Cretaceous basin evolution in northeast Asia: Tectonic responses to the paleo-Pacific plate subduction

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Abstract

Cretaceous rift basin evolution was an important part of tectonic history of NE Asia in the late Mesozoic. Three types of rift basins are identified, active, passive and wide rift basins, and they developed in different regions. Passive rift basins in the eastern North China craton are thought of as the consequence of crustal stretching and passive asthenospheric upwelling. Wide rift basins in the eastern Central Asian orogen are assumed to originate from gravitational collapse of the thickened and heated orogenic crust. Active rift basins in the northern North China craton are attributed to uprising of the asthenospheric materials along a lithospheric-scale tear fault. Slab tearing of the subducting paleo-Pacific plate is postulated and well explains the spatial distribution of different types of rift basins and the eastward shifting of magmatism in the northern North China craton. The Late Cretaceous witnessed a period of mild deformation and weak magmatism, which is possibly due to kinematic variation of the paleo-Pacific plate.

Keywords: NE Asia, Cretaceous, rift basin, volcanism, paleo-Pacific plate

Introduction

The northeastern Asian continent experienced alternating crustal contraction and extension as well as sporadic magmatism in the Mesozoic [1-4]. The multiple tectono-magmatic processes are ascribed to the near-field and far-field effects of the changes in subduction angles of the paleo-Pacific plate [5,6], continent-continent collisions and the resulting escape tectonics [7-9], subcontinental thermos-tectonic processes [10-12], and a combination of diverse tectonic drivers [13]. Two phases of strong crustal shortening have been identified and extensively studied, which took place in the late Middle Jurassic and at the end of the Late Jurassic, respectively [2,14,15]. The end-Jurassic contraction was intense and extensive, as indicated by widespread folding and thrusting as well as a regional angular unconformity beneath Lower Cretaceous strata [2,16]. This phase of shortening, termed as Phase B of the Yanshanian orogeny in the literature [17], resulted in two main consequences: crustal...
thickening of the eastern Central Asian orogen (ECAO) and onset of destabilization of
the North China craton (NCC). Extensive rifting occurred in the aftermath of this
contractional event [18,19]. Early Cretaceous rift basins developed throughout the
northeastern Asian continent and expressed themselves in general as disparate small-
and mediate-scale basins (Fig. 1). Vigorous volcanism accompanied the rifting
[3,12,20], with volcanic/volcaniclastic rocks making up significant parts of most basin
successions. Previous studies focused mainly on individual rift basins in different
regions, such as the Erlian, Hailar and Songliao basins in the ECAO [21-23], the
Luanping basin in the northern NCC [24], and the Hefei and Jiaolai basins in the
eastern NCC [25].

Distinct rift basins are distributed in different regions, as hinted by diverse Lower
Cretaceous volcano-sedimentary sequences. The basins in the eastern NCC started
with clastic sedimentation, which was followed by volcanic eruption [25,26]; By
contrast, volcanism marked the initiation of the rift basins in the northern NCC, and
clastic deposition then succeeded [24]. Volcaniclastic and volcanic rocks are present
throughout basin sequences in the ECAO [21,23]. The existing tectonic models,
however, seldom explicate how the diverse rift basins are generated simultaneously
and why they are distributed in different areas. Early Cretaceous rifting in NE Asia is
commonly attributed to backarc extension induced by the westward subduction of the
paleo-Pacific plate [1,25]. Unfortunately, it remains poorly known why extension
basically came to an end during the Late Cretaceous and what caused differential
basin subsidence in space. This study takes a holistic treatment of tectonic evolution
of Cretaceous rift basins in NE Asia and attempts to explore the dynamic controls of
time-space variations of the rift basins.

Tectonic setting

The northeast Asian continent is made up of two tectonic domains, the NCC in
the south and the ECAO in the north (Fig. 1). The NCC developed as a single stable
tectonic domain from the Mesoproterozoic to Paleozoic, and had undergone little
crustal deformation and magmatism for over 1.20 Ga [1,3]. The NCC kept its stability as a whole in the early Mesozoic albeit its peripheral regions were affected by terrane accretion as a result of the closure of the paleo-Asian and paleo-Tethyan oceans [27]. The late Mesozoic was a period when the different portions of the NCC began experiencing diverse thermo-tectonic evolution. The western NCC still behaved as a stable element with few tectonic activities. In contrast, the eastern NCC was featured by lithospheric thinning and extensive magmatism, and had completely lost its stability by the Early Cretaceous [1,3,11]. The northern NCC manifests itself as a unique zone by virtue of strong extension and magmatic outpouring, which were interrupted by short-term crustal/lithospheric shortening [1,2]. Compared with the NCC, the ECAO was built up with a number of terranes that had been amalgamated by the end of Paleozoic [28]. The ECAO is therefore a wide orogenic domain with complex crustal compositions and fabrics.

Cretaceous extensional tectonics in NE Asia is evidenced by rift basins, metamorphic core complexes, and vigorous magmatism [2,24,29-33]. In addition, the NCC lithosphere was significantly attenuated and experienced a radical change from the continental to oceanic lithospheric mantle [34,35]. These tectonic processes happened mainly in the Early Cretaceous and led to total destabilization of the eastern NCC [36]. Early Cretaceous extension and magmatism in the eastern NCC were in essence the surface expressions of deep thermo-mechanic processes, which were possibly associated with a big mantle wedge system resulting from rollback and retreat of the subducting paleo-Pacific plate [1,10]. Coeval extension in the ECAO is thought of as the consequence of gravitational collapse of the thickened orogenic crust [29,37]. Crustal thickening might have resulted partly from the collision of the ECAO and Siberian craton along the Mongo-Okhotsk suture [38] and partly from the tectonic push due to flat subduction of the paleo-Pacific plate at the Jurassic to Cretaceous transition [1,39]. This shortening event is registered by a regional unconformity beneath the Lower Cretaceous in the ECAO [9] (Fig. 2). Late Cretaceous tectonics of NE Asia was featured by vertical crustal motion, with Early Cretaceous rift basins either undergoing uplift/erosion or subsidence. The small-scale basins in both the
ECAO and the northern NCC were uplifted or inversed at the end of Early Cretaceous, with a few Upper Cretaceous strata left (Fig. 2). The Songliao basin, situated in the east of the ECAO, is an exception in that it experienced pronounced sagging during the Late Cretaceous [21]. The Jiaolai basins in the eastern NCC also underwent striking subsidence in the Late Cretaceous, which is assumed to have born upon strike-slip motion of the Tanlu fault [26]. Large-scale sinistral transpression came about around 100 Ma along the eastern margin of the NE Asian continent, as manifested by occurrence/reactivation of left-slip faulting, such as the Tanlu fault [5], Dunhua-Mishan fault [40], and the Central Sikhote-Alin fault [41].

### Basin sequences

Cretaceous strata are well preserved in NE Asia, and both lithostratigraphic and biostratigraphic sequences have been intensively investigated. Basins in different regions display distinct volcanic–sedimentary sequences (Fig. 2). The ages of lithostratigraphic units are tightly constrained by precise U-Pb zircon and Ar-Ar dating of volcanic and volcanioclastic beds in conjunction with fossil assemblages. Cretaceous successions are separated from the underlying units by a regional angular unconformity, which registers a strong shortening event just prior to the Early Cretaceous rifting. Another unconformity occurs between the Lower and Upper Cretaceous, and manifests itself as either a parallel or low-angle discordant surface (Fig. 2). Cretaceous strata are unconformably covered by or pass upward conformably to Tertiary sediments [25,42].

Complete Cretaceous successions in the eastern NCC are best preserved in the Jiaolai and Hefei basins (Fig. 2). Lower Cretaceous succession displays two distinct parts, with the lower dominated by clastic rocks and the upper by volcanic and volcanioclastic rocks. The clastic parts are represented by the Laiyang Group in the Jiaolai basin and by the Zhuxiang Formation in the Hefei basin. Fluvial conglomerate and sandstone facies associations make up the lower part of the Laiyang Group,
whereas the upper part consists primarily of meandering fluvial and lacustrine facies [43]. The Shuinan Formation, a unit in the middle Laiyang Group, contains a basalt layer that yields a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of $129.7 \pm 1.7$ Ma [26]. The Zhuxiang/Fenghuangtai Formation in the Hefei basin shares similar facies to the lower Laiyang Group, and has an accumulative thickness up to 2500 m [44,45]. Clastic sedimentation was suppressed by vigorous volcanism, as indicated by a rapid change from siliciclastic to volcanoclastic and/or volcanic rocks that dominate the upper parts of the Lower Cretaceous successions of both the Hefei and Jiaolai basins (Fig. 2). The Maotanchang volcanics, up to 1000 m thick, represent late volcanism in the Hefei basin, and range in age from 130 to 120 Ma [45]. The Maotanchang volcanics pass upward into the Heishidu Formation, which is dominated by lacustrine fine-grained facies and contains abundant pyroclastic rocks [44]. The Qingshan Group, up to 1500 m thick, comprises basic and felsic volcanic rocks that yield $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages from 122 to 105 Ma [26,46,47]. Lower Cretaceous sequences are overlain unconformably by Upper Cretaceous strata, such as the Wangshi Group in the Jiaolai basin and the Zhangqiao Formation in the Hefei basin (Fig. 2). The Wangshi Group consists mostly of alluvial–fluvial coarse-grained facies, with its depositional ages ranging from 107 to 73.5 Ma based on radiometric ages of volcanic beds and detrital zircon ages [48,49]. An angular unconformity separates the Lower from Upper Cretaceous units in the eastern NCC [26]. The discordant contacts are both observed at outcrops and identified on seismic profiles that are near or within the Tanlu fault zone [26,50].

Cretaceous sequences commence with volcanics in the northern NCC, as recorded by the Donglingtai Formation in the western segment, the Zhangjiakou Formation in the middle segment, and the Yixian Formation in the eastern segment or the Liaoxi belt (Fig. 2). The Zhangjiakou and Donglingtai volcanics in the western Yanshan belt are dated at $143 \pm 0.67$ Ma, $143.4 \pm 0.65$ Ma, and $140.7 \pm 0.64$ Ma
whereas the Zhangjiakou rhyolite and ignimbrite in the eastern Yanshan belt yield U-Pb zircon ages ranging from 136 to 131 Ma [24,56,60]. The Yixian volcanics give both $^{40}\text{Ar}^{39}\text{Ar}$ plateau ages and U-Pb zircon ages ranging from 126 to 124 Ma [61,78]. Accordingly, Early Cretaceous volcanism became younger eastward in the northern NCC [10,11]. Clastic sedimentation then took the place of volcanism with time, and prevailed in the late stage, as recorded by the Xiguayuan and Jiufotang formations in different basins (Fig. 2). The clastic units are collectively assigned to the Hauterivian to Aptian ages based on radiometric ages and fossil assemblages [64], and characterized by fluvial-lacustrine facies associations [24,79]. The Qingshila, Shahai and Fuxin formations represent the uppermost portions of Lower Cretaceous successions, and are made up mostly of fluvial facies associations. The Upper Cretaceous, if present, is separated from older units by either disconformities or low-angle unconformities (Fig. 2).

Lower Cretaceous strata are extensively preserved in the ECAO, and composed dominantly of clastic facies [29,37,80]. Volcanics, usually present as interlayers, also occur in Lower Cretaceous successions of the East Gobi, Erlian, and Hailar basins, and are largely basalt and basaltic andesite, yielding the $^{40}\text{Ar}^{39}\text{Ar}$ ages from 142 to 113 Ma [22,29,65,66,80-82]. Early Cretaceous volcanics and volcaniclastic rocks are widespread in the Great Xing’an Range, and dated at 135–115 Ma [20,68,69,81]. Lower Cretaceous succession of the Songliao basin contains thick volcanic and volcaniclastic rocks, such as the Huoshiling and Yingcheng formations albeit clastic facies are also commonplace (Fig. 2). The Huoshiling volcanics are recently dated at 133–129 Ma [71,72], much younger than previous age assignment of ~150 Ma [21]. The Yingcheng volcanics are constrained at 120–105 Ma [21], indicating the persistence of volcanism to the end of the Early Cretaceous. The Upper Cretaceous well developed in the Songliao basin, up to 3 km thick [83]. In contrast, the rift basins in the western portion of the ECAO possess meager Upper Cretaceous strata, which are usually less than 500 m thick [29]. A regional unconformity separates the Lower from Upper Cretaceous [21,29].
Magmatism

Vigorous volcanism and plutonism characterized the NE Asian continent during the Early Cretaceous [3,20,32]. Volcanic rocks are widely distributed in the northern NCC, as represented by the Donglingtai andesite in the western Hill, Zhangjiakou rhyolite in northern Hebei, and Yixian basalts in western Liaoning. Volcanism in the eastern NCC took place in the late stage of rift basin development, as recorded by the Qingshan rhyolite and basalt in the Jiaolai basin, the Maotanchang andesite in the Hefei basin and the Laohutai basalts in the Fushun basin [84] and the Xiaoling Formation in eastern Liaoning [85]. Early Cretaceous volcanism was vigorous in the Great Xing’an Range and the Songliao basin [20,21,70,81], but declined significantly westward. Volcanic and/or volcaniclastic rocks are only present as interlayers in the lower successions of the East Gobi [80] and Erlan basins [66].

Early Cretaceous intrusions are also extensive in NE Asia [3,32]. Mafic intrusives occur in the eastern NCC, such as gabbro-pyroxenite complexes in the Taihang Shan belt and diorite/gabbro bodies in western Shandong [86,87]. Granitoids are distributed in the peripheral of the eastern NCC [3,32], such as the Fangshan granite in the western Yanshan belt [88] and the Sanguli granite in the eastern Liaoning belt [11] in the northern NCC, the Guojialing granite in the Jiaodong Peninsula in the NCC eastern margin [89], and the Huashan and Heyu granites in the southern edge of the NCC [90]. Early Cretaceous granitoids are also widely documented in the ECAO, particularly in NE China [32,91].

Growing geochronologic data show that Early Cretaceous magmatism took place in a wider range of time although it mainly happened from 130 to 120 Ma [32]. An east-younging polarity in magmatic activity has been recognized [10,11], and is best demonstrated by eastward progression of Early Cretaceous volcanism in the northern NCC (Fig. 3). Volcanism started at 143–140 Ma in the Yinshan and western Yanshan belts [3,54,77], around 136 Ma in the eastern Yanshan belt [56], ~126 Ma in the
Liaoxi region, and ~120 to 110 Ma in the Liaodong region [32,85]. Early Cretaceous magmatism in the eastern NCC commenced around 138 Ma in the Taihangshan belt [92], and appeared to have not started until ~130 Ma in the easternmost NCC [87]. No matter when it began, Early Cretaceous magmatism had been lasting until ~110 Ma ago within and around the eastern NCC [11,32]. Early Cretaceous magmatism in the ECAO occurred from ca. 130 to 110 Ma albeit it was vigorous in the east [70,81].

Also noticeable is the time-space variation of magma types in the eastern NCC. Felsic and intermediate magmatism was prevailing in the west from 143 to 136 Ma, whereas mafic magmatism took place largely in the east from 130 to 110 Ma [87]. The eastward migration of magmatism was also associated with an increase in alkaline and mafic rocks like syenite and gabbro [93]. This situation is well exemplified by ~143 Ma rhyolites and granitoids in the western Yanshan and Taihangshan belts [3,54] and ~130 to 110 Ma mafic rocks in the easternmost NCC [87]. Magmatism persisted in the western portion of the eastern NCC when migrating eastwards [11]. Felsic volcano-plutonic associations are also common in the easternmost NCC, coeval with mafic and alkaline magmatism [32,87].

Early Cretaceous granite in the northern NCC is shown to have formed at high temperature ranging from 640 to 1,100 °C with a peak at ~770 °C [11]. This deduction is supported by the co-occurrence of mafic rocks that originate from high-temperature melts [87]. Coexistence of felsic and mafic magmas in the northern NCC indicate intense crust-mantle interaction [94], thereby hinting at uprising of the hot asthenospheric materials.

Magmatism declined significantly throughout the NCC and ECAO in the Late Cretaceous [3,4], and occurred largely along the eastern edge of the NE Asian continent, such as the Sikhote Alin belt [95], Korea [96], and southwestern Japan [91]. Late Cretaceous igneous rocks are mostly granitoid, andesite, and pyroclastic rocks, representing island-arc magmatic activities triggered by the paleo-Pacific plate subduction [69,97].
Basin evolution

Rift basins are usually classified on the basis of dynamic, geometric and kinematic aspects, such as active and passive rifts \cite{98} and wide and narrow rifts \cite{99,100}. Active rifting is attributed to active uprising of mantle plume, which first leads to doming and then induces supracrustal stretching \cite{101}. Passive rifting is ascribed to lithosphere extension as a result of horizontal in-plane far-field forces, with the asthenospheric materials rising passively due to the lithosphere thinning \cite{101}. Wide rift systems develop owing to gravitational collapse of the orogenically thickened crust. Tensile deviatoric stress field in the thickened crust is produced by lateral variation in gravitational potential energy \cite{102}. By contrast, narrow rifts result from necking of the lithosphere with normal geotherm and crust thickness \cite{100}, and therefore fit passive rifting mode. Merle (2010) proposes a rift classification in the context of tectonic settings, such as subduction-, mantle- transform- and mountain-related rifts \cite{103}. However, it is a purely interpretive classification and can’t help explore real mechanism of continental rifting. Moreover, wide rifts are neither taken into account in the Merle’s classification nor readily fall into the category of the Sengör and Burke’s (1978) classification \cite{98}. Active and passive rifting modes do have drawbacks and can’t successfully explain the whole evolution of continental rifts \cite{103,104}. However, this simple classification proves quite useful for the first-order assessment of continental rifting \cite{105}. Obviously, no existing rift classifications can encompass all types of continental rifts and no single driving force can account for all aspects of rift basins. We thus take a pragmatic approach in dealing with Cretaceous rift basins in NE Asia by adopting the categorization of active, passive and wide rifting. Our rationale is that the investigated basin successions appear well compatible with the distinct rifting modes. The three types of rifting are thus considered to originate from three driving forces: (1) far-field forces originating at plate boundaries; (2) forces acting on the base of the lithosphere due to the asthenospheric uprising, and (3) buoyancy forces arising within the thickened orogenic crust. Different drivers may work together to control the development of
some rift basins.

The relative timing of extension and volcanism is pivotal to discriminate different types of rift basins, which can be readily recognized by their distinct stratigraphic sequences (Fig. 4). Passive rift basins develop when the lithosphere is stretched and thinned, with the asthenosphere rising passively (Fig. 4A-a). Magma is then generated either by melting of the crust and lithospheric mantle due to asthenospheric heating or by decompressional melting of the asthenosphere. As a result, volcanic eruptions take place in the late stage of rifting when the lithosphere is considerably attenuated (Fig. 4A-b). Passive rift basin development is thus recorded by basin sequences typified by the lower clastic rocks and the upper volcanic/volcaniclastic rocks (Fig. 4A-c). By contrast, extensive volcanism usually precedes subsidence of active rift basins as a consequence of the active asthenospheric upwelling and crustal doming (Fig. 4B-a). The domed upper crust then experiences horizontal stretching owing to gravitational instability and collapse, thereby forming active rift basins in the extended areas. Clastic sedimentation is therefore characteristic of the late stage of active rift basins (Fig. 4B-b). Typical volcano-sedimentary sequences of active rift basins are accordingly marked by a lower volcanic part and an upper clastic part (Fig. 4B-c). As regards wide rift basins, they initiate and develop owing to gravitational collapse of the thickened orogenic crust, as manifested by broad occurrence of small-scale disparate rift basins in the upper crust (Fig. 4C-a). The isolated basins expand through lateral linkage of adjacent basins, and thus often express themselves as elongated or narrow basins in map view (Fig. 5). Continued gravitational spreading can result in stress localization and may eventually give rise to metamorphic core complexes (MCC) [99]. The close associations of MCCs with wide rifting can be exemplified by the presence of a number of Early Cretaceous MCCs, like the Yagan MCC [29,106], Ereendavaa MCC [107] and Ulan-Ude MCC [33] in the ECAO. Magmatism also occurs simultaneously with wide rifting (Fig. 4C-b) and is well documented [108-110]. Potential heat sources for partial melting of thickened crust might be internal heat production by radioactive decay [111] and/or heat flux related to the asthenospheric upwelling triggered possibly by plate subduction [112]. Widespread volcanism in the
ECAO is commonly attributed to subduction-induced delamination [69]. Wide rifts are marked by basin sequences dominated by clastic facies, with volcanic interlayers being present at different stratigraphic levels (Fig. 4C-c).

Early Cretaceous rift basins in NE Asia are categorized into three types in this study, passive, active, and wide rift basins. Rift basins in the eastern NCC display similar synrift stratigraphic successions that begin with clastic units characterized by alluvia/fluvial and lacustrine facies associations. The clastic units are overlain by upper units dominated by volcanic and volcaniclastic rocks. This typical synrift sequences are well manifested in the Jiaolai and Hefei basins (Fig. 2). The Laiyang Group and Zhuxiang Formation represent the lower clastic units, while the Qingshan Group and Maotanchang Formation exemplify the upper volcanic units (Figs. 2 and 4A-d). Rift basins in the eastern NCC thus fall into passive rift basins. Rift basins in the northern NCC show synrift sequences typified by a lower volcanic unit and an upper clastic unit, contrasting strikingly with rift basin sequences in the eastern NCC. The lower unit is represented by the Donglingtai, Zhangjiakou and Yixian volcanics, while the Dabeigou, Xiguayuan, and Jiufotang formations make up the upper clastic units in the Luanping and Beipiao basins, respectively (Figs. 2 and 4B-d). The rift basins in the northern NCC are therefore considered as active rift basins. Early Cretaceous basins in the ECAO have been well investigated and classified as wide rift basins [29,37,80]. The extensive distribution of small-scale basins, as manifested by Early Cretaceous basin families in the Yingen and Songliao basins (Fig. 5), typifies the wide rift basins. Volcanic layers of various thicknesses occur at different levels of successions of the wide rift basins (Figs. 2 and 4C-d), as displayed by Lower Cretaceous sequences in the Songliao basin [21,71,72], the Great Xing’an Range [68], the Hailar basin [66,67] and the Erlian basin [66].

It is noteworthy that the distinct types of rift basins occurred in different regions in NE Asia during the Early Cretaceous: wide rift basins developed in the ECAO, active rift basins in the northern NCC, and passive rift basins in the eastern NCC (Fig.
1). The wide rift basins are reminiscent of the Tertiary Basin and Range Province of the United State [113,114], and attributed to gravitationally-driven collapse of thickened and heated orogenic crust [29,37,115,116]. Other drivers are also proposed for the Early Cretaceous extension, such as back-arc crustal extension [21,117] or transtension in association with escape tectonics [9,118]. However, these mechanisms can hardly explain the extensive distribution of these supracrustal basin families. Passive rift basins in the eastern NCC resulted from backarc extension triggered by high-angle subduction of the paleo-Pacific plate [18,119], with regional tensional stress being oriented NW to SE [120,121]. The Tanlu fault behaved as a major normal fault in the Early Cretaceous, playing a major role in subsidence of the Hefei, Jiaolai, and other adjacent basins [25]. It has been bewildering how active rift basin was induced in the northern NCC.

The Late Cretaceous saw a period when most rift basins experienced vertical motion in NE Asia [21,29]. Basin subsidence and sedimentation in eastern NCC were partly associated with normal faulting [25,26]. Magmatism became quiet, and only active in the eastern edge of the NE Asian continent, such as the Sikhote Alin belt, southeast Korea and southwest Japan [3,4,91]. The passive rift basins in the eastern NCC subsided as a result of N–S extension, as exemplified by the Jiaolai basin where the Upper Cretaceous Wangshi Group was deposited under the control of east–west-striking normal faults like the Baichihe and Pingdu faults [26]. The N–S extension was postulated to result from transcurrent tectonics [5]. East–west-trending normal faulting also took place in the Hefei basins, and controlled sedimentation of the Zhangqiao Formation [25]. Contraction happened in the easternmost NE Asian continent at the end of the Early Cretaceous, as registered by a regional unconformity beneath Upper Cretaceous strata in a number of basins, such as the Hefei, Jiaolai, Songliao, and Sanjiang basins [21,26,122]. Strong transpression occurred along strike-slip fault zones, leading to folding and uplifting of Lower Cretaceous successions of the basins near or within the fault zones, as indicated by intense
deformation of Lower Cretaceous strata in the Sanjiang basin [122] and the Yīsu basin [26]. The basins far away from the strike-slip faults only experienced a short-lived vertical uplift, with no obvious break in the Lower–Upper Cretaceous successions. For instance, Lower and Upper Cretaceous strata are conformable in the Gyeongsang basin in SE Korea [52], and Cretaceous synrift and postrift sequence is only separated by a short-termed disconformity in the Songliao basin [21].

Most rift basins in the ECAO underwent minor subsidence in the postrift stage, with postrift successions usually less than 800 m thick [29]. The insignificant postrift subsidence resulted possibly from lower-crustal flows directed toward the strongly attenuated regions from the less stretched areas [29]. The lower-crustal flows prevented the crust of the rift basins from further thinning, thereby reducing postrift tectonic subsidence. The Songliao basin is an exception in that it underwent striking postrift subsidence with sedimentary successions up to 5000 m thick [21]. Opinions diverge on the origins of large-magnitude postrift subsidence of the Songliao basin. It is assumed that the lithosphere of the Songliao basin had been significantly thinned due to backarc extension, and subsequent thermal contraction of the asthenosphere was thus responsible for the pronounced postrift subsidence [21]. Li and Liu attributed the marked postrift subsidence to superposition of dynamic subsidence induced by downward dragging of the subducting paleo-Pacific plate [123]. It is also argued that west-verging thrusting on the eastern margin of the Songliao basin might have made some contribution to the postrift subsidence albeit thermal subsidence was dominant in the early stage [122]. Transpressional deformation was localized along the strike-slip fault zones in the easternmost margin of NE China at the Early to Late Cretaceous boundary, like the Yīlán–Yǐtóng and Dūnhuā–Mǐshān faults [5,40], and led to inversion of the Sanjiang basins in between [122]. The Songliao basin appeared to have not undergone shortening until ~80 Ma when the whole basin fills were folded to various degrees and partially uplifted under roughly west–east compression [21].

Upper Cretaceous strata are considerably thin and only present in a few rift basins in the northern NCC (Fig. 2). It is unclear why the active rift basins largely came to an end in the Late Cretaceous. Most Early Cretaceous successions remain fairly flat,
indicating weak deformation. It is plausible that the active rift basins terminated as a result of vertical crustal motion rather than horizontal shortening. The northern NCC in practice experienced polyphase rapid uplifting in the Cretaceous, starting around 120 Ma based on low-temperature thermochronologic data [124]. The episodic vertical motion might be responsible for the lack of Upper Cretaceous strata. More work is obviously needed to explore the driver for the polyphase uplift/denudation of the northern NCC. The end-Early Cretaceous thrusting was rarely recorded in the northern NCC except a few localities where sinistral transpressive faults, such as the Nantianmen and Yaowangmiao faults in western Liaoning, displace the Mesoproterozoic dolostones over Lower Cretaceous strata [125].

Dynamics of Cretaceous basins

Distinct types of rift basins developed in different regions in NE Asia during the Early Cretaceous, and there should be a coherent mechanism that governed spatial distribution of the diverse rift basins. We here advance a tectonic model that seems to better explain why different rifting took place in different regions in the Early Cretaceous (Fig. 6). The NE Asian continent was bounded on the east by a subduction zone, which presumably initiated in the Early Jurassic, as implied by the presence of Early Jurassic accretionary complexes and arc/backarc igneous associations at the eastern margin of the ECAO [4,14,126]. Early Cretaceous arc volcanic rocks are rarely documented in the eastern edge of the NCC, but mafic and felsic intrusives in the eastern NCC implicate active subduction of the paleo-Pacific plate [87]. One possibility is that the subduction zone was far away from the present-day eastern edge of the NCC continent, and Early Cretaceous island-arc belt might have been destroyed by later subduction and/or transform processes due to reorganization of the western Pacific plate [127,128]. This situation hints at a change in the paleo-Pacific plate subduction process along the subduction zone (Fig. 6A). The whole subduction zone could be divided into the northern and southern segments (Fig. 6). The northern subduction zone east of the ECAO was relatively fixed in consideration of complete
preservation of Jurassic–Early Cretaceous accretionary complexes in the Nadanhada and Sikhote Alin belts [41,126]. In contrast, the subduction zone east of the NCC might have been located far away from the continental margin because of the lack of geologic records of Jurassic–Early Cretaceous arc systems. It is thus plausible that a transfer zone developed to accommodate the different subduction processes at the northern and southern subduction zones. The transfer zone just occurred beneath the northern NCC (Fig. 6A).

An internal connection might exist between the paleo-Pacific plate subduction and extensional tectonics in the ECAO during the Early Cretaceous (Fig. 6B). The paleo-Pacific plate subduction not only produced an accretionary prism, as evidenced by the Late Jurassic–Early Cretaceous Nadanhada and Sikhote-Alin complexes [41,126], but also induced backarc extension, as implicated by Early Cretaceous bimodal volcanism and A-type rhyolite [4,20]. The free eastern boundary could have facilitated extensional collapse of the thickened ECAO crust, leading to the formation of wide rift basins. The superposition of backarc extension and gravitational collapse brought about significant thinning of the whole lithosphere in the eastern ECAO (Fig. 6B), thereby resulting in uprising of the asthenosphere and voluminous volcanic eruption in both the Songliao basin and Great Xing’an Range [20,69,81]. This mechanism offers a satisfactory explanation for intense volcanism in the Great Xing’an Range in the Early Cretaceous and the pronounced thermal subsidence of the Songliao basin in the Late Cretaceous.

It was argued that Early Cretaceous magmatism became younging to the east in the ECAO [69]. Close scrutiny of available geochronologic data, however, shows that magmatism occurred throughout the ECAO mainly in the timespan from 135 to 110 Ma [32,69,81,97,110] and did not display the marked eastward progression. Extensive volcanism across the ECAO is attributed either to break-off of subducting plate [20] or delamination of subcontinental lithosphere [23]. Although the two tectonic models could explain extensive magmatic outpouring and uplifting of wide rift systems in the
late Early Cretaceous, but it can hardly account for why significant thermal subsidence only happened in the Songliao basin. We tentatively ascribe Early Cretaceous magmatism in the ECAO interior to the combination of internal heating due to radioactive decay in the thickened crust and heat flux of the asthenospheric upwelling triggered by plate subduction.

Passive rifting in the eastern NCC resulted from horizontal lithospheric extension, which was presumably induced by rollback and retreat of the subducting paleo-Pacific plate [10,25]. The westward decrease in the intensity of crustal stretching implies that horizontal tensile force must have been applied from the east. Given no records of Early Cretaceous arc magmatism in the present-day eastern edge of the NCC, the subduction zone must have been located far to the east during the Early Cretaceous. It is conjectured that the southern subduction zone had continued migrating eastward with time owing to persistent rollback and/or retreat of the subducting paleo-Pacific plate (Fig. 6C). Continued rollback and/or retreat of the paleo-Pacific plate subduction might also have led to the formation of a big mantle wedge beneath the NCC in the Early Cretaceous, which in turn promoted lithospheric thinning of the eastern NCC by means of water-assisted thermal erosion [10].

Two-dimensional thermal mechanical modeling was recently performed to investigate behaviors of the overriding continent with differing thermal states in the process of oceanic plate subduction [129]. It is shown that: (1) trenchward thrusting of overthickened and hot (>17.5 °C km\(^{-1}\)) crust will slow down the trench retreat; and (2) decoupling could occur between the overriding continents and subducting oceanic plates if continents possess low thermal gradients (~10–15 °C km\(^{-1}\)) and normal crustal thickness. The modeling results carry important implications for subduction processes of the western paleo-Pacific plate. As discussed earlier, complete Jurassic–Cretaceous accretionary complexes are well preserved at the eastern margin of the ECAO. This fact implicates that the northern subduction zone must have been relatively fixed or experienced little eastward retreat during the late Mesozoic, compatible with the prediction of the modeling [129]. By contrast, the NCC was a domain with relatively normal geotherm and crustal thickness as whole. Given few
geologic records of arc systems have been identified along the eastern margin of the NCC, the southern subduction zone is thus inferred to have undergone eastward migration as a result of continuous trench retreat and subduction rollback of the paleo-Pacific plate. Both geologic observations and interpretations seem consistent with the numerical modeling [129].

Tearing of subducting lithospheric slab has been widely documented by geophysical observations in many subduction zones in the world [130,131], and is attributed to the variation in rates of subduction rollback and trench retreat along the length of subduction zones [132]. We conjecture that the subducting paleo-Pacific plate experienced vertical slab tearing beneath the northern NCC as a result of different rollback and/or retreat velocities of the northern and southern subduction zones (Fig. 7). The northern subduction zone was relatively fixed during the period from the Late Jurassic to Early Cretaceous, whereas the southern subduction zone continued migrating to the east, with only backarc system left in the eastern NCC (Fig. 6A). Persistent eastward retreat of the southern subduction zone eventually led to segmentation of the subduction zone and the formation of a lithospheric-scale tear fault that split the subducting paleo-Pacific plate beneath the NE Asian continent (Fig. 7). One of the direct consequences is the ascent of the hot asthenospheric materials along the tear fault, which heated the overlying lithosphere and triggered vigorous magmatism in the northern NCC (Fig. 6). The plausibility of tearing of the subducting paleo-Pacific plate is sustained by several geologic facts. First, Early Cretaceous volcanism and plutonism occurred mostly in the northern NCC, as indicated by linear distribution of igneous rocks (Fig. 3). Second, Early Cretaceous volcanism showed an eastward younging polarity, taking place first in the west and shifting to the east [10,11] (Fig. 3). Third, Early Cretaceous igneous rocks in the northern NCC were formed at high temperatures and sourced partially from depleted mantle materials [11]. All the geologic records are compatible with the proposed slab tearing process. Tearing of the subducted paleo-Pacific plate happened first in the west, thus permitting asthenospheric materials to penetrate through slab gap produced by lithospheric-scale tearing (Fig. 7). Consequently, vigorous magmatism occurred first
in the western segment of the northern NCC as a result of heating of the asthenospheric uprising, giving rise to the voluminous Donglingtai and Zhangjiakou volcanics. Tearing then propagated eastward and upward through time, and brought about eastward migration of magmatic activities (Fig. 7). Slab tearing thus offers a good explanation for the generation of voluminous volcanism and active rift basins in the northern NCC (Fig. 7).

Also noticeable is the occurrence of a number of Early Cretaceous metamorphic core complexes (MCC) in the northern NCC (Fig. 1), such as the Hohhot [133], Yunmengshan [134,135], Yiwulushan [136], and Liaonan MCCs [137], indicating that the northern NCC was a highly-extended corridor. The MCCs possess two important aspects: (1) footwalls or the lower plates usually contain Early Cretaceous plutons; and (2) detachments experience high-temperature (up to 600 °C) ductile shearing [109]. The facts imply that magmatism must have played an important role in the MCCs’ formation by thermally weakening the lithosphere/crust. MCCs preferentially form in the hot and thickened crust, as revealed by both natural examples and numerical modelling [99,100,138]. The northern NCC had experienced two strong shortening events prior to the Early Cretaceous [2,15,16], and had already evolved into an intraplate orogen with the considerably thickened crust. Subsequent voluminous magmatic activity must have further weakened the northern NCC [109]. Therefore, the northern NCC behaved as a unique extensional corridor affected by both magmatic uprising and gravitational collapsing in the Early Cretaceous, and was thus prone to active rifting and MCC formation.

A global plate reorganization event happened at ~105–90 Ma, and the paleo-Pacific plate began moving to the north or north-northwest [127]. The N- or NNW-directed movement of the paleo-Pacific plate strongly sheared the eastern margin of the NE Asian continent since the beginning of the Late Cretaceous [41,127,139], contrasting with the dominant NW-directed subduction in the Early Cretaceous [25]. The kinematic change in direction, rate and subduction angle of the
paleo-Pacific plate led to two prominent consequences in the eastern margin of NE Asia in Late Cretaceous time: (1) reactivation and/or initiation of a number of large-scale left-slip faults, such as the Tanlu fault [5], Dunhua-Mishan fault [40], Median tectonic lines [140], South Korea tectonic line [141], and Central Sikhote Alin fault [41]; (2) transpressional deformation in the period from 97 to 80 Ma, which presumably resulted from an abrupt increase in subduction rate of the paleo-Pacific plate [139]. The transgression resulted in inversion of Early Cretaceous rift basins in the eastern margin of the NE Asian continent, such as the Hefei, Jiaolai, Yisu, Sanjiang and Songliao basins [21,26,122]. Following the shortening event, rifting resumed as a consequence of N-S extension in some localities, and possibly bore upon persistent large-scale left-slip faulting [26,120,141]. Late Cretaceous magmatism was thus concentrated along the easternmost margin of the NE Asian continent [41,96], and became significantly weak toward the interior due to localization of transcurrent deformation [3,5]. The Songliao basin underwent marked postrift subsidence in the Late Cretaceous tectonic quiescence [21]. Most of the NE Asia continent experienced vertical uplift or minor subsidence in the Late Cretaceous on account of the scarcity of Upper Cretaceous strata [122].

Admittedly, uncertainties and disagreements remain regarding subduction history of the western paleo-Pacific plate in the late Mesozoic. The existing reconstructions of the paleo-Pacific plate subduction need to be refined when new data are available. A more feasible mechanism for tectonic development of Cretaceous basins in NE Asia awaits a better understanding of subduction processes and kinematic history of the paleo-Pacific plate in the late Mesozoic.

Conclusions

Cretaceous rift basins characterize the NE Asian continent. Three types of rift basins are identified according to their distinct volcano-sedimentary sequences and subsidence history, and termed as passive, active and wide rift basins. Passive rift basins in the eastern NCC commenced with clastic deposition, which was followed by
volcanic eruption. Active rift basins were formed in the northern NCC and marked by vigorous volcanism at the beginning of basin history. Clastic sedimentation then took place and became more prevalent with time. Wide rift basins occurred in the ECAO and were mostly filled with clastics. Volcanic and volcanioclastic layers were present throughout basin successions, and abundant in the eastern ECAO. The passive rift basins are attributed to horizontal lithospheric stretching induced by rollback and retreat of the subducting paleo-Pacific plate. The wide rift basins originate from gravitational collapse of the hot and thickened crust. Development of active rift basins is presumably related to the asthenospheric uprising through a lithospheric-scale tear fault. Late Cretaceous was a period of tectonic quiescence, and most of the Early Cretaceous rift basins experienced either sagging or uplift. Late Cretaceous crustal deformation was localized along the eastern margin of the NE Asian continent in response to kinematic change of the paleo-Pacific plate that began moving to the north or north-northwest. Basins near or within major strike-slip faults in the eastern margin were either inversed or developed into strike-slip basins.

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The ideas and concepts of this study stem from long-term collaboration of all the authors. Qing-Ren Meng drafted the manuscript and designed the illustrations based on the repeated discussion among the authors. All the authors contributed to the completion of final version of the manuscript.

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REFERENCES

1. Zhu RX, Zhu G and Li JW et al. Destruction of the North China Craton. Beijing: Science China Press, 2020.
2. Davis GA, Yadong Z and Cong W et al. Mesozoic tectonic evolution of the Yanshan fold and thrust belt, with emphasis on Hebei and Liaoning provinces, northern China. Memoirs-Geological Society of America 2001: 171-98.
3. Zhang SH, Zhao Y and Davis GA et al. Temporal and spatial variations of Mesozoic magmatism and deformation in the North China Craton: Implications for lithospheric thinning and dekratonization. Earth-Sci Rev 2014; 131: 49-87.
4. Tang J, Xu WL and Wang F et al. Subduction history of the Paleo-Pacific slab beneath Eurasian continent: Mesozoic-Paleogene magmatic records in Northeast Asia. Sci China Earth Sci 2018; 61: 527-59.
5. Zhu G, Liu C and Gu CC et al. Oceanic plate subduction history in the western Pacific Ocean: Constraint from late Mesozoic evolution of the Tan-Lu Fault Zone. Sci China Earth Sci 2018; 61: 386-405.
6. Zhu R, Zhou Z and Meng Q. Destruction of the North China Craton and its influence on surface geology and terrestrial biotas. Chinese Science Bulletin 2020; 65: 2954-65.
7. Kimura G, Takahashi M and Kono M. Mesozoic collision—extrusion tectonics in eastern Asia. Tectonophysics 1990; 181: 15-23.
8. Li S, Zhao G and Dai L et al. Mesozoic basins in eastern China and their bearing on the deconstruction of the North China Craton. J Asian Earth Sci 2012; 47: 64-79.
9. Yang Y, Guo Z and Song C et al. A short-lived but significant Mongol – Okhotsk collisional orogeny in latest Jurassic – earliest Cretaceous. Gondwana Res 2015; 28: 1096-116.
10. Zhu RX and Xu YG. The subduction of the west Pacific plate and the destruction of the North China Craton. Sci China Earth Sci 2019; 62: 1340-50.
11. Wu FY, Yang JH and Xu YG et al. Destruction of the North China Craton in the Mesozoic. Annual Review of Earth and Planetary Sciences, 2019; 47: 173.
12. Ma Q and Xu Y. Magmatic perspective on subduction of Paleo-Pacific plate and initiation of big mantle wedge in East Asia. Earth-Sci Rev 2021; 213: 103473.
13. Dong S, Zhang Y and Zhang F et al. Late Jurassic – Early Cretaceous continental convergence and intracontinental orogenesis in East Asia: A synthesis of the Yanshan Revolution. J Asian Earth Sci 2015; 114: 750-70.
14. Hao W, Zhu R and Zhu G. Jurassic tectonics of the eastern North China Craton: Response to initial subduction of the Paleo-Pacific Plate. Geological Society of American Bulletin 2021; 133: 19-36.
15. Wu G, Meng Q and Zhu R et al. Middle Jurassic orogeny in the northern North China block. Tectonophysics 2021; 801: 228713.
16. Li CM, Zhang CH and Cope TD et al. Out-of-sequence thrusting in polycyclic thrust belts: An example from the Mesozoic Yanshan belt, North China Craton. Tectonics 2016; 35: 2082-116.
17. Dong S, Zhang Y and Li H et al. The Yanshan orogeny and late Mesozoic multi-plate convergence in East Asia—Commemorating 90th years of the “Yanshan Orogeny”. Science China Earth Sciences 2018; 61: 1888-909.
18. Ren J, Tamaki K and Li S et al. Late Mesozoic and Cenozoic rifting and its dynamic setting in
Eastern China and adjacent areas. *Tectonophysics* 2002; 344: 175-205.

19. Lin W and Wei W. Late Mesozoic extensional tectonics in the North China Craton and its adjacent regions: a review and synthesis. *Int Geol Rev* 2020; 62: 811-39.

20. Xu WL, Pei FP and Wang F et al. Spatial-temporal relationships of Mesozoic volcanic rocks in NE China: Constraints on tectonic overprinting and transformations between multiple tectonic regimes. *J Asian Earth Sci* 2013; 74: 167-93.

21. Wang P, Mattern F and Didenko NA et al. Tectonics and cycle system of the Cretaceous Songliao Basin: An inverted active continental margin basin. *Earth-Sci Rev* 2016; 159: 82-102.

22. Guo ZX, Yang YT and Zhao XZ et al. Early Cretaceous tectonostratigraphic evolution of the Erlian Basin, NE China: A record of Late Mesozoic intraplate deformation in East Asia. *Mar Petrol Geol* 2019; 110: 539-64.

23. Ji Z, Meng QA and Wan CB et al. Generation of late Mesozoic felsic volcanic rocks in the Hailar Basin, northeastern China in response to overprinting of multiple tectonic regimes. *Sci Rep-Uk* 2019; 9.

24. Wei H, Meng Q and Wu G et al. Multiple controls on rift basin sedimentation in volcanic settings: Insights from the anatomy of a small Early Cretaceous basin in the Yanshan belt, northern North China. *GSA Bulletin* 2012; 124: 380-99.

25. Zhu G, Jiang DZ and Zhang BL et al. Destruction of the eastern North China Craton in a backarc setting: Evidence from crustal deformation kinematics. *Gondwana Res* 2012; 22: 86-103.

26. Zhang YQ, Li JL and Zhang T et al. Cretaceous to Paleocene tectono-sedimentary evolution of the Jiaolai Basin and the contiguous areas of the Shandong Peninsula (North China) and its geodynamic implications. *Acta Geologica Sinica* 2008; 82: 1229-57.

27. Meng QR, Wu GL and Fan LG et al. Tectonic evolution of early Mesozoic sedimentary basins in the North China block. *Earth-Sci Rev* 2019; 190: 416-38.

28. Zhou J, Wilde SA and Zhao G et al. Nature and assembly of microcontinental blocks within the Paleo-Asian Ocean. *Earth-Sci Rev* 2018; 186: 76-93.

29. Meng QR. What drove late Mesozoic extension of the northern China-Mongolia tract? *Tectonophysics* 2003; 369: 155-74.

30. Davis GA, Cong W and Zheng YD et al. The enigmatic Yinshan fold-and-thrust belt of northern China: New views on its intraplate contractional styles. *Geology* 1998; 26: 43-46.

31. Cope TD, Shultz MR and Graham SA. Detrital record of Mesozoic shortening in the Yanshan belt, NE China: testing structural interpretations with basin analysis. *Basin Res* 2007; 19: 253-72.

32. Wu FY, Lin JQ and Wilde SA et al. Nature and significance of the Early Cretaceous giant igneous event in eastern China. *Earth Planet Sci Lett* 2005; 233: 103-19.

33. Wang T, Zheng YD and Zhang JI et al. Pattern and kinematic polarity of late Mesozoic extension in continental NE Asia: Perspectives from metamorphic core complexes. *Tectonics* 2011; 30.

34. Griffin WL, Andi Z and O'Reilly SY et al. Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton. *Mantle Dynamics and Plate Interactions in East Asia* 1998; 27: 107-26.

35. Zhang HF. Transformation of lithospheric mantle through peridotite-melt reaction: A case of Sino-Korean craton. *Earth Planet Sci Lett* 2005; 237: 768-80.

36. Zhu R, Xu Y and Zhu G et al. Destruction of the North China Craton. *Science China Earth Sciences* 2012; 55: 1565-87.

37. Graham SA, Hendrix MS and Johnson CL et al. Sedimentary record and tectonic implications of Mesozoic rifting in southeast Mongolia. *Geol Soc Am Bull* 2001; 113: 1560-79.
38. Van der Voo R, van Hinsbergen DJ and Domeier M et al. Latest Jurassic – earliest Cretaceous closure of the Mongol-Okhotsk Ocean: A paleomagnetic and seismological-tomographic analysis. Geological Society of America Special Papers 2015; 513: 589-606.
39. Kusky TM, Windley BF and Wang L et al. Flat slab subduction, trench suction, and craton destruction: Comparison of the North China, Wyoming, and Brazilian cratons. Tectonophysics 2014; 630: 208-21.
40. Liu C, Zhu G and Zhang S et al. Mesozoic strike-slip movement of the Dunhua-Mishan Fault Zone in NE China: A response to oceanic plate subduction. Tectonophysics 2018; 723: 201-22.
41. Khanchuk AI, Kemkin IV and Kruk NN. The Sikhote-Alin orogenic belt, Russian South East: Terranes and the formation of continental lithosphere based on geological and isotopic data. J Asian Earth Sci 2016; 120: 117-38.
42. Heumann MJ, Johnson CL and Webb LE. Plate interior polyphase fault systems and sedimentary basin evolution: A case study of the East Gobi Basin and East Gobi Fault Zone, southeastern Mongolia. J Asian Earth Sci 2018; 151: 343-58.
43. Ren F, Liu Z and Qiu L et al. The prototype character of Jiaolai Basin in Cretaceous Laiyang period. Acta Sedimentologica Sinica 2008; 26: 221.
44. Meng Q, Li S and Li R. Mesozoic evolution of the Hefei basin in eastern China: Sedimentary response to deformations in the adjacent Dabieshan and along the Tanlu fault. Geol Soc Am Bull 2007; 119: 897-916.
45. Wang W, Zhu G and Zhang S et al. Detrital zircon evidence for depositional time and provenance of Mesozoic sediments in the Hefei Basin. Geol Rev. 2017; 63: 955-77.
46. Wang J, Chang SC and Lu HB et al. Detrital zircon provenance of the Wangshi and Laiyang groups of the Jiaolai basin: evidence for Early Cretaceous uplift of the Sulu orogen, Eastern China. Int Geol Rev 2016; 58: 719-36.
47. Zhang JD, Hao TY and Fan DH et al. Identification of geological time of Mesozoic strata in Hefei Basin and its significance. Acta Geologica Sinica 2009; 83: 599-608.
54. Qu H, Wang E and Zhang L et al. Zircon geochronology and its structural implications of Late Mesozoic andesite from the Beijing plain (in Chinese with English Abstract). Acta Petrol Sin 2016; 32: 3547-56.
55. Yuan H, Liu X and Liu Y et al. Geochemistry and U-Pb zircon geochronology of Late-Mesozoic lavas from Xishan, Beijing. Science in China Series D 2006; 49: 50-67.
56. Niu B, He Z and Song B et al. SHRIMP dating of the Zhangjiakou Formation volcanic rocks and implications. Geological Bulletin of China 2003; 22: 140-41.
57. He HY, Wang XL and Zhou ZH et al. Ar-40/Ar-39 dating of lujiatun bed (Jehol group) in Liaoning, northeastern China. Geophys Res Lett 2004; 31.
58. He HY, Wang XL and Zhou ZH et al. Timing of the Jiufotang Formation (Jehol Group) in Liaoning, northeastern China, and its implications. Geophys Res Lett 2004; 31.
59. Liu YQ, Li PX and Tian SG. SHRIMP U-Pb zircon age of Late Mesozoic tuff (lava) in Luaping basin, northern Hebei, and its implications. Acta Petrol. Mineral 2003; 22: 237-44.
60. Zhang H, Yuan HL and Hu ZC et al. U-Pb zircon dating of the Mesozoic volcanic strata in Luaping of North Hebei and its significance. Earth Science 2005; 30: 707-20.
61. Swisher CC, Wang YQ and Wang XL et al. The appearance and duration of the Jehol Biota: Constraint from SIMS U-Pb zircon dating for the Huajiying Formation in northern China. P Natl Acad Sci Us 2006; 113: 14299-305.
62. Chang SC, Zhang HC and Renne PR et al. High-precision Ar40/Ar39 age for the Jehol Biota. Palaeogeogr Palaeocl 2009; 280: 94-104.
63. Eberth DA, Russell DA and Braman DR et al. The Age of the Dinosaur-Bearing Sediments at Tcch, Inner-Mongolia, Peoples-Republic-of-China. Can J Earth Sci 1993; 30: 2101-06.
64. He HY, Wang XL and Zhou ZH et al. Timing of the Jiufotang Formation (Jehol Group) in Liaoning, northeastern China, and its implications. Geophys Res Lett 2004; 31.
65. Chen ZG, Zhang LC and Wu HY et al. Jurassic-earliest Cretaceous tectonostratigraphic evolution of the Erlian Basin, Northeast China: Records of polyphase intracontinental deformation in Northeast Asia. Mar Petrol Geol 2018; 96: 405-28.
66. Zhu JC, Meng QR and Peng YL et al. Decoding stratigraphic evolution of the Hailar Basin: Implications for the late Mesozoic tectonics of NE China. Geol J 2020; 55: 1750-62.
67. Zhang JH, Gao S and Ge WC et al. Geochronological framework of Mesozoic volcanic rocks in the Great Xing’an Range, NE China, and their geodynamic implications. J Asian Earth Sci 2010; 39: 786-93.
68. Yang XP, Jiang B and Yang YJ et al. Geochronological evolution of the Hailar Basin: Implications for subduction-induced delamination. Chem Geol 2010; 276: 144-65.
69. Ying JF, Zhou XH and Zhang LC et al. Geochronological framework of Mesozoic volcanic rocks in the Great Xing’an Range, northeastern China: Implications for subduction-induced delamination. Chem Geol 2010; 276: 144-65.
70. Wang C, Zhang M and Sun K et al. Latest Zircon U-Pb Geochronology of the Huoshiling
Formation Volcanic Rocks in the Southeastern Margin of the Songliao Basin. *Acta Geologica Sinica (English Edition)* 2017: 30.

73. Yu ZQ, He HY and Deng CL et al. New SIMS U-Pb geochronology for the Shahezi Formation from CCSD-SK-IIe borehole in the Songliao Basin, NE China. *Sci Bull* 2020; 65: 1049-51.

74. He HY, Deng CL and Wang PJ et al. Toward age determination of the termination of the Cretaceous Normal Superchron. *Geochem Geophy Geosy* 2012; 13.

75. Yu ZQ, He HY and Deng CL et al. New geochronological constraints for the Upper Cretaceous Nenjiang Formation in the Songliao Basin, NE China. *Cretaceous Res* 2019; 102: 160-69.

76. Qi GW, Zhang JJ and Wang M. Mesozoic tectonic setting of rift basins in eastern North China and implications for destruction of the North China Craton. *J Asian Earth Sci* 2015; 111: 414-27.

77. Lin Y, Zhang CH and Li CM et al. From dextral contraction to sinistral extension of intracontinental transform structures in the Yanshan and northern Taihang Mountain belts during Early Cretaceous: Implications to the destruction of the North China Craton. *J Asian Earth Sci* 2020; 189.

78. Renne PR, Mundil R and Balco G et al. Joint determination of $^{40}$K decay constants and $^{40}$Ar/$^{39}$Ar for the Fish Canyon sanidine standard, and improved accuracy for $^{40}$Ar/$^{39}$Ar geochronology. *Geochim Cosmochim Ac* 2010; 74: 5349-67.

79. Cope TD and Graham SA. Upper crustal response to Mesozoic tectonism in western Liaoning, North China, and implications for lithospheric delamination. *Mesozoic Sub-Continental Lithospheric Thinning under Eastern Asia* 2007; 280: 201.

80. Johnson CL. Polyphase evolution of the East Gobi basin: sedimentary and structural records of Mesozoic-Cenozoic intraplate deformation in Mongolia. *Basin Res* 2004; 16: 79-99.

81. Wang F, Zhou XH and Zhang LC et al. Late Mesozoic volcanism in the Great Xing’an range (NE China): Timing and implications for the dynamic setting of NE Asia. *Earth Planet Sci Lett* 2006; 251: 179-98.

82.Johnson CL, Webb LE and Graham SA et al. Sedimentary and structural records of late Mesozoic high-strain extension and strain partitioning, East Gobi basin, southern Mongolia. *Geological Society of America Memoirs* 2001; 194: 413-33.

83. Song Y, Ren J and Liu K et al. Post-rift anomalous thermal flux in the Songliao Basin, NE China, as revealed from fission track thermochronology and tectonic analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 2018; 508: 148-65.

84. Kuang YS, Wei X and Hong LB et al. Petrogenetic evaluation of the Laohutai basalts from North China Craton: Melting of a two-component source during lithospheric thinning in the late Cretaceous-early Cenozoic. *Lithos* 2012; 154: 68-82.

85. Pang CJ, Wang XC and Xu YG et al. Pyroxenite-derived Early Cretaceous lavas in the Liaodong Peninsula: Implication for metasomatism and thinning of the lithospheric mantle beneath North China Craton. *Lithos* 2015; 227: 77-93.

86. Xu YG, Huang X and Ma J et al. Crust-mantle interaction during the tectono-thermal reactivation of the North China Craton: constraints from SHRIMP zircon U-Pb chronology and geochemistry of Mesozoic plutons from western Shandong. *Contrib Mineral Petr* 2004; 147: 750-67.

87. Zheng YF, Xu Z and Zhao ZF et al. Mesozoic mafic magmatism in North China: Implications for thinning and destruction of cratonic lithosphere. *Sci China Earth Sci* 2018; 61: 353-85.

88. Sun JF, Yang JH and Wu FY et al. Magma mixing controlling the origin of the Early Cretaceous
Fangshan granitic pluton, North China Craton. In situ U-Pb age and Sr-, Nd-, Hf- and O-isotope evidence. Lithos 2010; 120: 421-38.

89. Li H, Li D and Geng K et al. The Mesozoic Magmatic activities Framework in Jiaodong Area: SHRIMP Chronology Recording of Single Particle Zircon (in Chinese with English Abstract). Acta Geologica Sinica 2017; 91: 163-79.

90. Gao XY and Zhao TP. Late Mesozoic magmatism and tectonic evolution in the Southern margin of the North China Craton. Sci China Earth Sci 2017; 60: 1959-75.

91. Jahn BM, Valui G and Kruk N et al. Emplacement ages, geochemical and Sr-Nd-Hf isotopic characterization of Mesozoic to early Cenozoic granitoids of the Sikhote-Alin Orogenic Belt, Russian Far East: Crustal growth and regional tectonic evolution. J Asian Earth Sci 2015; 111: 872-918.

92. Shen ZC, Hou ZQ and Yu F et al. SHRIMP zircon U-Pb ages and Hf isotopes of the intermediate-acidic rocks of Wanganzhen complex in northern part of Taihang Mountains and their geological implications. Acta Petrol Sin 2015; 31: 1409-20.

93. Chen B, Tian W and Jahn BM et al. Zircon SHRIMP U-Pb ages and in-situ Hf isotopic analysis for the Mesozoic intrusions in South Taihang, North China craton: Evidence for hybridization between mantle-derived magmas and crustal components. Lithos 2008; 102: 118-37.

94. Yang JH, Wu FY and Chung SL et al. Multiple sources for the origin of granites: Geochemical and Nd/Sr isotopic evidence from the Gudaoling granite and its mafic enclaves, northeast China. Geochim Cosmochim Ac 2004; 68: 4469-83.

95. Khanchuk AI, Grebennikov AV and Ivanov VV. Albian-Cenomanian Orogenic Belt and Igneous Province of Pacific Asia. Russ J Pac Geol 2019; 13: 187-219.

96. Sengör AMC and Burke K. Relative Timing of Rifting and Volcanism on Earth and Its Tectonic Implications. Geophys Res Lett 1978; 5: 419-21.

97. Buck WR. Modes of Continental Lithospheric Extension. J Geophys Res-Sol Ea 1991; 96: 20161-78.

98. Ruppel C. Extensional processes in continental lithosphere. J Geophys Res-Sol Ea 1995; 100: 24187-215.

101. Rey P, Vanderhaeghe O and Teyssier C. Gravitational collapse of the continental crust: definition, regimes and modes. Tectonophysics 2001; 342: 435-49.

103. Merle O. A simple continental rift classification. Tectonophysics 2011; 513: 88-95.

104. Ziegler PA and Cloetingh S. Dynamic processes controlling evolution of rifted basins. Earth-Sci Rev 2004; 64: 1-50.

105. Frizon De Lamotte D, Fourdan B and Leleu S et al. Style of rifting and the stages of Pangea breakup. Tectonics 2015; 34: 1009-29.

106. Webb LE, Graham SA and Johnson CL et al. Occurrence, age, and implications of the Yagan-Onch Hayrhan metamorphic core complex, southern Mongolia. Geology 1999; 27: 143-46.
et implications géodynamiques. Université Rennes 1, 2011.
108. Daoudene Y, Gapais D and Ruffet G et al. Syn-thinning pluton emplacement during Mesozoic extension in eastern Mongolia. Tectonics 2012; 31.
109. Wang T, Guo L and Zheng Y et al. Timing and processes of late Mesozoic mid-lower-crustal extension in continental NE Asia and implications for the tectonic setting of the destruction of the North China Craton: Mainly constrained by zircon U–Pb ages from metamorphic core complexes. Lithos 2012; 154: 315-45.
110. Yang X, Jiang B and Yang Y. Spatial-Temporal Distribution Characteristics of Early Cretaceous Volcanic Rocks in Great Xing’an Range Area (in Chinese with English Abstract). Earth Science 2019; 44: 3237-51.
111. Jamieson RA, Beaumont C and Fullsack P et al. Barrovian regional metamorphism: Where’s the heat? Geological Society, London, Special Publications 1998; 138: 23-51.
112. Vanderhaeghe O and Teyssier C. Partial melting and flow of orogens. Tectonophysics 2001; 342: 451-72.
113. Sonder LJ and Jones CH. Western United States extension: How the west was widened. Annu Rev Earth Pl Sc 1999; 27: 417-62.
114. Liu M. Cenozoic extension and magmatism in the North American Cordillera: the role of gravitational collapse. Tectonophysics 2001; 342: 407-33.
115. Traynor JJ and Sladen C. Tectonic and stratigraphic evolution of the Mongolian People's Republic and its influence on hydrocarbon geology and potential. Mar Petrol Geol 1995; 12: 35-52.
116. Zorin YA. Geodynamics of the western part of the Mongolia–Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia. Tectonophysics 1999; 306: 33-56.
117. Ma L, Yang J and Ding Z. Songliao Basin—an intracontinental sedimentary basin of combination type. In: Zhu X (ed.). Chinese Sedimentary Basins. Amsterdam: Elsevier Science Publishing Company, Inc., 1989.
118. Lamb MA, Hanson AD and Graham SA et al. Left-lateral sense offset of upper Proterozoic to Paleozoic features across the Gobi Onon, Tost, and Zuunbayan faults in southern Mongolia and implications for other Central Asian faults. Earth Planet Sc Lett 1999; 173: 183-94.
119. Watson MP, Hayward AB and Parkinson DN et al. Plate tectonic history, basin development and petroleum source rock deposition onshore China. Mar Petrol Geol 1987; 4: 205-25.
120. Zhang YQ, Dong SW and Shi W. Cretaceous deformation history of the middle Tan-Lu fault zone in Shandong Province, eastern China. Tectonophysics 2003; 363: 243-58.
121. Zhu G, Niu M and Xie C et al. Sinistral to normal faulting along the Tan-Lu fault zone: Evidence for geodynamic switching of the East China continental margin. The Journal of geology 2010; 118: 277-93.
122. Zhang FQ, Dilek Y and Chen HL et al. Structural architecture and stratigraphic record of Late Mesozoic sedimentary basins in NE China: Tectonic archives of the Late Cretaceous continental margin evolution in East Asia. Earth-Sci Rev 2017; 171: 598-620.
123. Li C and Liu SF. Cretaceous anomalous subsidence and its response to dynamic topography in the Songliao Basin, Northeast China. J Asian Earth Sci 2015; 109: 86-99.
124. Wu L, Wang F and Lin W et al. Rapid cooling of the Yanshan Belt, northern China: Constraints from Ar$^{40}$/Ar$^{39}$ thermochronology and implications for cratonic lithospheric thinning. J Asian Earth Sci 2014; 90: 107-26.
125. Su N, Zhu G and Liu C et al. Alternation of back-arc extension and compression in an overriding...
In J Earth Sci 2020; 109: 707-27.

126. Zhou JB, Cao JL and Wilde SA et al. Paleo-Pacific subduction-accretion: Evidence from Geochemical and U-Pb zircon dating of the Nandahada accretionary complex, NE China. Tectonics 2014; 33: 2444-66.

127. Engebretson DC. Relative motions between oceanic and continental plates in the Pacific basin: Geological Society of America, 1985.

128. Matthews KJ, Seton M and Muller RD. A global-scale plate reorganization event at 105-100 Ma. Earth Planet Sc Lett 2012; 355: 283-98.

129. Tang JX, Chen L and Meng QR et al. The effects of the thermal state of overriding continental plate on subduction dynamics: Two-dimensional thermal-mechanical modeling. Sci China Earth Sci 2020; 63: 1519-39.

130. Rosenbaum G, Gasparon M and Lucente FP et al. Kinematics of slab tear faults during subduction segmentation and implications for Italian magmatism. Tectonics 2008; 27.

131. Jolivet L, Faccenna C and Huet B et al. Aegean tectonics: Strain localisation, slab tearing and trench retreat. Tectonophysics 2013; 597: 1-33.

132. Govers R and Wortel MJR. Lithosphere tearing at STEP faults: Response to edges of subduction zones. Earth Planet Sc Lett 2005; 236: 505-23.

133. Davis GA, Darby BJ and Yadong Z et al. Geometric and temporal evolution of an extensional detachment fault, Hohhot metamorphic core complex, Inner Mongolia, China. Geology 2002; 30: 1003-06.

134. Davis GA. Mesozoic deformation and plutonism in the Yunmeng Shan: a metamorphic core complex north of Beijing, China. Tectonic Evolution of Asia. 1996: 253-80.

135. Zhu G, Chen Y and Jiang D et al. Rapid change from compression to extension in the North China Craton during the Early Cretaceous: Evidence from the Yunmengshan metamorphic core complex. Tectonophysics 2015; 656: 91-110.

136. Darby B, Davis G and Zhang X et al. The newly discovered Waziyu metamorphic core complex, Yiwulu Shan, western Liaoning province, North China. Earth Science Frontiers 2004; 11: 145-56.

137. Liu JL, Davis GA and Lin ZY et al. The Liaonan metamorphic core complex, Southeastern Liaoning Province, North China: A likely contributor to Cretaceous rotation of Eastern Liaoning, Korea and contiguous areas. Tectonophysics 2005; 407: 65-80.

138. Gans PB. Synextensional magmatism in the Basin and Range province: A case study from the eastern Great Basin. Geological Society of America, 1989.

139. Yin H, Zhu G and Wu X et al. Continental response to mid-Cretaceous global plate reorganization: Evidence from the Tan - Lu Fault Zone, eastern China. Gondwana Res 2020; 86: 23-45.

140. Kubota Y, Takeshita T and Yagi K et al. Kinematic Analyses and Radiometric Dating of the Large - Scale Paleogene Two - Phase Faulting Along the Median Tectonic Line, Southwest Japan. Tectonics 2020; 39: e2018T-e5372T.

141. Lee DW. Strike-slip fault tectonics and basin formation during the Cretaceous in the Korean Peninsula. Isl Arc 1999; 8: 218-31.
Figure 1 Tectonic map showing distribution of Cretaceous basins in NE Asia. The NE Asian continent is divided into two main domains, the North China craton (NCC) and eastern Central Asian orogen. The NCC can be further divided into three parts, the western, eastern and northern NCC, based on their distinct tectonic evolution in late Mesozoic. Note that passive, active and wide rift basins are distributed in different regions, with metamorphic core complexes being closely associated with active rift basins.
Figure 2 Stratigraphic correlation of Cretaceous sequences in NE Asia. Lower Cretaceous strata in the eastern North China craton start with clastic rocks, which are followed by volcanic and volcaniclastic rocks. In contrast, Lower Cretaceous sequences in the northern North China craton are marked by volcanic and volcaniclastic rocks in the lower part and clastics in the upper. In the eastern Central Asian orogen, clastic rocks dominate Lower Cretaceous successions in the western portion, whereas volcanic and volcaniclastic rocks are prevalent in the eastern portion. The Songliao basin possesses thick Upper Cretaceous strata in contrast with other basins. The number in square bracket just refers to the number of the paper in the reference.
Figure 3 Distribution of Early Cretaceous igneous rocks in the North China craton (NCC). Note that igneous rocks are particularly abundant in the northern NCC and both intrusive and extrusive rocks display a marked east-younging polarity.
Figure 4. Models for tectonic subsidence of different types of rift basins and resultant volcano-sedimentary sequences. (A) Passive rift basin; (B) Active rift basin; (C) Wide rift basin.

Refer to text for detailed explanation. eNCC = eastern North China craton; nNCC = northern North China craton; ECAO = eastern Central Asian orogen
Figure 5 Diagrams showing structures of rift basins in the eastern Central Asian orogen. (A) Map view of the Yingen basin, which is made up of many individual subbasins and associated with metamorphic core complexes; (B) Map view of Early Cretaceous Songliao basin. Note the individualities of subbasins. (C) A geologic section across the Yingen basin (a-a’ profile in A), showing marked synrift subsidence and minor postrift subsidence. (D) A geologic section across the southern Songliao basin (b-b’ profile in B) that is typified by pronounced postrift subsidence.

Abbreviations: K1=Lower Cretaceous, K1y=Yixian Formation, K1j=Jiufotang Formation, K1s=Shahai Formation, K1f=Fuxin Formation
Figure 6 Diagram showing a possible linkage between Early Cretaceous basins and the paleo-Pacific plate subduction. (A) Passive rift basins occur in the North China craton (NCC) bounded on the east by the southern subduction zone. Wide rift basins develop in the eastern Central Asian orogen (ECAO) bounded by the northern subduction zone. Active rift basins happen in the northern NCC. (B) A sketch showing that wide rift basins result from supracrustal stretching due to gravitational collapse of the thickened ECAO crust. The Songliao basin crust is significantly thinned owing to the superposition of backarc extension induced by the paleo-Pacific plate subduction. Note that the northern subduction zone was relatively fixed in Jurassic to Early Cretaceous times. (C) A sketch showing that passive rift basins originate from backarc extension triggered by a combination of rollback and retreat of the subducting paleo-Pacific plate. A big mantle wedge might have begun developing beneath the NCC since the Early Cretaceous.
Figure 7 A tectonic model showing that slab tearing played an important role in controlling active rift basin evolution and high-flux magmatism in the northern North China craton in the Early Cretaceous. Slab tearing possibly resulted from higher rate of rollback and retreat of the subducting paleo-Pacific plate at the southern subduction zone. Hot mantle materials ascended through tear fault and impinged on the overlying lithosphere, thus triggering magmatism and eastward-younging polarity as slab tearing progressed from west to east. Passive rift basins in the eastern North China craton were generated by horizontal extension induced by rapid trench retreat in conjunction with subduction rollback. Wide rift basins developed due to gravitational collapse of thickened crust of the eastern Central Asian orogen and the northern subduction zone underwent little eastward migration.