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The subduction of the west Pacific plate and the destruction of the North China Craton

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Abstract While a general concensus has recently been reached as to the causal relationship between the subduction of the west Pacific plate and the destruction of the North China Craton, a number of important questions remain to answer, including the initial subduction of west Pacific plate beneath the eastern Asian continent, the position of west Pacific subduction zone during the peak period of decratonization (i.e., Early Cretaceous), the formation age of the big mantle wedge under eastern Asia, and the fate of the subducted Pacific slab. Integration of available data suggests that the subduction of the western Pacific plate was initiated as early as Early Jurrasic and the subduction zone was situated to 2,200 km west of the present-day trench in the Early Createaceous, as a result of eastward migration of the Asian continent over a distance of ca. 900 km since the Early Cretaceous. The retreat of the subducting west Pacific plate started ~145 Ma ago, corresponding to the initial formation of the big mantle wedge system in the Early Cretaceous. The subduction of the Pacific slab excerted severe influence on the North China Craton most likely through material and energy echange between the big mantle wedge and overlying cratonic lithosphere. The evolution history of the west Pacific plate was reconstructed based on tectonic events. This allows to propose that the causes of phases A and B for the Yanshanian orogeny were respectively related to rapid low-angle subduction and to lowering subduction angle of the west Pacific plate. At ca. 130–120 Ma, the subduction of the west Pacific plate was characterized by increasing subducting angle, slab rollback and rapid trench retreat, leading to the final stagnation of the subducting slab within the mantle transition zone. This process may have significantly affected the physical property and viscosity of the mantle wedge above the stagnant slab, resulting in non-steady mantle flows. The ingression of slab-released melts/fluids would significantly lower the viscosity of the mantle wedge and overlying lithosphere, inducing decratonization. This study yields important bearings on the relationship between the subduction of the west Pacific plate and the evolution of the lithospheric mantle beneath the North China Craton.

Keywords Early Createeous, Cratonic destruction, Subduction of west Pacific plate

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1. Introduction

Earth's surface compries two parts: continents and oceans. The plate tectonic theory, established in the 1960s, successfully explains the birth, growth and death of oceanic plate. It is generally regarded as a revolutionary benchmark in earth science, given its major contribution to understanding global tectonic scheme. Nevertheless, traditional plate tectonic theory does not fully account for the evolution of continents, such as basic problems of continental re-

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working or destruction, continental growth and mineralization in intracontinental setting.

Since continents are the principle living places of human being and resource-energy provider, understanding its evolution is not only one of fundamental issues in earth science, but also is essential to meet major national demands in resource and energy. Continent consists of cratons and orogenic belts, and cratons comprise crust and underlying lithospheric mantle. Cratonic lithosphere is characterized by old formation age, low density, low water content, thick lithospheric root, tectonic quiescence (e.g., lack of large-scale volcanics and earthquake). These features lead to the classic view that cratons are stable. By salient contrast, in the North China Craton (NCC) large-scale magmatism and seismicity (e.g., Tangshan and Xingtai quakes) occurred, suggesting a destabilized craton. Such a phenomenon is not yet explicitly explained by classic geologic and/or plate tectonics theory.

In recent decades, systematic investigations into the NCC have been carried out by domestic and international earth scientists applying an earth system philosophy. Now it becomes clear that lithospheric thinning, large-scale magmatism and structural deformation are just the surface expression of destruction of the NCC. The essential governing factor of the destabilization and destruction of the cratons is the fundamental changes to lithospheric composition and physical-chemical property of the lithospheric mantle. These progresses help to establish theoretical framework of cratonic destruction, in which ocean-continent interaction triggered the destruction of cratons and continental growth. These findings present new assets to the plate tectonic theory and are useful for understanding global continental evolution (Zhu et al., 2017).

It is noteworthy that, during the period of destruction of the NCC, the lithospheric extensional direction was in pace with the movement direction of the Pacific Plate, the orientation of the destructed portion of the NCC is parallel to that of the paleo-subduction belt and subducted paleo-Pacific slab which is now stagnated within the mantle transition zone (MTZ) (Zhu et al., 2012, 2015). All these observations confirm the influence exerted by the Pacific subduction on the extension and destruction of the NCC, that is, the subduction of west Pacific plate during the Early Cretaceous is the principle external driving force and controlling factor (Xu, 2001; Niu, 2005, 2014; Zhang et al., 2009; Zhu and Zheng, 2009; Zheng and Wu, 2009; Wu et al., 2014, 2019). Nonetheless, a number of important questions remain to be resolved, for instance, when did the west Pacific plate start to subduct underneath the Asian continent? Where was the subduction zone in the Early Cretaceous? When was the big mantle wedge (BMW) under east Asia formed? What is the fate of subducted Pacific plate? The answers to these questions are of crtical importance in reconstructing the subduction history of the west Pacific plate, unraveling the interaction between west Pacific subduction and destruction of the NCC and assessing the mechanism of formation and enrichment of mineral resource in eastern China (Zhu et al., 2015). These issues have been addressed in a special volume published in 2018 in Science China: Earth science entitled "Cratonic destruction and the west Pacfic subduction" (Li and Wang, 2018; Liu and Li, 2018; Liu et al., 2018; Tang et al., 2018; Wang K et al., 2018; Wang Y et al., 2018; Xu et al., 2018; Zheng and Dai, 2018; Zheng et al., 2018; Zhu et al., 2018; Zong and Liu, 2018).

2. The onset of subduction of the west Pacific underneath Asian Continent

It is widely believed that subduction of the west Pacific plate had played a critical role in the Mesozoic geological evolution in eastern China. However, the onset of this process remains a subject of debate, with diverse opinions including Permian (Li and Li, 2007; Li et al., 2012), Triassic (Zhou et al., 2014), Jurassic (Zhou et al., 2006; Xu et al., 2013; Wang F et al., 2015) and Cretaceous (Chen et al., 2008). The reasons for such great discrepancies are multiple but will not be discussed here. We emphasize, in this paper, that the best constraint on the onset of subduction is accretionary prism which is directly related to subduction, and arc magmatism along continental margin.

The Nadanhada Terrane, located in eastern margin of NE China and next to Far-East Russia, is a part of late Paleozoic-Mesozoic circum-Pacific accretionary orogenic belt. It is the unique occurrence of accretionary complex in China, which is definitively related to the subduction of west Pacific underneath east Asian margin (Liu and Ma, 1997). It consists of the Raohe Complex and Cretaceous postcollisional igneous rocks. The Yuejinshan ophiolitic Complex to the west of the Raohe Complex probably represents earlier (Permian) products of accretion. The metabasalts in the Yuejinshan Complex show mid-ocean ridge basalts (MORB) and oceanic island basalts (OIB) geochemical character (Bi et al., 2017). The associated gabbro has a Permian emplacement age (Sun et al., 2015a; Bi et al., 2016).

The Raohe Complex consists of accreted Triassic to Jurassic radiolarian chert, mudstone and volcanics, and the Yongfuqiao Formation of terrestrial-sourced clastic rocks. Being a part of accetionary prism the former experienced strong deformation, the latter may represent trench-slope sedimentary deposition. The pillow lavas in the Raohe complex show OIB-type geochemical and isotopic signatures with an emplacement age of 167 Ma. The detrital zircons from the Yongfuqiao Formation sandstone have distribution pattern of U-Pb isotopic age and Hf isotopes similar to those of granites in NE China, with a youngest age of 140–137 Ma (Zhou et al., 2014; Sun et al., 2015b). The accretion timing of the Raohe complex is therefore constrained at late Jurassic-Early Cretaceous and the position of accretion at the east of Jiamusi Terrane. Similarly, according to radiolarian studies, the youngest age of the deformed strata of Harba complex in Far-East Russia is Late Jurassic-Early Cretaceous, suggesting the emplacement age of this complex later than the early Cretaceous (Zyabrev and Matsuoka, 1999). It has been recently pointed out, based on combined paleo-geomagnetic, stratigraphic and paleontology studies, that during the late Jurassic-early Cretaceous, the Nadanhada Terrane in margin of east Asian continent, the Mino Complex in Japan and Sikhote-Alin Terrane constitute a unified belt of accretionary complex, which is a part of circum-Pacific belt (Ren et al., 2015; Sun et al., 2015b).

The emplacement timing of the Raohe complex does not represent the onset of Paleo-Pacific subduction underneath Asian continent. The Mino Complex in Japan arrived first at the trench at ~190 Ma, and its tectonic accretion took place at ~175 Ma (Isozaki, 1997). These suggest that the initiation of Paleo-Pacific subduction was no later than early Jurassic (Xu et al., 2013; Zhou et al., 2014; Sun et al., 2015a), similar to the result reached based on metamorphic age of the blueschist in Heilongjiang complex (Zhou et al., 2009).

Another approach to determine the initiation of the west Pacific subduction is to examine the subduction-related magmatism (Xu et al., 2013; Wang F et al., 2015; Wang T et al., 2015). The difficulty associated with this approach is that the Mesozoic magmatism in NE China and northern North China may have been influenced by superimposition of three tectonic regimes, namely Paleo-Asian Ocean, Mongol-Okhotsk, and Pacific. Therefore it is critical to decipher the tempo-spatial range dominated by each of these tectonic regimes. Since the closure of the Paleo-Asian Ocean took place in the Late Triassic (Xu et al., 2013), to distinguish the influence of Mongol-Okhotsk and Pacific regimes is thus the key.

Figure 1 illustrates the migration of Mesozoic igneous rocks from eastern Liaoning, through west Liaoning to north Hebei (Ma and Xu, 2017). Before discussing the significance of this magmatic pattern, it is imperative to evaluate the influence of the Mongol-Okhotsk tectonic regime on the pattern. Based on the following considerations, we propose that the influence of the Mongol-Okhotsk tectonic regime is rather limited on the NCC.

(1) The Mongol-Okhotsk ocean represents a suture along the southern margin of Siberian craton from Paleozoic to early Mesozoic (Gordienko, 1994). van der Voo et al. (1999) identified the presence of the subducted Mongol-Okhotsk oceanic plate in the deep mantle. The geometry of this oceanic slab remnant suggests a subduction direction towards Siberia. The distribution and orientation of the Hangay-Hentey accretionary belt is also consistent with a northward subduction (Ruppen et al., 2014). Xu et al. (2013) proposed that there are double direction of subduction of the Mongol-Okhotsk Ocean. However no solid evidence exists for southward subduction. Available data are consistent with a passive, rather than active continental margin in the south of the Mongol-Okhotsk Ocean (Wu et al., 2011).

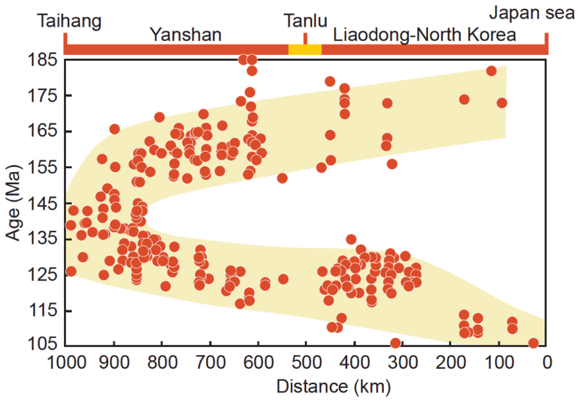

Figure 1 Tempo-spatial migration of Mesozoic magmas in east Asian continental margin (Ma et al., 2019).

(2) Although some paleo-geomagnetic studies suggest that the Mongol-Okhotsk Ocean prevailed until the early Cretaceous, the sedimentologic data and geochronology of igneous rocks suggest the closure of this ocean in the mid-Jurassic and it closed diachronously starting from southwest and propagating towards Northeast. For instance, late Triassic-Early Jurassic calc-alkaline magmatism occurred in Muhe-Erguna area in northwest Heilongjiang province, whereas A-type granites dominated the late Jurassic-Early Cretaceous magmatism. This marked the final closure of the Mongol-Okhotsk Ocean in the mid-Jurassic (Sun et al., 2013; Tang et al., 2014). In NE China, from the Zhangguangcai Range via Lesser Xing'an Range to Great Xing'an Range, magmatism becomes younger in age (Wu et al., 2011). The younging trend of magmatism is also observed from Erguna to the Great Xing'an Range. These observations suggest that to the east of the Great Xing'an Range magmatism was predominated by the Pacific tectonic regime, whereas to the west of the Great Xing'an Range it was controlled by the Mongol-Okhotsk tectonic regime. The next question is which regime dominated the Great Xing'an Range, or the Great Xing'an Range represents the superimposed area of the two tectonic regimes. Given the fact that the Mongol-Okhotsk suture zone runs northeastly, in contrast to the NNE orientation of the Great Xing'an Range, it is postulated that the magmatism in the Great Xing'an Range is largely controlled by the Pacific tectonic regime. This idea gets its support from the study of ore deposits: Late Jurassic-Early Cretaceous W-Sn deposits widely occur in southern segment of the Great Xing'an Range, which is consistent with temporal and spatial distribution pattern of the giant W-Sn deposit belt in eastern China which is related to the Pacific subduction (Mao J W, 2018, personal communication).

If it is attributed to the results of the Pacific tectonic regime, the late Jurassic-early Cretaceous magmatism in the Great Xing'an Range is consistent with the magmatic migration from the Zhangguangcai Range via Lesser Xing'an Range to Great Xing'an Range. By contrast, if the late Jurassic-early Cretaceous magmatism in the Great Xing'an Range resulted from the Mongol-Okhotsk tectonic regime, the northwest to southeast magmatic migration contradicts with northward subduction of the Mongol-Okhotsk Plate.

(3) Wang T et al. (2015) identified two episodes of magmatism in the Mongol-Okhotsk tectonic belt, namely 200–170 and 150–110 Ma, respectively, and attributed them to the products of two different geodynamic settings, i.e., syn-subduction and post-subduction stages. There is a magmatic hiatus (165–150 Ma) between the two episodes. Interestingly this magmatic hiatus corresponds to the magmatic climax of the Tiaojishan Formation which is widespread in the northern margin of the NCC. In this sense, the Tiaojishan Formation cannot be related to the Mongol-Okhotsk tectonic regime. Even the Tiaojishan Formation in the Yanliao area is assumed to result from orogenic collapse, however, the closure of the Mongol-Okhotsk Ocean run from southwest to northeast. A similar spatial magmatic migration would be expected for orogenic collapse-related magmatism. However, such a pattern is not observed.

The above discussions therefore preclude the influence of the Mongol-Okhotsk tectonic regime on the east Liaoning and Yanliao regions. The magmatic migration shown in Figure 1 reflects the processes of Pacific plate subduction. From 180 to 145 Ma magmas migrated landward, representing magmatic responses to progressive subduction of the Pacific subduction (see below). This suggests that subduction of the west Pacific plate beneath eastern Asian continent started as early as the early Jurassic, in good agreement with the conclusions drawn from studies on the accretionary complex.

3. Position of Pacific subduction zone during early Cretaceous

It is crucial to define the position of the subduction zone of the paleo-west Pacific plate if subduction served as the first-order control on the NCC destruction. Based on the thickness of denuded molasses accumulations, Chen (2000) suggested that the coastal mountains along the East Asian margin during the Late Cretaceous attained elevations between 3,500 and 4,000 m above sea level and width of 500 km from east to west. Recently, Zhang et al. (2016) used carbonate clumped isotope paleo-thermometry to estimate that the paleo-elevation of remnant coastal mountain along East Asia was ≥2,000 m at about 80 Ma. Considering the present-day subduction situation in east Pacific, we infer that the subduction zone had existed near the coastal mountains of the NCC since the Late Jurassic and Early Cretaceous, which was far to the west of its present position (Figure 2). Based on the studies of geomagnetic anomalies in the oceanic crust, reconstruction of global plates, numerical modeling, dynamics of oceanic basins, petrologic and geochemical data, and geomagnetic observations (Funiciello et al., 2003; Seton et al, 2012; Müller et al., 2008a, 2008b; Bird, 2003; Yang, 2013; Tarduno, 2007; Liu S F et al., 2017), it is proposed that the age of the subducting oceanic crust at west Pacific trench was ~160 Ma in the Early Cretaceous (~140 Ma), and became gradually young away from the subducting zone to the east. The age of the subducting oceanic crust at the trench was ~130 Ma at 130 Ma, ~10 Ma in the early Cenozoic (~60 Ma). During the period of 130 Ma to 60 Ma, the age of the subducting oceanic crust at the subducting zone was gradually younger from the trench to east. The subduction of the mid-ocean ridge occurred at ca. 45 Ma, after which the age of the crust at the subduction zone became progressively older. The age of the subducting oceanic crust at the trench was ~10 Ma at 40 Ma, ~70 Ma at 20 Ma, and ~130 Ma at the present day. From 40 Ma to the present, the age of the subducting oceanic crust became progressively older.

The restoration of the evolution of the subducting west Pacific plate helps constrain the position of the Paleo-Pacific subduction zone during the early Cretaceous. Since 40 Ma the Pacific plate has experienced rapid retreat (second most rapid retreat event since the late Cretaceous), resulting in the opening of the Japan Sea as a back-arc basin. The NCC was located to west of this back-arc basin at that time. The distance of the subduction retreat during the Cenozoic can be estimated from the E-W width of the Japan Sea and is up to 1,300 km. Taking into account ca. 880 km retreat during 130–120 Ma (Zhu et al., 2015), we conclude that the subduction zone of the paleo-western Pacific plate may have retreated eastward by ca. 2,200 km (1,300+880 km) since 130 Ma. Accordingly, the Eurasian continent migrated eastward over a distance of ~900 km since 130 Ma.

4. Formation age of the BMW under eastern Asia

The geological records mentioned above suggest that the west Pacific plate started to subduct underneath eastern Asian continent at least from the early Jurassic. The next question to answer is the timing of stagnation of Pacific slab within the MTZ, or when the BMW was formed. This is critically relevant to the mechanism of the destruction of the NCC.

Global seismic tomography reveals stagantion of Pacific plate within the MTZ (410–660 km) horizontally extending over a distance of >1,500 km from the Western Pacific

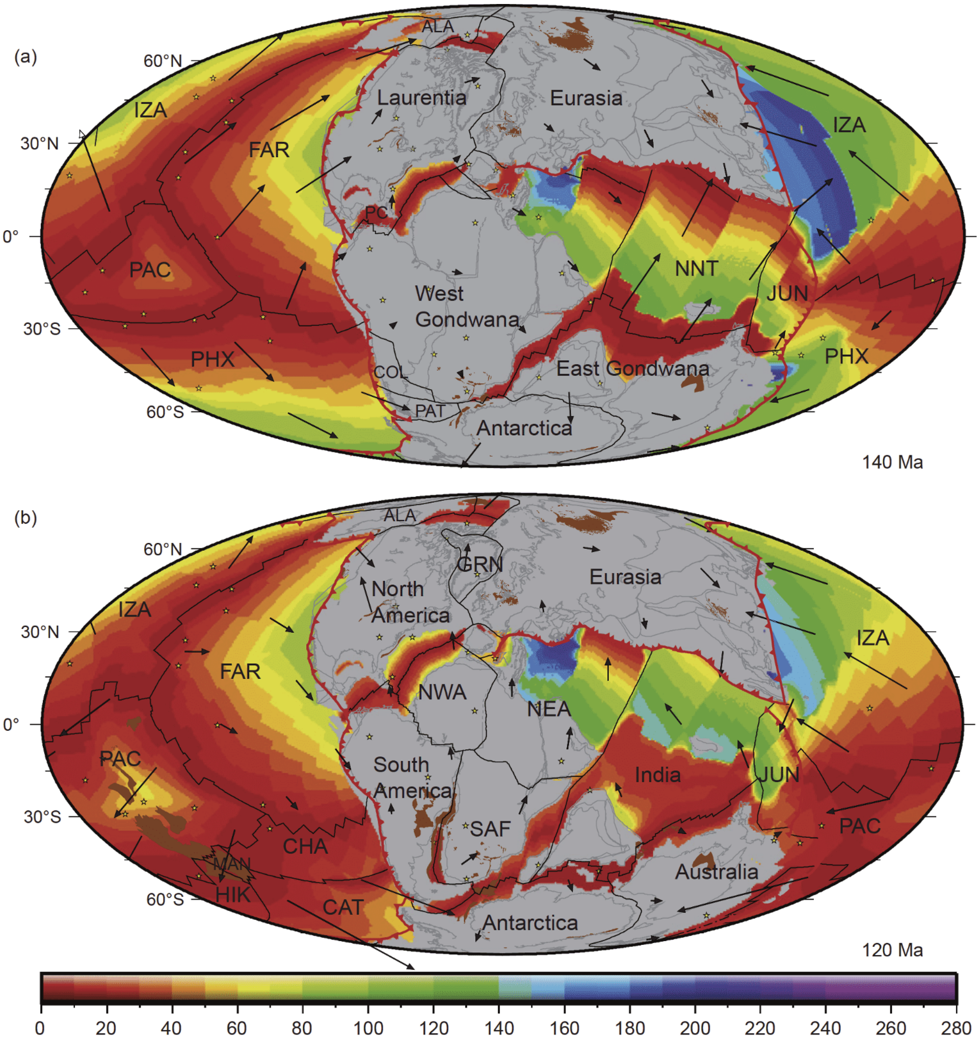

Figure 2 Position of subduction zones of the paleo-Pacific plate in the Cretaceous. Modified after Seton et al. (2012), Zhu et al. (2017). ALA: Alaska; CAR: Caribbean plate; CHA: Chaska plate; COL: Colorado; FAR: Farallon plate; IZA: Izanagi plate; JUN: Junction; MANHIK: Manihiki; NNT: North Neo-Tethys; PAC: Pacific plate ; PAT: Patagonia; PHX: Phoenix.

subduction zone. Zhao et al. (2004) , Ohtani and Zhao (2009) referred to the upper mantle above the stagnant slab as BMW. The BMW system is different from the so-called small mantle wedge which is geographically close to the trench. With a distance of over 1,000 km from the trench, the relevant area of the BMW is in general considered as an intraplate setting. The BMW, the flat-flying slab in the MTZ and the lower mantle consist a peculiar "sandwich-like" mantle structure beneath eastern Asia (Xu et al., 2018).

At present, there are two opinions regarding the formation age of the BMW under eastern Asia. The first suggests that the BMW structure revealed by seismic tomography reflects the present-day image of the deep structure (Zheng et al., 2018). Using a high-resolution model of P-wave tomography and paleo-age data of ancient seafloor, Liu X et al. (2017) suggested the flat slab in the MTZ is no more than 20 million years, and it is the subducted Pacific plate rather than the proposed Izanagi plate. The others (Zhu et al., 2012; Ma and Xu, 2017; Xu et al., 2018) suggested that the BMW was formed as early as in the early Cretaceous. By the definition (Zhao et al., 2004; Ohtani and Zhao, 2009), the formation of BMW means the stagnation of the slab. The pre-request for the stagnation of subducting slab within the MTZ is trench retreat (Griffiths et al., 1995). Accordingly the initiation of retreat of west Pacific plate subduction zone can be used to constrain the formation age of the BMW beneath eastern Asia (Ma and Xu, 2017; Ma et al., under review).

Ma and Xu (2017) examined the tempo-spatial migration pattern of the late Mesozoic magmatism in eastern Asian margin. The compilation of age data for Mesozoic igneous rocks from this area reveals a magmatic belt that migrated over 1000 km inland-ward during 185–145 Ma and then backward after 145 Ma (Figure 1), coherent with the transition from contractional to extensional deformation regime at the very early Cretaceous. These two stages of magmatism are interpreted as responses to forward subduction towards continental margin and to trench retreat, respectively. This interpretation is confirmed by other studies (Zheng and Dai, 2018; Zheng et al., 2018). For instance, Zheng et al. (2018) argued that Paleo-Pacific slab was subducted beneath the eastern Asian continent in the Jurassic. At ~144 Ma the subducting Paleo-Pacific slab started to rollback.

Although there is an agreement as to the timing of Paleo-Pacific slab rollback, how long it takes for the slab to stagnate within the MTZ remains highly debated, which stimulates discussion on the formation age of the BWM under eastern Asia (Xu et al., 2018; Zheng et al., 2018). This issue has recently been addressed by Mao and Zhong (2018) who simulated the slab stagnation processes. The results suggest that the observed stagnant slabs in the transition zone and other slab structures in the lower mantle can be explained by the presence of a thin, weak layer at the phase change boundary that was suggested by mineral physics and geoid modelling studies. Their results imply that the stagnant slabs mostly result from subduction in the past 20–30 million years, inferring that its takes about tens of millions of years for stagnated slab to descend to the lower mantle. If their modeling results are reasonable in the first order, it can be inferred that the BMW was formed at ~120 Ma, given the onset of Pacific slab rollback at ~145 Ma. Such a time constraint is consistent with the geochemical studies on Mesozoic basalts in eastern China. Dai et al. (2016) found a dramatic change in the nature of mantle sources at ~121 Ma. Mafic igneous rocks emplaced at this age start to show OIB-like geochemical compositions. In contrast, mafic igneous rocks emplaced before this age exhibit island arc basalts (IAB)-like compositions. Li et al. (2017) carried out systematic Mg isotope analyses on late Mesozoic-Cenozoic continental basalts and circum-Pacific island arc basalts. They outline a large-scale region of low δ^{26}Mg anomaly extending from Heilongjiang province near the Sino-Russian broader in the north to Hainan island in the south with the Great Xing'an Range-Taihangshan gravity lineament as its western limit. Since only sedimentary carbonate possesses very light δ^{26}Mg and there is no Mg isotopic fractionation during subduction, the low δ^{26}Mg is thus interpreted to reflect the presence of recycled sedimentary carbonate in magma source, most likely derived from the stagnant slab within the MTZ (Li et al., 2017). The first basalt showing light δ^{26} Mg signature was erupted at 106 Ma (Li and Wang, 2018). Li and Wang (2018) examined the Mg-Sr isotopic composition of basalts from this region and suggested that since 106 Ma the carbonated mantle with light Mg isotopic anomaly started to melt at a depth of 300–360 km, meaning that the subducted Paleo-Pacific slab already started to react with the ambient mantle as early as 106 Ma. Considering the time needed for magmatic ascent and eruption, they inferred that the BMW structure was already present in the early Cretaceous. At the depth of 300–360 km, dehydration melting of the crustal rock of the upper part of subducted slab takes place, and rutile in ultra-pressure metamorphosed eclogite decompresses. The resultant silicate and carbonatite melt mixture metasomatized the overlying BMW, leading to the formation of mantle source with OIB-like signature (Xu et al., 2018; Zheng et al., 2018).

The stagnated slab within the transition zone is not forever and it descends to the lower mantle after a period of about 10 million years. In this sense, the structure of the deep mantle under eastern Asia is transient in nature. Nevertheless, this does not preclude the possibility that the upper mantle beneath this region since the Cretaceous is overall characterized by a BMW structure, given the dominant tectonic setting of trench retreat of the Pacific subduction system since late Mesozoic (Seton et al., 2012).

In the model of Mao and Zhong (2018), the thin, weak layer immediately beneath the MTZ is the key to the stagnation of subducting slab. If this layer did not exist, the stagnated slab within the MTZ could have resulted from continuous subduction of Pacific plate over a period of 120–100 Ma (Seton et al., 2012), and the interval between the slab stagnation and its descent to the lower mantle is also probably much greater than the time scale of 10 million years. Whether this weak layer exists and its property are the key questions which deserve further study in future.

The tempo-spatial migration pattern of the late Mesozoic magmatism in eastern Asian margin (Figure 1) has two implications. (1) The subducting Pacific plate began to retreat since 145 Ma, earlier than the peak-time of the destruction of the NCC. This illustrates the control of roll-back of subducting slab on the destruction of the NCC. (2) The period of 130–120 Ma corresponds to the enlargement of the BMW due to the rollback of the subducting west Pacific plate. At that time, the influence exerted by the subduction of the west Pacific plate on the NCC is most likely the extensive exchange of energy and material between stagnated slab and overlying upper mantle. Carbonatite metasomatism could be one of reactions between stagnated slab and the BMW. It created carbonated peridotites, which would experience partial melting due to its low solidus and trigger the dramatic changes in physical and chemical properties of the lithospheric mantle, ultimately leading to cratonic destruction. At that time, the lower part of the lithospheric mantle beneath the NCC is similar to the asthenosphere. These studies therefore not only place constraints on the formation age of the BMW beneath eastern Asia, but also provide evidence for the linkage between west Pacific subduction, destruction of the NCC and deep carbon cycling (Li and Wang, 2018; Xu et al., 2018; Zheng et al., 2018). On the other hand, the metasomatism involving carbonatite melts is also crucial in the formation of giant gold deposits during the destruction of the NCC (Zong and Liu, 2018).

The BMW structure in eastern Asia formed by the west

Pacific subduction, not only played an important role in destruction of the NCC, but also controlled the generation of intraplate basalts in this region. Xu et al. (2018) summarized geochemical characteristics of Cenozoic intraplate basalts from eastern China and identified abundant recycled components in the magma source, including oceanic crust, water and sedimentary carbonate, whose provenance is related to the stagnant slab in the MTZ. They further proposed that Cenozoic basalts from eastern China can be best interpreted as a mixture of high-Si and low-Si end-member melts. The former shows an Indian mantle-type composition, and the latter has Pacific mantle-type composition. They come from the upper and lower part of the BMW, respectively. In this vertical heterogeneous BWM model, dehydration and decarbonization of the subducted slab within the MTZ and associated melting and metasomatism are main driving forces of the generation of intraplate basalts within the BMW system. This model partly accounts for some long-lasting questions, such as why the Cenozoic basalt generated in a continental setting possessed an OIB-like geochemical signature. Further understanding of interaction of diverse components, magmatic generation and geodynamic driving forces in the BWM system has great implication in developing the plate tectonic theory.

5. The subduction of the west Pacific plate and the destruction of the NCC

So far, we have discussed the initial subduction of the west Pacific plate beneath the eastern Asian continent, the position of paleo-subduction zone in the Early Cretaceous, and the formation time of the BMW. All these support a linkage between the subduction of the west Pacific plate and the destruction of the NCC. The following discussion will focus on how the subduction of the west Pacific plate would have evolved with respect to the destruction mechanism of the NCC.

If the BMW under eastern Asia was indeed formed in the Early Cretaceous, its role in the destruction of the NCC cannot be ignored. The BWM is a huge reservoir of carbon and water (Li et al., 2017; Xia et al., 2017). In particular, it is rather unusual that the water content in the intraplate upper mantle like in eastern China is comparable to that in subarc mantle (Xia et al., 2013). The high water content is possibly related to the dehydration and decarbonization of the stagnant Pacific slab within the MTZ (Xia et al., 2019; Xu et al., 2018; Li and Wang, 2018). These processes would release significant amounts of water and carbonatite melts into the overlying mantle, triggering partial melting of the BMW and facilitating upward migration of deep fluids/melts into the shallow lithospheric mantle. Consequently, the cratonic lithosphere is severely hydrated and non-steady mantle flow forms, resulting in metasomatism, melting and weakening of the lithosphere, which ultimately led to lithospheric thinning and cratonic destruction.

According to Zhu et al. (2015), the subducting west Pacific plate has retreated by 880 km during 130 and 120 Ma. This suggests a high rate of trench retreating during this period which may have left severe influence on the BMW. If the non-steady convection within the wedge system during this period exerted significant physio-chemical influence on the overlying cratonic lithosphere, it may be the principle factor causing the cratonic destruction.

Here we attempt to describe the evolutionary processes of the west Pacific plate subduction into deep earth's interior, based on observed tectonic events. According to the structural geology and geochronological dating, the Phase A of the Yanshanian orogeny took place at ~165 Ma (Dong et al., 2010; Yang and Li, 2008; Zhang et al., 2008; Zhao et al., 2010), corresponding to the late Middle Jurassic angular unconformity beneath the Upper Jurassic strata throughout the eastern NCC. The Phase A of the Yanshanian orogeny is marked by contractional deformation and lasted for about 5 million years, and is roughly coincident with strike-slip movement of the Tanlu Fault. The whole series of continental deformation is likely caused by rapid, low angle subduction of the west Pacific Plate beneath the eastern Asian margin (Figure 3a).

Vigorous Late Jurassic volcanism took place in the eastern NCC and was associated with development of rift basins (Wu et al., 2007; Yang et al., 2012), indicating extensive lithospheric extension during this period. The change from contraction to extension in the Latest Jurassic to the earliest Early Cretaceous is thought to be the result of changing from low to high angle subduction of the paleo-west Pacific slab (Zheng et al., 2018), which might be accompanied by slab rollback and trench retreat processes (Figure 3b). The widespread ca. 138 Ma crustal shortening in the NCC, folding of pre-Cretaceous strata and an angular unconformity beneath the Early Cretaceous sequence registered the Phase B of the Yanshanian orogeny. During this period, east China experienced another compression event, sinistral movement along the Tanlu fault, basin inversion and transient regional uplift. The Phase B of the Yanshanian orogeny might be triggered by decreasing subduction angle of west Pacific Plate (Figure 3c).

Given that the peak age for the destruction of the NCC is ~125 Ma and during this period the age and subduction rate of the paleo-west Pacific plate were 160 Ma and 60–120 km/Ma, respectively (Zhu et al., 2017), and based on re-analyses of the seismic tomography of Huang and Zhao (2006) (Zhu et al., 2015), it is inferred that during the Early Cretaceous (130–120 Ma) paleo-western Pacific plate was subducted beneath the Asian continent at a high angle and was accompanied by slab retreat and rollback (Figure 3d). The re-

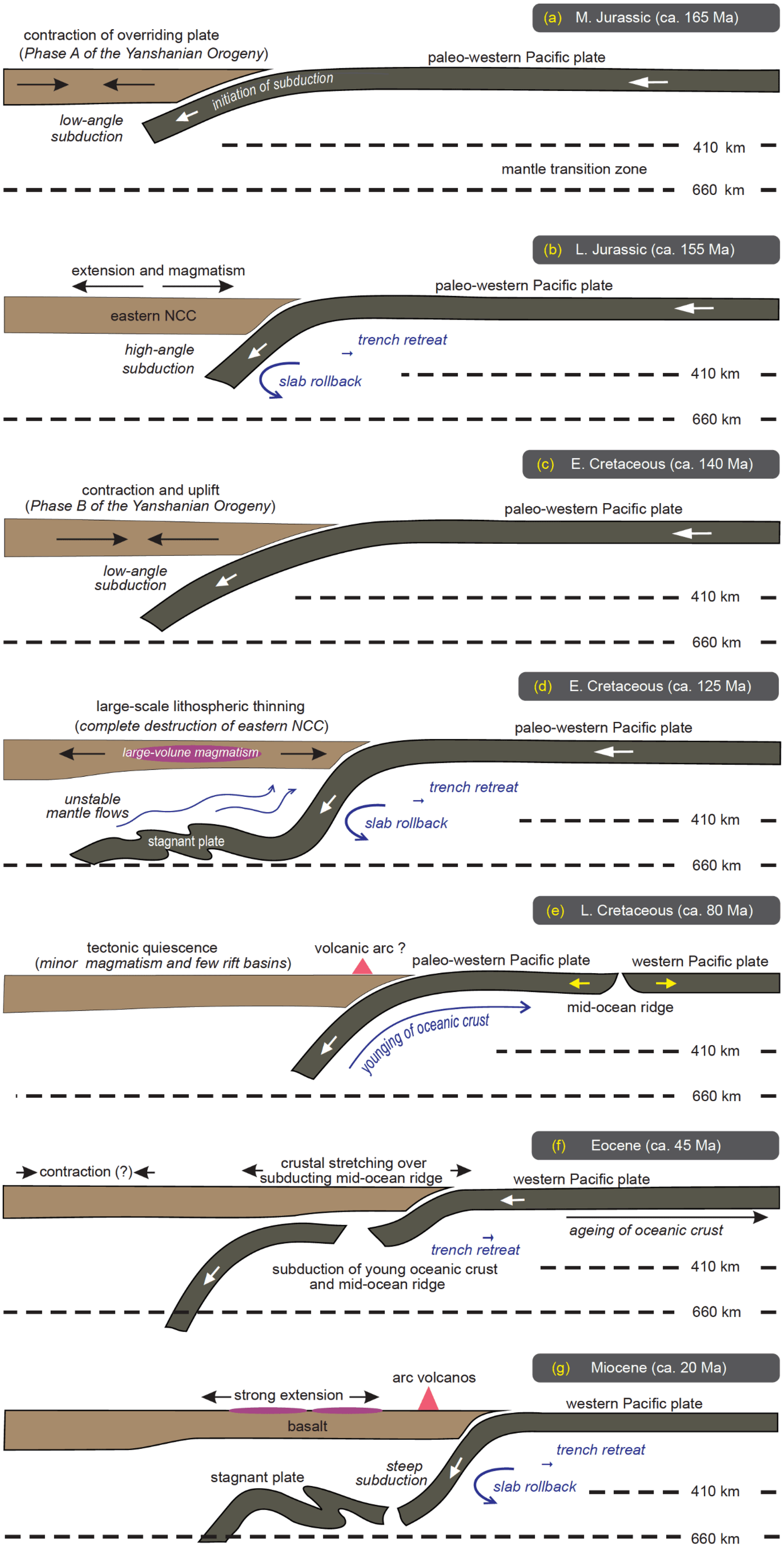

Figure 3 Subduction processes of the west Pacific plate since the late Jurassic. Modified after Zhu et al. (2017).

treat of the subducting plate would have eventually led to slab stagnation in the MTZ. The resulting bimodal magmatism occurred throughout the eastern and central parts of the NCC, including large-volume intrusive (about 80% Phanerozoic intrusive rocks formed during this period) and thick layer of basalts. Meanwhile, dehydration of the stagnant subducted slab in the MTZ could significantly modify the physical property and viscosity of the overlying mantle, and generated non-steady mantle flows. Slab dehydration and non-steady flows in the overlying mantle wedge would further dramatically increase contents of fluids/melts in the lithospheric mantle, lower the viscosity, increase regional thermal anomaly and lithospheric extension. All these processes would have transformed the old cratonic lithosphere to the young mantle, a process now known as the cratonic destruction (Zhu et al., 2017).

The NCC during 120–105 Ma is characterized by weak crustal extension and isostatic uplift (Liu J et al., 2013; Liu S F et al., 2017). This is followed by a period (especially from about 80 Ma) of tectonic and magmatic quiescence, with significant reduction of both magmatism and extension. This is probably associated with the arrival of young and buoyant portions of the Paleo-Pacific oceanic plate at the trench (Figure 3e). Subduction of the mid-ocean ridge occurred during the Eocene (Figure 3f) and had caused extension and magmatism in east segment of the NCC, as implied by development of the Bohai Bay rift system. Increasingly older portions of the west Pacific plate began subducting after 40 Ma, with a gradual increase in subduction angle and rate. Retreat of the subduction zone and slab rollback led to the slab stagnation within the MTZ (Figure 3g). In the late Cenozoic, the NCC was located far from the subduction zone, and therefore underwent little crustal stretching. In that time, the NCC is featured by large-scale depression.

The above-mentioned conclusions are supported by the investigations into the Tanlu fault, which cross-cut the east segment of the NCC. The importance of the Tanlu Fault has been recognized for longtime as it provides a key window to understand the relationship between cratonic destruction and west Pacific subduction. Zhu et al. (2018) identified the sinistral motion of the Tanlu Fault at the end of Middle Jurassic and interpreted it as a result of initiation of the Paleo-Pacific (Izanagi) Plate subduction beneath the East China continent. The fault zone experienced two episodes of sinistral movements at the beginning and end of Early Cretaceous, respectively. Both two deformations correspond to regional compression that resulted from the low-angle, high-speed subduction of the Paleo-Pacific Plate. It experienced extensive extension in the rest of Early Cretaceous, which was simultaneous with the peak destruction of the NCC caused by backarc extension that resulted from rollback of the subducting Izanagi Plate. The fault zone suffered local and weak extensional faulting in the Late Cretaceous. The evolution of the Tanlu Fault is characterized by several times of alternated compression and extension events, with each of the sinistral faulting event in a relatively short period, whereas extensional deformation lasted in a longer period. The complex deformation history of the Tanlu Fault mirrors varying rate and subduction angle of the Paleo-Pacific Plate in the Mesozoic.

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