal seas (Li et al., 2018) similar to Cenozoic SE Asia (Hall, 2012; Pubellier et al., 2004; Wu et al., 2016) could be possible. It may also be possible to invoke an opposite (i.e. seaward-dipping) subduction polarity for the intra-oceanic subduction zone. Under a more complex scenario with multiple oceanic plates, some of the 132–99 Ma adakitic rocks (purple and yellow diamonds in Fig. 4) could be generated by collisions between intra-oceanic arcs (Sajona et al., 2000). Regardless of plate tectonic complexities, any reconstructed scenario would imply a 130–100 Ma reorganization in plate tectonic boundary conditions along the NE Asian margin that is more complex than depicted in popular Andean-style subduction models (Fig. 2a).

5.1.3. Philippine Sea and western Pacific modern analog

The present Philippine Sea plate and western Pacific subduction systems along East Asia (Appendix 3) shows the importance of recognizing the more complex plate tectonic boundary conditions envisioned in our Early Cretaceous plate reconstruction along NE Asia (Figs. 10,11). North of the Japan trench-trench-trench triple junction (TTT), a relatively straightforward subduction system is formed by Andean-style subduction and a single mantle wedge (Appendix 3). The subducting Pacific oceanic lithosphere is older (>100 Ma) and colder (Appendix 3). In contrast, south of the Japan TTT, a more complex double subduction system is formed that includes the Pacific, a marginal sea (i.e. the Philippine Sea plate), and the Izu-Bonin-Marianas intra-oceanic subduction zone (Appendix 3). Recognition of the additional plate tectonic complexities south of the Japan TTT is critical for petrogenesis, since the subducting Philippine Sea oceanic lithosphere is significantly warmer and younger (<55 Ma) compared to the Pacific Ocean lithosphere. Furthermore, near the Japan TTT, overlap of the Pacific and Philippine Sea mantle wedges produces a mixing zone that shows elevated slab-derived fluid fluxes and variable magmatic compositions and geochemistry (Nakamura et al., 2008; Nakamura et al., 2019). Other petrological complexities are introduced by the collision of the Izu-Bonin intra-oceanic arc and Japan continental arc near the Japan TTT (Tamura et al., 2010). In the same way, a clearer recognition that NE Asian plate tectonics during Early Cretaceous times was more complex than generally recognized (e.g. Figs. 9, 10) may allow new details to emerge when these conditions are implemented into future regional tectonic and geodynamic models.

5.2. Implications for North China Craton destruction models

Recently proposed mechanisms for the NCC destruction typically consider continuous Izanagi /paleo-Pacific plate subduction under an Andean-type margin (Fig. 2a) (Liu et al., 2019; Wu et al., 2019; Zheng et al., 2018). In this study, we show that intra-oceanic arc(s) accreted along the NE Asian Eurasian margin during the Early Cretaceous 130–100 Ma (Fig. 7). These island arc accretions overlap with the peak of the North China craton destruction between 130 and 120 Ma (Dai et al., 2016; Liu et al., 2019; Ma et al., 2016a; Zheng et al., 2018). Therefore, NCC destruction models must be considered in the context of changing plate boundary conditions during Early Cretaceous times (Figs. 9, 10). In other words, published NCC destruction models that rely on straightforward Andean-style subduction (Fig. 2a) are likely

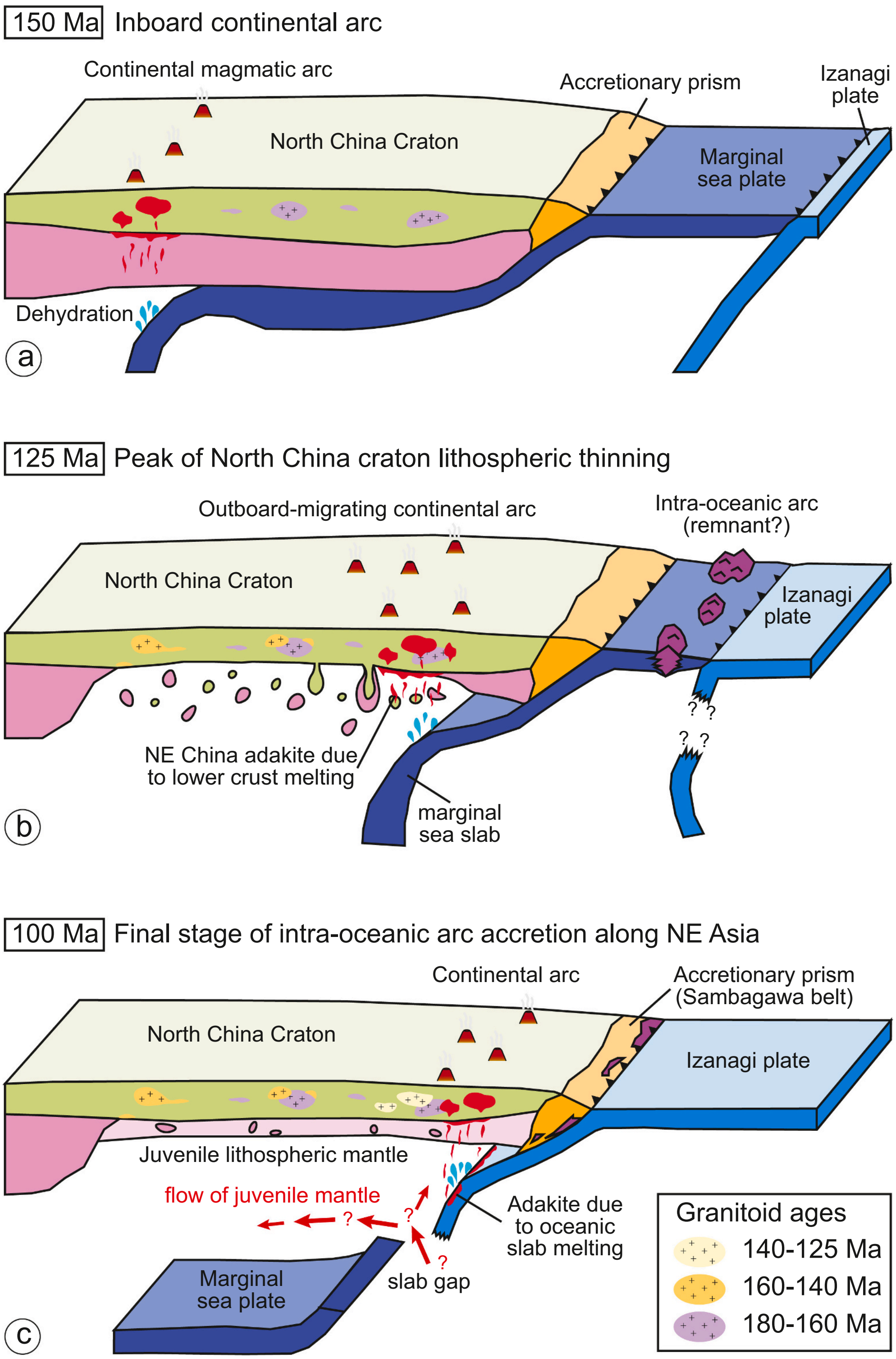


Fig. 10. Schematic tectonic evolution of NE Asia during the Early Cretaceous based on our Fig. 9 plate reconstruction at: a) 150 Ma, b) 125 Ma, and c) 100 Ma. In a), we reconstruct the subduction of a marginal sea plate. The continental arc has migrated inboard due to flat-slab subduction, following Wu et al. (2019). In b), the peak of North China craton lithospheric thinning occurred ~130 Ma, after the continental arc migrated outboard due to rollback of the marginal sea slab between ~150–135 Ma. An intra-oceanic arc approaches the Eurasian margin and diachronously accretes between 130 and 100 Ma, producing a plate boundary reorganization. c) shows the final stages of intra-oceanic arc accretion at 100 Ma. The Izanagi plate is now subducting along Eurasia. The former accretionary prism is metamorphosed and forms the Sambagawa belt, Japan. A possible slab gap formed during the plate reorganization allows new flow of juvenile mantle into the mantle wedge, which was formerly enriched. Granitoid magmatic intrusions are color-coded by age.

oversimplified.

Specifically, our results challenge NCC destruction models that rely on 'big mantle wedge'-style subduction with a stagnant slab (He, 2014; Li and Wang, 2018; Liu et al., 2019), since these models rely on continuous, long-lived subduction of a single plate beneath the Eurasian margin (e.g. Andean-style models in Fig. 2a). In contrast, our models suggest a more complex Early Cretaceous reorganization of the subduction zone, and possible slab detached occurred (Fig. 10). Some NCC destruction models invoke back-arc extension and rollback of the Izanagi plate relative to NE China to explain the outboard migration of continental arc magmatism during the Early Cretaceous (Zhu et al., 2012a). Such models may require revisions since our models indicate that the Izanagi plate was not subducting beneath the NE Asian margin before 130 Ma (Fig. 10), therefore, reconstructed East Asia-Izanagi convergence rates (Engebretson, 1985) should not be applied to geodynamic models of NCC destruction.

Moreover, the geodynamic evolution of the mantle beneath NE China is likely more complex than generally recognized if intra-oceanic arc accretion is considered. Details for the replacement of old NCC subcontinental lithospheric mantle (SCLM) by juvenile material at ~115 Ma (Event 3in Fig. 5) (Dai et al., 2016; Liu et al., 2019; Ma et al., 2016a; Zheng et al., 2018) remains controversial. Previously proposed ideas include: (1) mantle metasomatism with oceanic slab-derived adakitic melt (event 5in Fig. 5) (Zheng et al., 2018); and, (2) lateral filling of asthenospheric mantle induced by slab rollback (Event 1in Fig. 5) (Dai et al., 2016). Indeed, both of these mechanisms can replace the old NCC SCLM with juvenile mantle lithosphere. However, the juvenile adakitic melt is unlikely to have replaced the entire SCLM. On the other hand, the ~115 Ma SCLM replacement (Event 3in Fig. 5) started 20 Myrs after the beginning of slab rollback at 140 Ma (Event 1 in Fig. 5). Considering models of instantaneous return flow induced by slab rollback (Kincaid and Griffiths, 2003), the 20 Myrs delay seems too long for slab rollback to be the main mechanism. Instead, a double subduction system similar to Figs. 9, 10 can allow for sufficient exchange of asthenospheric mantle beneath the oceanic and continental crust by toroidal flow (Holt et al., 2017; Zhang et al., 2017), or by direct flow through a slab gap that forms after intra-oceanic arc accretion, when the marginal sea is fully subducted and breaks off (Fig. 10c). These mantle evolution scenarios beneath the NCC during its destruction should be further investigated by geodynamic modeling.

From the perspective of continental lithospheric evolution, the Early Cretaceous was a critical time for the growth of the modern Eurasian continental lithosphere along NE Asia. Juvenile mantle lithosphere was added beneath the eastern Eurasian continent during the Early Cretaceous and Archean mantle lithosphere was lost. Intra-oceanic arc(s) floored by juvenile lithosphere accreted along the NE Asian continental margin. Juvenile magmatism derived from partial melting of the oceanic slabs, newly linked here to intra-oceanic arc accretion (i.e. 132–99 Ma adakitic rocks with depleted isotopic composition, purple and yellow diamonds in Fig. 4d-e), was also emplaced along the NE Asian continental margin. It is reasonable to conclude that accretion of one or several intra-oceanic arcs during Early Cretaceous times along East Asia, as shown in this study, is a sufficiently large tectonic event to have induced the addition of juvenile material to the NE Asian lithosphere, either directly or indirectly. More work is needed to further investigate these links.

6. Conclusion

The accretion of intra-oceanic arcs along Japan, Sikhote-Alin, and the Russian Far East during 130–100 Ma is incompatible with popular Andean-style plate models of the NE Asian margin during Cretaceous times. Here we present an alternative NE Asia plate tectonic reconstruction during Cretaceous times that synthesizes available constraints on regional intra-oceanic arc accretions and timings. This model provides a more geologically plausible plate tectonic context for North China craton peak destruction and thinning ~125 Ma. During the Early Cretaceous, subduction boundary conditions along the eastern Eurasian continental margin were perturbed by the intra-oceanic arc accretion(s); subduction was not continuous. Slab melting during 132–99 Ma produced adakitic rocks that show depleted Nd—Sr isotopic compositions in Japan and Sikhote-Alin. Changes in mantle circulation due to the intra-oceanic arc accretion(s) and subduction zone reorganizations may have added juvenile mantle to the NE Asian continental lithosphere. Geodynamic models incorporating intra-oceanic subduction and additional plates may help to further understand the role of island arc accretion in cratonic lithosphere thinning, destruction, and evolution of the subcontinental lithospheric mantle.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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