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What drove late Mesozoic extension of the northern China–Mongolia tract?

Qing-Ren Meng*

Institute of Geology and Geophysics, Chinese Academy of Sciences, PO Box 9825, Beijing 100029, China

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Abstract

The northern China–Mongolia tract exhibited a tectonic transition from contractional to extensional deformation in late Mesozoic time. Late Middle to early Late Jurassic crustal shortening is widely thought to have resulted from collision of an amalgamated North China–Mongolia block and the Siberian plate, but widespread late Late Jurassic–Early Cretaceous extension has not been satisfactorily explained by existing models. Some prominent features of the extensional tectonics of the northern China–Mongolia tract are: (1) Late Jurassic voluminous volcanism prior to Early Cretaceous large-magnitude rapid extension; (2) overlapping in time of contractional deformation in the Yinshan–Yanshan belt with development of extension-related basins in the interior of the northern China–Mongolia tract; and (3) widespread occurrence of alkali granitic plutonism, extensional basins and metamorphic core complexes in the Early Cretaceous. A new explanation is advanced in this study for this sequence of events. The collision of amalgamated North China–Mongolia with Siberia led to crustal overthickening of the northern China–Mongolia tract and formation of a high-standing plateau. Subsequent breakoff at depth of the north-dipping Mongol–Okhotsk oceanic slab is suggested as the main trigger for late Mesozoic lithospheric extension of that tract. Slab breakoff resulted in mantle lithospheric stretching of the adjacent northern China–Mongolia tract with subsequent ascent of hot asthenosphere and magmatic underplating at the base of the crust. Collectively, these phenomena triggered gravitational collapse of the previously thickened crust, leading to late Late Jurassic–Early Cretaceous crustal extension, and importantly, coeval contraction along the southern margin of the plateau in the Yinshan–Yanshan belt. The proposed model provides a framework for interpreting the spatial and temporal relationships of distinct processes and reconciling some seemingly contradictory phenomena, such as the synchronous extension of northerly terranes during major contraction in the neighboring Yanshan–Yinshan belt.

Keywords: Crustal extension; Gravitational collapse; Yinshan; Daqing Shan; Northern China and Mongolia

1. Introduction

The northern China–Mongolia tract (NCMT) consists of eastern and southern central Mongolia and northern China. It is a composite terrane bounded on the north by the Mesozoic Mongol–Okhotsk suture zone (Fig. 1). Previous work has tended to focus on specific tectonic processes, such as thrust systems (Zheng et al., 1998; Chen, 1998; Davis et al., 1998), basin structures and sedimentation (Traynor and Sladen, 1995; Hendrix et al., 1996; Jin et al., 2000;

* Fax: +86-010-662010846.
E-mail address: qrmeng@mail.igcas.ac.cn (Q.-R. Meng).

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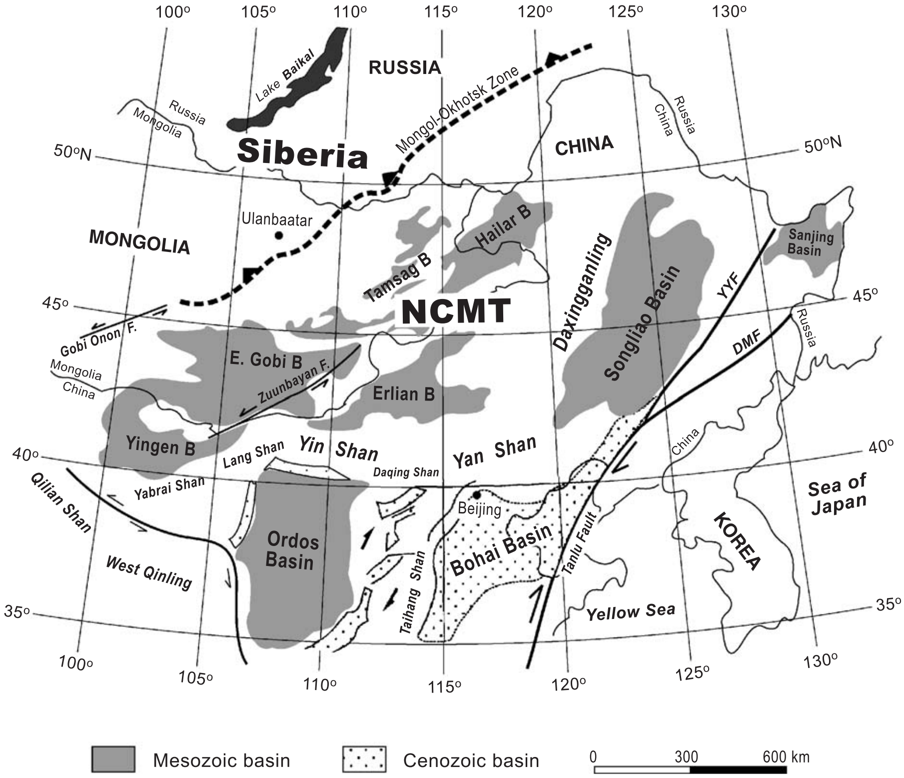

Fig. 1. Tectonic framework of the northern China–Mongolia tract (NCMT). The NCMT, separated from Siberia by the Mongol–Okhotsk suture zone, consists primarily of eastern and south-central Mongolia and northern and northeastern China, and is marked by the Yinshan–Yanshan belt on the south and by the Daxingganling belt on the east. YYF = Yilan–Yitong fault; DMF = Dunhua–Mishan fault; HSZ = Honam Shear Zone; B = basin; F = fault.

Graham et al., 2001), metamorphic core complexes (Zheng et al., 1991; Davis et al., 1996, 2001a, 2002; Van der Beek et al., 1996; Webb et al., 1999), and magmatism (Xu et al., 1994; Chen and Chen, 1997; Zhu et al., 1999; Dergunov, 2001).

Following Middle–early Late Jurassic crustal contraction (Zorin et al., 1995; Zorin, 1999), the NCMT experienced intensive extensional deformation and magmatism in late Late Jurassic and Early Cretaceous times, as manifested by development of extensional basins and metamorphic core complexes, and widespread alkali volcanism and plutonism. Middle Jurassic contractional deformation within the NCMT is widely considered a consequence of collision of the NCMT and Siberia along the Mongol–Okhotsk suture (Zorin et al., 1995; Yin and Nie, 1996; Zorin, 1999). This inference is acceptable because the collisional event appears to be coincident with crustal shortening of the NCMT in both time and space. Kravchinsky et al. (2002) recently provided new pieces of paleomagnetic evidence to the Middle Jurassic collision of the NCMT and Siberia along the Mongol–Okhotsk suture in the Trans–Baikal region. However, there is no agreement about the driver for Late Jurassic–Early Cretaceous extension. A number of thermo-mechanic models have been proposed, such as back-arc extension caused by subductive rollback of the Paleo-Pacific plate (Watson et al., 1987; Traynor and Sladen, 1995), magmatic underplating of unknown origins (Shao et al., 2000), gravitational collapse of tectonically thickened crust (Graham et al., 2001), and transtensional faulting related to collision–extrusion tectonics (Kimura et al., 1990).

It is considered that there could have existed a Mongol–Okhotsk ocean, separating the NCMT from Siberia since the latest Paleozoic (Zorin et al., 1995;

Zorin, 1999). Some attempts to reconstruct the history of this ocean (Zonenshain et al., 1990; Enkin et al., 1992; Zorin, 1999; Kravchinsky et al., 2002) have concluded that it was diachronously closed from west to east from the Middle Jurassic up to Early Cretaceous, thereby leading to oblique collision of the NCMT and Siberia. The diachronous collisional procession is further supported by simultaneous occurrence of different types of magmatism along the Mongol–Okhotsk suture zone in the Central Mongolia. Yarmolyuk and Kovalenko (2001) show that early Mesozoic subduction-related calcakaline volcanism in eastern segment of the suture zone is coeval with syn- and post-collision granitoid plutonism in the west. Polarity of northward subduction is deduced by Jurassic arc magmatism along the southern edge of Siberia (Ziegler et al., 1996) and tomographic identification of a subducted oceanic slab (Van der Voo et al., 1999). A new tectonic model is proposed here that invokes breakoff of the subducted Mongol–Okhotsk oceanic slab as the main trigger of late Mesozoic extension in the NCMT, coupled with gravitational collapsing and spreading of the previously overthickened crust. This model renders a satisfying explanation for the interrelationships of distinct geologic processes across the NCMT.

2. Early Mesozoic tectonics

2.1. Late Triassic–Early Jurassic extension

The North China block and southern Mongolia terranes were amalgamated by the end of Paleozoic time (Wang and Liu, 1986; Pruner, 1992; Wang and Mo, 1995; Lamb and Badarch, 1997), and subsequently behaved as a combined block with the NCMT being its northern part (Fig. 1). The NCMT itself is actually a collage of a number of arc terranes, with gradual exhaustion of the so-called Paleo-Asian Ocean Realm (Wang and Mo, 1995). Existence of many discrete middle-late Paleozoic suture zones in the NCMT appears consistent with the accretional tectonics (Tang, 1990; Buchan et al., 2001).

Early Mesozoic extension in the NCMT was widespread. Triassic strata are mostly missing in the Yinshan–Yanshan belt, but the extensional regime is inferred from synchronous occurrence of alkali igneous intrusions, such as nepheline syenites and monzonites (Yan et al., 2000), diabase dikes (Shao et al., 2000), and alkaline basalts (Zhu et al., 1999). These alkali intrusives yield U–Pb and K–Ar ages clustering in the range of 205–250 Ma (Yan et al., 2000). Similar Triassic alkali bodies are also documented in the Mongolian territory south of the Mongol–Okhotsk suture (SMJGRT (Soviet–Mongolia Joint Geoscience's Research Team), 1980; Yarmolyuk and Kovalenko, 2001). In addition, Davis et al. (2001b) report a Late Triassic metamorphic core complex in the Sonid Zuoqi area in the eastern Inner Mongolia, further supporting the inference of crustal stretching in this period. Early Jurassic sedimentation is regarded to have occurred in rifted basins, in that it was clearly controlled by normal faulting, as convincingly illustrated on seismic sections in the Yingen Basin (Jin et al., 2000). Early Jurassic rift basins are also recognized recently in the southwest of the Daqing Shan (Darby et al., 2001a; Ritts et al., 2001). It is still uncertain what caused the regional crustal extension in the NCMT during Early Jurassic time, but it is likely that the whole NCMT was a passive margin to the south of the Mongol–Okhotsk ocean that was subducting beneath the Siberia to the north during that time interval, as postulated by Zorin et al. (1995). Early Jurassic basins experienced strong contraction, inversion and erosion to various extents in the Middle to early Late Jurassic period. This contractional event, well known in China as the Yanshanian Orogeny, resulted in extensive inverse faulting throughout the NCMT.

2.2. Mid–Late Jurassic contraction

Crustal shortening prevailed in the NCMT during Middle to early Late Jurassic time (the Yanshanian period) in response to the continental collision of Siberia and the NCMT along the Mongol–Okhotsk suture (Yin and Nie, 1996; Zorin, 1999). The resulting thrust systems are well investigated in China–Mongolia border areas, such as in the Beishan (Zheng et al., 1996), the Daqing Shan (Zheng et al., 1998; Darby et al., 2001a), and the Yanshan (Davis et al., 1996, 2001a; Chen, 1998). Thin-skinned thrusts are believed to be the dominant structures, and displacement of some thrusts is estimated as large as 40 km (Davis et al., 2001a). Vergence of the thrusts is toward both north and south in the Yinshan–Yanshan belt, but strikes of the faults turn toward the northeast in the western Liaoning or eastern segment of the Yanshan where thrust systems are mostly east- and southeast-vergent (Davis et al., 2001a; Yang et al., 2001). Contractional structures are also observed on seismic sections of Mesozoic basins, such as the Yingen Basin (Jin et al., 2000), the Erlian Basin (Song and Dou, 1997), and the southern Mongolian basins (Traynor and Sladen, 1995), manifesting themselves as inversion of Early Jurassic rift basins that are unconformably overlain by uppermost Upper Jurassic–Lower Cretaceous sedimentary successions.

Fold-thrust deformation seems to have been distributed over the whole interior of the NCMT. It is thought that the contraction must have resulted in considerable crustal shortening and thickening of the NCMT. Present crustal thickness is around 45 km in the Yinshan belt (CNSB (Chinese National Seismological Bureau), 1991) and increases to ~ 60 km in the Khangai belt in the Central Mongolia (Zorin et al., 1993). Considering that the NCMT has not undergone significant contraction since late Mesozoic time, the crust must have been overthickened to at least 60 km as a result of Middle–early Late Jurassic collision-related contraction. The crustal overthickening, in conjunction with thermal perturbation related to late Mesozoic magmatism, would have profound influence on subsequent extensional tectonism in the NCMT, as discussed in the following sections.

3. Late Mesozoic extensional tectonics

3.1. Basins

Following the contractional event, extensional basins began developing during late Late Jurassic and Early Cretaceous times in areas north of the Yinshan–Yanshan belt, such as the Yingen, Erlian, Hailar, and Eastern Gobi basins (Figs. 1 and 2). The timing of basin initiation is constrained by both plant fossil assemblages and radiometric dating of intercalated volcanic rocks within sedimentary sequences of the basins. In Eastern Gobi basin, a volcanic interlayer at the lower part of basin fills yields a $^{40}Ar/^{39}Ar$ age of 155 ± 1 Ma, indicating that the basin started in Late Jurassic time (Graham et al., 2001). Rift sequences of the Erlian basin, east of the East Gobi basin in China, begin with the Xingganling Group consisting thick pyroclastics and volcanics with interlayered coarse-grained sedimentary rocks, up to 4 km (Fig. 2). Although the cored volcanic rocks of the basin have not yet been dated, equivalents of the Xingganling Group in outcrops in West Liaoning are well constrained by radiometric dating, yielding $^{40}Ar/^{39}Ar$ and K/Ar ages from 156 to 145 Ma (Chen and Chen, 1997). In addition, the interlayered sedimentary rocks contain abundant fossils assemblages, such as *Ferganoconcha subcentralis–F. sibirica*, *Magumbonia levidensa–M. paramecia*, *Ephemeropsis trisetalis*, *Czekanowskia rigida*, which are also indicative of Late Jurassic age of the Xingganling Group (Wang et al., 1995a,b). Upper Jurassic sedimentary rocks in the Yingen basin are dated by spore and pollen assemblages (Wu et al., 1998), and are characterized by sedimentation of alluvial and fluvial deposits (Jin et al., 2000). Therefore, crustal extension of the NCMT interior commenced at least from the late Late Jurassic and was marked by vigorous volcanism. Uncertainty, however, still exists about the correlation among the basins. Radiometric dating is thus needed to constrain the precise ages of the cored volcanics from individual basins in order to confirm the timing of their initiation.

The Early Cretaceous was the main phase of basin subsidence in the NCMT interior. Both stratigraphy and sedimentation of Lower Cretaceous sequences within those basins are well studied owing to their oil–gas potentials. Detailed analyses of fossil assemblages make it possible to make reliable correlation of stratigraphic formations of different basins, and radiometric dating of volcanic interlayers helps constrain absolute ages of the strata (Fig. 2). In general, basin subsidence was fault-controlled and continued until ~ 100 Ma. Sedimentary sequences of the basins usually display several depositional cycles, starting with fluvial conglomerates and then passing upward into lacustrine fine-gained sedimentary rocks. Multiphase rifting processes are thus inferred for the Late Jurassic–Early Cretaceous basin evolution (Graham et al., 2001). The basins were inverted at the end of Early Cretaceous time, and then overlapped by relatively thin Upper Cretaceous sedimentary rocks (Meng et al., 2002).

Individual basins in the NCMT are in reality swarms of various-scale subbasins with areas ranging

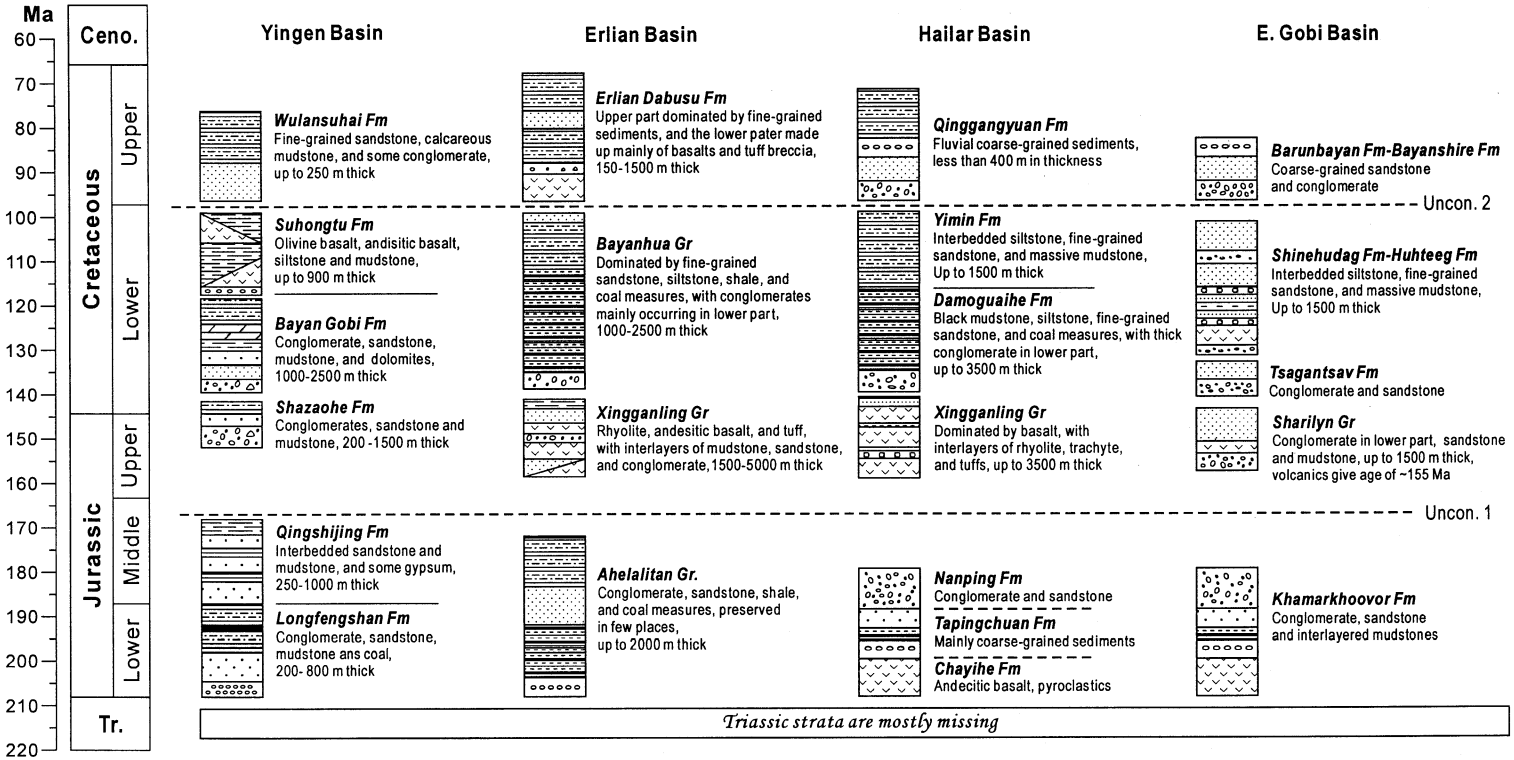

Fig. 2. Stratigraphy and lithology of four Mesozoic basins in the northern China–Mongolia tract (NCMT). Note that there exist two regional unconformities, Unconformity 1 (Uncon. 1) and Unconformity 2 (Uncon. 2), respectively, but the duration of the unconformities is uncertain. Uncon. 1 corresponds to the Middle Jurassic compressional event (Yanshanian orogen) that resulted in widespread thrusting throughout the NCMT. However, the reason for Uncon 2 remains unclear. Breaks are also present in the Upper Jurassic–Lower Cretaceous sequences, but their stratigraphic positions vary from basin to basin. Stratigraphic sequences are after Wang et al. (1995b), Wu et al. (1998), and Graham et al. (2001).

from ~30 to ~3500 km^2. Larger subbasins apparently evolved from lateral coalescence of adjoining subbasins, showing a relative narrow shape in plan view and containing several depocenters along the basin strike (Fig. 3). Cross-sections of the subbasins mostly display half-graben geometries and bounding faults usually display listric shapes (Fig. 4). High-strain extension was localized on the linked through-going bounding faults of the larger subbasins, some of which may eventually have evolved into shallow-dipping detachments. Also, subbasins above them would have developed into supradetachment basins, as defined by Friedmann and Burbank (1995). Fig. 5 shows a subbasin in the Yingen basin, which is clearly bounded on one side by a shallow-dipping normal detachment fault. Supradetachment basins are also observed in association with development of the Hohhot metamorphic core complex in the Daqing Shan area (Darby et al., 2001b; Davis et al., 2002).

Notwithstanding that they are very pronounced in the NCMT, the normal faults seldom penetrate into the deep crust but commonly sole out at depths of 6–8 km as observed on seismic profiles. Subbasins are relatively shallow, with sedimentary successions rarely exceeding 5 km in thickness (Fig. 4). Another noticeable characteristic of the subbasins is that they underwent no or little post-rift thermal subsidence usually quite striking in rifted basins (McKenzie, 1978). As shown in Fig. 4, the Erlian Basin is floored by volcanics that occurred mainly in Upper Jurassic but could continue into Lower Cretaceous strata, indicative of an active rifting regime of the basin. In reality, the volcanics are broadly distributed both in the highs and lows within and outside the Erlian Basin, and may or may not be influenced by normal faulting. Normal faulting became prevailed in the Early Cretaceous (Fig. 4), and apparently controlled subsidence and deposition. The rift fills were then covered with Upper Cretaceous sedimentary rocks usually less than 500 m thick. The regional unconformity is believed the result of uplifting of the basins, although the reason for the uplift is uncertain. Upper Jurassic volcanics also occur

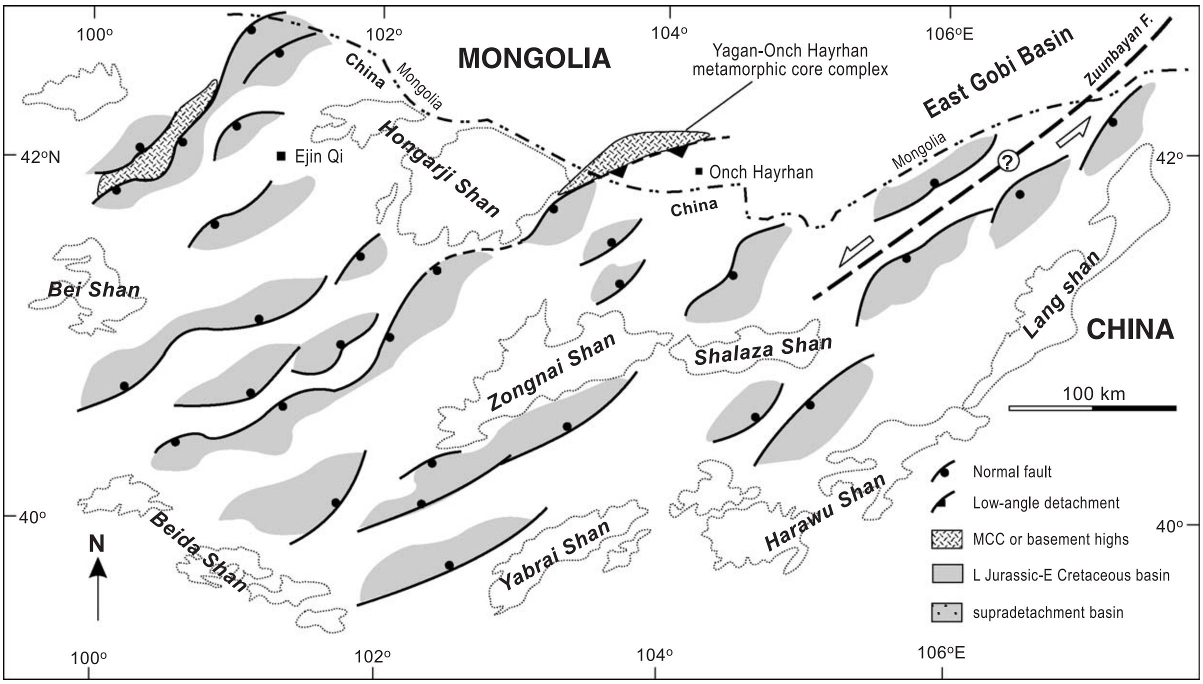

Fig. 3. Diagram showing distribution of subbasins within the Yingen Basin, westernmost Inner Mongolia. Note that subbasins are relatively isolated from each other, and that some larger ones are apparently due to lateral linkage of adjacent subbasins forming narrow sedimentary zones bounded by linked faults. Metamorphic core complexes (MCC) tend to be exhumed in the footwalls of larger linked subbasins, such as the Yagan–Onch Hayrhan MCC. Refer to Figs. 4 and 5 for cross-sectional geometry of the faults.

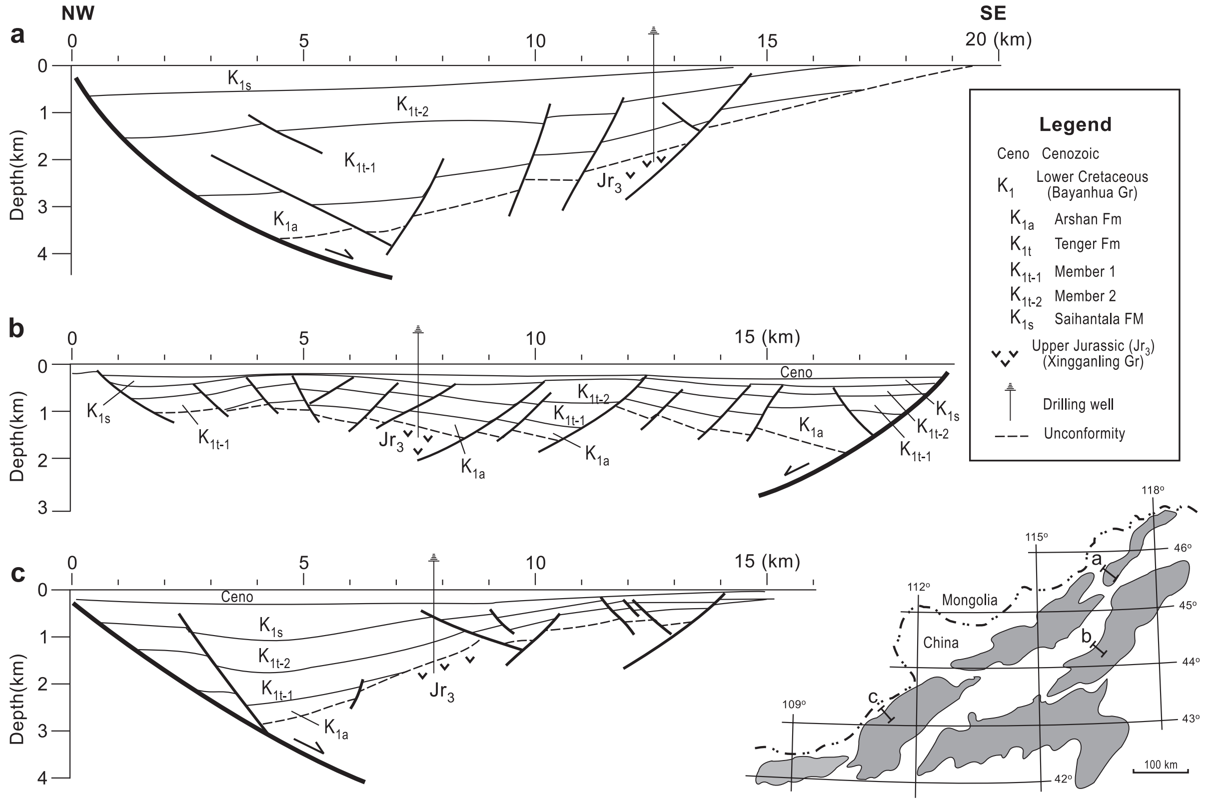

Fig. 4. Geological cross sections according to the interpretation of seismic profiles from the Erlian Basin. Subbasins are clearly bounded by listric normal border faults, and sediment fills are less than 5 km in thickness. Also noticeable is insignificance or lack of post-rifting subsidence. Note that Upper Jurassic volcanics develop at the base of basins, marking initiation of this active rift basin. Refer to index map for localities of the sections.

at the base of the Songliao Basin (Fig. 6), and can be as thick as 2 km (Xie, 2000). There exist, however, differences in subsidence history between the basins in the NCMT and the Songliao Basin in northeastern China, in that the latter experienced significant thermal subsidence following Early Cretaceous initial rifting (Fig. 6). The thermal subsidence persisted until the end of the Late Cretaceous and received sediments up to 6 km (Zhang et al., 1996). Cretaceous development of the Songliao basin, characterized by early-stage rifting and late-stage sagging, seems in accord with mode of extensional basins of McKenzie (1978) and Roydon and Keen (1980). Diverse tectonic subsidence of these distinct basins reflects differing thermo-tectonic processes beneath the two regions.

Widespread distribution of the shallow-crustal extensional basins is a remarkable feature of the NCMT in Early Cretaceous time and is also characteristic of extended terranes with thickened crust and elevated geothermal gradient (Buck, 1991). Individual basins, such as the East Gobi, Erlian, and Yingen basins, possibly together made up a shallow-crustal extensional basin system in the NCMT during the period from late Late Jurassic to Early Cretaceous time. Normal faults bounding subbasins in the NCMT might have arisen in part from reactivation of preexisting thrust fabrics, as suggested by their shallow-angle nature and parallelism with strike of neighboring thrusts. Some faults, as inferred from seismic sections, controlled not only Early Cretaceous basins but also clearly served as a normal bounding faults of Early Jurassic half-grabens, though some appear to have been reactivated as reverse faults in Middle Jurassic contractional event. Thus, some Early Creta-

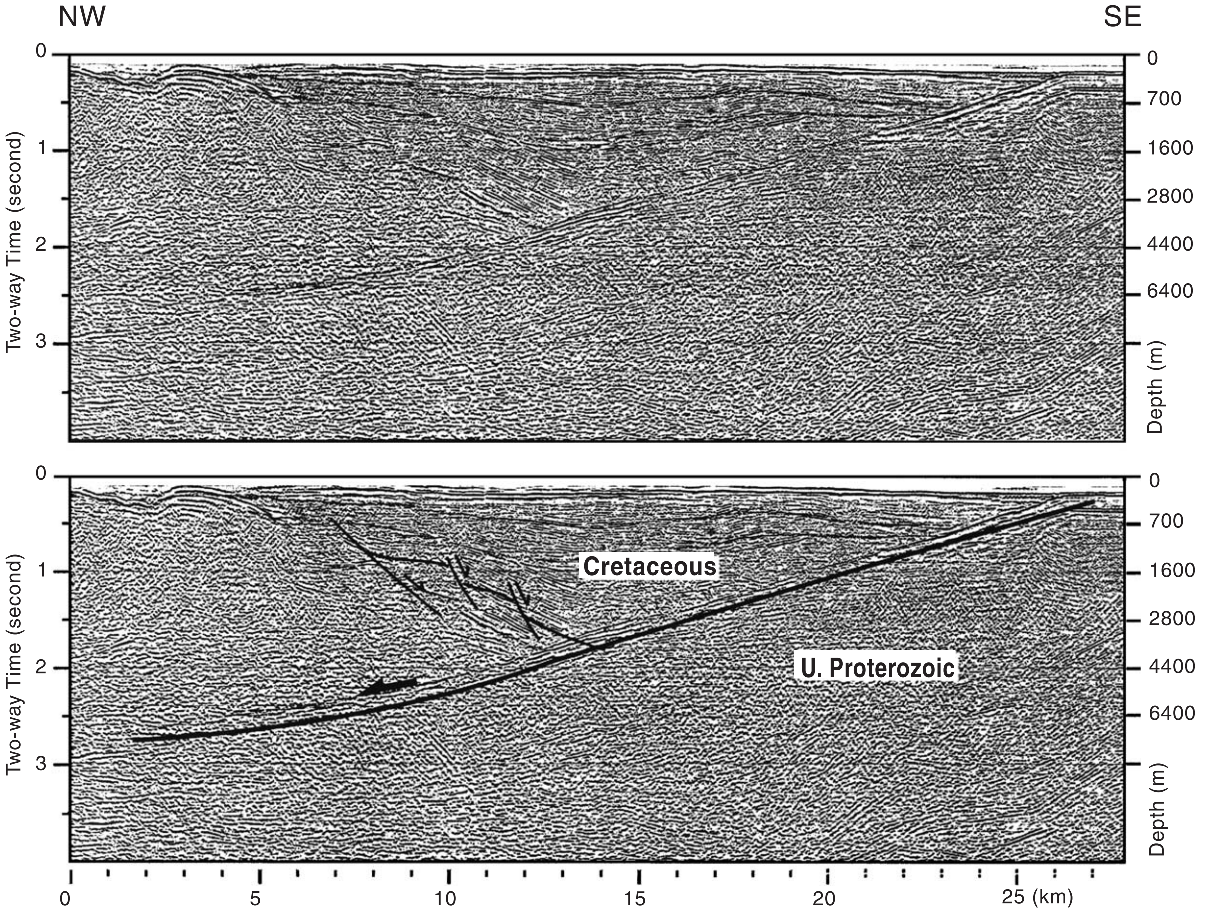

Fig. 5. Seismic section from the Yingen Basin, showing typical low-angle normal detachment fault that controls deposition of the Lower Cretaceous sequence. Internal unconformities are also evident, possibly implying multi-phase rifting processes. Note that there is no or little post-rifting subsidence.

ceous faults in the NCMT might have had a complicated kinematic history.

3.2. Metamorphic core complexes

Early Cretaceous metamorphic core complexes have been widely recognized in the Yinshan and Yanshan belt (Davis et al., 1996, 2001a, 2002; Darby et al., 2001b), China–Mongolia border areas (Zheng et al., 1991; Webb et al., 1999), and in Central Mongolia north of the Mongol–Okhotsk suture (Van der Beek et al., 1996; Zorin, 1999). For instance, the Hohhot core complex is beautifully exposed in the eastern portion of the Daqing Shan north of Hohhot, the capital city of Inner Mongolia. The Hohhot detachment, with its strike running roughly from east to west, manifests itself as a typical shallow-angle normal fault (Fig. 7). The lower plate is composed mostly of mylonitized Precambrian crystalline rocks and granitic intrusions, whilst the upper plate consists mainly of non-metamorphosed and faulted Mesozoic strata. Lower Cretaceous sequences that were deposited synchronously with activity of the Hohhot detachment are actually the products of a supradetachment basin. Displacement on the Hohhot detachment is estimated at ~40 km (Darby et al., 2001b; Zheng et al., 2001; Davis et al., 2002).

Exhumation of the core complexes implies rapid extension of the NCMT crust in the Early Cretaceous. This timing is constrained by $^{40}Ar/^{39}Ar$ dating of synkinematic biotites at 129 to 126 Ma for the

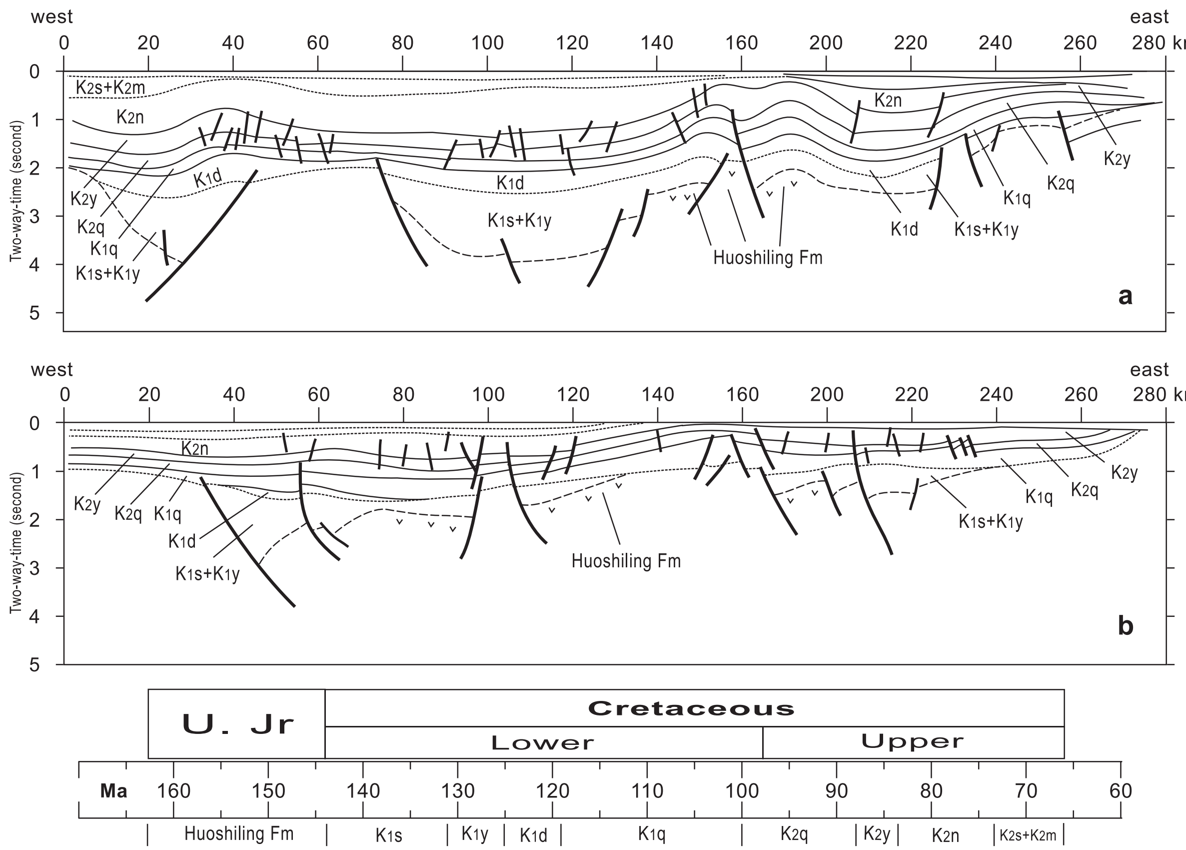

Fig. 6. Line drawing of two seismic profiles across the Songliao Basin in the northeast China. The Shahezi (K_1s) and Yingkou (K_1y) Formations represent the rifting period of the basin, whereas higher Lower–Upper Cretaceous strata were deposited in post-rifting (thermal subsidence) phase with sedimentary thickness up to 6000 m. This subsidence history strikingly contrasts with that of basins in the interior of the northern China–Mongolia tract (compared with Fig. 4 to see their difference in tectonic subsidence histories). The Upper Jurassic Huoshiling Formation marks the lowest portion of the Songliao Basin and is mostly composed of volcanic and pyroclastics rocks, indicating initiation of this active rift basin. Numerous small-scale normal faults are present and largely confined in post-rifting sequence. The basin was inverted toward the end of the Late Cretaceous. Lower Cretaceous: K_1s = Shashiling Fm; K_1y = Yingkou Fm; K_1d = Denglouku Fm; K_1q = Quantou Fm; Upper Cretaceous: K_2q = Qingshan Fm; K_2y = Yaojia Fm; K_2n = Nenjiang Fm; K_2s = Sifangtai Fm; K_2m = Mingshui Fm. Cross sections are after Zhang et al. (1996) and ages of Cretaceous stratigraphic intervals are from Wang et al. (1995a,b).

Yagan–Onch Hayrhan core complex (Webb et al., 1999), by $^{40}Ar/^{39}Ar$ rapid cooling ages of K-feldspar in footwall granodiorite at ca. 118–116 Ma in the Yunmeng Shan core complex (Davis et al., 1996), and by U–Pb and $^{40}Ar/^{39}Ar$ age controls of ca. 120 Ma for the Hohhot core complex of the Yinshan belt (Davis et al., 2002).

Rapid exhumation of the core complexes might be caused by extensional collapse of thickened crust (Buck, 1991; Morley, 2002) and/or promoted by plutonism (Lister and Baldwin, 1993). Both mechanisms may apply to the formation of metamorphic core complexes in the NCMT. The NCMT crust is shown to have experienced shortening and thickening prior to the Early Cretaceous extension, thus being susceptible to gravity collapse. Davis et al. (2002) show that extension in the Daqing Shan area occurred in less that 4 Ma after preceding thrust deformation. Apatite fission track (AFT) thermo-chronology study of the Baikal region also reveals a rapid cooling process from temperature >120 °C at ca. 140 Ma to 70 °C at ca. 120 Ma, indicating that extensional denudation immediately followed the contraction along the Mongol–Okhotsk suture (Van Der Beek et

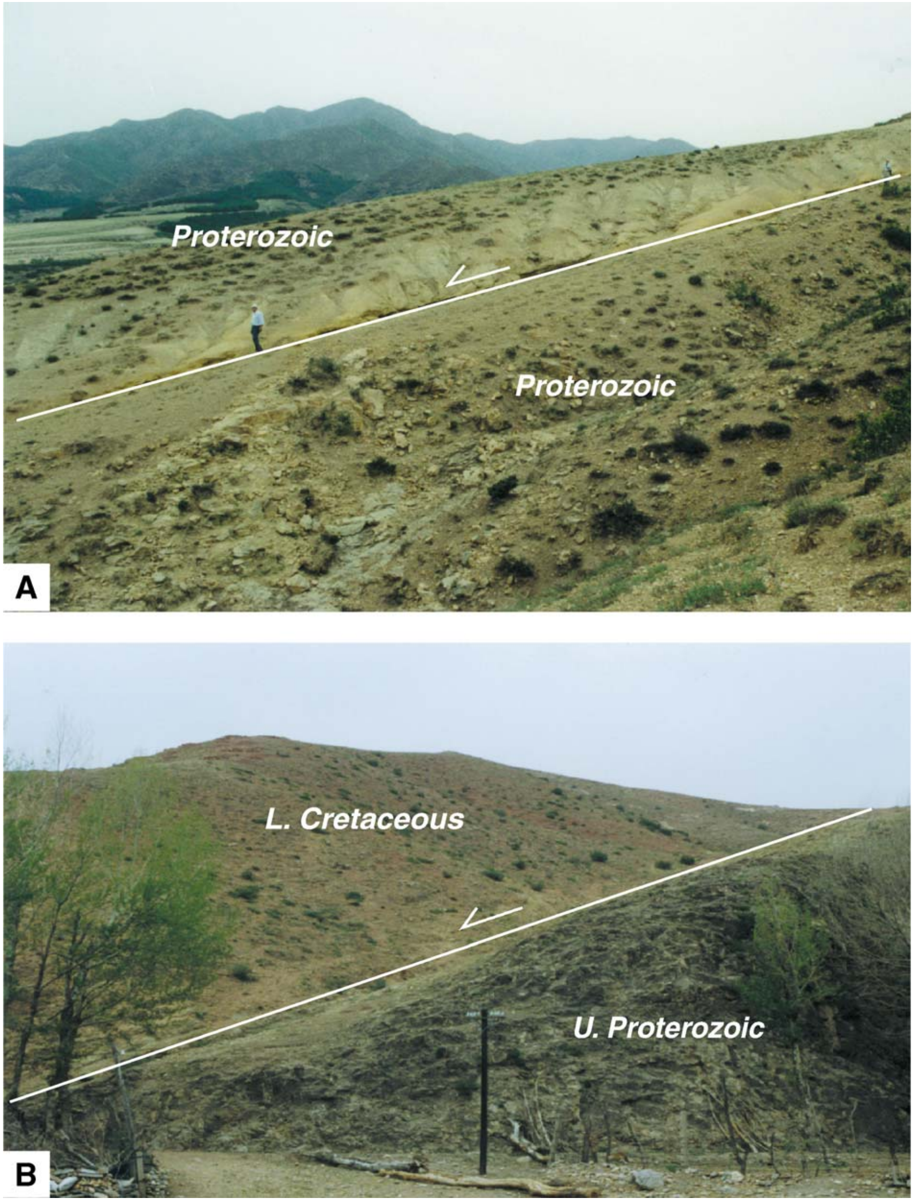

Fig. 7. Field photos showing typical normal detachment faults, dipping southward (A) and separating Lower Cretaceous alluvial and fluvial sediments from underlying upper Proterozoic metamorphic rocks (B) in the Daqing Shan, Inner Mongolia.

al., 1996). Granitoid intrusions are sometimes observed within or closely adjacent to the core complexes and shortly predate occurrence of the complexes. For instance, undeformed elliptical granite intrusion within the Yagan–Onch Hayrhan metamorphic core complex yields a zircon U–Pb age of 135 ± 7.6 Ma (Wang et al., 2001), several million years earlier than the formation of the complex that was exhumed during 129–126 Ma (Webb et al., 1999). Granitoids in the Yanshan belt yield a cluster of U–Pb ages from 140 to 120 Ma, also predating the Yunmeng Shan core complex there (Davis et al., 2001a). Implicitly, Early Cretaceous plutonism in the NCMT might have exerted some impacts on exhumation of the metamorphic core complexes by lowering crustal strength and facilitating ductile shearing along normal detachment faults and rapid denudation of footwalls.

3.3. Magmatism

Large-volume rift-related volcanic eruption was particularly striking in the Late Jurassic, and continued into Early Cretaceous time. The volcanics are distributed over a vast region south of the Mongol–Okhotsk suture and floor many late Mesozoic sedimentary basins, such as the Erlian Basin (Fig. 4). Cumulative thickness of the volcanic successions is up to ~ 5 km in the Erlian basin, ~ 4 km in the Yanshan, and ~ 3.5 km in the Daxingganling (Song and Dou, 1997; Xie, 2000). Timing of the volcanism is bracketed by Late Jurassic fossils from sediments intercalated with the volcanics and by radiometric dating that exhibits a cluster of ages from ~ 150 to 130 Ma (Ren et al., 1995; Chen and Chen, 1997; Davis et al., 2001a; Graham et al., 2001). The volcanics consist mostly of alkaline basalts, andesite, trachyandesite, potassic trachyte and subordinate rhyolite (Chen and Chen, 1997), and are geochemically characterized by initial $^{87}Sr/^{86}Sr$ ratios of 0.7045–0.7059 and $\varepsilon_{Nd}(t)$ values of -8.47 to $+3.88$, clearly indicative of the involvement of mantle-derived melts (Shao et al., 2001).

Late Mesozoic volcanics are also widespread in Central and South Mongolia south of the Mongol–Okhotsk suture, and consist mostly of basic and alkaline rocks, such as alkali and peralkaline olivine- and pyroxene-basalts, tephrites, nephelinite, and basanites with K–Ar ages from 155 to 115 Ma (Yarmolyuk and Kovalenko, 2001). These volcanics are characterized by low $^{87}Sr/^{86}Sr$ and high $\varepsilon_{Nd}(t)$ values, displaying geochemistry similar to that of their equivalents in northern China. Study of isotopic composition of these volcanics and associated mantle xenoliths like Iherzolites suggests that the melts should have derived from EM II-type mantle, presumably pertaining to mantle plume (Yarmolyuk and Kovalenko, 2001).

Granitic plutonism also accompanied eruption of the volcanic rocks, but became more vigorous in Early Cretaceous time following the peak of volcanism. The plutons are mainly alkali and peralkaline and geochemically resemble the volcanics, with low ratios of $^{87}Sr/^{86}Sr$ (~ 0.705) and high positive value of $\varepsilon_{Nd}(t)$ (~ 2.5), implying considerable mixing of the mantle and crustal materials (Shao et al., 2001). The most distinctive intrusives are syenites and syenogranites, which occur in broad areas including the Yanshan–Yinshan belt, northeast China, and eastern Mongolia regions (SMJGRT, 1980; Wu et al., 1999; Yarmolyuk and Kovalenko, 2001). Some boreholes penetrating into the basement of Mesozoic basins in the NCMT also prove the existence of Late Mesozoic granites in addition to synchronous volcanic rocks. The plutonic activity can also be depicted from seismic profiles, on which igneous bodies apparently intrude sedimentary layers. Granitic plutons in the Yinshan–Yanshan ranges exhibit a cluster of ages from ~ 151 to 125 Ma (Zheng et al., 2000) and Rb–Sr isochron ages from 130 to 120 Ma in Central and South Mongolia (Yarmolyuk and Kovalenko, 2001). Voluminous alkali and peralkaline granitic plutons suggest considerable melting of the lower crust, possibly as a result of decompression of extending and/or delaminating lithosphere and high heat influx, or their combined effects. Extensive basalt underplating, accompanied by lithospheric extension, has been invoked to explain the late Mesozoic plutonism (John et al., 2000; Shao et al., 2000).

It is interesting to note that Late Jurassic–Early Cretaceous magmatism was quite more vigorous in the early stage of the extensional basin development in the NCMT. This situation is particularly evidenced by evolution of the basins, such as the Erlian, Hailar, and East Gobi basins (Figs. 2 and 4), whose initial faulting-induced subsidence started synchronously with large-volume rift-related volcanic outburst. The progression from early-stage vigorous volcanism to late-stage development of strongly rifted basins and metamorphic core complexes suggests an active mode of rifting, as defined by Sengör and Burke (1978).

As show in Fig. 8, late Mesozoic volcanic rocks are not restricted to the NCMT in East Asia, and synchronous volcanics are also distributed along the eastern coast of China. This pattern of volcanic distribution makes many researchers attribute the late Mesozoic magmatism in East Asia, including the NCMT, to the westerly subduction of paleo-Pacific plate as a whole (Wu et al., 1982; Lapierre et al.,

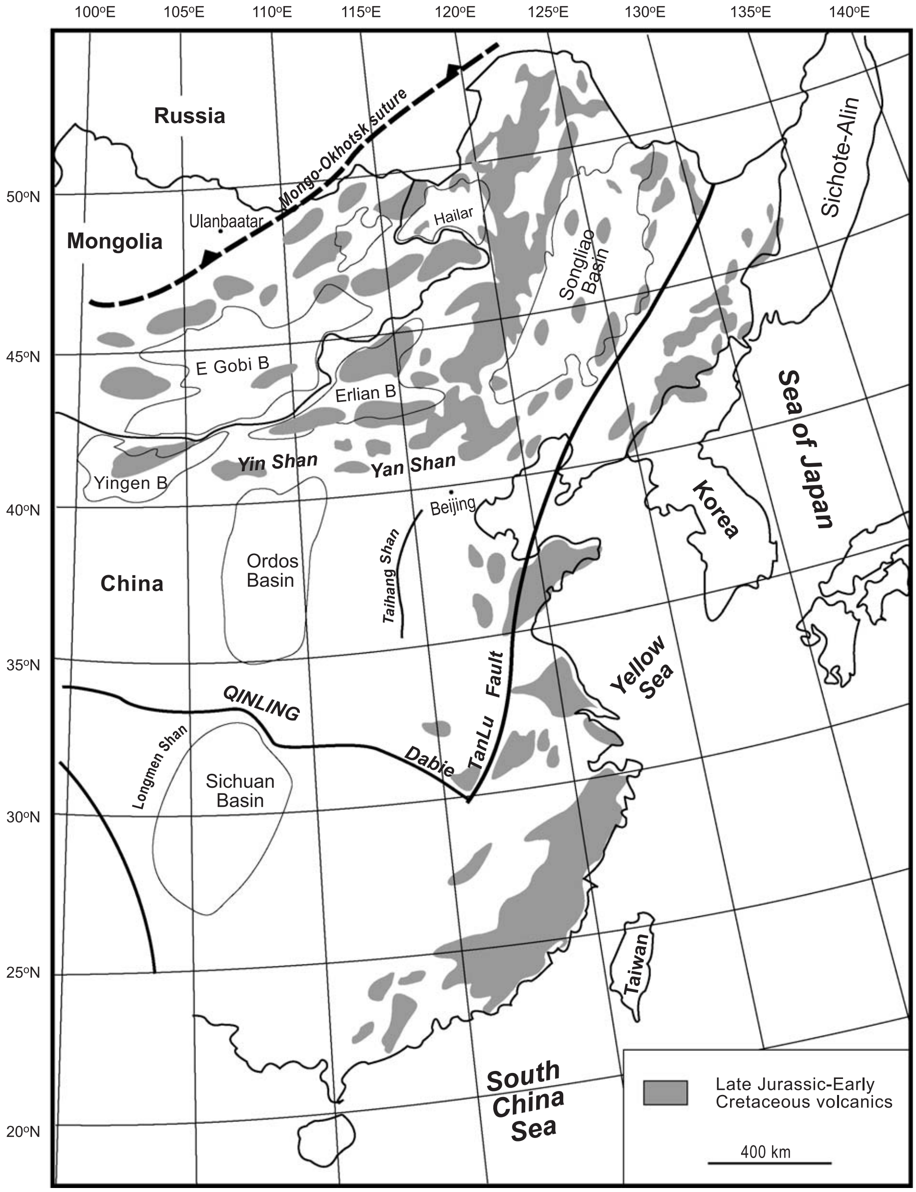

Fig. 8. Diagram showing distribution of Late Mesozoic volcanic rocks in eastern margin of China and the northern China and Mongolia tract (NCMT). It is noteworthy that Late Mesozoic volcanism occurs over a broad area south of the Mongol–Okhotsk suture, and that the westernmost occurrence of the volcanics in the NCMT is as far as up to 2000 km away from the eastern coast of Asia. Refer to the text for distinction in geochemistry of the volcanic rocks in the NCMT and the eastern margin of Asia. Compiled mainly from Wu et al. (1982), SMJGRT (1980) and Yarmolyuk and Kovalenko (2001).

1997; Zhou and Li, 2000, Ratschbacher et al., 2000). It is true that the late Mesozoic magmatism along the eastern margin of China, in particular, in the south-eastern China, might be subduction-related, in that this inference is consistent with the results of relevant geochemical studies (Lapierre et al., 1997). Late Jurassic–Early Cretaceous volcanics in SE China are mostly porphyritic rocks and some are isotopically characterized by negative $\varepsilon_{Nd}(t)$ values (-5.3 to -4.7) and high initial $^{87}Sr/^{86}Sr$ ratios (0.7079 to 0.7084). Associated and contemporaneous granitoids display quite similar isotopic features, with their $\varepsilon_{Nd}(t)$ values ranging from -8.8 to -7.1 and initial $^{87}Sr/^{86}Sr$ ratios from 0.7081 to 0.7089 (Lapierre et al., 1997). These isotopic features are clearly indicative of a continental magma-arc setting, often referred to as an Andean-type continental arc for the eastern margin of China. By comparison, the concurrent magmatism in the NCMT, marked by high $\varepsilon_{Nd}(t)$ values and low initial $^{87}Sr/^{86}Sr$ ratios, strikingly contrast the continental magmatic-arc rock associations along the eastern margin of China. This distinction in isotopic chemistry implies that late Mesozoic magmatism in these two regions owed their origin to differing thermo-tectonic processes. In other words, the westerly subduction of the paleo-Pacific plate might be the cause of Late Jurassic–Early Cretaceous volcanism and plutonism in the eastern margin of China, but contemporaneous magmatism in the NCMT was related to another kind of thermo-tectonic process to be dealt with later in this paper.

4. Crustal contraction coeval with extension

Late Mesozoic crustal extension has been shown to postdate the Middle Jurassic contractional deformation in the NCMT and is convincingly recorded by the basin tectono-sedimentary development. However, recent studies of the Yinshan–Yanshan fold-and-thrust belt, lying along the southern and southeastern edge of the NCMT (Fig. 9), show that the compressional deformation there persisted into Early Cretaceous time (Davis et al., 2001a), apparently synchronous with the development of extensional basins and rift-related magmatism in the interior of

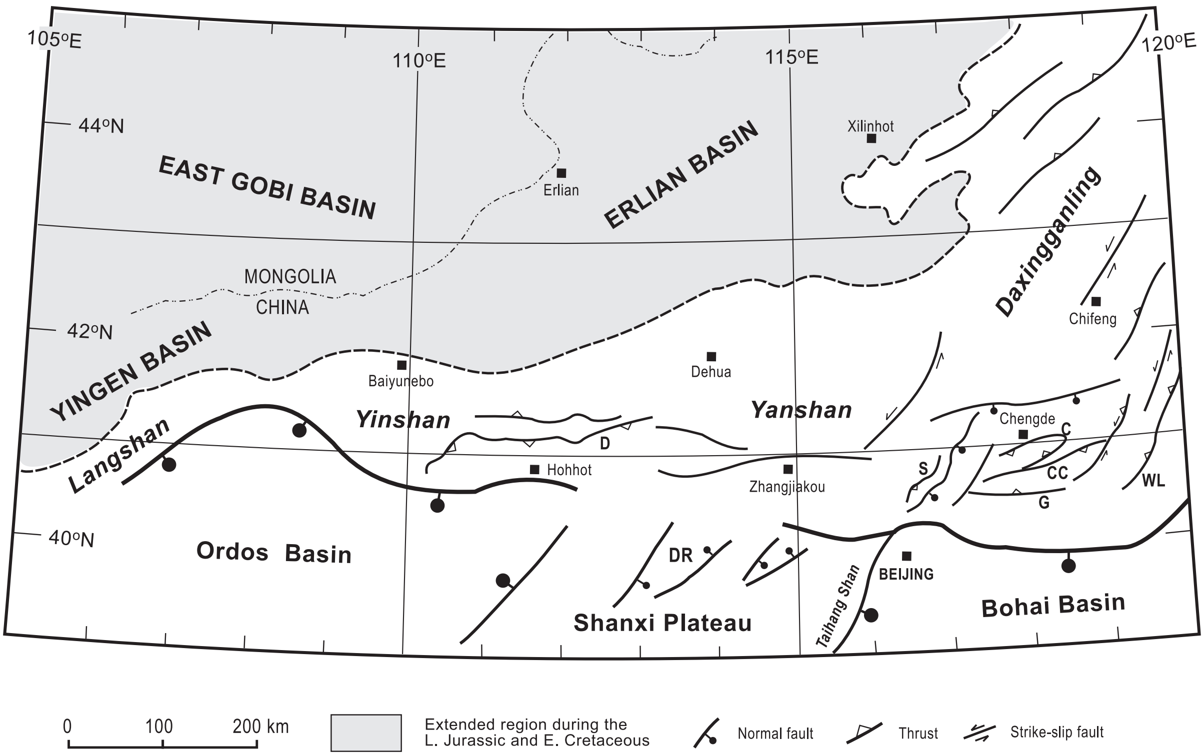

Fig. 9. Diagram showing spatial relation of coeval internal extension (East Gobi and Erlian basins) and peripheral contraction (Yinshan–Yanshan belt) in the south of the northern China–Mongolia tract in Early Cretaceous time. D = Daqing Shan thrust; C = Chengde thrust; CC = Chengde County thrust; WL = West Liaoning thrust; G = Gubaikou thrust; S = Shisanling thrust; HD = Hefangkou detachment; HMCC = Hohhot metamorphic core complex.

the NCMT. This time overlapping has been a dilemma in the study of the Yanshan belt (Davis et al., 2001a).

Chronology of the thrusting and folding in the Yanshan belt was previously constrained on the basis of structural crosscutting relationships and ages of strata and volcanic layers uncomfortably overlying some thrust faults. These approaches are themselves effective and provide first-order controls on the timing of the compressional event. Recently, additional radiometric dating of volcanic ($^{40}Ar/^{39}Ar$) and plutonic (U/Pb) rocks, which overlie or cut the thrusts, and has imposed tighten constraints on chronology of the thrusting deformation (Davis et al., 2001a). The chronological results confirm that major contraction in the Yanshan belt took place in Middle to Late Jurassic time, but continued into the earlier Early Cretaceous when the crustal extension prevailed in the interior of the NCMT (Fig. 9). For instance, the Chengde thrust in the northern Hebei province are of Late Jurassic age because they override Middle Jurassic strata and are cut by plutons dated at ca. 132 Ma (Davis et al., 2001a). In addition, there are also a number of thrust faults (Fig. 9) that were active during the period from Late Jurassic to Early Cretaceous time, such as Yunmeng Shan thrust, Sihetang nappe, Miyun Reservoir thrust, and Gubeikou reverse fault in the Yanshan belt, and northeast-striking reverse faults in western Liaoning province (Davis et al., 1996, 2001a). Some localized contractional deformation is as young as ca. 115–120 Ma (Davis et al., 2001a). In the Yinshan region (Fig. 1), the thrusting is also demonstrated to be active in Early Cretaceous time (Davis et al., 2001a).

Mechanism for Late Jurassic–Early Cretaceous crustal contraction in the Yinshan–Yanshan belt has long been unclear. Prolonged diachronous collisional process between the Siberia and the amalgamated North China and Mongolia blocks has been invoked to account for the compressional deformation in the Yanshan (Zheng et al., 2001), but this speculation is apparently implausible because the Late Jurassic–Early Cretaceous NCMT between the Mongol–Okhotsk suture and the Yinshan–Yanshan belt was clearly in extensional regime, as evidenced by widespread development of extensional basins. This dilemma, however, can be well resolved in the new model presented below.

5. Mechanisms for late Mesozoic extension

5.1. Previous models

Among the drivers possibly responsible for the late Mesozoic extension in the NCMT, Pacific backarc extension is the most popular one (Watson et al., 1987; Traynor and Sladen, 1995; Ratschbacher et al., 2000). Backarc extension has been attributed to subduction of “the paleo-Pacific plate” (Watson et al., 1987; Traynor and Sladen, 1995), but this mechanism fails to account for the fact that late Mesozoic extension occurred over a vast area, affecting regions like the Yingen basin more than 2000 km from the eastern margin of the NCMT, as manifested by distribution of extensional basins and rift-related volcanic and plutonic rocks (Figs. 1 and 8). In practice, the late Mesozoic was a period when the Izanagi plate primarily moved toward the north or north–northeast, thereby resulting in large-scale sinistral transpression at the eastern edge of the NCMT (Maruyama and Seno, 1986; Kimura et al., 1990) and giving little chance for inducing broad backarc extension throughout the NCMT. Prevalent Early Cretaceous (~ 132–100 Ma) left-lateral strike-slip faulting in NE China, such as the Dunhua–Mishan and the Yilan–Yitong faults (Fig. 1), is consistent with such plate boundary kinematics (Kimura et al., 1990; Song and Dou, 1997). The Tanlu fault, a major middle Mesozoic crustal-scale sinistral strike-slip fault in East Asia, is considered to be related to the collision of the North and South China blocks (Gilder et al., 1999), but its late Mesozoic activity might have been significantly affected by the north–northeastward motion of the Izanagi plate (Xu and Zhu, 1994; Ratschbacher et al., 2000). Oblique motion of the Izanagi plate relative to the Asian continent is also regarded to be the cause of large-scale sinistral strike-slip shearing along the Honam Shear Zone in Korea Peninsular (Otoh and Yanai, 1996).

Although not influencing areas in the interior, the oblique subduction of the Izanagi plate might have resulted in late Mesozoic magmatism and basin formation along the eastern edge of the East Asia. The Kyongsang Basin, one of the Early Cretaceous pull-apart basins in the southeastern of Korean Peninsular is attributed to the transtensional tectonics pertaining to the oblique subduction of the Izanagi plate (Chough et al., 2000). The Songliao Basin in the northeast China could have developed in a similar tectonic setting. Unlike coeval internal basins of the NCMT, the Songliao Basin underwent very pronounced thermal subsidence after earliest Early Cretaceous rifting (Fig. 6). The distinct subsidence history of the Songliao Basin indicates that its underlying lithosphere might have been thinned to a considerable degree, and subsequent thermal contraction could have led to significant post-rift thermal subsidence and thick sediment infilling. Backarc transtensional force might be responsible for initiation of the Songliao Basin, analogous to the development of the synchronous Kyongsang Basin in the southeastern Korean Peninsular. More orthogonal subduction of the paleo-Pacific plate became gradually dominant toward the end of the Late Cretaceous (Engebretson et al., 1985) and generated the Bohai Gulf Basin in eastern China during the early Tertiary (Allen et al., 1998).

5.2. New model

A new explanation is advanced here for late Mesozoic extension of the NCMT by taking into account the time–space relationships of all the key processes (Fig. 10) and invoking the breakoff of the northward subducting Mongol–Okhotsk oceanic slab as the main trigger of intraplate extension. Of great importance is the identification by seismic tomography imaging of a fossil oceanic slab in the lower mantle northwest of Lake Baikal (Van der Voo et al., 1999). This slab is considered to be the remnant of the

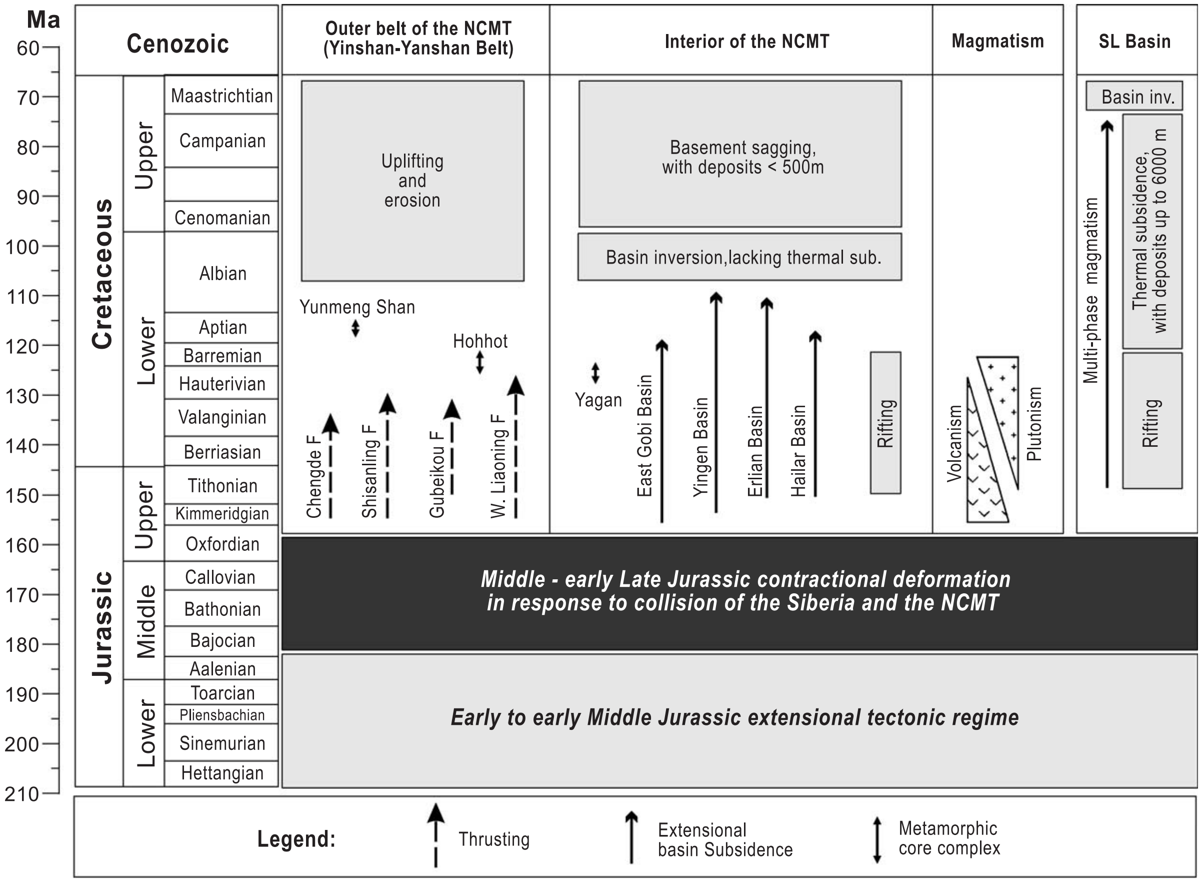

Fig. 10. Diagram showing the time–space relationships of diverse tectonic processes in the northern China–Mongolia tract (NCMT) and adjacent regions in late Mesozoic time. Refer to Figs. 1, 3 and 9 for localities of major thrusts, metamorphic core complexes, and basins. SL=Songliao.

Mongol–Okhotsk oceanic lithosphere subducted in the Middle–Late Jurassic times. This model attributes Late Mesozoic extensional tectonics of the NCMT in larger part to the progressive rupture and separation of this subducting oceanic slab (Fig. 11).

Slab breakoff is the negative buoyancy-driven separation of attached dense oceanic lithosphere from adjoining less-dense continental lithosphere during continent–continental collision (Davis and von Blanckenburg, 1994). Crustal compression dominates in the early stage of the collision, but with time the descending less-dense continental lithosphere may experience extension due to the pulling of the faster downgoing high-density oceanic slab. The resultant extension should mainly be concentrated within the lower and middle lithosphere by means of simple or pure shear, or their combination, whilst the upper lithosphere may still be in a compressional state. Mantle partial melting is induced by the lithospheric stretching in conjunction with conductive heating from the upwelling asthenosphere, leading to vigorous volcanism and plutonism with mantle parentage (Davis and von Blanckenburg, 1994). Once the oceanic lithosphere is completely detached from adjacent continental lithosphere, the hot rising asthenosphere further promotes uplift and high-rate extension of the upper lithosphere over a broad area.

The Mesozoic tectonic scenario of the NCMT can be envisaged as follows. Continued northward subduction of the Mongol–Okhotsk Ocean eventually led to collision of the NCMT and Siberia and brought about intensive contractional deformation and thickening within the NCMT, building up a high-standing plateau. Transition from crustal compression to extension occurred in Late Jurassic interval. It is speculated here that the pulling of the downgoing Mongolia–Okhotsk oceanic lithosphere eventually caused considerable stretching of mantle lithosphere of the NCMT, and as a result induced mantle partial melting and alkali magmatism (Fig. 11). The resultant extension influenced a broad area and so brought about widespread magmatism. Alkali granitic plutonism became more pronounced in Early Cretaceous time, indicative of existence of voluminous magma ponds

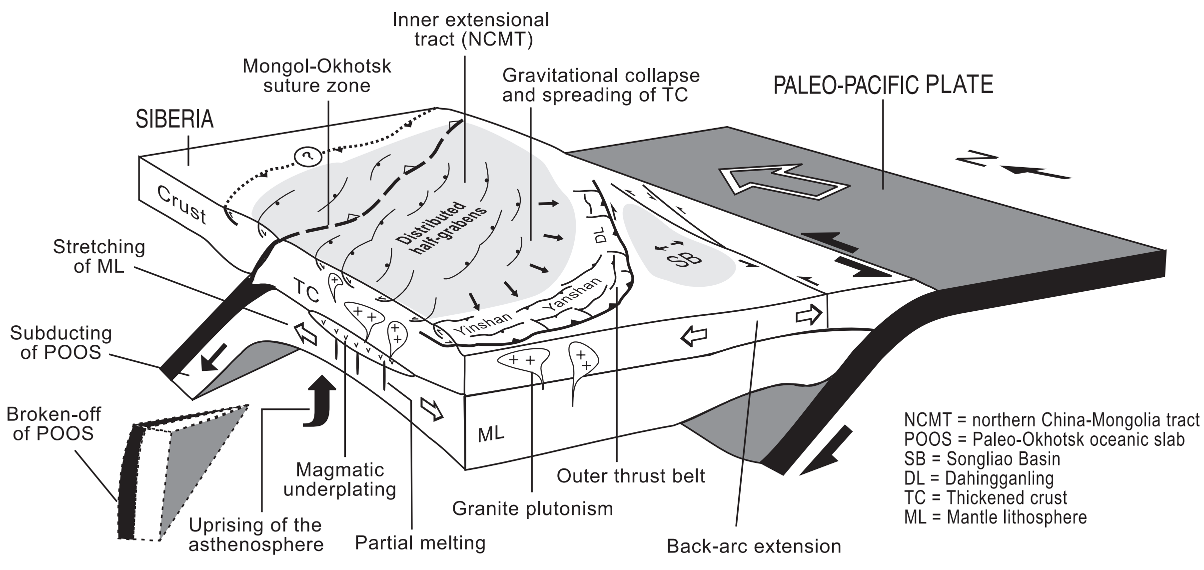

Fig. 11. Block diagram showing combined effects of distinct processes on extension of the northern China–Mongolia tract (NCMT) in late Mesozoic time. Collision of the NCMT and the Siberia led to crustal shortening and thickening of the NCMT. Continued subducting and final breakoff of the Mongol–Okhotsk oceanic slab resulted in stretching of the NCMB mantle lithosphere and upwelling of the asthenosphere, which promoted mantle partial melting, magmatic underplating, and voluminous volcanism and plutonism. Distributed extensional basins developed due to collapse of thickened and uplifted NCMT crust, and the coeval gravitational spreading led to formation of a peripheral thrust belt. The paleo-Pacific plate predominantly moved to the N or NNW, and its oblique subduction resulted in both left-lateral faulting and back-arc extension in the easternmost of East Asia.

in the lower crust and involvement of mantle melts. It is quite likely that the magmatic underplating might have played a crucial role in generation of the alkali granite plutons (Shao et al., 2000) albeit the mechanism has not been adequately portrayed.

Climax of plutonism was succeeded by widespread normal faulting, low-angle detachment, supradetachment basins and formation of metamorphic core complexes in the upper crust during the Early Cretaceous. Simultaneous occurrence of these distinct processes attests to large-magnitude high-rate extension, which can be related to thermal softening and ductile flow of the lower and middle crust. Thermal softening of the NCMT crust can be attributable to Early Cretaceous magmatic underplating and plutonism that in turn owe their origins to breakoff of the Mongol–Okhotsk oceanic slab.

Gravitational collapse must have played an important role in the extension because the NCMT might have been overthickened during late Middle–early Late Jurassic contractional deformation. It is likely that extensional collapse was responsible for development of extensional basins in the interior of the NCMT, such as the East Gobi Basin (Graham et al., 2001). Shallow-crustal or thin-skinned extension characteristic of the basins is implicitly indicative of its collapse origin (Buck, 1991). Nevertheless, gravitational collapse cannot be regarded as the only driver that caused the stretching of the whole lithosphere in the NCMT, inasmuch as collapse-related extension could not induce large-volume alkali magmatism that was characteristic of the whole processes of late Mesozoic extension.

In the Yinshan–Yanshan belt, upper-crustal contractional deformation persisted from Middle Jurassic into Early Cretaceous times and extension there did not occur until ca. 125 Ma (Fig. 10). The temporal overlapping of the adjacent contraction and extension in the NCMT has not been understood. It is known that the Yanshan–Yinshan belt lies along the southern edge of the NCMT (Fig. 1) or the outer margin of the inferred plateau. Thus, it is likely that the gravitational spreading or internal body force of the NCMT not only caused stretching in its high-elevation interior but also led to simultaneous thrusting along its lower-elevation margin (Fig. 11). As a consequence, the contractional deformation in the Yinshan–Yanshan belt was a natural corollary of gravitational spreading of the interior of the NCMT. Dewey (1988) elucidated this situation in considerable detail. With gradual thickening and elevating due to thrust stacking and granitic intrusions, the Yinshan–Yanshan belt itself then began extending. As a result, gravitational spreading provides an explanation for contemporaneity of internal extension and marginal contraction of the NCMT in Late Jurassic–Early Cretaceous time.

Accordingly, the oceanic slab breakoff in conjunction with gravitational collapse and spreading could serve as a satisfying driver for late Mesozoic extension of the NCMT as portrayed in Fig. 11. Diverse thermo-mechanical processes should have been interrelated in this dynamic framework, exhibiting coherent spatial and temporal relationships through the whole tectonic scenario. This model also has implications for reconciling some seemingly tectonic contradictory phenomena that have led to severe controversies regarding late Mesozoic history of the NCMT. For instance, widespread late Mesozoic vigorous volcanism has never been satisfactorily explained previously, but its occurrence is quite compatible with the model presented here. Recent discovery of the fossil Mongol–Okhotsk oceanic slab in the lower mantle lends further support to the model and makes it more appealing and viable.

6. Summary

Extensional tectonism occurred in the NCMT during the interval of the late Late Jurassic–Early Cretaceous, following Middle–early Late Jurassic crustal shortening and thickening related to the collision of the Siberian plate and the NCMT along the Mongol–Okhotsk suture. The development of rifted basins was apparently preceded by early-stage large-volume eruption of volcanics, suggesting an active rift setting. The rifted basins are distributed over a broad area, culminating in the Early Cretaceous. Attendant development of the metamorphic core complexes indicates large-magnitude high-rate crustal extension, which was presumably facilitated by thermal weakening of the crust as a result of pre- and syn-extensional granitic plutonism. Isotopic geochemistry of the late Mesozoic volcanics and intrusives shows that the magmatism might result from partial melting of mantle lithosphere and basalt underplating beneath the lower crust, presumably due to the stretching of mantle lithosphere and the upwelling of hot asthenosphere. Neither isotopic studies nor spatial distribution of the late Mesozoic magmatic rocks supports previous assumptions that extensional tectonism of the NCMT was caused by westerly subduction of the paleo-Pacific plate, although subduction might be responsible for coeval Andean-type magmatism along the eastern margin of China. Accordingly, the new model is proposed in this study that invokes the stretching and break-off of the subducted Mongol–Okhotsk oceanic slab, in conjunction with gravitational collapse and spreading, as the driver for late Mesozoic extension tectonism in the NCMT. Merits of this model are that it not only satisfactorily accounts for the genetic connections of diverse tectonic processes both in space and time, but also readily reconciles some seemingly contradictory phenomena, such as temporal overlapping of crustal extension in the interior and contraction in the peripheral zone.

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