Construction of the Continental Asia in Phanerozoic: A Review

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Abstract: This is a review of the formation and tectonic evolution of the continental Asia in Phanerozoic. The continental Asia has formed on the bases of some pre-Cambrian cratons, such as the Siberia, India, Arabia, North China, Tarim, South China, and Indochina, through multi-stage plate convergence and collisional collages in Phanerozoic. The north-central Asia had experienced the expansion and subduction of the Paleo-Asian Ocean (PAO) in the early Paleozoic and the closure of the PAO in the late Paleozoic and early Mesozoic, forming the PAO regime and Central Asian orogenic belt (CAOB). In the core of the CAOB, the Mongol-Okhotsk Ocean (MOO) opened with limited expansion in the Early Permian and finally closed in the Late Jurassic–Early Cretaceous. The south-central Asia had experienced mainly multi-stage oceanic opening, subduction and collision evolution in the Tethys Ocean, forming the Tethys regime and Himalaya-Tibetan orogenic belt. In eastern Asia, the plate subduction and continental margin orogeny on western margin of the Pacific Ocean, forms the West Pacific regime and West Pacific orogenic belt. The PAO, Tethys, and West Pacific regimes, together with Precambrian cratons among or surrounding them, made up the major tectonic and dynamic systems of the continental Asia in Phanerozoic. Major tectonic events, such as the Early Paleozoic Qilian, Uralian, and Dunhuang orogeneses, the late Paleozoic East Junggar, Tianshan and West Junggar orogeneses, the Middle to Late Permian Ailaoshan orogeny and North-South Lhasa collision, the early Mesozoic Indochina-South China and North-South China collisions, the late Mesozoic Mongolia-Okhotsk orogeny, Lhasa-Quingtang collision, and intra-continental Yanshanian orogeny, and the Cenozoic Indo-Asian, Arab-Asian, and West Pacific margin collisions, constrained the formation and evolution of the continental Asia. The complex dynamic systems have left large number of deformation features, such as large-scale strike-slip faults, thrust-fold systems and extensional detachments on the continental Asia. Based on past tectonics, a future supercontinent, the Ameurasia, is prospected for the development of the Asia in ca. 250 Myr.

Key words: Paleo-Asian Ocean, Tethys, West Pacific, tectonic events, geodynamic systems, continental Asia, Phanerozoic

1 Introduction

Presently the continental Asia is mainly composed of eastern Eurasian plate, northwestern Indo-Australian plate, western margin of the Pacific plate, and a little piece of the North American plate (Fig. 1). It has experienced the Neoproterozoic opening, early Paleozoic expansion, and late Paleozoic to early Mesozoic closing of the Paleo-Asian Ocean (PAO) in the north (Xiao et al., 2015, 2018; Zhao et al., 2018), the opening and limited expansion of the Mongol-Okhotsk Ocean (MOO) in the Early Permian and its closing in the Late Jurassic to Early Cretaceous (Goldfarb et al., 2014), the multiple-stage opening and subduction of and collisions in the Proto-Tethyan (late Neoproterozoic to Silurian), the Paleo-Tethyan (Early Devonian to Triassic), the Meso-Tethyan (late Early Permian to Early Cretaceous), and the Neo-Tethyan (Late Triassic to Late Cretaceous) oceans in the south (Metcalfe, 2013; Goldfarb et al., 2014; Li et al., 2018; Zhao et al., 2018; Wang et al., 2018), and the subduction of the western Pacific plate and eastern Asian marginal orogeny since the Mesozoic (Goldfarb et al., 2014; Dong et al., 2015). Several tectonic regimes, such as the PAO regime in the north, the Tethys regime in the south, and the western Pacific regime in the east, were the major dynamic systems controlling the formation and evolution of the continental Asia in Phanerozoic, especially in the Mesozoic and Cenozoic. Major tectonic events, such as the collisional orogeny between the Siberian and the North China plates (i.e., the craton and surrounding regions) in the late Paleozieloc to the early Mesozoic (Xiao et al., 2009a, 2015, 2018), the North-South China and South China-Indosinian collisions in the early Mesozoic (Metcalfe, 2006, 2011, 2013; Zhao et al., 2018), intracontinental Yanshanian orogeny in late Mesozoic (Dong et al., 2008a, 2015, 2018), and the Indo-Asian and...
Arab-Asian collisions in the Cenozoic (Yin and Harrison, 2000; Tappanier et al., 2001; Yin, 2010), have shaped the tectonic geomorphological features of the continental Asia.

In this paper, we collected a series of newly achieved progresses on tectonics of the Asia in Phanerozoic. Through comparative analyses of the deformation characteristics and tectonic evolution of the PAO, the Tethys, and the West Pacific regimes, and internal blocks among or surrounding them, we make a brief summary of the dynamic systems controlling of the tectonic evolution in different periods. Considering of the supercontinent cycle, we propose the formation of a new supercontinent in the future.

2 Major Tectonic Regimes of Asia

2.1 The Paleo-Asian Ocean regime

The PAO regime, mainly the Central Asian orogenic belt (CAOB; Figs. 1 and 2) or the Altaids (Sengör et al., 1993; Xiao et al., 2009a; Kröner, 2015), is one of the prominent tectonic features of the continental Asia in Phanerozoic. The CAOB, also known as the Ural-Mongolia fold belt, is located among the East European, the Siberian, the Tarim, and the North China cratons. It is mainly composed of the Ural, Tianshan, Altay, and Great Xing’an mountains, and the Mongolian Plateau, extending more than 5000 km from east to west and covering an area of tens of million km². The CAOB contains continental blocks, ophiolitic mélangé belts, and multi-stage magmatic activities and crust-mantle interactions, reflecting multiple subduction and continuous continental crust accretion in the PAO, following by continental collage and subsequent intracontinental deformation (Wang T et al., 2017; Han and Zhao, 2018; Furnes and Safonova, 2019; Ding et al., 2020; Zhang J et al., 2020). It was considered as the most significant region of Phanerozoic continental crust accretion and the largest accretionary orogenic belt in the world, through the collision and collage of continental blocks in the Paleozoic and Mesozoic (Sengör et al., 1993; Hu et al., 2000; Chen and Jahn, 2004; Jahn et al., 2004; Windley et al., 2007; Xiao et al., 2015, 2018, 2019; Khanchuk et al., 2015; Wilhem and Windley, 2015; Yakubchuk, 2017; Zhao et al., 2018).
It is also one of the regions with the largest mineral resource potential in the world (Goldfarb et al., 2014; Chen et al., 2017). The Precambrian terrane remnants and micro-continental blocks involved in the CAOB include the combined Northeast Asia blocks of the Erguna, Xing’an, Songliao, and Jiamusi-Khanka, Kazakhstan-Yili-Central Tianshan, Tuvan-Mongolian, Beishan, North Transbaikalian, Khangai, Issedonian, Ulutau-M, and other blocks (Zhou et al., 2018; Yarmolyuk and Degtyarev, 2019).

2.2 The Tethys regime

The Tethys regime, mainly the Himalayan-Tibetan orogenic belt (Yin and Harrison, 2000), is another prominent tectonic feature of the continental Asia in Phanerozoic. It is located in eastern Europe, and western, southern, eastern, and southeastern Asia (Figs. 1 and 2), surrounded by the Arabia, India, North China, Tarim, and East Europe cratons, with the South China block, i.e., the Yangtze craton and the Cathaysia block (Wang K et al., 2020), and the Indosinian craton involved in. It is mainly composed of the Alps, Zagros, Hindu Kush, Himalaya, and Qinling-Dabie mountains, and the Iranian, Pamir, and Qinghai-Tibetan plateaus, extending more than 15000 km from east to west. It is originated from the Proto-Tethyan Ocean in the late Neoproterozoic. It has experienced several stages of evolution in the Tethyan Ocean, such as the Proto-Tethyan (late Neoproterozoic to Silurian; Li et al., 2018; Zhang et al., 2022), Paleo-Tethyan (Devonian to Triassic; Masatoshi and Metcalfe, 2008; Chen et al., 2015, 2019b; Wang et al., 2018), Meso-Tethyan (late Early Permian to Early Cretaceous; Wang Y et al., 2021), and

Fig. 2. Phanerozoic dynamic systems of continental Asia.
Dynamic systems (alphabets in circle): A, North Qilian ocean plate subduction; B, Uralian ocean plate subduction; C, Paleo-Asian ocean plate subduction and Siberia-Kazakhstan collision; D, Paleo-Tethyan ocean plate subduction and North-South China collision; E, closure of Meso-Tethyan ocean and Lhasa-Qiangtang collision; F, closure of Mongol-Okhotsk ocean and Siberia-North China collision; G, intracontinental compression and strike-slip faulting in North Central Asia; H, Arab-Asian collision; I, Indo-Asian collision; J, Western Pacific plate subduction. Based on geological map of Asia (Ren et al., 2013). Far-field affected regions under Indo-Asian and Arab-Asian collisions are modified from Yin (2010). The fault systems are modified from Chen et al. (2019a). MOS, the Mongol-Okhotsk suture zone.
Neo-Tethyan (Late Triassic to Late Cretaceous) oceans (Metcalfe, 2013; Goldfarb et al., 2014; Zhao et al., 2018; Wang R et al., 2020). The subduction initiation occurred in the western Proto-Tethys Ocean in the Late Cambrian (ca. 494–485 Ma; SWKL in Fig. 3; Zhang et al., 2022). The Tethys and PAO regimes meet at the northern margin of the Western Himalayan Syntaxis in the west, and the Hexi Corridor, northern margin of the Qilian Mountains in the east, respectively.

2.3 The West Pacific regime

The West Pacific regime refers to the tectonic regime in the eastern margin of the continental Asia. It is mainly composed of the western Pacific subduction zone, the West Pacific orogenic belt, and a series of marginal seas. The West Pacific orogenic belt (WPOB; Figs. 1 and 2), or the western Circum-Pacific orogeny, is a several-thousand kilometers-long accretionary complex and fold-and-thrust belt in western Pacific region. It could be divided into two belts, the inner belt in the Pacific side and the outer belt in the continental side. The inner WPOB consists of the Kamchatka Peninsula, the Kuril Islands, the Japan Arcs, the Taiwan orogenic belt, the Philippines, and multiple Cenozoic sutures within eastern Indonesia, New Guinea, and the Melanesian arcs (Hall, 2002). The outer WPOB is distributed in the vast regions across the marginal seas, from the northern margin of the Sea of Okhotsk, through the Sakhalin Island, Northeast China, Korea, North China, the middle and lower reaches of the Yangtze River, and South China. The West Pacific regime exerts its tectonic influence on the continental Asia, with the farthest westward influence traced to the Taihang and Lüliang mountains, i.e., the Trans-North China orogenic belt (Chen et al., 2019a), or even far to the west.

3 Paleozoic Orogeny and Post-orogenic Extension

3.1 Closure of the North Qilian Ocean and collages in the Tethys Ocean

The Qilian orogenic belt is a key tectonic feature in northeastern margin of the Qinghai-Tibetan Plateau (Figs. 2 and 3). It is originated from the North Qilian Ocean, a northern Proto-Tethyan Ocean expanded in Neoproterozoic between the East Kunlun-Qaidam-Qilian and the Alxa blocks, with passive continental margins on both sides (Zhang Y P et al., 2020). It had experienced the subduction of the North Qilian Ocean, the formation and evolution of the arc-basin system, and the collisional orogeny and continental subduction in the early Paleozoic (Fig. 4; Gehrels et al., 2003a, b; Xiao et al., 2009b; Song et al., 2014; Wu et al., 2016, 2017; Li et al., 2018, 2021; Yu et al., 2021). The polarities of the ocean subduction were suggested as bi-lateral subduction, with northward subduction in the north and southward in the south (Chen et al., 2019b; Li et al., 2021; Yu et al., 2021), though there are still many argues about this question. The distribution of magmatic arcs supports the bi-lateral subduction of the North Qilian Ocean. For example, the Corridor Nanshan island arc in North Qilian Shan and the Beida Shan-Daqing Shan arc in southern margin of the Alxa block, indicates the northward subduction of the North Qilian Ocean underneath the Alxa block in the early Paleozoic. Meanwhile, the early Paleozoic Central Qilian magmatic arc and South Qilian continental arc, implies the southward subduction of the North Qilian Ocean underneath the East Kunlun-Qaidam-Qilian block (Fig. 4). At this time, the Lower Ordovician sediments in Sunan area, North Qilian mainly came from the Central Qilian block in the south, only a small amount of them came from the North Qilian island arc in the north. High and ultrahigh pressure (HP-UHP) metamorphism formed simultaneously in the North Qaidam Basin and the North Qilian Shan, with metamorphic ages of oceanic crust-based eclogites concentrated at 470–460 Ma (Yang et al., 2002; Song et al., 2013, 2014; Zhang C et al., 2017). Further in the north, the Alxa block formed as the boundary between the Paleo-Asian and the Tethyan oceans (Fig. 4).

3.2 Amalgamation in the Paleo-Asian Ocean

3.2.1 Major subduction and collisional orogenies in the Paleo-Asian Ocean

The evolution of the PAO had lasted for ca. 800–1000 Ma, with the continental margin accretion in the whole Paleoasian, oceanic subduction initiated in the early Paleozoic, collision and post-collisional extension in the late Paleozoic and early Mesozoic, and intracontinental orogeny in the Mesozoic and Cenozoic (Fig. 3). It is controlled by the dynamic system related to the PAO plate subduction and Siberia-Kazakhstan collision in the Paleoasian (Figs. 2 and 3). A multiple-island ocean model could be applied for the most time of the evolution of the PAO (Xiao et al., 2015). The long-term complex evolution resulted in the vertical double-layered crust structure and lateral tectonic zoning of the CAOB.

The CAOB has suffered multiple-phase orogenies in Neoproterozoic and Paleozoic (Fig. 3). There are two orogenies in Neoproterozoic, recorded by the Muya eclogite in southern Siberian craton and the Gorny Altai eclogite in southwestern Mongolia, with ages of 650 Ma and 630 Ma, respectively (Liu et al., 2011). In the early Paleozoic, the orogeny may start at Kokchetav, western CAOB, with age of 530 Ma, followed by that at Chara in southwestern Mongolia with ages of 510–485 Ma (Liu et al., 2011). Then, collisional orogenies occurred in southern CAOB, with ages of 480 Ma at Mkalbal, and 465 Ma at the Beishan orogenic belt (Liu et al., 2011). The Dunhuang orogeny took place at ca. 428–391 Ma in the southernmost CAOB (DHO in Fig. 3; Wang H Y C et al., 2017). Meanwhile, the subduction of the PAO took place in Chifeng-Ongniud area, Inner Mongolia during 420–400 Ma (Yan et al., 2020). After that, the Magnitogorsk arc-Baltica collisional orogeny took place at Maksyutov, southern Urals with eclogite age of 380 Ma (MBC in Fig. 3). In southern CAOB, the collision between the Tarim craton and the Central Tianshan-Yili block caused western South Tianshan orogeny (WSTO in Fig. 3), with eclogites of 345 Ma or 240 Ma at southwestern Tianshan, and of 270 Ma at Atbashy (Liu et al., 2011).
Fig. 3. Tectonic evolution of continental Asia in Phanerozoic.

Tectonic regimes: PAO, the Paleo-Asian ocean regime; Tethys, the Tethys regime; WP, the West Pacific regime. Dynamic systems and tectonic events: ACCT, arc-continent collision in Taiwan; WPMC, West Pacific margin collisions in SE Asia and SW Pacific regions; WPME, West Pacific margin extension; RSR, Red Sea rifting; TICO, Turkish-Iranian-Caucasus orogeny; AAC, Arab-Asian collision; IAC, Indo-Asian collision; OEAC, Okhotsomsk-East Asia collision; SNCC, Siberia-North China collision; WPSCC, West Philippines-South China collision; HCE, Hexi Corridor extension; PNSCE, Pan-North and South China extension; TBE, Transbaikalia extension; WPBAE, West Pacific back-arc extension; LQC, Lhasa-Qiangtang collision; YSO, Yanshanian orogeny; NSQC, North China-Songnen massif collision; ICSCC, Indochina-South China collision; NSLC, North-South Lhasa collision; ALO, Ailaoshan orogeny (collisional); WJO, West Junggar orogeny; WSTO, western South Tianshan orogeny (collision between Tarim craton and CTS-Yili block); TFF, Talas-Ferghana fault (early stage); DHO, Dunhuang orogeny; NSLC, North-South Lhasa collision; CSNQD, continental subduction/collision in North Qaidam and South Qilian; UO, Ural orogeny; QLO, Qilian orogeny; SWKL, subduction initiation in western Kunlun orogen; QLO, North Qilian oceanic-type subduction. Faulting: EKF, East Kunlun fault; QTR, Qinghai-Tibetan rift system; BR, Baikal rift system; MHT, Main Himalayan Thrust; ATF, Altyr Tagh fault; LPD, Lapeiquan Detachment (North Ailhan Tagh); TLF, Tan-Lu fault; JF, Junggar fault; KHF, Kangxuantage-Huangshan fault; TFF, Talas-Ferghana fault (early stage); DF, Da-rabat fault; TSFS, Tianshan strike-slip fault system (Main Tianshan shear zone); BR, Baikal rift system. The apparent growth curve and volume of continental crust of the Earth are from Maruyama et al. (2014). LIPs are mainly from Ernst et al. (2013). The “Cretaceous superplume” is from Bleeker (2003). Proportions of extinction are from Melott and Bambach (2014). The ages of eclogites are mainly from Liu et al. (2011).
Fig. 4. Tectonic evolution of the Qilian orogenic belt since Neo-Proterozoic (modified from Chen et al., 2019b).
During the continental margin accretionary orogeny through the Paleozoic era, and post collisional vertical accretion of the continental crust in the late Paleozoic, large-scale oceanic crust subduction and strong crust-mantle interaction took place in the CAOB. Through Early Carboniferous to Early Triassic (ca. 325–245 Ma), the PAO closed gradually from the west to the east, resulting in the convergence of the East Europe, Siberia, Tarim, and Aksu-North China cratons, and the formation of the supercontinent Pangea (Xiao et al., 2015, 2018; Han and Zhao, 2018; Zhao et al., 2018). The initial closure of the PAO took place in the South Tianshan orogenic belt, with the occurrence of the western South Tianshan orogeny (WSTO in Fig. 3) due to the collision between the Tarim craton and the Central Tianshan-Yili block in ca. 325–310 Ma (Han and Zhao, 2018). Bidirectional subduction model has been proposed for the evolution of the southern Tianshan Ocean (Wang Z P et al., 2021). Then, the closure might take place in the West Junggar orogenic belt in the Late Carboniferous (ca. 300 Ma; Chen et al., 2017; Ma et al., 2020), and in the Beishan orogenic belt in the Late Permian to Early Triassic (Xiao et al., 2015, 2018). The bidirectional subductions of the PAO on both sides of the Solonker suture (Ye et al., 2019), resulted in the final closure of the PAO in the Early Triassic (Eizenhöfer and Zhao, 2018). The dominant subduction-related ophiolite mélanges (79%; basically backarc type) formed through Neo-proterozoic to Triassic (Furnes and Safonova, 2019), manifest the subductional reduction of the PAO and the continental accretion history in the CAOB. A large number of Paleozoic island arc volcanic rocks, granites, adakites, Nb-rich basalts, and high Mg andesites and picrites, characterized by isotope ratios of high Nd and low Sr, and subductions of mid-ocean ridges, should be some important indicators of oceanic subduction.

A series of large-scale strike-slip faults formed in the Central Asia in the late Paleozoic and early Mesozoic, due to the significant ocean-continental transformation during the closure of the PAO (Chen et al., 2017; Xu et al., 2019). In western part of the CAOB, the dextral Main Tianshan shear zone of the Tianshan strike-slip fault system and the Balkhash (Kazakhstan) oregone formed in the Late Carboniferous and Early Permian (Liu T L et al., 2021; TSFS in Fig. 5). The tectonic bending of the Kazakhstan orogene left the trapped oceanic crust beneath the Junggar Basin (Han and Zhao, 2018). The left-lateral strike-slip faults and sinistral ductile shearing zones, generally extending NW–SE in the Altay Mountains, such as the Ertix fault, and NE–SW in the West Junggar, north Xinjiang, such as the Darabut fault, had formed in this time (Figs. 3 and 5; Ding et al., 2020; Wang Y et al., 2020b). The Trans-Eurasian strike-slip fault, with the Ertix fault in its central segment, had offset sinistrally the Kuznetsk Alatau as much as 1000 km from its bulk body in the Kazakh Uplands, Tian Shan and Mongolian Gobi in Permian (282–264 Ma; Yakubchuk, 2008), resulting in westward escaping of crustal materials in the north side of the Tianshan Mountains. The formation of large-scale strike-slip fault systems indicates that the region had entered intracontinental evolution since the Early Permian (Chen et al., 2017; Ding et al., 2020).

### 3.2.2 Subduction of the Uralian Ocean and formation of the Uralian orogenic belt

The Uralian orogenic belt, located between the continental Asia and Europe (Figs. 1 and 2), is an important tectonic feature in the construction of the continental Asia. It is originated from the Uralian Ocean, the western part of the PAO formed during the rifting of the passive margin of the Baltica, i.e., the East European craton, in the Late Cambrian to Early Ordovician (Puchkov, 2009). The initiation of subduction in the Uralian Ocean could be traced back to the Middle to Late Ordovician at ca. 460 Ma (Puchkov, 2009), resulting in the Ural orogeny in early Paleozoic (UO in Fig. 3). In the Magnitogorsk arc, one major intra-oceanic arc in the Uralian Ocean, initiation of subduction occurred at ca. 416–410 Ma (Scarrow et al., 2002; Brown et al., 2006).

The Uralian orogenic belt could be considered as the most western end of the CAOB (Figs. 1 and 2). It records the Paleozoic collisions of at least two intra-oceanic arcs with the Baltica in the Late Devonian in the south (MBC in Fig. 3) and Early Carboniferous in the north, and its subsequent continental collisions with the Kazakhstan and Siberian plates during the assembly of Pangea (Brown et al., 2006; Puchkov, 2009). Therefore, the closure of the Uralian Ocean should be in the early Late Carboniferous (Puchkov, 2009), though it was believed before that the closure occurred in the Early Permian–Late Triassic (Otto and Bailey, 1995). It preserves a late Paleozoic collision with a well-preserved crustal root, composed mainly of mafic granulite metamorphosed from subducted oceanic crust (Scarrow et al., 2002). The final collision between the Baltica and the Siberian and Kazakhstan cratons occurred in Late Carboniferous to Permian (ca. 300–280 Ma), with the totally formation of the supercontinent Pangaea (Puchkov, 2009). The Main Uralian fault, a N–S-trending major thrust, formed in the Urals during continental collision in the Late Carboniferous (Friberg and Petrov, 1998).

### 3.3 Formation of Permian–Early Triassic large igneous provinces and rift systems

Backarc and post-orogenic extensions are popular in the CAOB. Prior to the closure of the PAO in its central and eastern parts, remarkable backarc extension occurred in the Hegenshan ophiolite-arc-accretionary belt adjacent to the Solonker suture in Late Carboniferous and Early Permian (305–274 Ma; Wang Y et al., 2020a). Simultaneously, the Tarim large igneous provinces (LIP, or mantle plumes) developed on south side of the CAOB (Pirajno et al., 2011; Xia, 2013; Qin et al., 2015). Large-scale basalt eruption of the Tarim LIP is concentrated at 290 Ma (Fig. 3; Xia, 2013). Permian mafic dyke swarms and continental basalt eruptions are widespread in the region between the Siberia and the Tarim cratons (Zhang Y P et al., 2017), composing the Central Asian rift system, from Transbaikalia and Mongolia, to the Tarim Basin (Yarmolyuk et al., 2013). For example, the Early Permian (297–290 Ma) basalts and andesites indicate post-orogenic extension in the central and eastern Kazakhstan, which is consistent with the initiation of the Tarim LIP (Khromykh et al., 2020). Associated with the Tarim LIP, post-
collisional and intraplate alkali-rich volcanic rocks, A-type granitoids, continental basalts, and mafic dyke swarms, with ages of 290–270 Ma, widely developed in the Central Asia (Wang T et al., 2017). With a similar age of the Tarim/Qiangtang LIP (Fig. 3; Ernst et al., 2013), the Woniusi flood basalts formed in the Baoshan terrane, representing late Paleozoic rifting of the Cimmeria from northern margin of East Gondwana (Cao et al., 2020).

In north side of the CAOB, the Siberian LIP, which is the largest volcanic eruption in Phanerozoic, is active in 248–247 Ma (Fig. 3; Nokleberg, 2010). The flood basalt event of the Siberian LIP has a consistent age with the mass extinction at P-T boundary (Fig. 3; Melott and Bambach, 2014). The basalt-filled rifts formed due to N–S-trending right-lateral strike-slip faulting and E–W oblique extension between the Urals and the Siberian craton during the Late Permian–Early Triassic (Allen et al., 2006). The P-T boundary rifting, therefore, is attributed to
be the cause of the world-class hydrocarbon province, the West Siberian Basin (Allen et al., 2006).

In southern Asia, the Permian is the most prosperous period of the Paleo-Tethyan ocean. The North and the South China blocks became two isolated continental blocks in the Paleo-Tethyan ocean (Fig. 6). The Emeishan mantle plume and LIP, represented by a large area of continental overflow basalts of Late Permian and Early Triassic (260–251 Ma; Fig. 3), formed in the western Yangtze craton, South China (Xu, 2002; Xia, 2013). The Western Pacific plate began its subduction beneath the eastern margin of the Eurasian continent in Late Permian (Fig. 3), which is consistent with the Permian magmatic arc in the eastern margin of the Bureya-Jiamusi-Xingkai block. Meanwhile, the Songjianghe ophiolite (260–245 Ma) formed in the northeastern margin of the North China craton (Dong et al., 2016).

4 Closure of Oceans and Formation of Orogenic Belts in the Mesozoic

4.1 The Indosinian orogeny and formation of the main continental Asia in the early Mesozoic

The Indosinian is an important tectonic period for the formation of the main body of the Asian continent (Dong et al., 2016). The Triassic closure of the Paleo-Tethys ocean in southern Asia, resulted in the North-South China collision (T3–J1), the collisions among several micro-blocks (T3–J2), and the giant Indosinian orogenic system in Southeast Asia (Fig. 3; Dong et al., 2008a; Xu et al., 2012; Dan et al., 2018). The MOO, a remnant of the PAO, gradually closed eastward in north central Asia, resulting in extensive Indosinian deformation in the CAOB.

4.1.1 The South China-Indosinian collision

The Indosinian blocks in the Indosinian peninsula are mainly the Indosinia craton and the Sibumasu massif (Fig. 1), originated from the blocks such as the Indochina block in the Paleo-Tethys Ocean (Fig. 6). They were continuously amalgamated with the South China block from the Late Permian to Middle Triassic, composing the Indosinian collage system (Carter et al., 2001; Carter and Clift, 2008; Masatoshi and Metcalfe, 2008; Metcalfe, 2006, 2011, 2013; Shu et al., 2008, 2009a, b; Shu, 2012; Faure et al., 2014; Wang et al., 2018). There are several suture zones among the Indosinian and the South China blocks, representing several closed branches of the Paleo-Tethys ocean in this region. From the west to the east, they are the Changning-Menglian-Chiangmai, the Jinhong, and the Jinshaijiang-Ailaoshan-Song Ma sutures. Among them, the NW–SE-trending Jinshaijiang-Ailaoshan-Song Ma suture is a suture zone between the Indochina and the South China blocks, consisting of the Jinshaijiang, Ailaoshan, Song Ma, and Song Chay ophiolitic mélanges. It is characterized by highly strained ductile deformation and metamorphism in the Early and Middle Triassic (Lepvrier et al., 2004; Roger et al., 2007). Up-thrusting polarity of the suture zones suggests southwestward subduction of the South China block underneath the Indochina block. The Song Ma and the Song Chay sutures in northern Vietnam formed in the Early to Middle Triassic, with an initiation age at ca. 250 Ma (Faure et al., 2014). They were truncated by the left-lateral strike-slip Red River fault, with a strike slip of ca. 600–700 km. The metamorphism of the crystalline basement of the Kon Tum block in north-central Vietnam reached granulite facies, implying significant crustal thickening there (Carter et al., 2001; Tich et al., 2012).

The ages of initial collision, syn-collision, and post collision are suggested as ca. 253 Ma, ca. 253–237 Ma, and ca. 237–200 Ma, respectively, between the South China and the Indochina blocks along the Jinshaijiang-
4.1.2 The North-South China collision

The closure of a branch sea of the Paleo-Tethyan ocean between the North and the South China (e.g., the Mianlu or Qinling sea) at ca. 230 Ma (Figs. 2, 3 and 6), resulted in the continental collision between the North and the South China cratons in Middle Triassic, and the formation of the Central China Orogenic System (CCOS; Zhao et al., 2018). The CCOS is an Indosinian orogenic belt in central China. The East Kunlun, Qinling, Tongbai and Dabie mountains are the major mountains in the CCOS. The deep continental subduction of the South China block underneath the North China craton (block), led to the formation of the Hongan-Dabie-Sulu high and ultrahigh pressure metamorphic eclogite belt in the CCOS, with prograde metamorphism of 257–242 Ma, UHP metamorphism of 244–225 Ma, and post-orogenic denudation and retrogression metamorphism of 220–202 Ma (Dong et al., 1998; Liu et al., 2004, 2007, 2008; Liou et al., 2009; Liu and Liou, 2011; Leech et al., 2012). The Tan-Lu fault formed with its major left-lateral strike-slip due to the oblique collision between the North and the South China cratons (Fig. 3). Two large-scale Indosinian foreland basins, such as the Sichuan and the Ordos basins, formed on the north and south sides of the hinterlands of the Qinling Mountains, respectively (Zhang Y P et al., 2019). As a foreland of the Qinling orogenic belt, the Dabashan and the Dangyang basin in the south experienced approximately N-S compression and crust shortening in the Early–Middle Triassic (ca. 245 Ma; Shi et al., 2012, 2013; Li et al., 2013a). The Early–Middle Triassic compressional deformation also occurs in northern margin of the North China craton (Zhang S H et al., 2014), represented by the nearly E–W-trending folds and thrust belts, such as the Panshan and the Malanuy anticlinorium. Meanwhile, the Yangtze foreland fold-and-thrust belt and stacked crustal slabs developed along the southern margin of the CCOS (Dong et al., 2004). In the Korean Peninsula, the Indosinian deformation is expressed by intense mylonitization and medium to high grade metamorphism of Precambrian basement orthogneisses during the Middle to Late Triassic Songnim orogeny (ca. 239–210 Ma; Kim J et al., 2011; Chang and Zhao, 2012).

4.1.3 Indosinian deformation in the Central Asian orogenic belt

The Indosinian deformation in the CAOB is considered to be the effects of the eastward closure of the MOO. Although there are many arguments about the belonging of the MOO, it is better to consider that the MOO is a part and a remnant of the PAO in the Early Mesozoic, rather than the Paleo-Pacific Ocean. A distinct feature of the CAOB is the initial development of large-scale dextral strike-slip faults with activity ages of ca. 250–245 Ma (Fig. 3), in western and central parts of the CAOB (Fig. 5), especially in the eastern Tianshan Mountains (Laurent-Charvet et al., 2002). Timing of Triassic growth strata in the Kuqa Depression indicates far field effects of the Indosinian Mongolia-Okhotsk orogeny responded in Southern Tianshan (Qin et al., 2021). Correlation of Apparent Polar Wander Paths (APWP) of Early Carboniferous, Late Permian, and Middle Triassic, suggests that there is a 32° anticlockwise rotation of eastern Hexi Corridor-Alxa block related to the Ordos block, western part of the North China craton (with the point 44°N and 84°E as the reference Euler pole), due to the oblique collision between the Alxa and the Ordos blocks in the Middle Triassic (Dong et al., 2016). In the Langshan region, northwest to the Ordos block, the NE-striking ductile left-lateral strike slip marked the Middle–Late Triassic deformation of south-central margin of the CAOB (Zhang J et al., 2014). A branch of the PAO had closed along the NE-trending Solonker–Xar Moron suture in the Permian to Triassic in Northeast China. Sedimentary provenance analysis indicates that the closure of the PAO at Jiuai area, eastern CAOB is constrained in Middle-Late Triassic (ca. 245–219 Ma; Zhang Q et al., 2019).

The main suture should be lying in the core of the Mongolia-Okhotsk orogenic belt (MOS in Fig. 2 and MOO in Fig. 3), along which there are black shale formation of the Permian residual sea basin and syn-orogenic granoids with ages of 230–205 Ma (Chen et al., 2000; Miao et al., 2008), while the Mesozoic remnant of the paleo-subduction zone formed a cold mantle plume, down to the core-mantle boundary (van der Voo, 1999). Large scale Permian–Triassic island arc volcanic rocks erupted on the Qinggele block, SE side of the Ereendavaa metamorphic belt in the Mongolia-Okhotsk orogenic belt, indicating southeastward subduction (present position) of the MOO plate in the Permian and Triassic. The early Mesozoic magmatic and metamorphic events (236–180 Ma) in the Ereendavaa area, eastern CAOB reflect the formation of the superterrane Amur and its colliding with the North Asian (i.e., Siberian) craton (Sorokin et al., 2018). Therefore, there is diachronous closing of the Paleo-Tethys Ocean branches among different blocks related to the Ordos block, western part of the North China craton (with the point 44°N and 84°E as the reference Euler pole), due to the oblique collision between the Alxa and the Ordos blocks in the Middle Triassic (Dong et al., 2016). In the Langshan region, northwest to the Ordos block, the NE-striking ductile left-lateral strike slip marked the Middle–Late Triassic deformation of south-central margin of the CAOB (Zhang J et al., 2014). A branch of the PAO had closed along the NE-trending Solonker–Xar Moron suture in the Permian to Triassic in Northeast China. Sedimentary provenance analysis indicates that the closure of the PAO at Jiuai area, eastern CAOB is constrained in Middle–Late Triassic (ca. 245–219 Ma; Zhang Q et al., 2019).

4.1.4 Late Triassic to Early Jurassic extensional deformation

Late Triassic to Early Jurassic (T₃–J₁) extensional deformations are widespread in the North China craton, South China block, and northern Qinghai-Tibetan Plateau. The early Mesozoic post-collisional alkaline magmatic
belt (ca. 235–220 Ma) in northern part of the North China craton, could be the delamination of the subducted lithospheric mantle root, indicating the destruction and thinning of the North China craton initiated in the Late Triassic (Zhang S H et al., 2012, 2014). Leucogranites from the Altakhinsky complex and trachyrrholites from the Talovsky complex in the Bureya terrane have synchronous ages of ca. 173–178 Ma, and subalkaline leucogranites from the Kharninsky complex have relatively younger ages of ca. 199 Ma (Sorokin et al., 2016), reflecting the Late Triassic and Early Jurassic post-orogenic magmatism in the eastern CAOB. In central Mongolia and Transbaikalia, bimodal volcanic rocks, alkaline magmatic rocks and A-type granites with ages of 195–178 Ma imply regional extensional setting in the Early Jurassic (Yarmolyuk et al., 2000, 2002). The widespread mafic dike swarms (ca. 198–180 Ma) in the North China craton, implies the regional weak extension continued into the Early Jurassic, which was recorded by the deposition of the Early Jurassic Xingshihoku Formation (less than 198 Ma) in the Xiabancheng basin, northern Hebei Province, China. In South China block, the intraplate basalts and bimodal magmatic rocks with ages of ca. 200–170 Ma, indicate post-collisional intracontinental extension in the Early Jurassic (He et al., 2010; Zhu W G et al., 2010). In northern Qinghai-Tibetan Plateau, the Late Triassic and Early Jurassic (ca. 220–187 Ma; Chen et al., 2003) extension occurred in a backarc setting during the northward subduction of the Meso-Tethyan ocean plate, after the closure of the Paleo-Tethyan ocean (Fig. 3).

4.2 Late Mesozoic orogeny and expanding growth of continental Asia

4.2.1 Final closure of the Mongol-Okhotsk Ocean and Mongolia-Okhotsk orogeny

The Mongolia-Okhotsk orogenetic belt is considered as the youngest part of the CAOB. It is located in northern Mongolia, Transbaikalia, and the Sea of Okhotsk (MOS in Fig. 2). Although there are many different suggestions about the closing time of the MOO, e.g., in the Permian (Gordienko et al., 2010), Triassic (Maruyama et al., 1997), Middle Jurassic (Tomurtogoo et al., 2005), Late Jurassic (Zonenshain et al., 1990), or Late Jurassic to Early Cretaceous (Metelkin et al., 2010), most researchers suggest that the MOO closed gradually from the Middle Jurassic in the west, to Early Cretaceous in the east (Xiao et al., 2009a, 2015, 2018; Dong et al., 2016). The closure of the MOO, i.e., the eastern remnant of the PAO, was resulted from the continuous clockwise rotation of the Siberian craton (Xiao et al., 2015, 2018). It resulted in a relatively short-lived and significantly deformed Mongolia-Okhotsk collisional orogenic belt, i.e., the Mongolia-Okhotsk orogeny (MOO in Fig. 3), in eastern part of the CAOB (Tomurtogoo et al., 2005; Li et al., 2009; Xiao et al., 2015, 2018; Yang et al., 2015). The Mongolia-Okhotsk suture zone (MOS in Fig. 2), represented by ophiolitic mélanges, occur in the core of the Mongolia-Okhotsk orogenic belt. The distribution of Jurassic and Early Cretaceous magmatic rocks in the suture zone, e.g., synorogenic granites with ages of 173–153 Ma, implies northward subduction of the ocean plate and subsequent continental collision in the Middle to Late Jurassic (van der Voo et al., 1999; Donskaya et al., 2008; Daoudene et al., 2013; Berzina et al., 2014). Detrital zircon source analyses suggested continental collision along the Mongolia-Okhotsk orogenic belt may have occurred after 176 Ma (Prokopiev et al., 2008). The Keyihe adakitic rocks from northern Great Xing’an Range implies final closure of the MOO and the collision of the Siberian craton and the Mongolia block with the North China craton in the Early Cretaceous (ca. 128 Ma; SNCC in Fig. 3; Zhang L Y et al., 2019). After the final closure of the MOO, the CAOB became the largest and most active intracontinental orogenic system in the world (De Grave et al., 2007).

Paleomagnetic and geochronological studies show that the landmasses on both sides of the Mongolia-Okhotsk orogenic belt approached rapidly (15 cm/yr) in the Late Jurassic and closed at the end of Jurassic or in the Early Cretaceous (Metelkin et al., 2010; Pei et al., 2011). For example, Metelkin et al. (2010) suggested that the width of the MOO rapidly changed from 3000 km in the Middle Jurassic to 1500 km in the Late Jurassic (155 Ma). Most of the existing paleomagnetic studies show that the Apparent Polar Wander Path (APWP) of the Siberian craton in the Early Cretaceous is basically consistent with that of other parts of Eurasia, indicating that the landmasses on both sides of the MOO had been stably welded together at that time (Besse and Courtillot, 2002). However, Pei et al. (2011) suggested that the width of the MOO was about 3000 km in the Late Jurassic (155 Ma), and the subsequent closure process led to the collision of the two continental blocks and extensive crustal deformation near the Sino-Mongolian boundary.

The Jurassic was the youngest stratum involved in the thrusts and folds in the Mongolia-Okhotsk orogenic belt (Donskaya et al., 2008). In the Verkhoyansk fold and thrust belt, eastern margin of the Siberian craton, the Carboniferous to Middle Jurassic sedimentary rocks with a thickness >15 km, were involved in the folds due to the Mongolia-Okhotsk orogeny in the Late Jurassic (Parfenov et al., 1995; Toro et al., 2007; Prokopiev et al., 2008). In the Onon area, the Devonian–Carboniferous (D–T) island arc complexes were napped from north to south on the sedimentary rocks of the Upper Permian and Lower Jurassic (P1–J1), with a horizontal thrusting distance of ca. 200 km (Zorin, 1999; Donskaya et al., 2008). In Irkutsk area, 600 km north to the Mongolia-Okhotsk suture zone, the Precambrian basement complex was napped over the Upper Jurassic (J3) coal-bearing strata, with a horizontal thrusting distance of several hundred meters (Zorin, 1999). Large scale nappe structures have also been found in Northeast China. For example, the Heilongjiang group, previously considered as the metamorphic basement, is some rootless nappes formed at ca. 165 Ma in the Middle to Late Jurassic (Dong et al., 2016).

4.2.2 Closure of the Meso-Tethyan Bangong-Nujiang Ocean and collision of the Lhasa and Qiangtang terranes

The Qinghai-Tibetan Plateau (Fig. 1) is a result of multi
-stage collisions and orogenies. It is usually divided into four Precambrian terranes (or blocks) with nearly E–W striking. From north to south, they are the Songpan-Ganzi, Qiangtang, Lhasa, and Himalayan terranes. They are separated by the Jinsha, Bangong-Nujiang, and Yarlung Zangbo suture zones, which represent the remnants of the Paleo-Tethys, Meso-Tethys, and Neo-Tethys oceans, respectively (Yin and Harrison, 2000; Zhu et al., 2011). Among them, the Bangong-Nujiang suture zone, with a maximum width of >100 km and a SEE–NWW extending of >2500 km, is located in the central Qinghai-Tibetan Plateau, separating the Lhasa terrane in the south and the Qiangtang terrane in the north (Shi et al., 2008). It consists of several segments of ophiolitic mélanges, including the Bangong-Gertse, Dongqiao-Amdo, and Dingqing-Nujiang segments.

The Lhasa-Qiangtang collision (J1–K1; Figs. 2 and 3) resulted in strongly crustal shortening and thickening (Jiang et al., 2021), deposition of the Lower Cretaceous foreland basin on the Lhasa terrane (Leier et al., 2007), and intrusion of Early Cretaceous peraluminous S-type granites in central and northern Lhasa terrane (Zhu et al., 2011). The strongly deformed Lower Cretaceous strata and weakly deformed cover layers such as the Cenozoic Linzizong volcanic rocks in the Lhasa terrane, indicate a strong shortening (50%) of the crust during the Lhasa-Qiangtang collision (Kapp et al., 2007). The compressional stress propagated northward in a long distance, leading to regional contraction deformation in northwestern China and central Asia in the early Early Cretaceous. The thrust and nappe system in north Qilian Mountains and Hexi Corridor, and the large-scale thrust and nappe system, the Yagan nappe, in the Beishan field, indicate the structures, such as the folds, thrusts, and regional angular unconformities, the magmatism, and the mineralization developed in the Yanshan Mountains, North China in the Jurassic and Cretaceous (Wong, 1926, 1927, 1929). The late Mesozoic Yanshanian orogeny, formed during the multi-direction plate convergence in East Asia (Fig. 2), had affected not only the Chinese mainland (Dong et al., 2008a, 2015, 2016, 2018; Chen et al., 2019a), but also the other parts of Asia (Zorin, 1999; Tomurtogoo et al., 2005; Lim and Cho, 2011; Osozawa et al., 2012).

(1) Initiation of the Yanshanian orogeny
Wong (1926, 1927, 1929) recognized that the angular unconformity between the Middle Jurassic volcanic rocks (with basal conglomerates) and the underlying Middle to Lower Jurassic coal-bearing strata in the Yanshan area, North China marks the initiation of the Yanshanian orogeny. For example, the conglomerates at bottom of the Middle Jurassic Juulongshang or Yungang Formation represents the most beginning of the intracontinental Yanshanian orogeny at ca. 168 Ma (Fig. 3; Dong et al., 2016; Chen et al., 2019a). In South China, the Yanshanian orogeny is initiated at ca. 170 Ma (Zhou et al., 2006; Dong et al., 2016). In the Korean Peninsula, the Yanshanian orogeny, also named as the Daebu orogeny (Fig. 3), is further divided into two compressional stages (Chough et al., 2000; Lim and Cho, 2011). The Yanshanian orogeny is corresponding to the Nevada orogeny in North America (Schweickert et al., 1984).

(2) Influence of the Yanshanian orogeny and formation of intracontinental foreland basins
The Yanshanian orogeny triggered extensive late Mesozoic intracontinental deformation in East Asia (Dong...
et al., 2016, 2018). It led to the formation of several intracontinental orogenic belts, including the Daqingshan-Yinshan-Yanshan orogenic belt in northern North China (Davis et al., 2001; Zhang S H et al., 2014), the NNE–SSW-trending Lvliang-Taihang-Xuefeng-Wuling-Wuyi orogenic belt in central and eastern China (Yan J et al., 2003; Zhang et al., 2009; Chen et al., 2019a), the NW–SEE-trending Qinling-Tongbai-Dabie orogenic belt (Dong et al., 2011), the NNE–SSW-trending Helan orogenic belt, and the ringed orogenic belts around the Sichuan basins (Shi et al., 2012; Zhang Y Q et al., 2012; Dong et al., 2013a). Most of them are the reactivation of previous orogenic belts in the late Mesozoic (Dong et al., 2008a, 2013b). The influence of the Yanshanian orogeny can also be found in the Tianshan Mountains (Dumitru et al., 2001; Robinson et al., 2003), Mongolia (Tomurtogoo et al., 2005), the Korean Peninsula (Lim and Cho, 2011), Japan (Osozawa et al., 2012), and the Russian Far East (Sorokin et al., 2009).

During the Yanshanian orogeny (J3–K1), the continued intracratonic subsidence of the North China and the Yangtze cratons beneath both sides of the Qinling-Tongbai-Dabie orogenic belt, caused the formation of series intracontinental foreland basins (Liu et al., 2010; Li et al., 2012). They are the Sichuan Basin with the Dabashan foreland in the south, and the Ordos and the Hefei basins in the north (Dong et al., 2008a, 2013a, 2016, 2018; Zhang et al., 2008). In the following ca. 100 Ma, the Qinling orogenic belt and its surrounding areas underwent multiple-stage contraction deformation, forming the Dabashan arc-shaped tectonic belt (Shi et al., 2012).

(3) Large scale thrusts and folds

Large scale thrusts and folds are major deformation features of the Yanshanian orogeny in late Mesozoic. In the Daqingshan-Yinshan-Yanshan orogenic belt, northern North China, the Yanshanian folds mainly formed in the Middle to Late Jurassic (Dong et al., 2001), with the Middle Jurassic as the youngest stratum involved in the folds. In the Daqingshan area, the Middle Jurassic strata were intruded by an Early Cretaceous pluton with age of 119 ± 2 Ma. In the Helan Mountains, northwestern margin of the Ordos Basin and North China craton, intracratonic fold and thrust belt formed in the late Middle to Late Jurassic (Darby and Ritts, 2002; Zhang et al., 2008), leading to the inversion of Mesozoic basins there due to the limited eastward extrusion of the Alxa block (Liu, 1998; Darby and Ritts, 2002). In eastern North China, there are some Jura-type folds developed in the Jurassic strata in western Shandong (Li et al., 2012). In northern Taihang Mountains, central North China, the formation of the Jurassic fold and thrust belt was limited to at ca. 175–150 Ma, with intrusive magmatic rocks of ca. 146–142 Ma and regional cooling during 142–120 Ma (Wang and Li, 2008). The youngest stratum involved in the Wuling-Xuefengshan fold and thrust belt, South China, is the Upper Jurassic, implies the formation of the folds in the Late Jurassic (Yan D P et al., 2003; Lu et al., 2014).

In the Korean Peninsula, the late Mesozoic Daebo orogeny (DBO in Fig. 3) affected almost all tectonic units, such as the Chungnam and the Taebaeksan basins, the Ogcheon belt, and the Gyeonggi belt, and the Gyeonggi massifs (Chough et al., 2000; Ree et al., 2001). It is characterized by the NE-trending fold and thrust belt, and the involved early Middle Jurassic strata with tuff intercalation of 172 Ma, indicating NW–SE compression during the deposition of the Middle Jurassic Nampo group (Han et al., 2006; Jeon et al., 2007; Egawa and Lee, 2009; Lim and Cho, 2011). Therefore, the duration of the Daebo orogeny might be in the Middle and Late Jurassic (Lim and Cho, 2011), which is consistent with the Yanshanian orogeny in eastern China. Simultaneously, a large-scale folding and thrusting took place in Kitakami, Japan before the Early Cretaceous Aiptian (>125 Ma), involving the Silurian to Jurassic strata, some of the Lower Cretaceous, the Hayachine ophiolite, the accretionary complex including exotic terrains, cherts, basalts, and sandstone-mudstone fragments, and the volcanic layers (Osozawa et al., 2012). The late Mesozoic orogeny is also recorded in the Hida belt which was thrusted southward on the accretionary complex of Paleozone and early Mesozoic, in the Late Jurassic (Maruyama, 1997).

(4) Large scale strike-slip faulting

The subduction-related compression in the late Mesozoic led to the development of large-scale continental margin strike-slip faults and escape of continental blocks (Shang et al., 1997; Dong et al., 2005). For example, the continued strike-slipping on the Tanlu fault in eastern China (Zhu G et al., 2010), a series of large-scale strike-slip faults along the CCOS (Ratschbacher et al., 2000), the Ocheon fault zone in the Korean Peninsula (Lim and Cho, 2011), the early stage activities of the Altyng Tagh fault (Wang et al., 2005; Dai et al., 2017) and the East Kunlun faults (Mock et al., 1999), and the Xianshui River fault (Li H L et al., 2014), all of them may have their strike-slip faulting in the Late Jurassic to Early Cretaceous.

(5) Synorogenic Yanshanian magmatism

Late Jurassic–Early Cretaceous magmatic rocks of active continental margin, mainly adakitic rocks and S-type granitoids, are widely developed in East Asia (Wang Q et al., 2006; Wang X C et al., 2006). They are distributed in the Liaodong Peninsula (Wu et al., 2005), southern Liaoning (Lin and Wang, 2006), the basement of the Songliao Basin (Wu et al., 2001), eastern Great Xing’an Mountains and CAOB (Wu et al., 2011; Wang T et al., 2017), northern North China (Davis et al., 2001), central North China (Zhang S H et al., 2014), the East Qinling (Mao et al., 2010), South China (Zhou and Li, 2000; Cui et al., 2013), the Korean Peninsula (Ree et al., 2001), the Transbaikalia and central Mongolia (170–153 Ma) (Berezina et al., 2012; Stupak et al., 2020), the Ereendavaa Range in northeastern Mongolia (Daoudene et al., 2013), and the Russian Far East (Reichow et al., 2010). I-type granites from the Liaodong Peninsula yield zircon U-Pb ages of 179–156 Ma (Wu et al., 2005). Volcanic rocks of the Xinglonggou Formation from western Liaoning gives ages of 177–159 Ma (Gao et al., 2004). In South China, the Middle and Late Jurassic (165–150 Ma) magmatic rocks are mainly crustal remelting granites, exposed mostly in inland and rarely in coastal areas (Li, 2000; Zhou and Li, 2000), and closely related to the genesis of many super-large mineral deposits in this area (Hart et al.,...
4.2.5 Post-orogenic or back-arc extension in the Early Cretaceous

Post-orogenic extensions in the Early Cretaceous are widespread in continental Asia. After the final closure of the MOO and the collision of the Siberian craton and the Mongolia block with the North China craton, the Transbaikalia extension (TBE in Fig. 3), represented by metamorphic core complexes and alkaline-peralkaline magmatism with ages of 135–120 Ma, developed along the Mongolia-Okhotsk orogenic belt (Donskaya et al., 2008). Almost at the same time, intracontinental rifting volcanism at ca. 134–131 Ma erupted in eastern Transbaikalia (Stupak et al., 2020).

In eastern margin of continental Asia, the Early Cretaceous back-arc extension, or post-orogenic extension of the Yangshanian orogeny, mentioned as Pan-North and South China extension (PNSCE in Fig. 3), is resulted from steepening of subduction angles and roll-back of the Paleo-Pacific plate, and the strong craton destruction in eastern part of the North China craton (Zhu et al., 2012). In North China, the angular unconformity at the bottom of the volcanic rocks in the Lower Cretaceous Zhangjiakou Formation represents the transition of the Yangshanian Movement from orogeny to post-orogenic extension (Zhao et al., 2004), with an age of ca.136 Ma (Niu et al., 2004). In South China, regional angular unconformity between the volcanic rocks of the Lower Cretaceous Nanyuan Formation and the underlying coal-bearing Jurassic strata reflects the starting of regional extension at ca. 137 Ma (Cui et al., 2013; Li J H et al., 2014; Dong et al., 2016). For example, the Hengshan low-angle detachment fault zone developed at ca. 136 Ma (Li et al., 2013b). In the Korean Peninsula, there is an angular unconformity between the weakly deformed Lower Cretaceous strata and the strongly deformed sandstones and shales of the Upper Jurassic Myogog Formation (Lim and Cho, 2011). In Japan, the Lower Cretaceous Miyako Group overlies on Jurassic high-angle sandstones with an angular unconformity (Osozawa et al., 2012). A huge amount of gold deposits and oil and gas fields formed around rift basins such as the Bohai Bay and the Songliao basins (Zhu et al., 2020; Yang et al., 2021).

Simultaneously, the Early Cretaceous A-type granites (ca. 125 Ma) from the Demulha batholith in the Lhasa terrane (Lin et al., 2012; Zhang Z M et al., 2014), and marine transgressive event of the Lhasa terrane in late Aptian (125–115 Ma) (Leeder et al., 1988), indicate the post-collisional extension of the inner Qinghai-Tibetan Plateau region in the late Early Cretaceous. The post-orogenic extension is also popular in northern margin of the Qinghai-Tibetan Plateau region and southern margin of the CAOB. There are a large number of Early Cretaceous graben basins, such as the Hexi Corridor and the Yin’e basins in NW China, and widespread basalt eruption caused by post-collisional decompression melting of the mantle during 124–99 Ma, implying the intensive regional extension, such as the Hexi Corridor extension, in the late Early Cretaceous (HCE in Fig. 3; Chen et al., 2003; Wang Y et al., 2021). Cretaceous extension in Asia may have genetic connection with the global Cretaceous superplume (Bleeker, 2003).

5 Cenozoic Amalgamation of the Continental Asia

5.1 The Indo-Asian collision and formation of the Qinghai-Tibetan Plateau

5.1.1 The Indo-Asian collision

The continued subduction led to a transition from Neo-Tethyan oceanic flat subduction to slab rollback beneath the eastern Gangdese in the Late Cretaceous (ca. 71–66 Ma; Chen et al., 2021). After that, the Indo-Asian collision initiated at ca. 55 Ma, resulting in the formation of the Himalaya-Tibetan orogenic belt (HTOB) in the Tethys regime (Figs. 1 and 2; Yin and Harrison, 2000; Tapponnier et al., 2001; Wang et al., 2008; Yin, 2010; Hu et al., 2016; Xu et al., 2016). The N–S shortening of the HTOB led to the uplift and growth of the Qinghai-Tibetan Plateau, forming a continental crust with huge thickness twice the normal crust. In northern Qinghai-Tibetan Plateau, multi-phase out-of-sequence deformation of the Qilian Shan occurred in the Cenozoic (Li et al., 2020). Several large-scale strike-slip fault systems, e.g., the Altyn Tagh, the East Kunlun, the Xianshuihe River, and the Red River faults, etc., formed during the collision as the escaping routes of the large amount materials from the Qinghai-Tibetan Plateau in various directions (Fig. 5; Yin and Harrison, 2000; Tapponnier et al., 2001; Yin et al., 2002; Zhang J et al., 2020). The Pamir Plateau also formed during the Indo-Asian collision (Fan et al., 2021). The Altyn Tagh Fault, a strike-slip fault with a left-lateral slip of ca. 400 km, initiated in the northwestern boundary of the Qinghai-Tibetan Plateau at ca. 49 Ma, leading to the formation of the Qaidam Basin with huge-thickness Cenozoic sediments (Yin et al., 2002, 2008a, b; Chen et al., 2004, 2010; Yin, 2010; Cheng et al., 2021). Following the Altyn Tagh faulting, the thickened lower crust of the Himalayas began to melt from 46 Ma to 35 Ma, and a series of north-dipping imbricated thrusts formed in the HTOB. The Indo-Asian collision also resulted in lateral extrusion of the Southeast Asia during 32–17 Ma (Yin, 2010).

5.1.2 Formation of the Qinghai-Tibetan Plateau

In northern Himalaya, the Main Himalayan Thrust initiated in its root at ca. 34 Ma, prompting the southward back-turning of the High Himalayas. The Main Himalayan Thrust propagated into the Main Central Thrust between the Higher and the Lesser Himalayas at ca. 23 Ma, expanded forward in the Main Boundary Thrust, and spread ahead into the Main Frontal Thrust in the south, with gradually shallowing of tectonic levels from the north to the south (Fig. 5; Xu et al., 2016). The gravitational collapse of the HTOB began at ca. 28 Ma, leading to the
extensional detachment parallel to the orogenic belt along the High Himalayan layers and decompressional melting of metapelites, which induced the initiation of the South Tibet Detachment at ca. 23 Ma, almost at the same time with the Main Central Thrust (Xu et al., 2016). At ca. 14 Ma, the Qinghai-Tibetan rift system (QTR in Fig. 3) began to develop, forming normal faults, grabens and rifts in the N–S direction, which led to local uplift of the Moho surface by 5 km (Zhang et al., 2013). Then, the East Kunlun Fault began its left-lateral strike-slipping at ca. 10 Ma (EKF in Fig. 3), due to the tectonic transformation from NE compression in the East Kunlun thrust system to the strike-slip faulting (Mock et al., 1999).

The hinterland of the Qinghai-Tibetan Plateau had reached the elevation of the modern plateau at ca. 40 Ma, forming the prototype of the plateau (Wang et al., 2008). The continuous thickening and extensive viscous flow in the crust and upper mantle of the entire plateau, such as the lower crustal tunnel flow (Beaumont et al., 2001), or the development of localized shear zones and slip-line fields among surrounding lithospheric blocks at different times (Molnar and Tapponnier, 1975; Tapponnier et al., 1982, 2001), may be the main factors affecting the formation of the high altitude of the plateau.

5.1.3 Far-field effects of the Indo-Asian collision
The Indo-Asian collision has its widespread far-field effects in central Asia, including the formation of the Cenozoic Tianshan Mountains and Mongolia Plateau (Fig. 2; Cunningham, 2005; Yin, 2010; Chen et al., 2011). Growth strata from the Kuqa Depression, southern Tianshan imply the very quickly response to the Indo-Asian collision in the early Cenozoic (Qin et al., 2020).

5.2 The Arab-Asian collision and its far-field effects
The collision between the Arabia and the Eurasian plates is also one of the major dynamics constructing the continental Asia in the Cenozoic (Fig. 2). Collisional-related high-K calc-alkaline/shoshonitic magmatism during ca. 38–28 Ma indicates the Arab-Asian collision may initiate at ca. 40 Ma (AAC in Fig. 3; Rezzeghi et al., 2017). The collision resulted in the Turkish-Iranian-Caucasus orogen of ca. 30–20 Ma in West Asia and the Cenozoic Tianshan intracratonental orogeny of ca. 24–20 Ma in Central Asia (Yin, 2010). In the interim, the Arabian plate might rift from the NE Africa and formed the Gulf of Aden and the Red Sea at ca. 25 Ma (RSR in Fig. 3; Stern and Johnson, 2010). Up to now, the N–S convergence between the Arabian and the Eurasian plates is still having a rate of ca. 20–30 mm/yr (Reilinger et al., 2006). The combining action of the Arab-Asian and the Indo-Asian collisions controlled the extensive far-field deformation of the Asian continent in the Cenozoic (Fig. 2). A series of large-scale NW-trending right lateral strike-slip faults, extending more than 1500 km in Central Asia, reactivated in this time, being the most significant tectonic feature by the combined action of the collisions (Yin, 2010).

5.3 Subduction of the Western Pacific plate and formation of the trench-arc-basin system
The expansion of the mid-oceanic ridge of the Pacific Ocean and subduction of the Pacific plate underneath the Eurasian plate is the major geodynamical system acting on the East Asian lithosphere in the Cenozoic. It caused the complete formation of active continental margin of the Western Pacific, the West Pacific orogenetic belt, and the largest and most complex modern trench-arc-basin system in the world (Fig. 2). About 75% of the modern back arc basins in the world are concentrated in the Western Pacific. The basins of Andaman Sea, South China Sea, East China Sea, Bohai Bay, Sea of Japan, Sea of Okhotsk, and Bering Sea are some pull-apart back-arc marginal basins of the West Pacific (Yin, 2010; Xu et al., 2014).

The subduction of the western Pacific plate may begin in the Verkhoynsk-Kolyma Orogen, northeastern Russia, in the early Late Cretaceous (Filatova and Khain, 2008), resulting in the Okhotsk-Chukotka volcanic belt, a subduction-related volcanic province with ages of 89–87 Ma (Tikhomirov et al., 2008), and fold-and-thrust in the Verkhoynsk Mountains in the Late Cretaceous (Gaina et al., 2002). In the south, the subduction of the Pacific plate may cause the formation of the Proto-South China Sea as a back-arc basin in the Cretaceous (Tian et al., 2021). In the Cenozoic, there are three expansion episodes in 65–35 Ma, 32–15 Ma, and the past 5 Ma, respectively, and one compression tectonic event in 15–5 Ma in the Western Pacific, according to comparative analyses of the ages of magnetic anomaly bands (Yin, 2010; Shi and Yan, 2013).

In the first episode in 65–35 Ma, the West Philippine Basin migrated from the equator to its present position, and an E–W extensional zone with a width of ca. 500–800 km formed in eastern margin of Eurasia. During 32–15 Ma, the South China Sea, Bohai Sea, Sea of Japan, and Shikoku Basin formed due to regional extension in West Pacific margin and East Asia (Shi and Yan, 2013). The third episode is the formation of the Mariana and the Okinawa troughs in the past 5 Ma (Shi and Yan, 2013).

Alternating with the first and second extensional episodes, the East Asian continental margin has suffered an E–W shortening, which is characterized by the formation of continental margin fold and thrust belt. In the SE Asia and the SW Pacific regions, West Pacific margin collisions, such as the New Guinea passive margin collided with the East Philippines-Halmahera-South Caroline Arc System, the Australian margin (Bird’s Head region) collided with the SE Asian margin (Sulawesi), and the Ontong Java Plateau collided with the Melanesian Arc, caused the most important Cenozoic plate boundary change in these regions, in ca. 25–20 Ma (WPMP in Fig. 3; Hall, 2002). Meanwhile, the Australia block moved northwards, causing accretion of microcontinental fragments to SE Asia. At ca. 5 Ma, arc-continent collision occurred in Taiwan (ACCT in Fig. 3; Hall, 2002; Simoes et al., 2012).

High-velocity layer in the subducted Pacific slab and the activities of deep-focus earthquakes verified that the subducted oceanic slab can go into the mantle transition zone in the depth of 410–660 km. The deep subduction of the Pacific plate controls the distribution of Cenozoic alkaline basalt zone of thousands of kilometers in length, from the Hainan Island to Northeast China, and ca. 1000 km in width, reaching the continental interior of the
mainland China where the Zhangjiakou-Datong gravity gradient zone is located. The deep subduction also leads to deep recycling of subducted materials, forming large-scale Mg isotopic anomalies (Huang et al., 2015) and huge carbon sink of recycled carbonates (Xu and Fan, 2015; Li et al., 2017), in the upper mantle of eastern China.

In the enigmatic Northeast Asia, the modern boundary zones among the Pacific, Eurasian, and North American plates are diffuse and could not be sharply defined (Fig. 1). Two groups of active faults occur in this triple junction region (Kozhurin, 2004). One is a group of faults roughly parallel to the Pacific margin, with right-lateral strike-slip along most of them, implying oblique convergence of the Pacific plate with the Eurasian and the North American plates (Kozhurin, 2004). The Kurile Basin, a pull-apart basin in the Sea of Okhotsk, formed due to dextral motions along the Central Sakhalin Fault (Tužino and Murakami, 2008). Another one is a group of active faults, mainly with left-lateral strike-slip, as the continental extending of the active mid-ArcTic ridge (Kozhurin, 2004). The extrusion of the Okhotsk plate in the Pacific regime results in the convergence of the Eurasian and the North American plates and broad deformation in this region (Hindle et al., 2006; Yakubchuk, 2008).

6 Prospection of the Future Supercontinent Ameurasia

6.1 Prospection of the supercontinent in future

Following the plate tectonics theory, the most important development in Earth Science should be the recognition of supercontinents (Nance et al., 2014). Probably no other than the supercontinent cycle, including supercontinental assembly and break up, has left a greater imprint in deep Earth time (Murphy and Nance, 2013; Cawood et al., 2016; Condie, 2016). The past supercontinents have formed every ~500–650 Ma (Condie, 2016) or ~700–800 Ma (Yoshida, 2016) on the Earth. For example, the Pangea formed through the convergence of the Gondwana and the Laurasia in ca. 300–250 Ma (Rogers and Santosh, 2004; Condie, 2016; Zhao et al., 2018); the Rodinia formed at ca. 1.1–1.0 Ga (Rogers and Santosh, 2004; Nance et al., 2014; Cawood et al., 2016) or 850 Ma (Condie, 2016), and the Columbia (Nena, Nuna, Paleopangea) formed at 1.9–1.8 Ga (Rogers and Santosh, 2004) or ca. 1.8 Ga (Nance et al., 2014) or ca.1.6 Ga (Condie and Aster, 2013; Condie et al., 2015; Condie, 2016).

There are four main proposed scenarios for the formation of the next supercontinent within the next ca. 200–300 Myr, i.e., the Pangea Ultima by introversion with closure of the Atlantic Ocean, the Novopangea or the Ameurasia by extroversion with gradually closure of the Pacific Ocean, the Amasia by orthoversion with closure of the Arctic Ocean, and the Aurica through combination with closure of both the Atlantic and Pacific oceans (Murphy et al., 2009; Yoshida and Santosh, 2011a; Mitchell et al., 2012; Murphy and Nance, 2013; Davies et al., 2018). Among them, the Ameurasia is expected to form in the northern hemisphere in roughly 250 Myr (Caroline, 2007; Maruyama et al., 2007; Yoshida, 2016), or 200–250 Myr (Safonova and Maruyama, 2014) in the future, with the Asia in its center. The eastern Asia and western Pacific regions were growing up in multi-stage accretions (Figs. 2, 3 and 7), have been the frontier for the future supercontinent Ameurasia (Anderson, 1982; Hoffman, 1991, 1992; Wilde et al., 2003; Caroline, 2007; Maruyama et al., 2007; Dong et al., 2008a, 2015; Yoshida and Santosh, 2011b; Mitchell et al., 2012; Safonova and Maruyama, 2014; Yoshida, 2016; Condie, 2016).

During the formation of the supercontinent Ameurasia, following events will be important in the future. The Africa plate has begun colliding with the Eurasia plate in near future, which will result in fully close of the Mediterranean Sea and development of the collision de facto (Safonova and Maruyama, 2014). Then, the continent Australia will collide with the SE Asia in the future 50–70 Myr (Fig. 7; Scotese, 2001; Yoshida and Santosh, 2011a; Bally et al., 2012).

6.2 Significance of late Paleozoic and Mesozoic orogenies as nucleation and growth of the supercontinent Ameurasia

The formation of the future supercontinent Ameurasia could be tracked back into the time before continuous breakup of the Pangea, the youngest supercontinent formed at ca. 300–250 Ma on the Earth (Fig. 3; Zhao et al., 2018). The collisional Ailaoshan orogeny and/or the North-South Lhasa collision with an age of ca. 260 Ma could be the initiated nucleation of the future supercontinent in the Paleo-Tethys Ocean (Fig. 6). The South China-Indosinian and the North-South China collisions at ca. 250 Ma and ca. 230 Ma, respectively, also led to the nucleation of the East Asia continent in the Paleo-Tethys Ocean. Then, following the beginning of the breakup of Pangea at ca. 200 Ma in the Early Jurassic (Morgan, 1983; Marzoli et al., 1999; Seton et al., 2012; Yoshida and Santosh, 2018), some major tectonic events took place in the Early and Middle Jurassic. For example, the Central Atlantic and the Indian oceans opened at ca. 195 Ma, and the Pacific Ocean at ca. 170 Ma (Buitier and Torsvik, 2014). Meanwhile, the Yanshanian Orogeny took place in or around the North China craton at ca. 168 Ma, representing the convergence of East Asia since the late Middle Jurassic (Dong et al., 2015, 2018; Chen et al., 2019a). Therefore, the Indosinian and the Yanshanian orogenies should be considered as the two major milestones for the Mesozoic nucleation and growth of the supercontinent Ameurasia in eastern Asia.

7 Conclusion

(1) The continental Asia was formed on the bases of the Precambrian cratons, such as the Siberia, India, Arabia, North and South China, Tarim, and Indochina, through multi-stage plate convergence and collisional collages in the Phanerozoic. Three tectonic regimes, i.e., the PAO in the north, the Tethys in the south, and the West Pacific in the east, play as the major controlling dynamic systems for the formation and evolution of the continental Asia. Three major orogenic belts, i.e., the CAOB in the north, the HTOB in the south, and the WPBO in the east, developed
among or around the major cratons. In the core of the PAO regime, the Mongol-Okhotsk Ocean opened with limited expansion in the Early Permian and finally closed in the Early Cretaceous, resulting in the Mongol-Okhotsk orogenic belt there. The initiation and development of tectonic events are diachronic in the three tectonic regimes.

(2) Both the PAO and the Tethys regimes had suffered repeated opening and closure of oceans. All the orogenic cycles began with initiated subduction of an oceanic plate, followed by ocean closure, arc-continent and/or continent-continent collisions. Subduction initiation may occur first in the North Qilian Ocean, a Proto-Tethys Ocean, and then in the Uralian Ocean, a branch of the PAO, in the early Paleozoic. In the West Pacific regime, the initiated subduction may take place in the late Paleozoic. Almost all the collisional orogeny is followed by post-orogenic extensional deformation.

(3) Multi-plate convergence took place in the Paleo-Tethys Ocean since the breakup of the Pangea, leading to the amalgamation of the continental Asia. The multipoint continental nucleation started with the Middle to Late Permian Ailaoshan orogeny and North-South Lhasa collision, followed by the early Mesozoic Indochina-South China and North-South China collisions in the Paleo-Tethys Ocean. All these tectonic events represent the starting points for the growth of the supercontinent Ameurasia in the future.

(4) The late Mesozoic Mongolia-Okhotsk orogeny, Lhasa-Qiangtang collision, and intra-continental Yanshanian orogeny, and the Cenozoic Indo-Asian, Arab-Asian, and West Pacific margin collisions, have shaped the current continental Asia. All of them are the important milestones in the growth of the future supercontinent.

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