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SPECIAL TOPIC: Destruction of craton and subduction of western Pacific plate
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Subduction and retreating of the western Pacific plate resulted in lithospheric mantle replacement and coupled basin-mountain respond in the North China Craton

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Abstract The North China Craton (NCC) witnessed Mesozoic vigorous tectono-thermal activities and transition in the nature of deep lithosphere. These processes took place in three periods: (1) Late Paleozoic to Early Jurassic (~170 Ma); (2) Middle Jurassic to Early Cretaceous (160–140 Ma); (3) Early Cretaceous to Cenozoic (140 Ma to present). The last two stages saw the lithospheric mantle replacement and coupled basin-mountain response within the North China Craton due to subduction and retreating of the Paleo-Pacific plate, and is the emphasis in this paper. In the first period, the subduction and closure of the Paleo-Asian Ocean triggered the back-arc extension, syn-collisional compression and then post-collisional extension accompanied by ubiquitous magmatism along the northern margin of the NCC. Similar processes happened in the southern margin of the craton as the subduction of the Paleo-Tethys ocean and collision with the South China Block. These processes had caused the chemical modification and mechanical destruction of the cratonic margins. The margins could serve as conduits for the asthenosphere upwelling and had the priority for magmatism and deformation. The second period saw the closure of the Mongol-Okhotsk ocean and the shear deformation and magmatism induced by the drifting of the Paleo-Pacific slab. The former led to two pulse of N-S trending compression (Episodes A and B of the Yanshan Movement) and thus the pre-existing continental marginal basins were disintegrated into sporadically basin and range province by the Mesozoic magmatic plutons and NE-SW trending faults. With the anticlockwise rotation of the Paleo-Pacific moving direction, the subduction-related magmatism migrated into the inner part of the craton and the Tanlu fault became normal fault from a sinistral one. The NCC thus turned into a back-arc extension setting at the end of this period. In the third period, the refractory subcontinental lithospheric mantle (SCLM) was firstly remarkably eroded and thinned by the subduction-induced asthenospheric upwelling, especially those beneath the weak zones (i.e., cratonic margins and the lithospheric Tanlu fault zone). Then a slightly lithospheric thickening occurred when the upwelled asthenosphere got cool and transformed to be lithospheric mantle accreted (~125 Ma) beneath the thinned SCLM. Besides, the magmatism continuously moved southeastward and the extensional deformations preferentially developed in weak zones, which include the Early Cenozoic normal fault transformed from the Jurassic thrust in the Trans-North Orogenic Belt, the crustal detachment and the subsidence of Bohai basin caused by the continuous normal strike slip of the Tanlu fault, the Cenozoic graben basins originated from the fault depression in the Trans-North Orogenic Belt, the Bohai Basin and the Sulu Orogenic belt. With small block size, inner lithospheric weak zones and the surrounding subductions/collisions, the Mesozoic NCC was characterized by (1) lithospheric thinning and crustal detachment triggered by the subduction-induced asthenospheric upwelling. Local crustal contraction and orogenesis appeared in the Trans-North Orogenic Belt coupled with the crustal detachment; (2) then upwelled asthenosphere got cool to be newly-accreted lithospheric mantle and crustal grabens and basin subsidence happened, as a result of the subduction zone retreating. Therefore, the subduction and retreating of the western Pacific plate is the outside dynamics which resulted in mantle replacement and coupled basin-mountain respond within the North China Craton. We consider that the Mesozoic decratonization of the North China Craton, or the Yanshan Movement, is a comprehensive consequence of complex geological processes proceeding surrounding and within craton, involving both the deep lithospheric mantle and shallow continental crust.

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1. Introduction

The longevity of ancient cratons is generally ascribed to their cool, thick, refractory and rigid SCLM which has positive buoyancy (Griffin et al., 1999, 2003; Lee, 2006; Lee et al., 2011). However, decratonization of ancient continents did occur in North China and (Chen, 1956; Zheng et al., 2004b, 2015) and Wyoming (Hughes et al., 2014; Kusky et al., 2014; Dave and Li, 2016). The controlling factors of craton stability have long caught much attention (Wu et al., 2008; Lee et al., 2011; Zheng et al., 2015). As one of the most ancient cratons on Earth, the North China Craton (NCC) has rocks of Paleoarchean ages discovered in both shallow outcrops and deep crust as xenoliths (~3.8 Ga; Liu et al., 1992; Zheng et al., 2004a). After formation by amalgamation of several micro-blocks at the end of Paleoproterozoic (Zhai, 2008, 2011; Zhai and Santosh, 2011) or by the collision between the eastern and western blocks along the Trans-North Orogenic Belt (Zhao et al., 2005), the craton kept stable until the Mesozoic. The Mesozoic NCC witnessed vigorous crustal deformation (Davis et al., 2001; Xu G et al., 2006; Wang et al., 2011), ubiquitous magmatism (Zhang et al., 2014), widespread metallogenesis (Mao et al., 2005; Sun et al., 2007; Li L et al., 2015a; Wang C M et al., 2015), large-scale basin formation (Li et al., 2004; Liu et al., 2004a; Wang Y C et al., 2016) and the transition in the nature of lithospheric mantle (Zheng et al., 1998; Zheng, 1999). All these indicate the decratonization of the NCC in the Phanerozoic. The mechanism, temporal and spatial range and geodynamics accounting for these geological records have been extensively studied (Zheng, 1999; Xu, 2001; Zhang et al., 2002, 2008; Wu et al., 2008; Zhu and Zheng, 2009; Windley et al., 2010; Zhu et al., 2011). However, the synergistic effect of these complex processes, including the dynamics relationship between the inner part and margin of the block, and the deep mantle processes with shallow continental crust within the craton, is rarely discussed. This paper presents a study of these issues, and the results have important implications for thinning and destruction of the NCC and the nature of the Yanshan Movement.

2. Circle-craton subductions and collisions

The NCC is relatively small in size worldwide and it is surrounded by multiple tectonic regimes or orogenic belts (Figure 1a). To the north is the Central Asian Orogenic Belt generated by a series of subductions and collisions (Xiao et al., 2015), including the Late-Permian amalgamation and collision of the NCC and the Mongolia terrene at the expense of the Paleo-Asian Ocean (Windley et al., 2007) and the “scissor-like” suturing of the Mongol-Okhotsk Ocean from west to east (Yin and Nie, 1996; Yang et al., 1998; Kravchinsky et al., 2002; Tomurtogoo et al., 2005). On the south are the Dabie-Sulu orogenic belt and the Qinling-Tongbai-Hong’an orogenic belt, which were produced by multiple-stage subductions/collisions between the NCC and the South China Block (SCB) from the Cambrian to the Triassic (Wu and Zheng, 2013). The subduction polarity is generally believed to be northward (Li et al., 1993, 2000; Zheng et al., 2005; Wu et al., 2009; Dong and Santosh, 2016) though the possibility of southward subduction is also considered (Li et al., 2017a). The amalgamation of the NCC and SCB is mainly composed of three main stages: (1) the Early-Paleozoic welding of the Qinling terrene with the NCC along the Shangdan suture (Gao et al., 1995; Dong et al., 2011; Li Y et al., 2015); (2) the Late Silurian to Early Devonian opening of the Paleo-Tethys Ocean (Meng and Zhang, 2000; Wu et al., 2009); (3) the final collision between the NCC and SCB (Li et al., 2000; Zheng et al., 2003, 2014; Zheng, 2008). Li et al. (2017b) made a different tectonic subdivision of the Qinling orogen and its western extension.

To the east of the NCC, the subduction of the Paleo-Pacific beneath the eastern Asian continent began since Jurassic (Maruyama et al., 1997; Sun et al., 2007, 2015; Chough and Sohn, 2010; Safonova and Santosh, 2014). The Pacific drifting direction could have varied repeatedly (Northrup et al., 1995; Sun et al., 2007). At ~140 Ma, the NCC began to be in back-arc extensional setting from compresso-shear stress field (Zhu et al., 2005, 2010; Zhang and Dong, 2008; Xu, 2009). The “Large mantle wedge”, consisting of the NCC and the stagnant Paleo-Pacific slab in the mantle transitional zone and the asthenosphere in between (Fukao et al., 2009; Zhao et al., 2009; Kuritani et al., 2011; Tang et al., 2014), was assumed to account for the Mesozoic complex and vigorous tectono-thermal events (Figure 2, Zhao et al., 2009; Kusky et al., 2014). However, the assumption that the “Large mantle wedge” existed since Late Mesozoic (Liu et al., 2017) remains to be tested because the subducted Paleo-Pacific slab could have sunk into the lower mantle (Seton et al., 2015).

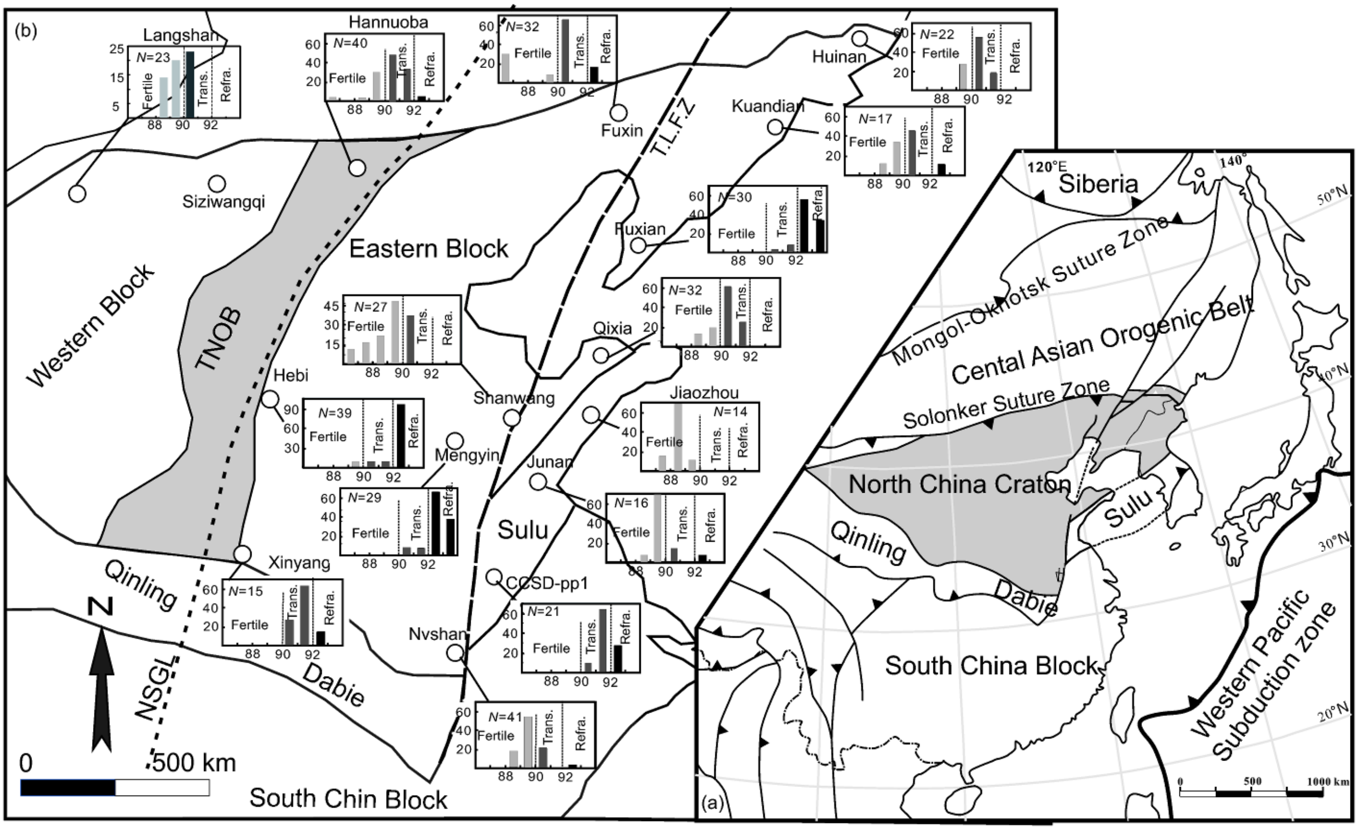

Figure 1 (a) The tectonic location of the North China Craton and (b) distribution of olivine-Mg$^{\#}$ in peridotite xenoliths from the craton (Zheng et al., 2007). Refractory (Refra.), olivine-Mg$^{\#}$>92; Fertile, olivine-Mg$^{\#}$<90; Transitional (Trans.), olivine-Mg$^{\#}$ 90–92. TNOB, Trans-North China Orogenic Belt; NSGL, North-South gravity lineament; T.L.F.Z, Tanlu fault zone. Data on the Langshan peridotite xenoliths is authors' unpublished materials while the others are the same as those in Zheng et al. (2007) and references therein.

3. Lithospheric thinning and mantle replacement

The thickness and composition of the SCLM have critical control on cratonic stability (i.e., supracrustal deformation, magmatism and basin subsidence). Compared with lherzolite, harzburgite usually represents the residue after high degree of partial melting and has low density, high solidus and viscosity and thus keep floated on the asthenosphere (Griffin et al., 1999; Lee, 2006; Pearson and Wittig, 2008). In addition, thick lithosphere could depress the partial melting of asthenosphere and thus enhance the stability by avoiding extensive asthenosphere-derived melt refertilization (Lee et al., 2011; Zheng et al., 2015). Ancient SCLM usually is composed of refractory harzburgite with large thickness and low geotherm while the Phanerozoic ones are thin and hot (high geotherm) with a fertile lherzolitic composition (Carlson et al., 1999, 2005; Zheng, 1999).

The mantle xenoliths carried by basalts of various eruption ages across from the NCC provide insight into the SCLM (Figure 1b). Those in the Paleozoic kimberlites are mainly composed of garnet harzburgite, indicative of thick lithosphere in Paleozoic (Griffin et al., 1999; Zheng et al., 1999). On the other hand, those in the Cenozoic basalts are dominated by spinel lherzolite, suggestive of a thin lithosphere (Xu et al., 2003; Zheng et al., 2007; Sun et al., 2012; Zou et al., 2016). Mineral compositions such as Mg$^{\#}$ of olivine, Mg$^{\#}$ and Cr$^{\#}$ of orthopyroxene, Al_2O_3 and CaO contents of clinopyroxene, are good proxies for melt extraction. In this regard, the Paleozoic SCLM is refractory while the Cenozoic counterpart is fertile (Zheng, 1999, 2009; Zhang H F et al., 2004; Tang et al., 2013). In terms of whole-rock trace elements and Sr-Nd-Pb isotopes, the former is enriched with long and complex metasomatism while the latter is depleted with weak metasomatism (Zheng, 1999, 2009). The Re-Os isotopes suggest that the mantle xenoliths in Paleozoic kimberlites have Archean formation age, consistent with those of the overlying continental crust. However, the crust-mantle age decoupling was widely recognized in Cenozoic when the ancient continental crust was underlain by young lithospheric mantle, except for few Archean mantle relicts in cratonic core, such as in Hebi (Zheng et al., 2001; Gao et al., 2002; Wu et al., 2003; Xu Y G et al., 2006; Xu et al., 2008; Zhang et al., 2008; Liu et al., 2011). *P-T* estimates showed that the Paleozoic NCC was cold, similar to the other typical ancient cratons worldwide (~40 mW m^{-2}, Griffin et al., 1999;

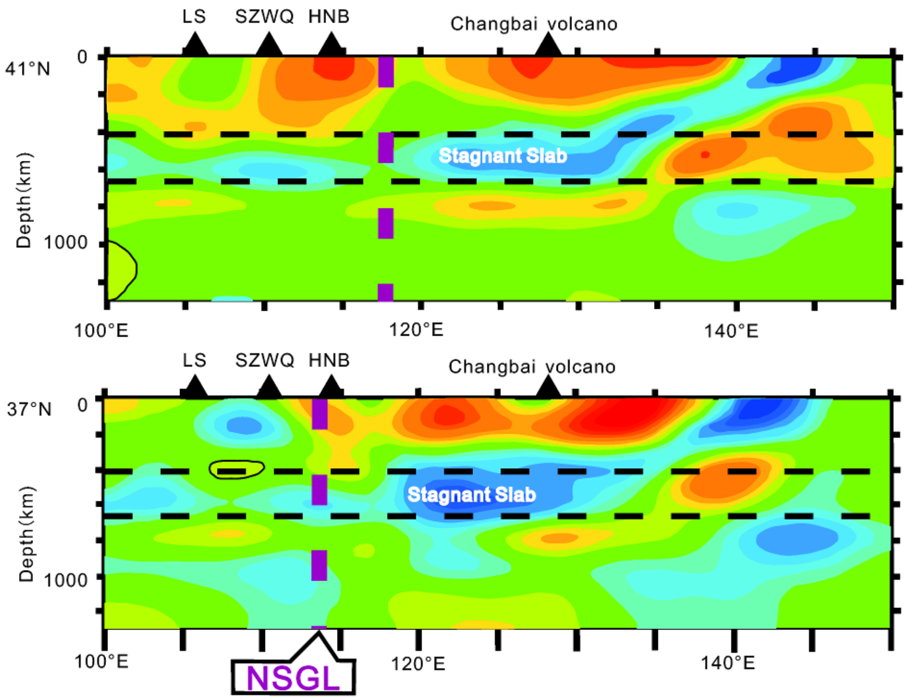

Figure 2 Western Pacific-eastern China mantle seismic tomography sections at the latitude of 41°N and 37°N (Zhao et al., 2009; Niu, 2014). LS, Langshan; SZWQ, Siziwangqi; HNB, Hannuoba; NSGL (the red dotted line), North-South gravity lineament.

Xu, 2001). However, the NCC got warm in Mesozoic-Cenozoic (~80 mW m^{-2}, Zheng, 1999, 2009; Xu, 2001; Zheng et al., 2007).

The mantle xenoliths in Cenozoic basalts distributed along the Tanlu faults zones, including Shanwang and Nvshan, mainly consist of fertile lherzolites (Rudnick et al., 2004; Xu X S et al., 2013; Park and Jung, 2015), suggesting the replacement of ancient SCLM by newly-accreted ones. The xenoliths located far from the faults are dominated by transitional lherzolites, including those from Fuxin, Huinan, Kuandian and Qixia. Those discovered in cratonic core are composed of refractory spinel harzburgites, assumed to be the shallow relicts of ancient SCLM (Zheng et al., 2001; Sun et al., 2012). The temporal and spatial variations in the nature of SCLM suggest the significant role of the trans-lithospheric Tanlu faults in the mantle replacement. That is, the trans-lithospheric fault zone served as a conduit for the asthenospheric upwelling and the ambient SCLM could be modified and replaced preferentially (Zheng et al., 1998, 2007).

The SCLM beneath the southern and eastern margins has suffered remarkable modification as those beneath the Tanlu faults zone. Based on the deep-seated xenoliths (i.e., peridotite and granulite) in the Xingyang volcanics (~160 Ma), Zheng et al. (2006a, 2008a, 2014) revealed that the lithosphere was upward aging and the SCLM, with obvious overprints of subducted SCB continental crust-derived fluids, was distinct from that of typical ancient craton. Besides, the peridotite terrenes in the Dabie-Sulu orogenic belt show apparent genetic affinity with the lithospheric peridotites from the southern margin of the NCC (Zheng et al., 2006b, 2006c, 2008b, 2014; Chen Y et al., 2017). The mantle xenoliths in the Triassic kimberlites from the North Korea suggested that ancient and newly-accreted mantle coexisted in that area (Yang et al., 2010).

The carborundum- and diamond-bearing carbonatite in the Hannuoba area resembles sedimentary carbonate in terms of trace elemental and isotopic compositions, and was interpreted to be recycled from limestones of the subducted Paleo-Asian oceanic slab (Chen et al., 2016). Recently, we discovered mantle xenoliths in Cenozoic basalt from the Langshan area, the northwestern NCC, where the continental crust is Archean to Paleoproterozoic (Wang Z Z et al., 2016). These peridotites are spinel lherzolites similar to those from the newly-accreted fertile SCLM beneath the eastern NCC, contrasting with the assumption that ancient continental crust is usually underlain by refractory lithospheric mantle (Griffin et al., 1999). In this regard, the SCLM could also be also replaced by newly-accreted one. We conclude that the accretion of the fertile SCLM beneath the eastern northern NCC (Xu et al., 2003; Zheng et al., 2007; Xu R et al., 2013) could be closely related to the subduction of the Pacific slab while the fertile SCLM of the northwestern NCC could be generated by the subduction of the Paleo-Asian Ocean because the part is tectonically near the Paleo-Asian Ocean regime while far from the Pacific regime (Zhu et al., 2012).

In summary, the deep lithosphere of the NCC is heterogeneous both temporally and spatially. Temporally, the

SCLM in Paleozoic was ancient, thick and refractory similar to those of typical cratons worldwide while it became young, thin and fertile in Cenozoic, resembling oceanic lithospheric mantle. Spatially, the ancient SCLM beneath cratonic margins and nearby the trans-lithospheric fault zone are preferentially modified and replaced while those beneath the cratonic core could survive. Therefore, we consider that the compositional and structural characteristics of the SCLM could be the combined products of circle-craton subductions/collisions and intraplate weak zones.

4. The Yanshan fold and thrust belt

Apart from the modifications of SCLM mentioned above, the Mesozoic shallow crustal deformation attracted much attention from the geological communities from across the world (Davis et al., 2001; Zhao et al., 2004; Dong et al., 2007; Zhang Y Q et al., 2007). This tectonic event is named "Yanshan Movement" by Chinese scholars and was initially proposed by Wong (1927). In the initial proposal, the Yanshan Movement referred to the Mid-Jurassic to Late-Jurassic crustal deformation occurring in the Yanshan area and it included two periods of contraction and the extension in between, that is, Episode A (contraction) in the Mid-Jurassic (~160 Ma), Episode B (contraction) in the latest Jurassic (~140 Ma) and the Middle Episode (extension).

The Episode A is recorded by the angular unconformity between the volcanics of the Tiaojishan Formation-Lanqi Formation-Jiulongshan Formation and the underlying Nandaling Formation-Xinglonggou Formation. The Episode B is evidenced by the angular unconformity between the volcanics of the Zhangjiakou Formation-Donglingtai Formation-Yixian Formation and the conglomerates of the beneath Houcheng Formation-Tuchengzi Formation. The Middle Episode is witnessed by the volcanics of the Tiaojishan Formation and the Lanqi Formation (Figure 3; Zhao et al., 2004; Zhang Y Q et al., 2007). As the lower limit of the Yanshan Movement, the Tiaojishan volcanics were inferred to erupt at around 160–152 Ma (Hu et al., 2010; Li Z H et al., 2014; Li C M et al., 2016). The conglomerates of the Jiulongshan Formation could correspond to the earliest responds of the Yanshan Movement (Zhang H R et al., 2013; Li H L et al., 2014; Li Z H et al., 2014; Li C M et al., 2016) and could form at about 170–161 Ma (Wang Y C et al., 2016). As the lower limit of the Episode B and the upper limit of the Middle Episode, the Zhangjiakou Formation and the Tuchengzi Formation could be generated at 135 Ma (Niu et al., 2003) and 147–136 Ma (Zhang H et al., 2009), respectively. In this context, the lower limit of the Episode B is referred to be ~136 Ma. Though the upper limit of the Episode B remains hotly debated, Dong et al. (2007) proposed it to be the termination time (~84 Ma) of the quiet period of earth magnetic field.

The Episode A is characterized by a series of regional crustal deformations, magmatism and sedimentary records. The large-scale east-west trending thrust-nappe structures in the Daqingshan area well developed in this episode and were assumed to be the far-field effects of the closing of the Mongol-Okhotsk Ocean (Zheng et al., 1996, 2000). In the northeastern China, this regional compression was recorded by the S-type granites outcropped in the Erguna area (Xu W L et al., 2013). Besides, the paleocurrent direction in the prototype basin of the Jiulongshan Formation is SSW trending, suggesting the obvious uplift in the northern part of the basin. The sedimentary analysis also suggested the conglomerates in this formation were rapidly accumulated in a compressional setting (Wang Y C et al., 2016). After the Episode A, the volcanics from the Tiaojishan Formation and Lanqi Formation and the coeval mafic enclave-bearing granitic plutons (i.e., Haitangshan pluton and Yiwulushan batholith in the western Liaoning area and the Yunmengshan batholith in the Beijing area) could be indicative of the stress relaxation (Wang Y C et al., 2016). Noteworthy, the compressional structures in the eastern NCC (i.e., western Liaoning area) is NE trending, which was proposed to be the overprints of the convergency of the "Big South China Block" (Li et al., 2017b).

The Episode B is featured with regional unconformity and thrust faults triggered by the NNW-SSE trending compression. The NNE-SSW trending Sihetang thrust on the north of the Yunmengshan batholith was active during 140–137 Ma (Zhu et al., 2015), coeval with the conglomerates from Houcheng Formation and Tuchengzi Formation (Zhang H et al., 2009), all assumed to be tectonic and sedimentary records of the Episode B. However, extensional environment was prevailing at the same time in the northeastern China, as indicated by the alkaline rhyolite from the Manitu Formation and the A-type rhyolite from the Jixiangfeng Formation. This was believed to be the post-collision extension of the Mongol-Okhotsk belt (Wang J G et al., 2013; Xu W L et al., 2013). From the Late Cretaceous to Cenozoic, normal faults (Zhang B L et al., 2012; Zhu et al., 2015), metamorphic core complexes (Wang et al., 2011, 2012), and extensional basins (Zhang Y Q et al., 2004; Zhang and Dong, 2008; Li L et al., 2015b) widely developed in the eastern China, suggesting a extensional setting. This was assumed to be related to the back-arc extension induced by the subduction of the Paleo-Pacific slab (Zhang Y Q et al., 2004; Zhang and Dong, 2008).

5. Magmatism

The Mesozoic NCC witnessed widespread magmatism. Zhang et al. (2014) concluded the temporal and spatial variations in the magmatism (Figure 4): (1) In the Triassic (250–

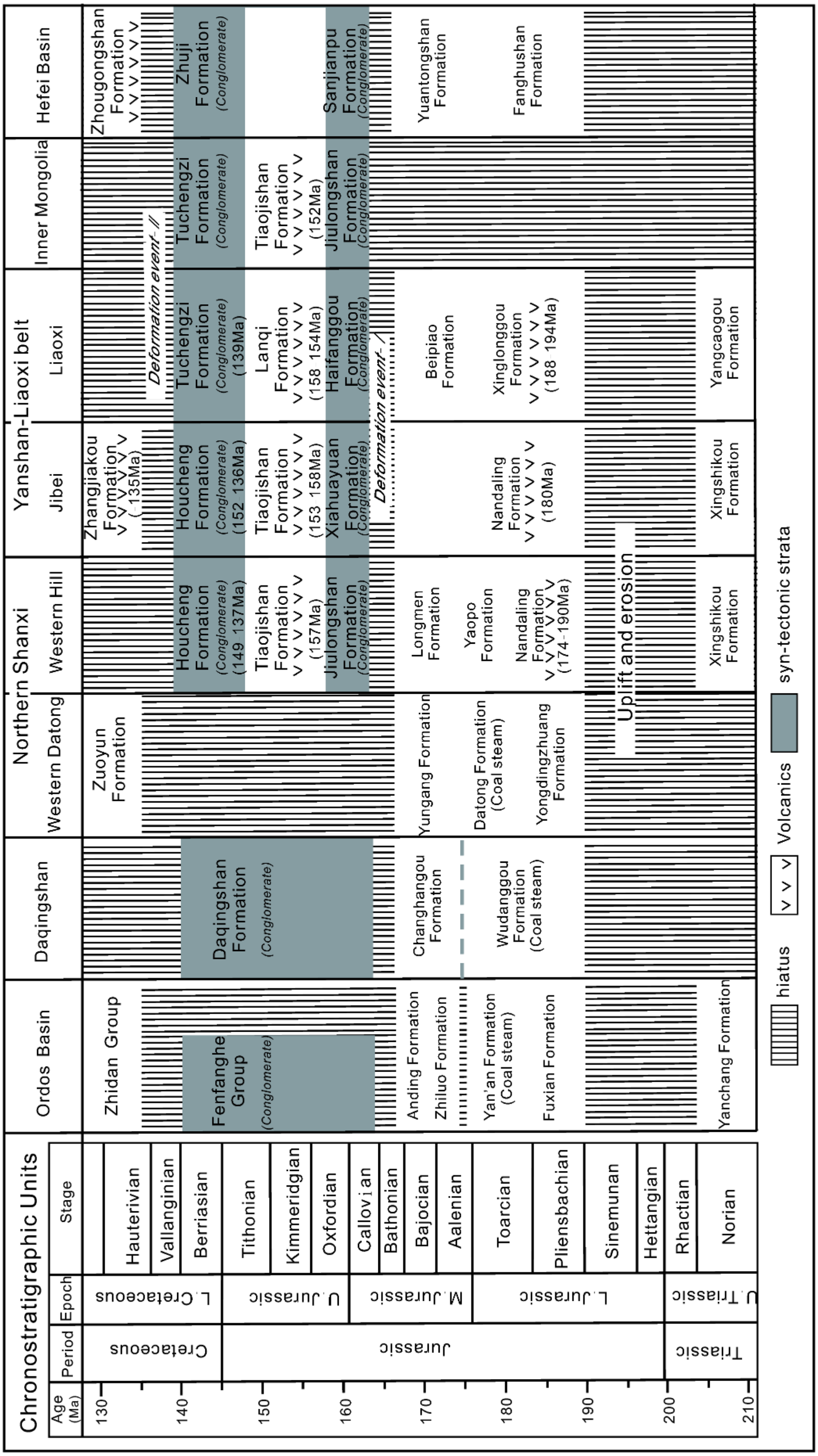

Figure 3 Comparison of the Jurassic and Early Cretaceous strata in the North China Craton (Zhang Y Q et al., 2007).

200 Ma) when the Paleo-Asian Ocean had been closed (Windley et al., 2007), the magmatic rocks were distributed along the northern margin (Figure 4a and 4b), which was parallel to the Solonker suture. This pulse of magmatism was assumed to be related to the post-collision extension of the NNC and Mongolia terrene (Zhang S H et al., 2009; Zhang et al., 2014). During this period, some kimberlites erupted in the North Korea (Yang et al., 2010), the easternmost part of the NCC. Kimberlite usually has genetic affinity with ancient refractory lithospheric mantle (Russell et al., 2012; Shirey et al., 2013; Sparks, 2013; Brett et al., 2015; Bussweiler et al., 2016). In this regard, refractory lithospheric mantle should exist beneath the North Korea area at that time. (2) The followed Early Jurassic (201–174 Ma) saw a trough in magmatism, which was constrained to the Yanshan area and northeastern China (Figure 4c). (3) Magmatism became more prevailing in Mid- and Late-Jurassic (174–145 Ma) and spread to the whole northeastern NCC (i.e., Yanshan area, Jiaodong Peninsula and Liaodong Peninsula) and the northeastern China (Figure 4d). (4) magmatism peaked at Early Cretaceous and covered the whole eastern China with greatest intensity in the Yanshan area and the two peninsulas (Figure 4e). (5) The Late Cretaceous (100–66 Ma) is a quiet period with little magmatism (Figure 4f).

During 200–140 Ma, magmatism continued migrating westward from the northeastern China to the inner part of the NCC. Since ~140 Ma, it began moving southeastward (Figure 5). The drifting direction of the Paleo-Pacific slab before ~140 Ma was parallel to the eastern Eurasian coast (Sun et al., 2007) and the subduction occurred only in the northeastern China (Tang et al., 2016; Wang et al., 2017). Then, the moving direction began to rotate anticlockwise and crosscut the coast (Northrup et al., 1995; Sun et al., 2007) and thus large-scale subduction spread to the whole eastern China. With the retreating of the subducted slab, the subduction zone migrated southeastward (Niu, 2014). Based on these considerations, the migration of the magmatism should be genetically related to the subduction and retreating of the Paleo-Pacific slab.

Mantle-derived magmas are good proxy for composition and evolution of their mantle sources (Yang and Li, 2008; Dai et al., 2016; Huang et al., 2017). Though with various components from depleted mantle sources (Zhang H H et al., 2006; Guo et al., 2007; Kuang et al., 2012; Zhang et al., 2014), the mafic and alkaline rocks from Triassic to Cretaceous show regular change in elemental (not shown) and Sr-Nd isotopic compositions (Figure 6; Liu et al., 2008; Yang and Li, 2008; Meng et al., 2015): Mantle-derived magmatic rocks with ages >110 Ma have arc-like trace-element patterns and enriched isotopic compositions, reminiscence of an ancient mantle source with long-term complex metasomatism (Zhang et al., 2004; Qian et al., 2017). By contrast, those with ages <110 Ma usually are characterized by oceanic island basalt-like trace-element patterns and depleted mantle-like isotopic ratios, suggestive of contributions from subducted oceanic crust (Guo et al., 2014; Zhang et al., 2015; Dai et al., 2016; Li H Y et al., 2016) or delaminated continental crust (Liu et al., 2008; Meng et al., 2015).

In summary, magmatism was centered on the northern and southern margins of the NCC in the Early Mesozoic, with genetically link to the subductions and collisions on the north and south respectively. Since the Late Mesozoic (~140 Ma), the temporal and spatial variations in magmatic distribution was coupled with the subduction and retreation of the Paleo-Pacific slab. Noteworthy, mantle-derived magmatism became increasingly remarkable since ~160 Ma, indicative of the continuing extension. The SCLM resembled newly-accreted lithospheric mantle rather than ancient one with obviously metasomatism, as recorded by the mafic magmatic rocks. This conclusion is in consistence with the investigations on mantle xenoliths (Zheng et al., 2007; Zheng, 2009).

6. Metamorphic core complex

The Mesozoic metamorphic core complexes (MCC) are widely distributed (Figure 7), which evidenced the prevailing crustal extension. Spatial distribution of these MCCs has two features: (1) occurrence in the whole eastern Asia; (2) preferential development in the plate margins (Lin et al., 2013b). In terms of kinematical characteristics, the MCCs show obvious *symmetry*, *isochronism* and *equivalence*. In the NCC, with the NE-SW Songliao basin and Bohai basin as the symmetry axis, the MCCs to the east of the axis have northwest-dip detachment faults while those of the MCCs to the west of the axis dip to the southeast (*symmetry*; Lin et al., 2013a; Zhu et al., 2015). The active time of these detachments are concentrated at ~131–115 Ma with a peak at 126 Ma (*isochronism*) and the results are to drag the middle and lower crust (25–30 Km in depth) to the surface (*equivalence*; Lin et al., 2013b). These kinematical features are also recognized in the Central Asian Orogenic Belt, where the symmetry axis is the Mongol-Okhotsk zone and the detachments are active during 131–125 Ma with a peak at 126 Ma. The consequences of these detachments are same as those in the NCC (Wang et al., 2011; Lin et al., 2013b). Besides, the ductile extension of these complexes become younger from the northwest to the southeast (Wang et al., 2012) and this variation was interpreted as the combined effects of the collapse of the Central Asian Orogenic Belt and the subduction of the (Paleo-) Pacific (Wang et al., 2011).

7. Mesozoic-Cenozoic basins

The main topographic units in the NCC include: (1) the

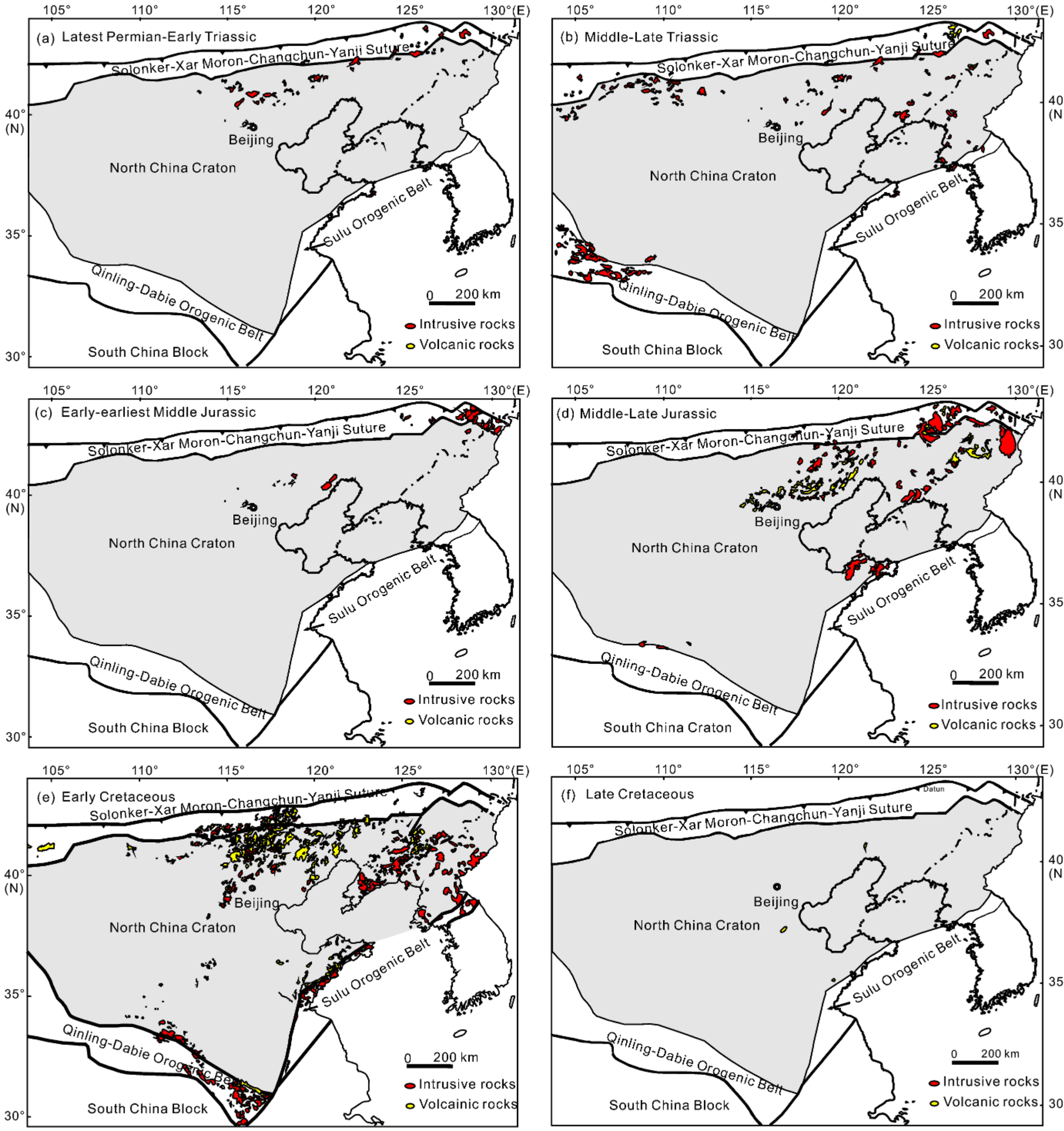

Figure 4 Temporal and spatial variation in the distribution of the Mesozoic magmatism (Zhang et al., 2014).

Ordos basin, (2) the Yanshan basin and range province, (3) the Hefei basin, (4) the Bohai basin, and (5) the Jiaolai basin (Figure 7). As the inland basin developing on the Precambrian basement, the Ordos basin has little magmatism and deformation and experienced uplift and subsidence as a whole in the Phanerozoic, except for some thermo-tectonic disturbance on its margins (Zhang and Liao, 2006).

The Yanshan basin and range province could be the combined consequence of multistage deformations (Liu et al., 2004a, 2004b). The Triassic prototype basin was widely distributed with an E-W trending and obvious crustal shortening was recognized (Cui et al., 2002; Zhang C H et al., 2004), which was ascribed to the closure of the Paleo-Asian Ocean (Zhao et al., 1994). However, recent study on the sediments and geochronology suggest that extension should be prevailing in this area until the Mid-Jurassic and

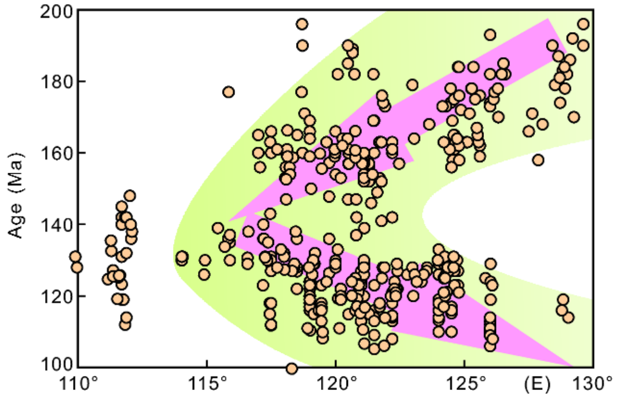

Figure 5 The migration of the Mesozoic magmatism (Zhang et al., 2014 and references therein).

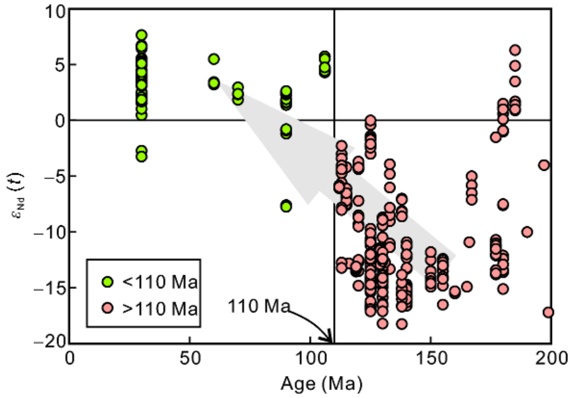

Figure 6 The variations in Nd isotopic compositions of Mesozoic to Cenozoic mafic and alkaline magmatic rocks (Zhang et al., 2014 and references therein).

there is no uniformity among the Mid-Triassic to Mid-Jurassic strata (Meng et al., 2014). In the Mid-Jurassic and the earliest Late Jurassic, the extensional basin was dismembered and controlled by thrust faults, suggesting the first regional compression (Liu et al., 2004a). At around the boundary between Jurassic and Cretaceous, the Sihetang thrust fault and the conglomerates from the Houcheng Formation and Tuchengzi Formation recorded the second phase of compression.

There is significant time overlapping among the Tiaojishan Formation, the Tuchengzi Formation and the Zhangjiakou Formation and no obvious sedimentary hiatus was recognized in these strata. The formation age of the Tuchengzi Formation is Early Cretaceous (Zhang H et al., 2009; Wang S E et al., 2013; Jiao et al., 2016), which could represent the initial extension time of the NCC. This extension was ascribed to the subduction of the Paleo-Pacific slab (Xu et al., 2011). The E-W trending basin changed into NE trending in Early Cretaceous, accompanied with half grabens (Liu et al., 2004a). At the same time, the Songliao basin (Li and Shu,

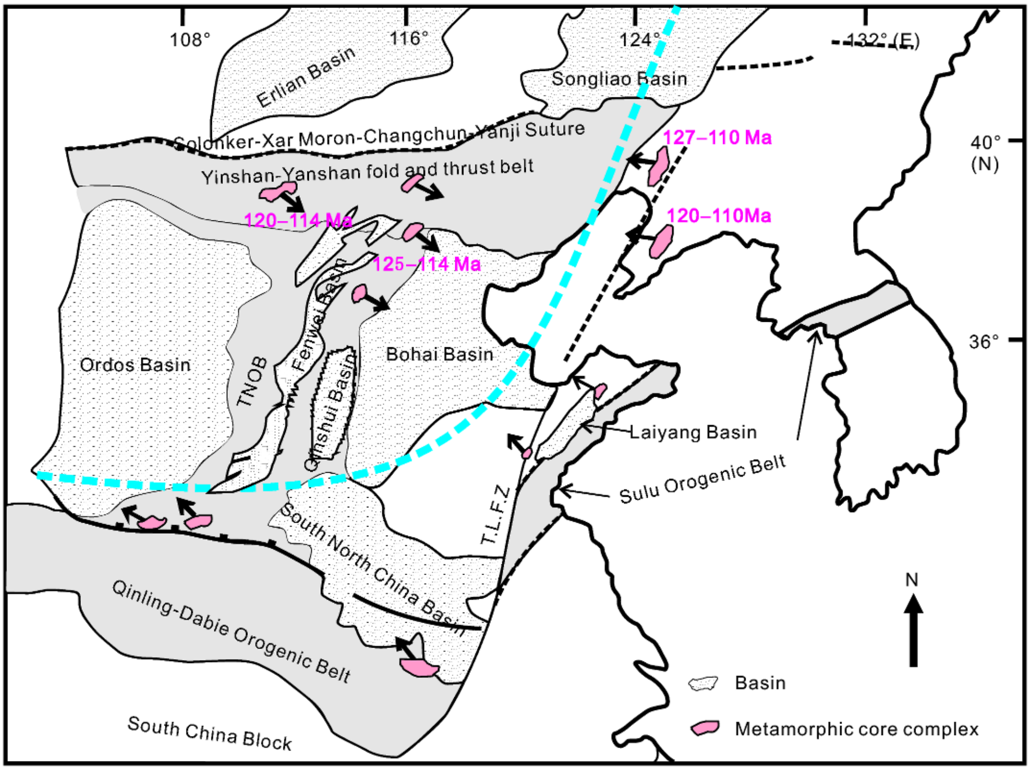

Figure 7 The distribution of metamorphic core complexes and basins. The exhumation time is put in purple words. The black arrows point to the dipping direction of the normal faults. The blue dotted line represents the symmetry axis. The distribution of metamorphic core complexes is according to Wang et al. (2012). The characteristics of the Fenwei Basin and Qinshui Basin are taken from He (2015) and the others are from Zheng et al. (2000).

2002; Meng, 2003; Li et al., 2012) and Kyongsang basin (Chough et al., 2000) started to subside and the left-lateral strike-slip movements of the Tanlu faults (Zhu et al., 2010), the Yilan-Yitong faults (Gu et al., 2016) and the Dunhua-Mishan faults (Sun et al., 2008; Wang F et al., 2016; Xu et al., 2017) began. All these could be the transtension structures induced by the oblique subduction of the Paleo-Pacific (Izanaqi) slab.

As an inland basin subsiding since the Early Jurassic, the Hefei basin was controlled sequentially by southward exhumation of the Dabie Orogenic Belt and the E-W extension of the Tanlu fault zone (Meng et al., 2007): (1) the early-stage strata in the basin was the detrital deposits derived from the Dabie Orogenic Belt due to its southward exhumation in the Jurassic (200–145 Ma); (2) the overlying strata is originated from the east of the Tanlu fault zone, which transformed from sinistral movement to normal faults with E-W trending extension in the earliest Cretaceous (~145 Ma; Zhu et al., 2005, 2010). Apart from this two-stage evolution model mentioned above (Meng et al., 2007), the Hefei basin was also believed to the foreland basin coupled with the Dabie Orogenic Belt (Wang et al., 1997; Zhao et al., 2000; Li et al., 2001; Liu et al., 2001; Liu and Zhang, 2013).

The Fenwei basin and the Qinshui basin in the Trans-North Orogenic Belt (Wang, 2013; Xu, 2015), the Bohai basin covering the eastern NCC (Zhu et al., 2010; Li L et al., 2015b) and the Jiaolai basin in the Sulu Orogenic Belt (Zhai, 2003; Tong, 2007; Ren et al., 2008) are generally the Late Mesozoic to Cenozoic rift basins in the lithospheric weak zones of craton. Before the Early Cretaceous (~140 Ma), NNE-striking crustal folds and thrust faults (the Taidong thrust zone) developed in the Trans-North Orogenic Belt (Zhang et al., 2011; Han, 2013) and the Tanlu fault zone (Qi et al., 2003). Since the Early Cretaceous (~140 Ma), NW-SE extension triggered the large-scale crustal detachment in the NCC and the subsidence of the Bohai basin. As a consequence, the Taidong thrust faults reversed to be normal faults (Yan et al., 2012). Suo et al. (2017) concluded the reverse structures and their spatial and temporal variation in the basins in the NCC. These reverse structures got younger eastward. The reverse of the western subsidence zone occurred at the end of the Mesozoic while those of the eastern subsidence zone took place in the Cenozoic (i.e., the Oligocene and Miocene). These reverse structures were believed to have genetic affinity with the drifting direction, the subduction and retreating of the Paleo-Pacific slab.

The Cenozoic widespread basalts witnessed the rifting of the NCC. In the Bihai basin, a series of rift basins and uplifts developed, including the Taihangshan uplift, the Jizhong depression, the Fucheng uplift, the Huanghua depression, the Ningjing uplift, the Jiyang depression and the Taishan uplift from northwest to southeast (Li et al., 2007; Suo et al., 2015). The Fenwei basin and Qinshui Basin in the Trans-North Orogenic Belt and the Jiaolai basin in the Sulu Orogenic Belt also developed in this stage. Thus, the mountain-basin alternated topographical frame formed in the Cenozoic.

8. The multiple-stage evolution since the Late Mesozoic

Since the cratonization in the Paleoproterozoic (Zhai and Santosh, 2011), the NCC kept stable until the Mesozoic when combined effect of multiple subductions/collisions triggered the tremendous magmatism, mineralization and deformation in the continental crust and the transition in the nature of the SCLM. The Mesozoic thus is believed to be the key period of geotectonic transformation (Zhao et al., 2004; Dong et al., 2007; Zhang Y Q et al., 2007). This period could be divided into three parts: (1) > ~170 Ma, when the northern and southern margins of the NCC were modified by the Paleo-Asian Ocean regime and the Paleo-Tethys Ocean regime; (2) 170–140 Ma, when the magmatism crustal deformations occurred due to the combined effect of compression triggered by suturing the Mongol-Okhotsk ocean and the shearing and magmatism induced by the Paleo-Pacific subduction (Meng, 2003; Li et al., 2012); (3) <~140 Ma, when continuous extension and magmatism driven by the subduction and retreating of the western Pacific took place (Figure 8).

8.1 Lithosphere modification beneath the northern and southern margins

The Paleo-Asian Ocean subducted southward and got closed in the Late Paleozoic and the Mongolia terrene collided with the NCC as a result (Zhao et al., 2013). This amalgamation triggered remarkable crustal shortening, uplift and erosion on the northern margin of the NCC. This phase of compression was recorded by the Late Permian and Early Triassic thrust faults (Davis et al., 2001) and the detrital zircons in the foremountain basin (Li et al., 2010). As the response to the subduction of the Paleo-Asian Ocean, the vigorous Permian magmatism occurred along the northern margin (Zhang S H et al., 2007; Zhao et al., 2007). In the Middle and earlier Late Triassic, voluminous alkaline magmatic rocks were likely derived from metasomatic SCLM. The partial melting was triggered by the asthenospheric upwelling during the collapse of the orogenic belt between the NCC and the Mongolia terrene (Zhang S H et al., 2012).

At the northern margin of the NCC, contrasting with the Early Triassic collision compression (Davis et al., 2001) and post-collision extension (Zhang, 2004; Zhang et al., 2010), the tectonic setting in Late Triassic is controversial. Compressional deformations (Li et al., 2008; Hu et al., 2010), the

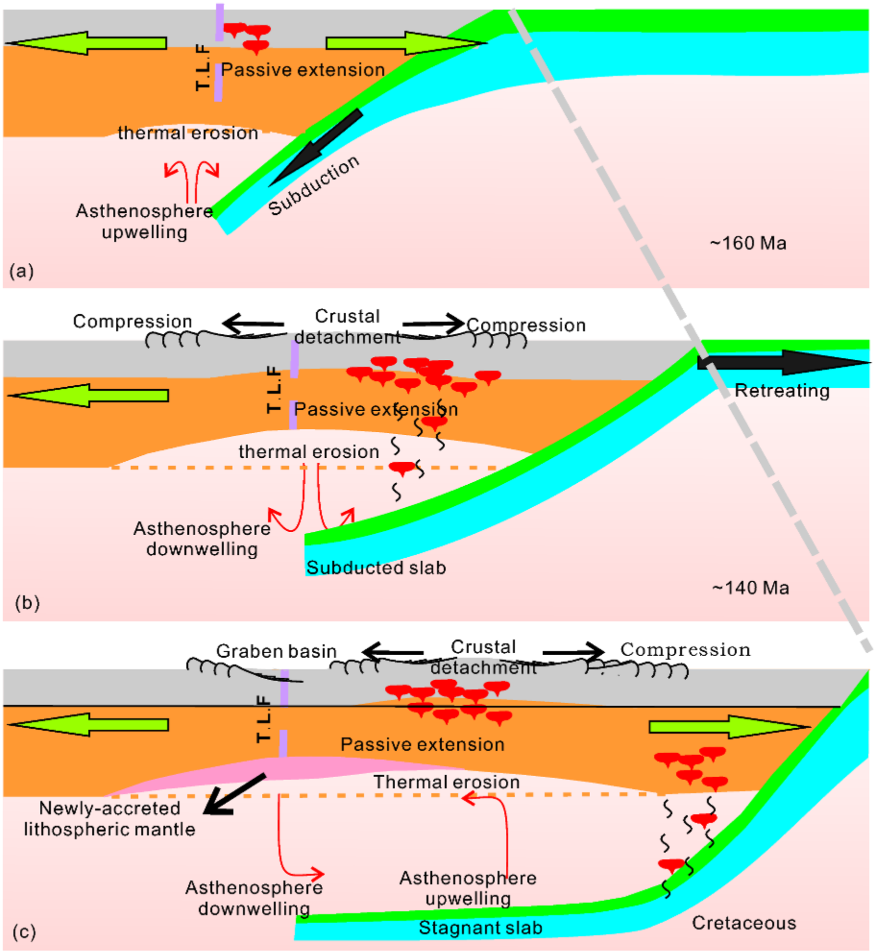

Figure 8 The cartoon illustrating the possible links between the deep geological processes and shallow responses of the North China Craton and the (Paleo-) Pacific subduction and retreating. (a) At ~160 Ma, the subduction of the Paleo-Pacific was constrained to northeastern China where there were plenty of subduction-related magmatic rocks. (b) The NCC was located in a back-arc extension setting when the drifting direction of the western Pacific changed to be northwest. The subduction-induced asthenosphere upwelling eroded the overlying ancient SCLM. The SCLM with the lithospheric weak zones (i.e., the Tanlu fault zone) was preferentially modified and thinned. The asthenospheric upwelling also caused the Moho uplift and crustal detachments. The regional contraction could appear when the crustal detachments took place in this extensional setting. (c) With continuous southeastward retreating of the subduction zone, the asthenospheric disturbance and the subduction-related magmatism migrated southeastward. As a result, the upwelled asthenosphere got cold and transformed to be lithospheric mantle accreted beneath the pre-existing SCLM. Graben basins developed as the extension continued. (T.L.F. Tanlu fault).

uniformity and molasses building (Liu et al., 2004a) was ascribed to records of the compression continuity after the collision between the Mongolia terrene and the NCC. On the other hand, rapid Late Triassic subsidence was indicated by the sedimentary records and volcanism of the Nandaling Formation (Meng et al., 2014). That is, the Late Triassic sediments are fluvial facies. The overlying conglomerates at the button of the Early Jurassic Xingshikou Formation have good rounding. Together with the overlying strata of the Nandaling Formation and the Xiahuayuan Formation, the sediments varied upward from sandstone to mudstone. In addition, the prevailing extension in Late Triassic to Early Jurassic is also evidenced by the metamorphic core complex in the Sonid Left Banner (Davis et al., 2004) and the pull-apart basin in the Daqingshan area (Ritts et al., 2001).

The mantle xenoliths carried by Mesozoic and Cenozoic basalts along the northern margin, including Langshan (authors' unpublished data), Siziwangqi (Chen et al., 2004; Wu et al., 2017), Hannuoba (Rudnick et al., 2004; Yu et al., 2006), Fuxin (Zheng et al., 2007), Kuandian (Xu R et al., 2013) and Huinan (Xu et al., 2003) from west to east, are dominated by fertile lherzolites contrasting with the ancient overlying continental crust. This contrast suggests the pre-existing ancient refractory SCLM could be replaced with newly-accreted fertile ones. The replacement in the cratonic northeastern margin could be triggered by subduction the Paleo-Pacific (Zheng, 1999; Zheng et al., 2007). However, the northwestern part of the NCC is far from the Pacific tectonic regime and the SCLM replacement is more likely related to the subduction of the Paleo-Asian Ocean (Chen et al., 2016; Wang C Y et al., 2016; Chen C F et al., 2017; Wu et al., 2017).

As the northern margin, the southern margin also experienced remarkably deep lithospheric modification induced by the Early Triassic continental deep subduction between the NCC and SCB (Li et al., 1993, 2000; Zheng et al., 2003). In Late Triassic and Early Jurassic, the Qinling Orogenic belt to the southwest witnessed the continent-continent collision (Jiang et al., 2010; Dong and Santosh, 2016) and vigorous magmatism caused by and the subducted slab break off (Zhang et al., 2014) while the Dabie Orogenic Belt to the southeast saw continuous continental deep subduction and ubiquitous contractional structures, such as the thrust nappes in the Xuzhou-Suzhou area (Chen and Shu, 2000), the thrust faults and folds in the western Shandong province, Liaodong peninsula (Li et al., 2009; Yang et al., 2011) and Jiaodong peninsula (Li et al., 2009). The subsidence of the Hefei basin during this period was likely related to the southward exhaustion of the Dabie ultrahigh-pressure terrene (Meng et al., 2007).

The deep lithospheric xenoliths in the Mesozoic volcanics in the Xingyang area reflect an upward aging structure. The SCLM (Zheng et al., 2006a) and the lowermost continental crust (Zheng et al., 2008a) have ~230 Ma zircon ages, coeval with the SCB continental deep subduction, reminder of their genetic affinity. The zircon archive of the peridotite terrene in the Sulu Orogenic Belt is similar to that reflected by the xenoliths in the kimberlites in Mengyin and Fuxian. The meaning of this similarity is twofold: (1) the peridotite terrene came from the southern margin of the NCC; (2) the deep subduction has intensively modified the SCLM of the southern margin (Zheng et al., 2014).

In conclusion, the southern and northern margins of the NCC experienced significant modifications induced by the Paleo-Asian Ocean regime and the Paleo-Tethys regime, respectively. Back-arc extension, collision contraction and post-collision extension took place sequentially in both margins, as evidenced by the magmatism, deformation, and basin evolution in shallow crust as well as deep lithospheric modification.

8.2 Impact from suturing of the Mongol-Okhotsk ocean and subduction of the Paleo-Pacific.

Middle-Late Jurassic and the earliest Cretaceous (170–140 Ma) is the key period of tectonics, magmatism and mineralization in the NCC, even the whole eastern Asian continent. The possible factors accounting for these processes includes: (1) the contraction and post-collision extension induced by the scissor-like suturing of the Mongol-Okhotsk ocean (Kravchinsky et al., 2002; Metelkin et al., 2010; Xu W L et al., 2013); (2) the shearing deformations (Xu, 2009; Zhu et al., 2010) triggered by the Late Jurassic oblique subduction of the Paleo-Pacific slab (Maruyama et al., 1997; Takashima et al., 2006; Sun et al., 2007).

During this period (170–140 Ma), the most striking geological event in the NCC is the Yanshan Movement, that is, the two phases (the Episode A and Episode B) of crustal contraction occurring at ~160 Ma and ~140 Ma and the extension in between (the Middle Episode) (Figure 3; Zhao et al., 2004; Dong et al., 2007; Zhang Y Q et al., 2007). Episode A took place coeval with the collision between the Siberia craton and the pre-welded NCC-Mongolia terrene along the Mongol-Okhotsk zone and could be the far-field effect of the induced compression (Zhu et al., 2015). The Middle Episode is interpreted as the release of this compression (Wang Y C et al., 2016). The Episode B should be related to the collapse of the Mongol-Okhotsk belt because the northern margin of the NCC, as lithospheric weak zone, could absorb the strain caused by the collapse and preferentially got lithospheric shortened (Meng, 2003). In the northeastern China, the prevailing extension was evidenced by the alkaline magmatism (Wang J G et al., 2013; Xu W L et al., 2013). The fact that compression in the west and extension in the east occurred at the same time could be reconciled by the scissor-like suturing of the Mongol-Okhotsk Ocean from west to east (Yang et al., 1998; Kravchinsky et al., 2002).

At ~140 Ma, magmatism migrated westward from northeastern China to the inner part of the NCC (Figure 5) with the anticlockwise rotation of the western Pacific drifting direction (Sun et al., 2007). The subduction gradually spread from the northeastern China to the whole coast of the eastern Asia. Magmatism in the northeastern China assumed to be generated by the subduction of the Paleo-Pacific (Figure 8a; Xu W L et al., 2013; Wang F et al., 2015). Before this time, the moving direction of the western Pacific slab was parallel to the eastern Asian coast and the NCC was located in a sinistral compresso-shear stress field. This strain changed pre-existing E-W trending structures to be NE trending (Liu et al., 2004a), triggered the NE trending thrust fault system (Han, 2013) and motivated the sinistral strike-slip movement of the Tanlu fault zone (Zhu et al., 2005, 2010).

8.3 Lithospheric mantle replacement and coupled basin-mountain respond caused by the subduction and retreating of the western Pacific

In the Cretaceous and Cenozoic, the western Pacific subduction and retreating likely accounted for the the vigorous magmatism (Xu, 2001; Zhang et al., 2014) and large-scale lithospheric extension (Xu, 2001; Liu et al., 2004a; Li et al., 2007; Zhu et al., 2010; Xu W L et al., 2013; Li L et al., 2015b). Contrasting with the Paleo-Asian Ocean regime and Paleo-Tethys Ocean regime whose impact was mainly restricted to the cratonic margins, the Paleo-Pacific regime had significant influence reaching the inner part of the craton and brought about the areally-distributed magmatism in the whole eastern China (Figure 4e). The magmatism preferentially took place in the weak zones (i.e., the margins, the deep lithospheric fault zone and the pre-existing suture zone) and migrated southeastward (Figure 5). This could result from the interplay between the intraplate weak zones and the subduction and retreating of the western Pacific, described as follows.

Dragged by the subducted slab, the western Pacific subduction zone retreated toward the ocean and thus the obducted eastern Asian continent got extension and drifted eastward (Niu, 2014; Figure 8b). The back-arc extension also caused the detachment of the shallow crust, the subsidence of the Bohai basin (Xu, 2009; Li L et al., 2015b) and the development of metamorphic core complexes (Lin et al., 2013b). With continuous retreating southeastward, the eastern China gradually got far from the subduction zone and subduction related magmatism also migrated southeastward (Figure 8c). As the extension continuing in the Cenozoic, pull-apart basins (i.e., the Fenwei basin) were brought up in the weak zones (i.e., the Trans-North Orogenic Belt). Besides, a series of rift basins and uplifts developed in the Bohai basin and the mountain-basin alternated topographical frame occurred. At this time, the lithospheric erosion triggered by the subduction-related upwelling asthenosphere migrated to the Zhejiang-Fujian region and the East Sea (Su et al., 2014).

Apart from the abovementioned processes in the shallow crust, the western Pacific subduction and retreating also have remarkable effect on the SCLM. The lithospheric weak zones served as conduits for the upwelling asthenosphere triggered by the subduction (Zheng et al., 1998; Zheng, 1999). For example, the ancient refractory SCLM beneath the Tanlu fault zone was preferentially eroded and thinned by the upwelling asthenosphere (Figure 8b; Zheng et al., 2007). Similar processes likely took place in the cratonic northern margin where the SCLM got fertile due to the Paleozoic modification. The fertile mantle would preferentially get partial melting when heated by the upwelling asthenosphere and supply the voluminous magmatism in the Yanshan area (Zhang et al., 2014). As the subduction zone retreated, the increased heat flow decreased. Consequently, the upwelling asthenosphere got cool and transformed to be newly-accreted SCLM at the button of the lithosphere and thus a small increase in lithospheric thickness could appear (Figure 8c; Zheng et al., 1998, 2007; Xu et al., 2001). The subducted slab could stagnate in the mantle transitional zone and contribute to the decratonization of the NCC by its liberating water (Niu, 2014).

As discussion above, we consider that the subduction and retreating of the western Pacific plate is the outside dynamics which resulted in mantle replacement and coupled basin-mountain respond within the North China Craton, and find that the Mesozoic decratonization of the North China Craton and the Yanshan Movement are a comprehensive consequence of complex geological processes proceeding surrounding and within craton, involving both the deep lithospheric mantle and shallow continental crust.

9. Conclusion

The decratonization of the North China Craton is the combined result of interactions between circle-craton subductions and intraplate weak zones. Before the Middle Jurassic (~170 Ma), both the northern and southern margins of the North China Craton underwent subduction, collision and post-collision extension. These complex processes triggered not only the latitudinal basins, folds and faults, and magmatism in the continental crust but also the vigorous chemical and mechanical modification on the beneath lithospheric mantle. The cratonic margins thus became weak zones and would be the preferential place for tectonic and magmatism. Since the Late Mesozoic, the crustal detachments coupled with local contractions in the cratonic weak zones occurred when the Moho uplift and asthenospheric upwelling were brought up by the subduction of the Paleo-Pacific slab. The sublithospheric mantle was eroded and thinned remarkably by the upwelling asthenosphere. With the southeastward retreating of the subduction zone, the lithosphere gained a small increase in thickness because the upwelled asthenosphere decreased and accreted as newly lithospheric mantle to the button. The extension caused by the continuous retreating could account for the large-scale basin subsidence and crustal deformations. Therefore, the subduction and retreating of the western Pacific plate is the outside dynamics which resulted in mantle replacement and coupled basin-mountain respond within the North China Craton. The Mesozoic decratonization of the North China Craton and the Yanshan Movement are a comprehensive consequence of complex geological processes proceeding surrounding and within craton, involving asthenosphere-lithosphere interaction in depth and the continental crustal responding in shallow.

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