SCIENCE CHINA
Earth Sciences

•REVIEW•

March 2020 Vol.63 No.3: 329–361
https://doi.org/10.1007/s11430-019-9524-6

Accretionary processes and metallogenesis of the Central Asian Orogenic Belt: Advances and perspectives

Wenjiao XIAO[1,2,3*], Dongfang SONG[2,3], Brian F. WINDLEY[4], Jiliang LI[2], Chunming HAN[2,3], Bo WAN[2,3], Ji'en ZHANG[2,3], Songjian AO[2,3] & Zhiyong ZHANG[2,3]

[1] *Research Centre for Mineral Resources, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China;*
[2] *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;*
[3] *College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China;*
[4] *Department of Geology, University of Leicester, Leicester LE1 7RH, UK*

Received June 18, 2019; revised November 25, 2019; accepted November 25, 2019; published online January 8, 2020

Abstract As one of the largest Phanerozoic orogens in the world, the Central Asian Orogenic Belt (CAOB) is a natural laboratory for studies of continental dynamics and metallogenesis. This paper summarizes the research progresses of the accretionary processes and metallogenesis of the CAOB since the People's Republic of China was founded, and puts forward the prospect for future research. During the early period (1950s–1970s), several geological theories were applied to explain the geological evolution of Central Asia. In the early period of China's reform and opening-up, the plate tectonics theory was applied to explain the evolution of the northern Xinjiang and Xingmeng regions, and the opinion of subduction-collision between Siberian, Kazakhstan, and China-North Korea-Tarim plates was proposed. The idea of the Solonker-Yanbian suture zone was established. In the 1990s, the study of the CAOB entered a period of rapid development. One school of scholars including geologists from the former Soviet Union proposed a multi-block collision model for the assemblage of the CAOB. In contrast, another school of scholars, led by a Turkish geologist, Celal Şengör, proposed that the Altaids was formed through the growth and strike-slip duplicates of a single island arc, and pointed out that the Altaids is a special type of collisional orogen. During this period, Chinese geologists carried out a lot of pioneering researches on ophiolites and high-pressure metamorphic rocks in northern China, and confirmed the main suture zones accordingly. In 1999, the concept of "Central Asian metallogenic domain" was proposed, and it became one of the three major metallogenic domains in the world. Since the 21st century, given the importance for understanding continental accretion and metallogenic mechanism, the CAOB has become the international academic forefront. China has laid out a series of scientific research projects in Central Asia. A large number of important scientific research achievements have been spawned, including the tectonic attribution of micro-continents, timing and tectonic settings of ophiolites, magmatic arcs, identification and anatomy of accretionary wedges, regional metamorphism-deformation, (ultra)high-pressure metamorphism, ridge subduction, plume-plate interaction, archipelagic paleogeography and spatio-temporal framework of multiple accretionary orogeny, continental growth, accretionary metallogenesis, structural superposition and transformation, etc. These achievements have made important international influences. There still exist the following aspects that need further study: (1) Early evolution history and subduction initiation of the Paleo-Asian Ocean; (2) The accretionary mechanism of the extroversion Paleo-Asian Ocean; (3) The properties of the mantle of the Paleo-Asian Ocean and their spatio-temporal distribution; (4) The interaction between the Paleo-Asian Ocean and the Tethys Ocean; (5) Phanerozoic continental growth mechanism and its global comparison; (6) Accretionary metallogenic mechanism of the Central Asian metallogenic domain; and (7) Continental transformation mechanism.

Keywords CAOB, Accretionary orogenic processes, Metallogenesis, Research progress, Research frontier

Citation: Xiao W, Song D, Windley B F, Li J, Han C, Wan B, Zhang J, Ao S, Zhang Z. 2020. Accretionary processes and metallogenesis of the Central Asian Orogenic Belt: Advances and perspectives. Science China Earth Sciences, 63: 329–361, https://doi.org/10.1007/s11430-019-9524-6

* Corresponding author (email: wj-xiao@mail.iggcas.ac.cn)

1. Introduction

The Central Asian Orogenic Belt (CAOB) is a giant orogenic collage located between the Eastern European (Baltica) Craton, Siberian Craton to the north, and the Tarim Craton and North China Craton to the south (Figure 1). It extends west-east from the Caspian Sea to the northern Western Pacific Ocean, and stretches across Russia, Kazakhstan, Kyrgyzstan, Uzbekistan, Tanzania, Tajikistan, Mongolia, and northern China, making the CAOB one of the largest orogens in the world. The CAOB has been given different names by different geologists. For example, the Central Asian Fold Belt (Khain et al., 2002) and Central Asian Mobile Belt (Kovalenko et al., 2004) were used by Russian geologists; Altaid tectonic collage (Şengör et al., 1993) or Altaids (Şengör and Natal'in, 1996; Şengör et al., 2018) were proposed by a Turkish research team to describe the main part of the CAOB; and the Central Asian Orogenic System (Zuza and Yin, 2017) was introduced by North American geologists. As the southernmost part of the CAOB, northern China is called the Tianshan-Xingmeng Orogenic Belt (Zuo et al., 1990). The term "Central Asian Orogenic Belt" (CAOB) (Jahn et al., 2000c; Windley et al., 2007; Windley and Xiao, 2018) is the most widely used one among the geoscience community.

The CAOB was defined as a special type of collisional orogenic belt by Şengör and Natal'in (1996), which is characterized by the presence of subduction-accretion complexes at large scales and arc magmatism, while collision-related foreland basins are relatively lacking. Different from the evolution of the Tethyan collisional orogenic belt, the CAOB is composed of a large number of accretionary complexes, magmatic arcs, arc-related basins, ophiolites, seamounts and continental fragments, and it is considered as a typical accretionary orogenic belt (Windley et al., 1990, 2007).

The formation of the CAOB is the result of the long-lived subduction of the Paleo-Asian Ocean (Dobretsov et al., 1995), and it is therefore also called the Paleo-Asian tectonic domain in Chinese community. The long-lived course of the Paleo-Asian oceanic subduction and final closure gave rise to giant subduction-accretionary complexes and island arc magmatite, resulting in significant growth of Asian continent by about 530×10^4 km^2 during the Paleozoic, half of which came from newly born crust (Şengör et al., 1993). Thus, the CAOB is considered to be the largest Phanerozoic continental growth region in the world (Şengör et al., 1993; Jahn et al., 2000c; Windley et al., 2007). Recent studies show that oroclinal bending along with ridge subduction during multiple oceanic basin subduction is an important mechanism of the accretion of the CAOB and the continental growth of Central Asia (Xiao et al., 2018, 2015; Windley and Xiao, 2018).

The CAOB contains abundant resources of mineral, oil and gas, forming the Central Asian metallogenic domain (Tu, 1999; Gao et al., 2018), which, together with the Circum-Pacific and the Tethyan metallogenic domains, constitute the three largest metallogenic domains in the world (Gao et al., 2018). The CAOB contains world-class Au-Cu and other deposits, and has become an important base for mineral exploration and metallogenic theory research (Gao et al., 2018).

The CAOB is a natural laboratory for studying continental dynamics and metallogenesis, which has drawn close attention of geologists around the world over a long period of time. It has become the frontier and hot topic of earth science. The Chinese scientists have been working on the tectonic evolution and metallogenic regularity of the CAOB for a long time, and have gained a series of important achievements. In this paper, we make a brief review over the research progresses of the accretionary orogenesis and metallogenic processes of the CAOB, which include an overview of the research since the founding of the People's Republic of China, the research progresses in the past 40 years, and the outstanding achievements since the 21st century. This contribution aims to present an overall review of the history of the CAOB research, and offers the prospect for the future study.

2. Overview since the founding of the People's Republic of China

The Chinese part of the CAOB includes the northern Xinjiang, northern Gansu, Inner Mongolia and the three provinces in northeast China. The Chinese scientists have been studying the CAOB for a long time. A large amount of research results have been achieved since the People's Republic of China was founded, especially after the reform and opening-up. Since the 21st century, the study of CAOB has entered the international academic frontier due to the implementation of a series of scientific research projects and international geological projects.

From 1949 to the 1970s, China's geological work made some important progresses, with the development of different geological schools of thoughts. Under different geological theoretical frameworks, the Chinese scholars discussed the basic tectonic problems and divided the main tectonic units of Central Asia, which provided a robust foundation for subsequent research.

He (1956) discussed the boundary between Tianshan geosyncline and the Qilian geosyncline; Yuan (1956) discussed the geological features of the Tianshan depression and Junggar Basin, and described the lithostratigraphic system in detail. These scholars became the founders of geological research work in Xinjiang.

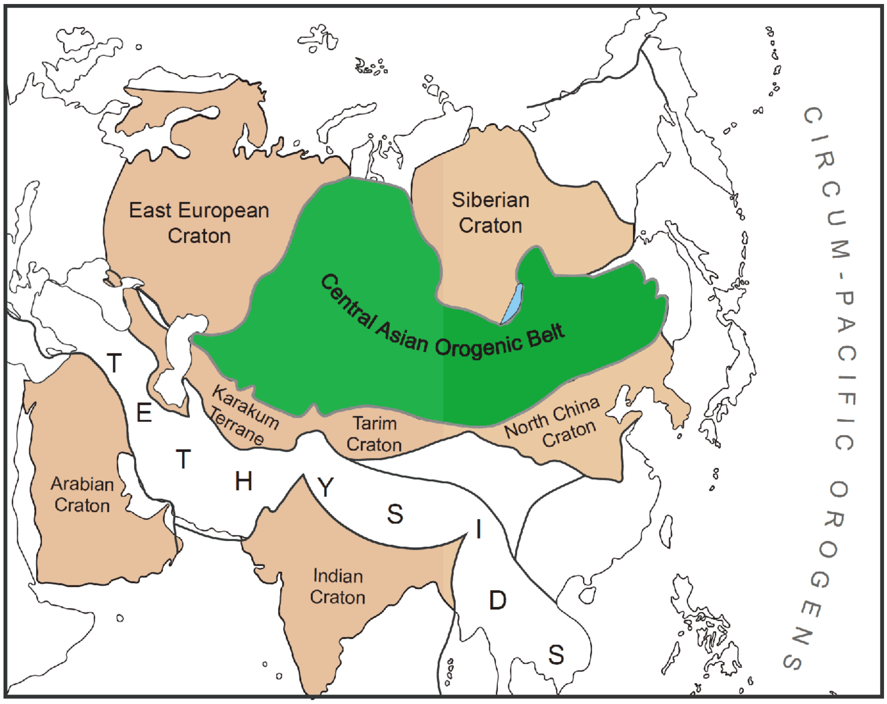

Figure 1 Simplified tectonic map of the Asia showing the location of the Altaids. Modified after Şengör and Natal'in (1996) and Xiao et al. (2009b).

According to the geomechanical view of Li (1962), there were the Tianshan and Kunlun latitudinal structures, and other rotational shear systems in the central, north and south sides of Xinjiang. Hu et al. (1964) divided Xinjiang into six tectonic units: The Altai geosynclinal fold belt, Junggar depression, Tianshan geosynclinal fold belt, Tarim platform, Kunlun geosynclinal fold belt and Karakorum geosynclinal fold belt. Each geosynclinal fold belt was further subdivided into several anticlines, synclines and depressions, and the Tarim platform was subdivided into several fault blocks and uplifts (Hu et al., 1964). Huang et al. (1974) considerd that the Altai, Tianshan and Kunlun were multi-cycle geosynclinal fold systems, Junggar was a depression and Tarim was a platform. Based on the geomechanics and geological history analysis, the Faulted Block theory was introduced and proposed. Xinjiang was named the Western China Faulted Block, which is subdivided into the Tianshan, Kunlun, Altai fault and fold belts and Tarim Block (Mapping Group of the IGCAS, 1974). Chen et al. (1975) divided Xinjiang into the northern and southern Xinjiang geodepressional regions and Kunlun geosynclinal region. Zhang and Wu (1975), based on the view of the crustal mosaic structure and wave movements, considered that there were intertwined structural belts with different directions forming a net-shaped tectonic domain in the Xinjiang region, as smaller terranes or belts in meshes were enclosed by bigger ones.

During this period, the demand for mineral resources had risen rapidly in order to support the national construction which had prompted remarkable achievements of mineral resources survey and exploration, especially in northwest China. Zhang and Wu (1975) summarized the emplacement ages, structural attributes and tectonic relationships of ultramafic rocks in Xinjiang. These ultramafic rocks were divided into 17 petrological zones, in which five types of chromium-bearing rocks were identified: Dunite-clinopyroxenite, dunite-harzburgite, harzburgite, harzburgite-peridotite and plagioclase-bearing ultramafic rocks, respectively. In 1979, a new 1:1000000 Geological Map of Xinjiang (first draft) was finished, which played an important role in advancing the geological research in Xinjiang (Xu, 1979).

Geological research in Xing'an-Inner Mongolia and its neighboring areas also reached a great development during this period. Xiao and Liu (1962) pointed out that the Variscan orogeny in Mongolia could be divided into three sub-cycles: Early Silurian to early Carboniferous, Carboniferous to early Permian, and late Permian to earliest Mesozoic. Xu (1963) made a brief review on the classification and identification of ultramafic rocks in Inner Mongolia.

In 1963, the national conference on chromium mining was held in Inner Mongolia, during which the experiences of geological survey and exploration for ultramafic rocks and chromite were presented and exchanged.

The studies on tectonic evolution of northeast China can be traced back to the 1950s. Zhang et al. (1959) divided northeast China into the northeast block (Pre-Sinian fold belt), Great Khingan fold belt (Late Hercynian), Inner Mongolia fold belt (Late Hercynian), Zhangguangcai Range fold belt (Late Hercynian), Hunchun fold Belt (Late Hercynian) and Nadanhada fold belt (Mesozoic). Huang et al. (1959) emphasized that the northeast China paraplatform was a multiple-cycle orogenic region consisting of a series of northeast-southwest trending uplifts and depressions.

In the 1980s, with the introduction of plate tectonics to China, the study of the CAOB entered a new era. Many geologists re-interpreted the previous geosyncline and platform theory, and tried to use plate tectonic theory to explain the geological evolution of Central Asia. Li (1980) pointed out, in his article "The Outline of Chinese Plate Tectonics", that "the China Plate was made up of the Tarim-Sino-Korea block in the core and the Tianshan-Inner Mongolia-Xing'an geosyncline in the north, where a series of Paleozoic subduction zones and sutures were presented; the Nadanhada Range in Heilongjiang Province was a north-south geosyncline, connecting to the Sikhote geosyncline in the Soviet Union to the east". Li (1980) proposed that an ocean 4000 km in width existed between the Tarim-Sino-Korea Plate and Siberian Plate during the Paleozoic; the Erqis Fault located in the south of Altai was a suture recording early Paleozoic northward subduction process; the Solonker-Hegenshan in northern Inner Mongolia was a late Paleozoic subduction zone originating from either northward or southward subduction. Tao et al. (1982) divided Xinjiang into four ancient plates, namely the Altai Plate, Junggar Plate, Tianshan-Tarim Plate and Qinling-Qilan-Kunlun Plate.

Wang et al. (1989) pointed out that the plate tectonics in Tianshan could be traced back to middle Neoproterozoic, and the plate tectonics of Tianshan was characterized by an accordion-style opening-closing which experienced seven cycles from Sinian to Permian. Liu (1984) considered that Beishan was part of the Paleozoic Tianshan-Inner Mongolian geosynclinal fold belt, and discussed the calc-alkaline magmatism in Beishan and its relationship to plate tectonics.

The study of ophiolites in Central Asia entered into a rapid development period from the 1980s. Zhang (1981) identified eleven ophiolite belts in Xinjiang: The Irtysh ophiolite belt, Barrek-Armantai ophiolite belt, Dalabut-Salbira ophiolite belt, Kelameili ophiolite belt, Mayili ophiolite belt, North Tianshan ophiolite belt, Central Tianshan ophiolite belt, South Tianshan ophiolite belt, West Kunlun ophiolite belt, Apa-Mangya ophiolite belt and Hongliugou ophiolite belt, and described the composition of the ophiolites. Since then, different geologists had carried out detailed petrological, mineralogical, chromite origin and geological background studies on the ophiolites in the CAOB (Zhu et al., 1987; Cui, 1988). Zhang and He (1988) firstly identified early Paleozoic ophiolite in the Beishan Orogen, and carried out research on the origin and evolution of the ophiolites. The Beishan ophiolite was regarded as a remnant of a small oceanic basin developed by continental rifting.

Tian and Yang (1983) initially divided the ophiolites in northeastern China into nine ophiolite belts and four formation stages. Neoarchean ophiolites include the Jianping, Tieling and Helong ophiolites, which were interpreted to form in an island arc setting. Neoproterozoic ophiolites include the Luobei and Yilan ophiolites, which were related to marginal sea or island arc setting. Early Paleozoic ophiolites include the Xar Moron River, Panshi and Wolong ophiolites, generated in subduction-accretion settings. The late Paleozoic ophiolite is the Raohe ophiolite, possibly related to the remnants of a small oceanic basin.

In 1985, the State Planning Commission of China (now the National Development and Reform Commission of China) and the State Science and Technology Commission of China (now the Ministry of Science and Technology) officially approved a new scientific program called the National Program 305. This scientific and technological program aims to accelerate the identification of geological, geophysical and geochemical characteristics of mineral resources in Xinjiang. The project of "The formation and evolution of Paleozoic lithosphere in the Xing'an-Mongolia-Xinjiang and neighboring areas of China" was carried out by the National Natural Science Foundation of China in 1987, which strongly promoted the basic geological research of the CAOB.

In the 1990s, the study of the CAOB became more prosperous with the conception of accretionary orogenesis. Different tectonic models were proposed to explain the formation and evolution of the CAOB. Based on the distribution of micro-continents within the CAOB, geologists from the former Soviet Union considered that there were several oceanic basins in Central Asia, and the micro-continents collided together to form the CAOB after the closure of these oceanic basins in the Paleozoic (Zonenshain et al., 1990). In contrast, a Turkish geologist, A.M. Celal Şengör, with the collaboration of some Russian colleagues, emphasized the important role of subduction-accretion complexes and magmatic arcs in constructing of the CAOB, and proposed that the CAOB (Şengör called it the Altaids or Altaid tectonic collage) was formed by the strike-slip duplicates of the single Kipchak-Tuva-Mongol arc ascribed to the subduction of the Turkestan Ocean beneath the Siberian Craton, known as the "single island arc accretion" model (Şengör et al., 1993).

Chinese geologists conducted a lot of studies on the geological evolution of the CAOB and achieved a series of new research results. Li et al. (1992) reconstructed the tectonic evolution of northern Xinjiang, and considered that its evolutionary history could have been traced back to the Neoproterozoic. The evolutionary history of Northern Xinjiang was divided into three stages: Cratonization stage, ocean-land transformation stage, and new cratonization stage. Based on those, Li et al. (1992) elaborated the formation, distribution and occurrence of ore deposits in Northern Xinjiang.

Gao (1993) and Gao et al. (1996, 1997) carried out detailed study on the plate tectonics and orogenic dynamics of the

Southwest Tianshan, and summarized the tectonic evolution of the lithospheric plate and orogenic dynamics in the Southwest Tianshan based on a comprehensive study of the tectonostratigraphy, ophiolites, deformation and blueschists. Based on geochemical and isotopic data, Hu et al. (1995) proposed a geological time scale related to major geological events in Northern Xinjiang. As part of the Tianshan-Xingmeng Orogenic Belt, the geological research in the Beishan Orogen had been widely valued. Zuo et al. (1990) and Zuo and He (1990) preliminarily established the geotectonic model of Beishan Orogen, and considered that Beishan was comprised of the northern margin of the eastern Tarim Plate in the south and the Hanshan microcontinent in the north, with Shibanjing-Xiaohuangshan ophiolitic mélange in between, during the early Paleozoic. The Beishan Orogen underwent Atlantic-type, Andean-type and the western Pacific-type continental margin evolution, and entered into the intraplate evolution stage in the late Paleozoic (Zuo and He, 1990). Liu and Wang (1995) suggested that the main part of Beishan Orogen was the eastern extension of the Kazakhstan Plate, which was composed of two geosynclines in the north and south and the Mazongshan block in the center. The plate tectonics in Beishan began in the Middle Ordovician, and the ocean was closed in the Carboniferous. The geological study on northern margin of the North China Platform had also made important progress. Meso-Neoproterozoic and Caledonian fold belts were established in the previous Xingmeng Variscan fold belt, and multiple-cycle opening-closing from the Proterozoic to the Paleozoic had been identified on the northern margin of the North China Platform (Niu et al., 1993). Li and Ouyang (1998) proposed that the Xingmeng orogenic belt was a tectonic collage composed of a series of medium and small-sized plates, rather than a simple suture between the Siberian Plate and the North China Plate. Tang et al. (1995) pointed out that northeast China and its adjacent regions contained two tectonic belts. The inner belt consisted of rifted continental fragments, of which the northern part was related to the evolution of the Paleo-Asian Ocean and the southern part was involved into the evolution of the Paleo-Pacific Ocean. The outer belt was composed of Mesozoic accretionary terranes. Li et al. (1998) firstly put forward that an ancient plateau similar to the Tibet Plateau existed in northeast China during the Late Jurassic, and discussed the concepts of "Paleo-Asian oceanic tectonic system" and "Circum-Pacific tectonic system". Moreover, "medium-small plate group" and "archipelago pattern" were used to explain the Paleozoic tectonic paleogeography of northeast China (Zhang et al., 1998).

Since the 21st century, with the rapid development of modern isotopic analysis techniques, a batch of high-resolution isotopic data were published, demonstrating that the CAOB was an important region of the Phanerozoic continental growth (Jahn et al., 2000b, 2000c). Khain et al. (2002) reported the oldest ophiolite of ~1020 Ma so far in the CAOB through zircon U-Pb and Pb-Pb dating methods, proving that the Paleo-Asian Ocean had existed as early as the latest Mesoproterozoic. Spatio-temporal evolution of the CAOB gradually became a hot topic at home and abroad. China increased the funding for the research of basic geological theory and metallogenic mechanism in the CAOB, which promoted the emergence of a great number of leading results into the international community. The 305 Project featuring a series of plans aimed at surveys of mineral resources and studies of geological evolution in Xinjiang were successively conducted. At the same time, the "Central Asian-type orogenesis and metallogenesis in western China" which was affiliated with the National Key Basic Research Development Program ("973 Program") was launched in 2002, heralding a new stage of the study of the CAOB. In 2007, the second round of "973 Program" highlighting the "Continental dynamic processes and metallogenesis of the CAOB" was launched. A systematical research focusing on the accretion processes and metallogenesis of the CAOB was carried out, and an abundance of important results were yielded. Based on the accretionary complexes, ophiolites and magmatic arcs, Xiao et al. (2003) suggested that the eastern segment of the CAOB was formed through accretionary wedge-wedge collision; while the western part of the CAOB was characterized by multiple subduction-accretion processes involving multiple oceanic basins, multiple subduction zones and multiple-directional subduction (Xiao et al., 2008, 2009b). Research of the CAOB stepped onto the academic frontier in the international community after the implementation of the "973 Program" projects and other national projects of science and technology.

In 2012 and 2014, the major projects of National Natural Science Foundation of China—"Reconstruction of Pangea in Eastern Asia" and "Large-scale porphyric metallogenesis in the Central Asian Metallogenic Domain"—were started, respectively. In 2013, a new "973 Program", named "Tectonic superimposition and large-scale metallogenesis in the Xingmeng orogenic belt" was approved. In 2014, the "973 Program" project "The metallogenic mechanism of ancient arc-basin system in northern Xinjiang" and "Carboniferous-Permian tectonic evolution and the epithermal metallogenic system in Western Tianshan" were launched. The implementation of the major projects above concerning the frontier issues of great importance had made China the leading group of the CAOB research. In 2017, the projects entitled "The deep structure and metallogenic processes of the North China accretionary metallogenic systems" and "The deep structure and metallogenic process of composite orogenic metallogenic system in eastern North China" started. The goals of these projects were to obtain the deep three-dimensional structure of the orogenic belt using integrated geophysical and geological exploration, and realize shallow "transparency" within 3000 m of major ore deposit clusters, finally provide constraints on the metallogenic background in accretionary orogens and expanding the depth mineral exploration, as well.

In a nutshell, the study of the CAOB in China advanced progressively from a foundation stage during the 1950s to 1970s, to a stage of rapid development in the 1980s–1990s, and gradually entered the frontier of the earth science research in the international community since the 21st century.

3. Research progresses in the past 40 years since the reform and opening-up

After China's reform and opening-up, the plate tectonics theory, hailed as a revolution of geoscience, was introduced to China. Some Chinese structural geologists such as Li Chun-Yu initially tried to use the theory of plate tectonics to explain the evolution of the CAOB. Li and Tang (1983) and Li et al. (1984) pointed out that the Altai, Tianshan and the regions from the Langshan to the Xing'an Range were the products of subduction-collision of the Siberian Plate, Kazakhstan Plate and the Tarim-Sino-Korea Plate in the Paleozoic, making it clear that the CAOB was the result of oceanic subduction and closure. Li et al. (1984) divided Asia into 12 ancient plates in the light of distribution of ophiolites, high pressure-low temperature metamorphic belts, island arcs or calc-alkaline magmatism and mélanges. Li and Tang (1983), for the first time, indicated that the suture zone between the Siberian Plate and the Tarim-Sino-Korea Plate started from Solonker in northern Inner Mongolia to Yanbian in Jilin. It extends westwards to the Gongpoquan area, east of Hami, before it branches off to two sutures. One trends along Kelameili, through southwestern Altai and Irtysh, into Russia, and then diverts northward to the Ob Bay, serving as the suture between the Siberian Plate and Kazakhstan Plate. The other trends westwards from the Tianshan along the south edge of the Kizilku desert, and then northwards into the Aral Sea, parallel to the eastern piedmont of the Ural Mountains, to the downstream of the Ob River, considered as the suture between the Kazakhstan Plate and the Tarim-Sino-Korea Plate (Li and Tang, 1983).

In 1989, the International Geological Correlation Program No. 283 (IGCP283)—"The tectonic evolution and geodynamics of the regions related to the Paleo-Asian Ocean"—was approved. The project was headed by Chinese geologist Xiao Xu-Chang teamed up with the former Soviet Union geologist N. L. Dobretsov, American geologist R. G. Coleman and He Guo-Qi from Peking University. The research area of the IGCP283 extended across the vast area between the Siberian Plate, North China Plate and Tarim Plate; and the study contents covered sedimentation, deformation, metamorphism, magmatism, deep structure and tectonic evolution of major orogenic belts. The project was aimed at clarifying structural features of the lithosphere and geodynamics of the upper mantle in the giant Paleo-Asian suture zone (Tang, 1989, 1990). In 1991, He Guo-Qi and Li Mao-Song summarized the research results of the major project of the National Natural Science Foundation of China—"Formation and evolution of the Paleozoic lithosphere in China's Xingmeng-Northern Xinjiang and adjacent areas". The results suggested that the eastern segment of the Inner Mongolia Orogen was the product of collision and docking between the northern margin of the North China Craton and the southern Mongolian microcontinent in the Late Devonian-Early Carboniferous. The orogen lacked obvious foreland thrust belt and associated foreland molasse basin, and metamorphism and magmatism associated with the crustal overlapping. This indicated that the tectonic features and the syn-orogenic lithology were different from common collisional orogenic belts, which might lead to the establishment of a new type of collisional orogeny (Xingmeng-Northern Xinjiang Research Group, 1991). At the same time, according to palaeobiogeographic studies, the Central Asia region was divided into the southern region (Paleo-Tethys biota, Tethys biota), the northern region (including North American biota and Siberian biota) and region of mixtures and complexes. These results provided fundamental information for subsequent research and were of great academic value.

In 1990, former Soviet Union scholar Zonenshain proposed the "multi-microcontinent collision model" to explain the formation and evolution of the CAOB (Zonenshain et al., 1990). The model emphasized that the orogen was formed by collision of micro-continents scattered across the Paleo-Asian Ocean, which was a kind of mosaic-like thought. Later, Şengör et al. (1993) considered that terranes of micro-continent affinity were very limited in the Central Asia. In contrast, he emphasized the important contribution of subduction-accretion complexes and magmatic arcs formed through oceanic lithosphere subduction processes. Based on spatio-temporal correlation of the accretionary complexes and magmatic arcs, Şengör et al. (1993) proposed the "single Kipchak arc accretionary model" to explain the formation and evolution of the Altaids. At the same time, Şengör et al. (1993) pointed out that Central Asia was the most prominent region of continental growth during Phanerozoic, which posed a challenge to the conventional theory that the growth of Earth continent had completed by the Precambrian and there was no significant continent addtion in the Phanerozoic. Şengör and Natal'in (1996) further emphasized the importance of large subduction-accretion complexes deficient in Alpine or Himalayan-type crystalline nappes or Indus-type suture in Central Asia. Thus, the Altaids was considered as a special type of collisional orogen, in which strike-slip deformation and associated oroclinal bending played important roles in the construction of the Altaids. The most representative oroclines were the Kazakhstan Orocline and the Tuva-Mongolian Orocline (Şengör et al., 1993).

Gao et al. (1993) discovered blueschists in the Kumish area in South Tianshan, which occurred as matrix of ophiolitic mélanges. Gao and Xiao (1994) and Xiao et al. (1994) systematically studied the mineral associations, P-T-t-D path and isotopic ages of the South Tianshan high P/T metamorphic rocks, and discussed the subduction and closure processes of the South Tianshan Ocean in the Paleozoic. In 1995, Gao Jun firstly discovered eclogites in the Southwest Tianshan. Further detailed research then were undertaken (Gao, 1997; Gao et al., 1999) and soon became one of the most prominent highlights in the field of UHP metamorphism and subduction fluids. The discovery of HP metamorphic blueschists and eclogites is of significant importance for exploring the plate tectonics, evolution of disappeared oceans and orogenic dynamics of Southwest Tianshan. Gao et al. (1998) discussed the tectonic evolution of the Tianshan Orogen, proposing that there were two late Paleozoic sutures: The South Tianshan Suture separating the Tarim passive margin to the south from the southern Ili-Central Tianshan active margin to the north, and the suture on the northern side of the Central Tianshan, documenting the amalgamation of the north Ili-Central Tianshan active margin and another intra-oceanic arc in the early Carboniferous.

In 1997, the International Geological Correlation Program IGCP420 project—"Phanerozoic continental accretion: Evidence from the East-Central Asia" was approved. The extensive regions from northeast China, Inner Mongolia to Xinjiang were the major targets of this project (Yao, 1997). The main research contents were included as: (1) Phanerozoic crust accretion; (2) Petrogenesis of alkaline and peralkaline granitoids; (3) Metallogenesis associated with granitic intrusions; and (4) Structural analysis and tectonic models. Geological research of the CAOB had gradually become a hot topic among the international communities of earth science.

In 1999, Tu Guang-Chi put forward the concept of "Central Asian Metallogenic Domain", which included vast areas from Ural, via Kazakhstan, Uzbekistan, Kyrgyzstan, northern Xinjiang, Qinghai, northern Gansu, Inner Mongolia, western Mongolia, to the eastern part of Lake Baikal and southern Siberia. The Central Asian Metallogenic Domain is characterized by the development of Meso-Neoproterozoic and Paleozoic metallogenesis, with ore deposits in black rock series, massive sulfide deposits, porphyry-type deposits, continental volcanic rock gold deposits, alkaline intrusive-related deposits, sandstone copper deposits, etc. (Tu, 1999). The Central Asian Metallogenic Domain, together with the Circum-Pacific Metallogenic Domain and the Tethyan Metallogenic Domain make up the world's three largest metallogenic domains.

Since 2000, the study of CAOB has continued and gradually become the research frontiers and a hot topic among the international geoscience societies. An array of important scientific research projects have been set up in Central Asia. Launched in 2002 and 2007, the national "973 Program" focused on the study of tectonic evolution and metallogenesis of the CAOB and summarized the basic characteristics of the CAOB: (1) The largest accretionary orogen in the world, (2) intense crust-mantle interaction; (3) significant Phanerozoic continental growth; and (4) Cenozoic tectonic reworking. These characteristics make the CAOB a natural laboratory for the study of continental accretion and metallogenic mechanisms. Chinese geologists have published a large number of contributions on the geology of Central Asia, and have become a major force to push forward the research in this field. The 2011 American Geological Society Penrose Conference was held in Urumqi, Xinjiang, China. The theme of the conference was the tectonic evolution of accretionary orogenic belts. The meeting focused on the comparison of tectonic evolution between the CAOB and the present Circum-Pacific Orogenic System. In 2013, "Tectonic evolution of the Central Asian Orogenic Belt" entered the top frontier of ESI in the area of earth science research, and most of the core papers were contributed by Chinese scientists.

In recent years, some major and key projects have been laid out by the National Natural Science Foundation of China on the CAOB. Important basic research projects for deep resource exploration and exploitation have been laid out by the Ministry of Science and Technology of China. These important projects are aimed at unraveling the evolution of orogen and mechanism of continental accretion, which will give birth to more important results.

4. Outstanding research achievements since the 21st century

Funded by a series of scientific research projects from the Chinese government, especially the Ministry of Science and Technology "973" project, the major and key projects of the National Natural Science Foundation of China, and the National 305 Project, the research on the tectonic evolution and metallogenesis of the CAOB has made appreciable achievements. These include ages and tectonic attributes of "microcontinents", ages and tectonic settings of ophiolites, properties of magmatic arcs, anatomy of accretionary complexes, regional metamorphism-deformation, (ultra-)high-pressure metamorphism in the subduction zone, ridge-trench interaction, mantle plume-plate interaction, spatio-temporal frame of accretionary orogeny, mechanism of continental growth, metallogenic mechanism, and tectonic superposition and reworking.

4.1 Ages and tectonic attributes of "microcontinents"

The CAOB contains a large number of metamorphic terranes mainly composed of gneiss-schist complexes. They are subjected to complicated deformation and high-grade metamorphism up to amphibolite-facies or even granulite-facies (Shu et al., 2002). Traditionally, these metamorphic terranes were regarded as orogenic basement or microcontinents. They are widely distributed in the Kyrgyzstan Tianshan, Altai, Yili-Central Tianshan, Tuva-Mongolia, Beishan Orogen and the Xingmeng Orogen.

Based on the study of Phanerozoic granites and basement rocks of the Altai, Junggar and Tianshan, Hu et al. (2000) postulated that the Altai and Tianshan were complex terranes composed of Phanerozoic accretionary complexes and Proterozoic metamorphic basements, the basement of the Junggar Basin might be a remnant ocean, and the Junggar terrane was mainly composed of juvenile island arc complexes.

Li et al. (2006) put forward the concept of Altai-Mongolian microcontinent in tems of zircon U-Pb upper intercept ages and Sm-Nd isochron ages for metamorphic complex. Kröner et al. (2013, 2017) reported Paleoproterozoic to Mesoproterozoic zircon U-Pb ages in Kyrgyzstan Tianshan. Sun et al. (2005) proposed the existence of the Neoarchean to Paleoproterozoic metamorphic basement in northern Beishan. Moreover, Mesoproterozoic gneisses were discovered in the southern part of Beishan (He et al., 2018b), which had similar Hf-O isotopic compositions to Mesoproterozoic rocks from Central Tianshan and the Xilinhot Block, and the microcontinents in Kyrgyzstan Tianshan. He et al. (2018a) proposed the existence of Mesoproterozoic juvenile crust in the southern CAOB.

Zhou et al. (2018) systematically summarized the nature of the microcontinents in the CAOB and their relationships with the supercontinental cycles. He pointed out that the microcontinents in the eastern part of the CAOB contained Archean-Paleoproterozoic crystalline basement and experienced Meso-Neoproterozoic tectonic events, which were involved in the Grenville-aged orogeny during the formation of Rodinian supercontinent. The microcontinents in the western part of CAOB also contained Archean to Paleoproterozoic crystalline basement and Meso-Neoproterozoic granites and metamorphic complexes. The microcontinents in the middle part of the CAOB were mainly composed of Neoproterozoic granitic gneisses.

A large number of high-resolution geochronological studies indicate that many terranes which were conventionally assigned as microcontinents in CAOB are actually composed of Paleozoic rocks and are the products of subduction-accretionary orogeny of the Paleo-Asian Ocean. For example, the earliest metamorphic age for the metamorphic complex from the Tuva-Mongolian terrane is 536±6 Ma, and the age of amphibolite facies metamorphism is 497±4 to 489±3 Ma. There is no basement-cover relationship for the Tuva-Mongolian terrane. Instead, the Tuva-Mongolian terrane is a product of structural stacking in the early Paleozoic, consisting of metasedimentary rocks with different tectonic-metamorphic history (Salnikova et al., 2001). High-resolution isotopic dating of gneisses from Altai indicated these metamorphic rocks were formed in the Cambrian-Devonian, and the Altai belongs to the Paleozoic active continental margin ascribed to the subduction of the Paleo-Asian Ocean beneath the Siberian plate (Long et al., 2007; Sun et al., 2008). According to the timing of high temperature metamorphism and abrupt change of Hf isotopic compositions, Sun et al. (2009) and Jiang et al. (2010) further pointed out that the Devonian high-grade metamorphic complexes in the Altai were formed by ridge subduction.

Detailed field geological study combined with high-resolution geochronological studies indicated that most of the high-grade metamorphic complexes in the Beishan Orogen were formed in the Paleozoic (Song et al., 2013, 2016), rather than in the Precambrian. In addition, some metamorphic complexes have complicated lithological compositions. For example, the Lebaquan metamorphic complex in the central Beishan contains not only felsic gneisses and mica-quartz schists, but also some oceanic plate rocks such as metachert, metabasite and marble. These oceanic crust rocks are mixed with strongly deformed schist, displaying a "block-in-matrix" structure (Figure 2). Meanwhile, different types of folds (including tight, asymmetric and open folds) and ductile shearing deformation of multiple stages are developed in the metamorphic complexes. These metamorphic complexes are similar in lithology and structural deformation patterns to accretionary complex formed by oceanic subduction. The timing of deformation of the metamorphic complex was constrained between 424 and 280 Ma, and the Lebaquan complex belongs to the Paleozoic forearc accretionary complexes (Song et al., 2014).

In the western part of the Xingmeng Orogenic Belt, the Xilingol complex, represented by the Xilinhot Group, consists of amphibolite-facies metasedimentary rocks, metamorphic basic-ultrabasic rocks and metamorphic felsic rocks. This metamorphic complex was traditionally regarded as the Precambrian basement and a part of the Xilingol microcontinent (Zhang and Wu, 2001). However, Paleozoic zircon U-Pb ages obtained in these metamorphic complexes (Shi et al., 2003; Xue et al., 2009) indicated that at least part of the Xilingol complex was formed in the Palaeozoic accretionary orogenic process. Detailed geochronological study demonstrated that the protolith of the Xilingol complex deposited in the southern active margin of Siberia plate during the Neoproterozoic. The timing of migmatization and

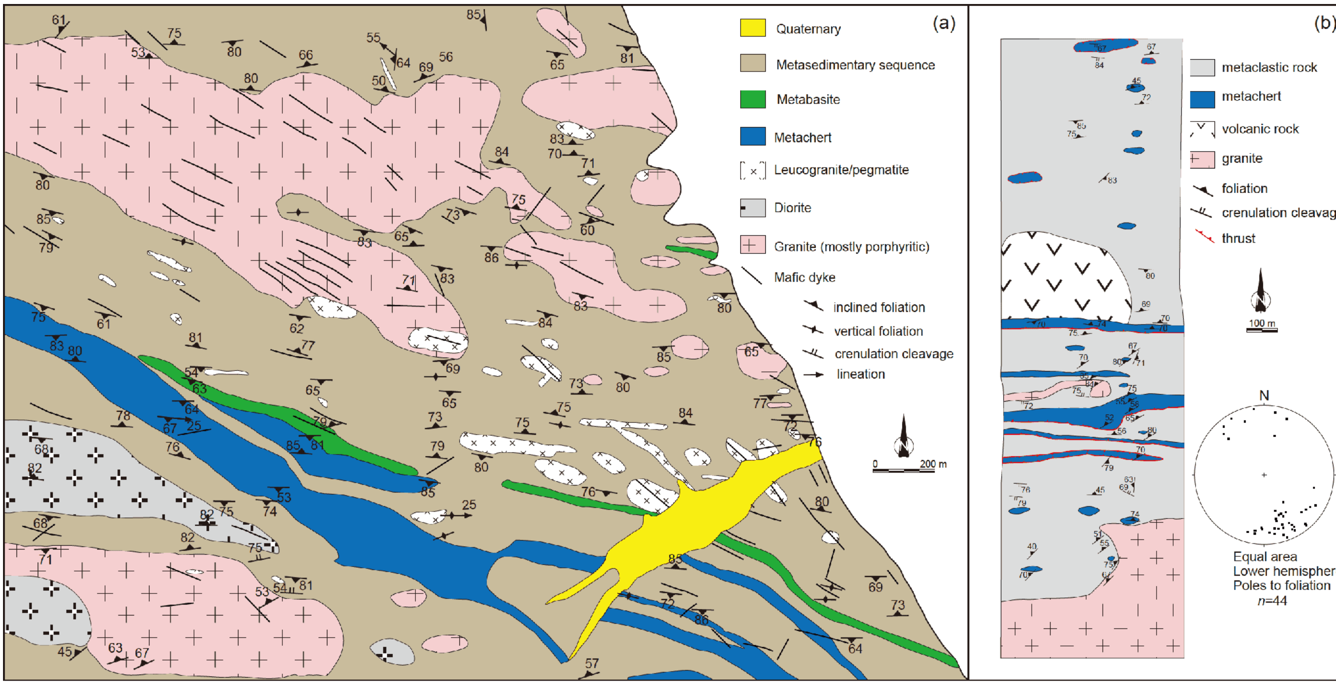

Figure 2 Lithological and structural geological map of the Lebaquan Complex in central Beishan Orogen. (a) An area of 2.5×2.3 km^2, (b) an area of 0.75×2.58 km^2.

metamorphism was constrained at ca. 452±5 Ma. The Xilingol Complex is a component of magmatic arc formed by the northward subduction of the Paleo-Asian Ocean, which recorded the long-term accretionary processes of the CAOB (Li et al., 2011). The eastern part of the Xingmeng Orogenic Belt comprises mainly the Ergun Block, Xing'an Block, Songnen-Xilinhot Block, and the Jiamusi Block (Figure 3). The Xing'an block was previously regarded as a Precambrian block (Zhou et al., 2011), although Precambrian magmatic events are not widely distributed. The previously regarded Precambrian Xinkailing Group, Luomahu Group, Ergun Formation, Wolegen Group and Fengshuigou River Group were all formed in the late Paleozoic-early Mesozoic (Xu et al., 2012; Sun et al., 2014; Cui et al., 2015; Feng et al., 2017). Provenance analysis of the early Paleozoic sedimentary rocks and Hf isotopic study of igneous zircons indicated that the source area is mainly juvenile crust (Zhang et al., 2013; Han et al., 2015). Therefore, the Xing'an Block may not contain a large scale of Precambrian basement, but a Phanerozoic accretionary terrane.

Obviously, the metamorphic terranes in the CAOB have many genetic types. Some metamorphic terranes may be continental ribbons or continental fragments. For example, the Kyrgyz Tianshan and Tuva-Mongolian tectonic belts have some Mesoproterozoic or even older metamorphic complexes (Levashova et al., 2011; Kröner et al., 2017). They constitute the basement of younger island arcs and provide detritus to accretionary wedges and forearc basins. Some metamorphic terranes belong to deep part of the forearc accretionary complexes or the root of island arcs. For example, most of the metamorphic complexes in the Beishan Orogen are the products of Paleozoic accretionary orogeny (Song et al., 2013, 2016).

4.2 Ages and tectonic settings of ophiolites

Ophiolite, as part of the most important evidence for the existence of ocean and its subduction, has long been a key content in the study of orogenic belts. Most of the ophiolites in the CAOB (Figure 4) do not have a complete sequence as defined by the Penrose Conference, from the bottom to the top, including mantle peridotite, sheeted dyke, cumulate gabbro, pillow basalt and pelagic chert. Instead, they have been broken up into tectonic mélanges, and most of them are a part of accretionary complexes or the basement of island arcs. A large number of high-resolution isotopic ages for ophiolites have been published since 2000, which provided critical constraints on the spatial and temporal evolution of the Paleo-Asian Ocean.

By comparing paleomagnetic data and rifting-related magmatic events between the northern margin of the NCC and the southern margin of the Siberian Craton, Wan et al. (2018) pointed out that the Paleo-Asian Ocean initially formed by rifting at ~1.35 Ga. The oldest ophiolite discovered in the CAOB is from the Dunzhugur Complex in the Sayan belt in the southern margin of the Siberian Craton (Banerjee and Matin, 2013). Its age is ~1020 Ma, documenting the Paleo-Asian Ocean had been existing at least

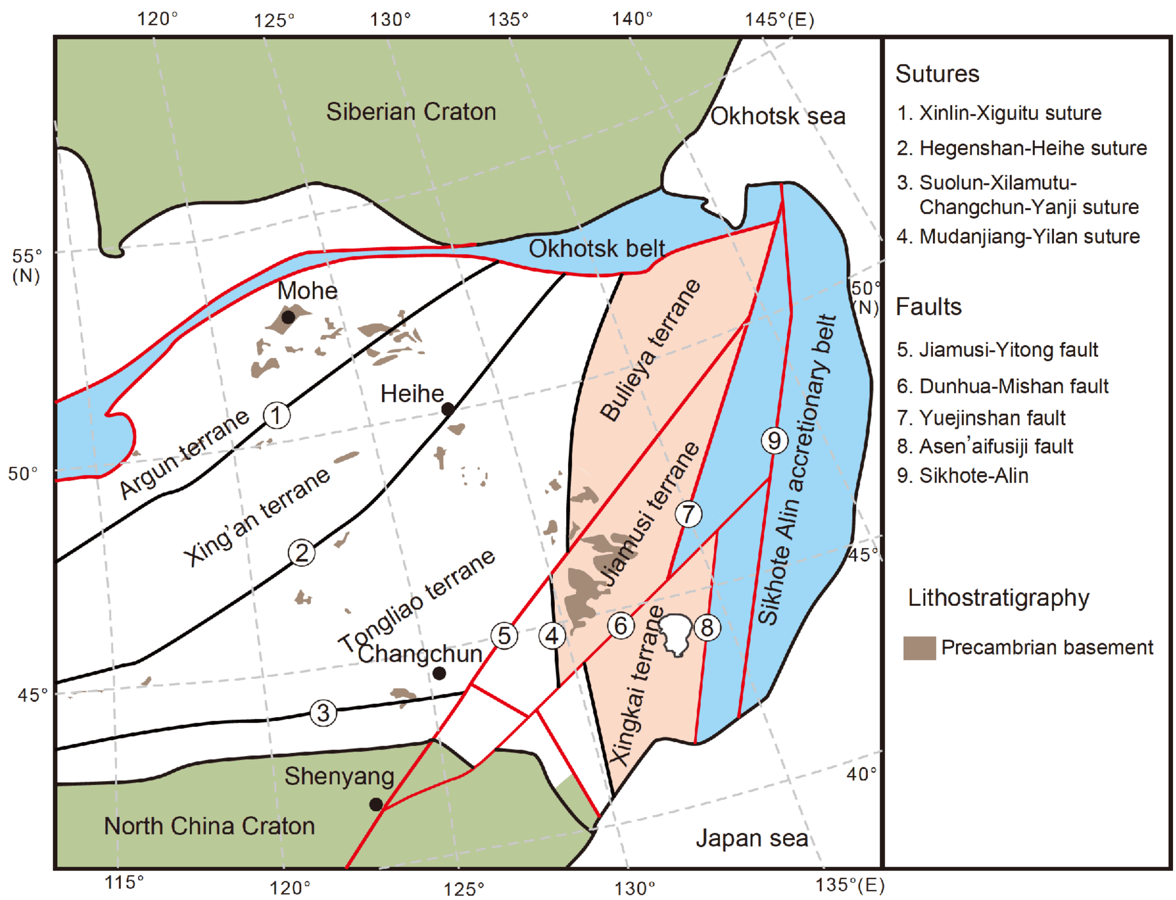

Figure 3 Tectonic division and distribution of Precambrian rocks in northeast China. Modified after Zhou et al. (2018), Liu et al. (2017) and Xu et al. (2019).

since the latest Mesoproterozoic (Khain et al., 2002).

The ophiolites in CAOB generally have a younging trend from the north to the south, reflecting that the CAOB had been growing gradually southwards. Neoproterozoic ophiolitic mélanges expose in the southern margin of Siberia and in Mongolia. For example, zircon U-Pb ages of plagiogranite, basalt and gabbro in the Shaman ophiolite are 971±14, 939±11 and 892±16 Ma, respectively (Gordienko et al., 2009). The ages of Dariv and Khantaishir ophiolites are 571±4 and 568±4 Ma, respectively (Jian et al., 2014). The ages of the ophiolites in the northern part of the Great Khingan Range (the Great Xing'an Range), such as Alihe, Jifeng and Huanerku, range within 697–628 Ma (Feng et al., 2017, 2019). The ophiolites in south Mongolia (Jian et al., 2014), West Junggar (He et al., 2007; Lei and He, 2014; Ren et al., 2014), East Junggar Almantai (Xiao et al., 2009b), Hongliuhe (Zhang and Guo, 2008) and Xichangjing (Ao et al., 2012) in the Beishan Orogen formed in the Cambrian.

Most of the ophiolites in the western part of the CAOB were formed in the Ordovician-Devonian. The age of gabbro from the Zhaheba ophiolite in East Junggar is 485±3 Ma (Ye et al., 2017). The plagiogranite from the Altai Kurti ophiolite has a zircon U-Pb age of ~390 Ma (Shen et al., 2018). The age of the West Junggar Darbut ophiolite is 391±7 Ma (Gu et al., 2009). The age of gabbro in South Tianshan Serikeyayilake and Altenks ophiolite is ~423 Ma (Jiang et al., 2014). The ages of plagiogranite and anorthosite from Yushugou ophiolite are 435±3 and 439±2 Ma (Yang et al., 2011), and these rocks have undergone granulite facies metamorphism (Zhang and Jin, 2016). The gabbro from the Heiyingshan ophiolite in South Tianshan was dated at 392±5 Ma (Wang et al., 2011). The Huoshishan-Niuquanzi ophiolite in the Beishan Orogen was formed at 444–411 Ma (Tian et al., 2014).

Carboniferous-Permian ophiolites are relatively minor in the western part of the CAOB, and they are mainly distributed along the Tianshan and Beishan orogens. For example, the age of the Bayingou ophiolite in North Tianshan is 343±2 Ma (Xu et al., 2006). The gabbro from the Guluogou ophiolite in the South Tianshan was dated at 332±7 Ma (Jiang et al., 2014), and the Xiaohuangshan ophiolite in the central Beishan Orogen was dated at 336±4 Ma (Zheng et al., 2013). The age of the Liuyuan ophiolite in the southern Beishan Orogen is ~286 Ma (Mao et al., 2012b).

The ophiolites in the eastern part of the CAOB mainly formed in Carboniferous-Permian. For example, the age of

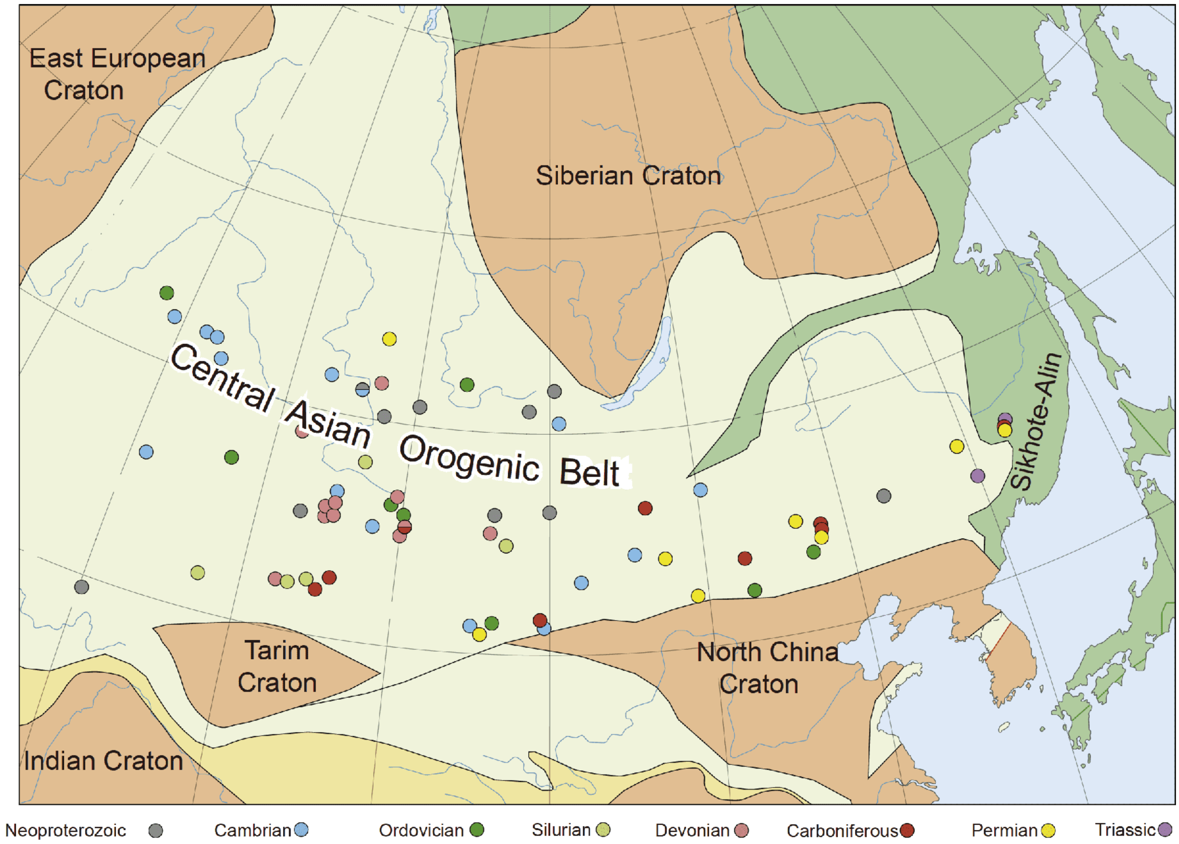

Figure 4 Spatiotemporal distribution of ophiolites in the Central Asian Orogenic Belt. Modified from Furnes and Safonova (2019).

the ophiolite in the West Ujimqin Banner of Inner Mongolia is 356–331 Ma (Song S et al., 2015). The age of the Erenhot ophiolite is 355–348 Ma (Yang et al., 2017). The pillow basalt from the Engger Us ophiolite in Alxa is 302±14 Ma (Zheng et al., 2014), and the age of the Hegenshan ophiolite is 298–295 Ma (Miao et al., 2007). The ages for the Solonker ophiolite are 279±10, 259±6 and 257±3 Ma (Miao et al., 2008; Luo et al., 2016; Xu et al., 2018). The age of the Mandula ophiolite is 274–253 Ma (Jian et al., 2010), and the age of the Ondor Sum ophiolite is 260–250 Ma (Miao et al., 2008).

Chu et al. (2013) obtained Late Permian to Early Triassic protolith ages for the Ondor Sum E-MORB (mid-ocean ridge basalt)/OIB (oceanic island basalt)-type metamafic rocks, which indicated that the oceanic basin might last to the Early Triassic. Only a few ophiolites formed in the early Paleozoic in the eastern part of the CAOB. For example, the age of the Sonid Zuoqi ophiolite is 483±2 Ma (Jian et al., 2008).

Most of the basites from the ophiolites in the CAOB have geochemical signatures of supra-subduction zone (SSZ) ophiolites (Khain et al., 2002; Ao et al., 2012; Song S et al., 2015). There are also some ophiolites that show geochemical characteristics similar to MORB or OIB (Furnes and Safonova, 2019; Safonova and Santosh, 2014; Feng et al., 2019). The ages and geochemical affinities of the ophiolites in the CAOB indicate that the subduction of the Paleo-Asian Ocean evolved from ~1020 Ma to the Early-Middle Triassic, and experienced a long-term evolution spanning about 800 Ma.

4.3 Properties of magmatic arcs

Magmatic arcs and related basins are essential geological units that constitute the CAOB. On the view of current understandings of the subduction zone along the Circum-Pacific Ocean, magmatic arcs can be divided into continental arcs and intra-oceanic arcs (Ducea et al., 2015). The continental arc, also known as Andean-type arc or Cordillera-type arc, is formed through the subduction of oceanic lithosphere beneath continental crust (craton). The South American Andean magmatic arc is a typical continental arc. In contrast, the Mariana arc is a typical intra-oceanic arc. The Japanese island arc is a special type of intra-oceanic arc. It was originally an Andean-type magmatic arc and split from the original continental margin later due to backarc rifting, forming a back-arc basin (Xiao et al., 2010a). Detailed study from petrology, isotopic geochronology and geochemistry in the past 20 years have prompted the identification of various types of magmatic arcs in the CAOB.

The Andean-type magmatic arcs in the CAOB are represented by the Northern Yili arc and the Bainaimiao arc in the southern Inner Mongolia. The Northern Yili arc is composed of Late Ordovician to Silurian granitoids and Devonian to early Permian volcanic-sedimentary rocks atop the basement of Paleoproterozoic to Neoproterozoic metamorphic rocks and early Paleozoic passive continental margin. The late Paleozoic volcanic rocks are mainly composed of basalt, trachyte, trachy-andesite, andesite and rhyolite, which constitute a continental magmatic arc up to 600 km long (Zhu et al., 2009). Devonian basalts contain inherited zircons and show enriched Nd isotopic composition, suggesting the contribution of ancient continental crustal materials to the arc magma (Zhu et al., 2009). The Northern Yili arc is an Andean-type magmatic arc formed on a Precambrian microcontinent (Xiao et al., 2013).

The Bainaimiao arc was formed during the subduction of the eastern branch of the Paleo-Asian Ocean beneath the northern margin of the NCC during the Paleozoic (Xiao et al., 2003). Voluminous diorites, granodiorites and tonalites intruded into the Archean-Paleoproterozoic high-grade metamorphic basement rocks in the northern margin of the NCC, generating a magmatic belt with a length of more than 1000 km and a width of 30–120 km (Zhang and Zhao, 2013). The ages of these intrusions are mostly from late Carboniferous to Permian (Zhang et al., 2009b), although a small amount of them were formed in Ordovician to Devonian (Jian et al., 2008; Miao et al., 2007). Geochemical characteristics show that they are calc-alkaline I-type granites with enriched isotopic compositions, which are considered as the products of interaction between the melts of ancient lower crust and enriched lithospheric mantle. The Bainaimiao arc is an Andean-type arc formed by the southward subduction of the Paleo-Asian Ocean (Zhang et al., 2007, 2009b).

In recent years, many Japan-type island arcs have been identified in the CAOB, such as the Altai arc, the Central Tianshan arc, the Gongpoquan arc in Beishan, etc. The Altai arc consists of a large number of gneisses and metasedimentary rocks, which were traditionally deemed to be the basement of a Precambrian microcontinent (Li et al., 2006). Detailed studies have shown that the protolith of the banded paragneisses and metasedimentary rocks are mainly low compositional maturity sedimentary rocks containing a large number of volcanic lithic fragments (Long et al., 2008). Detrital zircon U-Pb geochronology studies show that the ages of the banded paragneisses range from Cambrian to Ordovician (Sun et al., 2008). The provenance of the metasedimentary rocks is mainly sourced from Cambrian to Ordovician magmatic rocks, with subordinate detritus from Neoproterozoic Tuva-Mongolian terrane and a small number of detritus from Paleoproterozoic-Archean crust (Long et al., 2007). The protoliths for granitic gneisses are mainly I-type granite formed in a subduction setting during 453–380 Ma (Sun et al., 2008). Zircon Hf isotopes of metasedimentary rocks and granitic gneisses indicate significant contributions from Paleozoic juvenile crust (Sun et al., 2008; Long et al., 2010). The Altai is a Japan-type magmatic arc dominated by juvenile crust formed by the subduction of the Paleo-Asian Ocean during the Paleozoic. The Central Tianshan arc consists of a large number of Ordovician calc-alkaline basalts, andesites, pyroclastic rocks, greywackes and Silurian metaflysch. In addition, there are a large number of Ordovician to Permian subduction-related granitic rocks in the Central Tianshan arc (Dong et al., 2011; Lei et al., 2011). Early Paleozoic granites have enriched isotope compositions, while the late Paleozoic granites have a relatively depleted isotopic compositions, which generally shows the mixing of juvenile and ancient crust (Ma et al., 2014). The Permian copper-nickel ore related basic-ultrabasic complex with age of 285–281 Ma is considered as an Alaska-type complex formed in a subduction setting (Mao et al., 2006; Wu et al., 2005). The Central Tianshan arc is a Japan-type arc evolved from early Paleozoic to Permian related to the subduction of North Tianshan and the South Tianshan oceans (Xiao et al., 2013). The Gongpoquan arc in the central Beishan Orogen has a large number of metamorphic complexes such as gneisses and schists, volcanic rocks and granitic intrusions. The volcanic rocks are mainly basaltic andesites, andesites, pyroclastic rocks and diorites. Geochemical data show that they share the similar signatures with the volcanic rocks from subduction zones. Gneisses and granitic intrusions were dated at 462–398 Ma, and the pyroclastic rocks have youngest detrital zircon age peak of 441–446 Ma along with a certain amount of Precambrian ages (Song D et al., 2015). The Gongpoquan arc is interpreted as a Japan-type island arc related to the northward subduction of the Niujuanzi Ocean during Paleozoic, while the Jijitaizi-Xiaohuangshan ophiolite represents a Carboniferous back-arc basin (Song D et al., 2015). The Japan-type arc developed in the Great Khingan Range in the eastern CAOB includes an early Paleozoic arc and a late Paleozoic arc (Wu et al., 2011; Liu Y et al., 2017; Zhao et al., 2010).

The Japan-type arcs in the CAOB contain some ancient materials and show enriched isotopic compositions, which have been regarded as microcontinents for a long time. Detailed studies in the last two decades show that they may represent a special type of intra-oceanic arc formed by the subduction of the Paleo-Asian Ocean, which is of great significance for understanding the accretionary processes of the CAOB.

A large number of Mariana-type intra-oceanic arcs have been identified in the CAOB. Safonova et al. (2017) identified 21 intra-oceanic arcs in the CAOB, most of which contain boninite. The typical Mariana-type arcs in northwest China include the West Junggar arc and the Bogda arc in North Tianshan. The West Junggar arc, as a part of the Kazakhstan orocline, is a multiple oceanic subduction system including intra-oceanic island arcs, back-arc basins, accretionary complexes and ophiolites developed from Cambrian to Permian. The Barleik, Mayli and Tangbale ophiolite mélanges outcropping in the southwest of West Junggar consist a large number of Ordovician-Silurian pillow basalt, siliceous shale, chert, biolithite limestone, sandstone and mudstone, etc. These rocks were mixed in forms of thrust-imbrication or "block-in-matrix" structures (Zhang et al., 2018). A large number of Ordovician-Permian pillow basalt, biolithite limestone and arc volcanic rocks expose in the northwestern part of West Junggar, which form the northern limb of the Kazakhstan orocline (Chen et al., 2017). The southeastern part of West Junggar, including Karamay and Baijiantan, contains Devonian-late Carboniferous accretionary complexes, island arc and back-arc basins, constituting the multiple oceanic subduction system (Zhang et al., 2011a, 2011b). There are also a large number of granitic rocks with different geochemical signatures, such as adakite, charnockite and alkaline granite in West Junggar, all of which were formed at ~305 Ma and have depleted isotopic compositions (Geng et al., 2009). The Bogda arc in North Tianshan is an intra-oceanic arc consisting of pillow basalt, arc related granite and massive diorite dykes developed from Devonian to Carboniferous (Xiao et al., 2004a; Xie et al., 2016). The pillow basalts have high $\varepsilon_{\rm Nd}(t)$ values (+7.9–+9.4) (Chen et al., 2013). The Bogda arc is the product of southward subduction of the Paleo-Asian Ocean during the Paleozoic (Xiao et al., 2004a).

Cheng et al. (2019) reported an intra-oceanic arc formed by initial subduction in the Diyanmiao area in the eastern part of the CAOB. SHRIMP zircon U-Pb age of a MORB-like hornblende gabbro was 286.1±6.1 Ma, representing the timing of magmatism caused by initial intra-oceanic subduction. Zircon U-Pb age of the gabbro was 283.7±4.7 Ma, indicating the first magmatism after the initial subduction. Zircon U-Pb age of the island arc basalt is 241±5 Ma, which signals the timing of transition to the normal island arc tholeiite.

These different types of magmatic arcs in the Paleo-Asian Ocean may weld together (arc-arc collision) to form composite arcs, and the subduction zone also migrates (Xiao et al., 2010b).

4.4 Accretionary complexes

Accretionary complexes (also known as subduction-accretionary complexes, or accretionary wedges) represent the materials accreted at trenches and forearc regions during the oceanic subduction. The materials include rocks derived from both the subducting oceanic crust (mainly basalt, chert, limestone, etc.) and those eroded from the upper plate. Accretionary complexes include mélange units with "block-in-matrix" structures and coherent units such as turbidite or flysch. Unlike the classical collisional orogens, the most distinguishable feature of the CAOB is the extensively developed accretionary complexes that recorded the process of the oceanic subduction and continental growth. Şengör and Natal'in (1996) emphasized the important role of accretionary complexes in the construction of the CAOB, but no detailed study of them had been carried out by then.

Wang et al. (1991) pointed out that the southern margin of the Siberian Craton is similar to the eastern margin of Asia in the middle Cenozoic, while the northern margin of the NCC is similar to the Cordillera Orogen in North America with the development of ancient continental margin accretion. Xiao et al. (2003) made a detailed study on the composition, structure and distribution of Ondor Sum accretionary complex, Erdaojing accretionary complex and the Baolidao arc-accretionary in the Solonker suture zone in the northern margin of the NCC, and put forward the accretionary wedge-wedge collision model. Xiao et al. (2009b) performed detailed analyses on the kinematics and composition of the accretionary complexes in Altai and East Junggar, and reconstructed multiple subduction-accretionary processes of this area in the Paleozoic.

Zhang et al. (2011a) carried out large-scale geological mapping on the late Carboniferous Baijiantan accretionary wedge in the Karamay area of West Junggar. Both mélange units and coherent units have been identified. He systematically analyzed the thrust-imbrications, duplexes, shear deformation and folding developed in the accretionary wedge. The accretionary wedge shows a top-to-the-NW movement in kinematics (Figure 5). Based on these data and previous research, Zhang et al. (2011a) proposed a bipolar subduction model in the West Junggar region during the late Carboniferous.

Song et al. (2014) undertook geological mapping at a scale of 1:10000 in the Lebaquan area in the central part of Beishan Orogen, and identified different lithologies including metaclastic rocks, metabasite, metachert and marble that juxtaposed against each other with "block-in-matrix" structures. This accretionary complex was formed in the Paleozoic and underwent multi-stage deformation (Figure 2).

Cheng et al. (2019) reported a large number of ultramafic-mafic rocks with different lithologies, sizes and shapes in the Diyanmiao area in the eastern part of the CAOB, along with limestone and chert, siliceous mudstone and turbidite. They together form a typical subduction-accretionary complex.

A large number of Mesozoic accretionary complexes are exposed in northeast China, such as the Heilongjiang Complex, the Raohe Complex and the Yuejinshan Complex. The Heilongjiang Complex were subjected to amphibolite- and blueschist-facies metamorphism, and are important geological records for studying the tectonic superposition and transformation of the Paleo-Asian Ocean and the Paleo-Pacific Ocean (Wu et al., 2007a; Liu Y et al., 2017; Zhou and

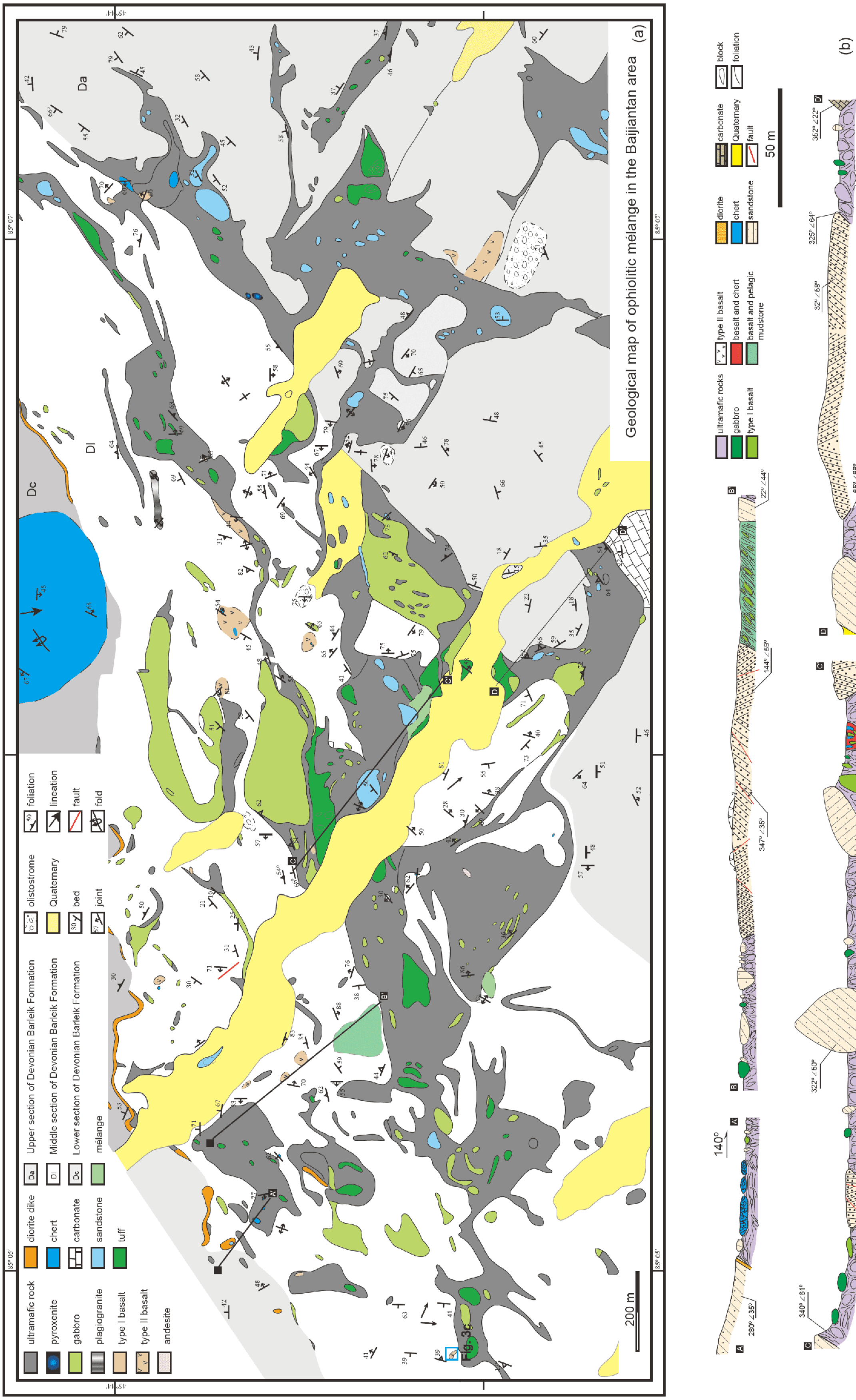

Figure 5 Composition and structure of the Baijiantan accretionary wedge in Karamay, West Junggar. (a) Detailed geological map of the Baijiantan ophiolitic mélange, (b) cross sections. Modified after Zhang et al. (2011a).

Li, 2017). The Raohe Complex and the Yuejinshan Complex constitute the main part of the Nadanhada (Wandashan) Orogen, which documented the subduction history of the Paleo-Pacific Plate (Zhou et al., 2014).

Studies of accretionary wedges have gradually developed into anatomy of oceanic plate stratigraphy (Wakita and Metcalfe, 2005; Kusky et al., 2013; Safonova et al., 2016; Li et al., 2019; Pan et al., 2019). An effective methodology for working with accretionary wedges has been gradually developed since the research of the typical accretionary complexes in the CAOB are carried on. It includes large-scale mapping of lithology and structure, analysis of geometry and kinematics, and studies of geochemistry and geochronology, which together are able to comprehensively determine the composition, deformation and timing of the accretionary complexes (Xiao et al., 2019).

4.5 Regional metamorphism and deformation

Regional metamorphism and deformation such as large-scale ductile shear zones, thrust nappes and folds commonly formed during the accretionary processes. They are essential geological records for reconstructing the history of oceanic subduction and establishing the spatio-temporal framework of the accretionary orogenesis.

The Chinese Altai contains a large number of orogeny-related metamorphism-deformation fabrics. Systematic studies of macroscopic and microscopic structures and the timing of deformation show that the Altai underwent east-west subduction-accretion in the Devonian and a north-south compression and shortening after ~380 Ma (Zhang et al., 2015a). The Erqis Fault, extending from Kazakhstan through Chinese Altai to the southwestern Mongolia with a total length of ~2500 km, plays a crucial role during the tectonic evolution of the CAOB. Detailed field mapping and kinematic analysis combined with chronology study indicate that the Erqis Fault is a crustal-scale thrust fault formed in the Permian. Its hanging wall preserved magmatic activities of two stages at ~450 and ~280 Ma, respectively. Consequent metamorphism with peak P-T conditions of 560–670°C/6.2–7.7 kPa superposed (Briggs et al., 2009). Jiang et al. (2019) identified four generations of deformation in the Altai. The first one is characterized by metamorphic fabrics of horizontal kinematics under medium pressures, which was related to crust thickening during the Early Devonian oceanic plate subduction. The second is indicated by migmatitic fabrics and HP/LT mineral assemblages, which was related to the crust extension-thinning in the Middle Devonian (400–390 Ma). The third is represented by a package of nearly vertical fabrics metamorphosed at high temperature and granite-migmatite domes at variable scales, which was related to the tectonic extrusion in a compressional background during the main orogenic events (390–380 Ma). Finally, the Devonian metamorphic-deformed fabrics were reworked by the Permian (290–270 Ma) deformation and metamorphism (Figure 6).

The Aqikekuduke-Weiya Fault is a large ductile strike-slip shear zone within the Tianshan orogen. It experienced two stages of ductile deformation during the Paleozoic, as a top-to-the-north shearing accompanied by granulite-facies metamorphism of the ophiolites at ~400 Ma, and a dextral strike-slip shearing in the late Carboniferous to early Permian (Shu et al., 2002). The kilometer-scale overprinted folds developed in the Permian Hongyanjin basin in the Beishan Orogen have been interpreted as compressional structures during accretionary orogenesis (Tian et al., 2013), or folding structures in association with the intraplate strike-slip faulting (Zhang and Cunningham, 2012).

4.6 High-pressure and ultrahigh-pressure metamorphism

HP-UHP metamorphic belts are critical petrologic indicators for locating the position of an ancient subduction zone. The HP-UHP metamorphic rocks associated with the subduction of the Paleo-Asian Ocean in the CAOB are mainly distributed in the Kazakhstan and Kyrgyzstan Tianshan, the Chinese southwestern Tianshan, the southern Beishan and the Xing'an-Mongolian Orogen (Figure 7).

The Aktyuz and Makbal metamorphic terranes in the Kazakhstan and Kyrgyzstan North Tianshan contain Ordovician (U)HP eclogites, blueschists and associated (U)HP metasedimentary rocks. Ordovician eclogites were found in Gubaoquan area of the Beishan Orogen. Early Carboniferous eclogites and blueschists of oceanic provenance are exposed at the Atbashi of Kyrgyzstan South Tianshan and the Akeyazhi metamorphic terrane in the Chinese Western Tianshan (Klemd et al., 2015). In the Xing'an Mongolian Orogen, the HP metamorphic rocks associated with the Paleo-Asian Ocean evolution have been found as the Ondor Sum blueschists and Toudaoqiao blueschists.

The eclogites, garnet amphibolites and amphibolites in the Aktyuz metamorphic terrane in the Kazakhstan and Kyrgyzstan North Tianshan are preserved in the form of tectonic lenses within the metasedimentary rocks and granitic gneisses. Rojas-Agramonte et al. (2013) obtained a clockwise P-T path with the peak metamorphic conditions of ~1.6 GPa and ~610°C from retrograde eclogites. Klemd et al. (2014) obtained a clockwise P-T path with the peak metamorphic conditions of ~2.1 GPa and ~670°C from prograde eclogites. The peak age of eclogite-facies metamorphism was constrained at 474±2 Ma based on garnet Lu-Hf isochron dating (Rojas-Agramonte et al., 2013). The Makbal metamorphic terrane contains a number of lenses and/or slices of HP and UHP metabasite, including retrograde eclogites, garnet amphibolites and eclogite-facies meta-

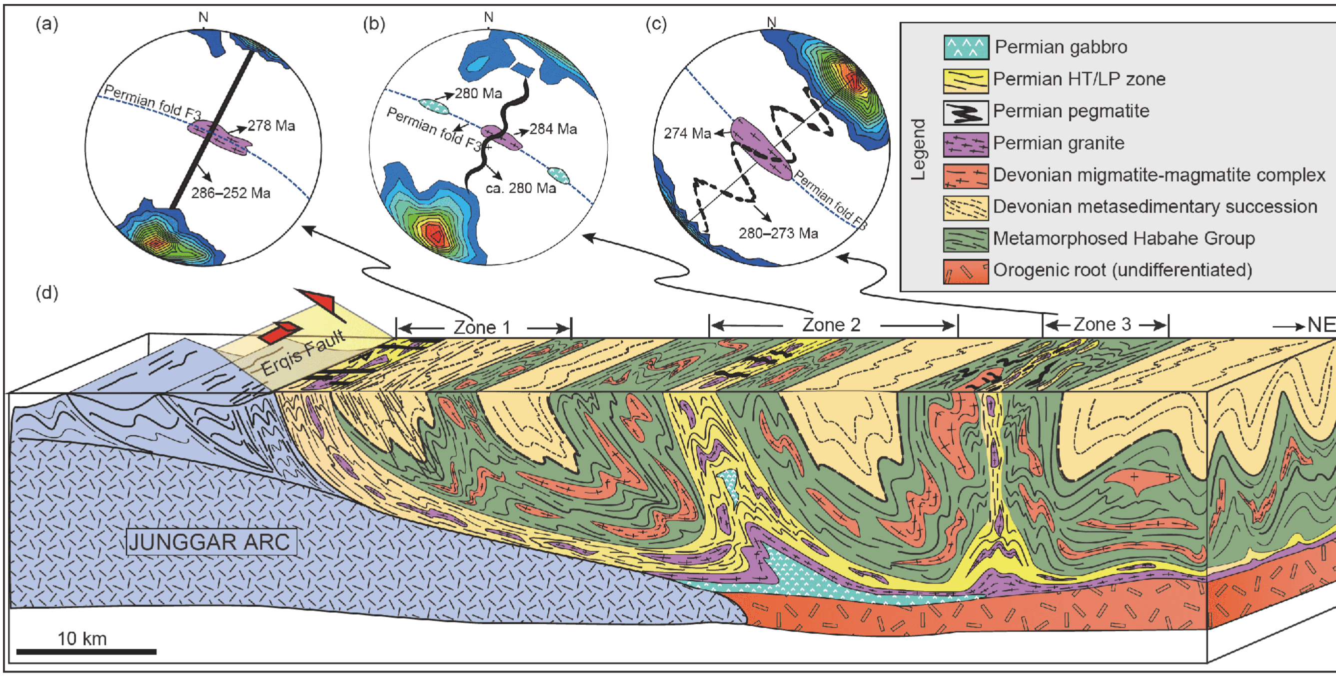

Figure 6 Geodynamic model of the Permian collision of the Junggar arc with the Altai accretionary wedge. (a) Stereographic projection of structural elements, (b) detailed structural map. Modified after Jiang et al. (2019).

morphic glaucophanites (Meyer et al., 2013). A trace of coesite inclusions in the garnet porphyroblasts of garnet-chloritoid-talcum schists were identified, indicating the rocks experienced UHP metamorphism (Konopelko et al., 2012; Meyer et al., 2014). The peak pressure of the Makbal HP metamorphic basic rocks was estimated as 2.2–2.5 GPa with the corresponding temperature of 520–560°C (Klemd et al., 2015). The garnet-chloritoid-talcum schists show a clockwise P-T path with peak metamorphic pressure at ~2.85 GPa (525°C) and peak temperature at ~580°C (2.4 GPa) (Klemd et al., 2015). The garnet Lu-Hf isochron age indicates that the peak metamorphic age is 470±3 Ma (Meyer et al., 2014). The Aktyuz and Makbal metamorphic complexes were originally derived from the preexisting oceanic and continental crust, which were subducted to different depths, and went through individual P-T evolutions, and finally resided as tectonic lenses in/between the metasedimentary rocks after their exhumation.

The main lithologies of the Atbashi HP metamorphic terrane in the Kyrgyzstan South Tianshan are HP eclogites, phyllites, marbles with subordinate metamorphic basic volcanic rocks in the form of tectonic lenses and boudins, and phengite-bearing schists and gneisses serving as the matrix. The rare earth elements and whole-rock Nd isotopic compositions of the eclogites indicate that the protoliths are normal mid-oceanic ridge basalts (Hegner et al., 2010). The peak metamorphic P-T conditions of the eclogites are 2.3–2.5 GPa and 510–570°C, respectively (Simonov et al., 2008). Hegner et al. (2010) obtained an age of 319±4 Ma for the peak metamorphism of the eclogites. This age is consistent with the $^{40}Ar/^{39}Ar$ age of 316±3 Ma from the phengites in the eclogites, indicating the eclogites have experienced a rapid exhumation (Hegner et al., 2010). Recently, Sang et al. (2017) obtained a Late Triassic age from the eclogites and blueschists in this HP metamorphic belt.

The Akeyazhi metamorphic terrane in the Chinese Western Tianshan contains blueschists, eclogites and greenschists, together with basic and ultrabasic rocks, which constitute a NE-SW trending accretionary complex extending over 200 km (Gao and Klemd, 2003). Most of the eclogites occur as pods, boudins or blocks within blueschist-facies metamorphic rocks (Gao and Klemd, 2000). The major and trace elements indicate that the protoliths of these eclogites and blueschists are MORB and OIB (Gao and Klemd, 2003; Ai et al., 2006; van der Straaten et al., 2008). Regionally, the peak metamorphic P-T conditions of the eclogites are 480–580°C and 1.4–2.1 GPa, respectively (Wei et al., 2003). The discovery of coesites in garnet porphyroblasts, quartz exsolution lamellae and magnesite in omphacites suggest that the eclogites have undergone UHP metamorphism (Zhang et al., 2002a, 2002b). Since 2008, coesites have been discovered in different types of rocks (Lü et al., 2008, 2009, 2012). Lü and Zhang (2012) calculated the P-T conditions of UHP metamorphism to be 2.4–2.7 GPa and 470–510°C. The metamorphic P-T conditions of the blueschists are 2.1 GPa and 480–540°C (Beinlich et al., 2010), 499–519°C and 2.3–2.5 GPa (Du et al., 2011), and 500–590°C and 1.7–2.2 GPa (Tian and Wei, 2014). The P-T paths of the HP/UHP metamorphic rocks display diverse prograde metamorphic evolutions but similar isothermal decompression

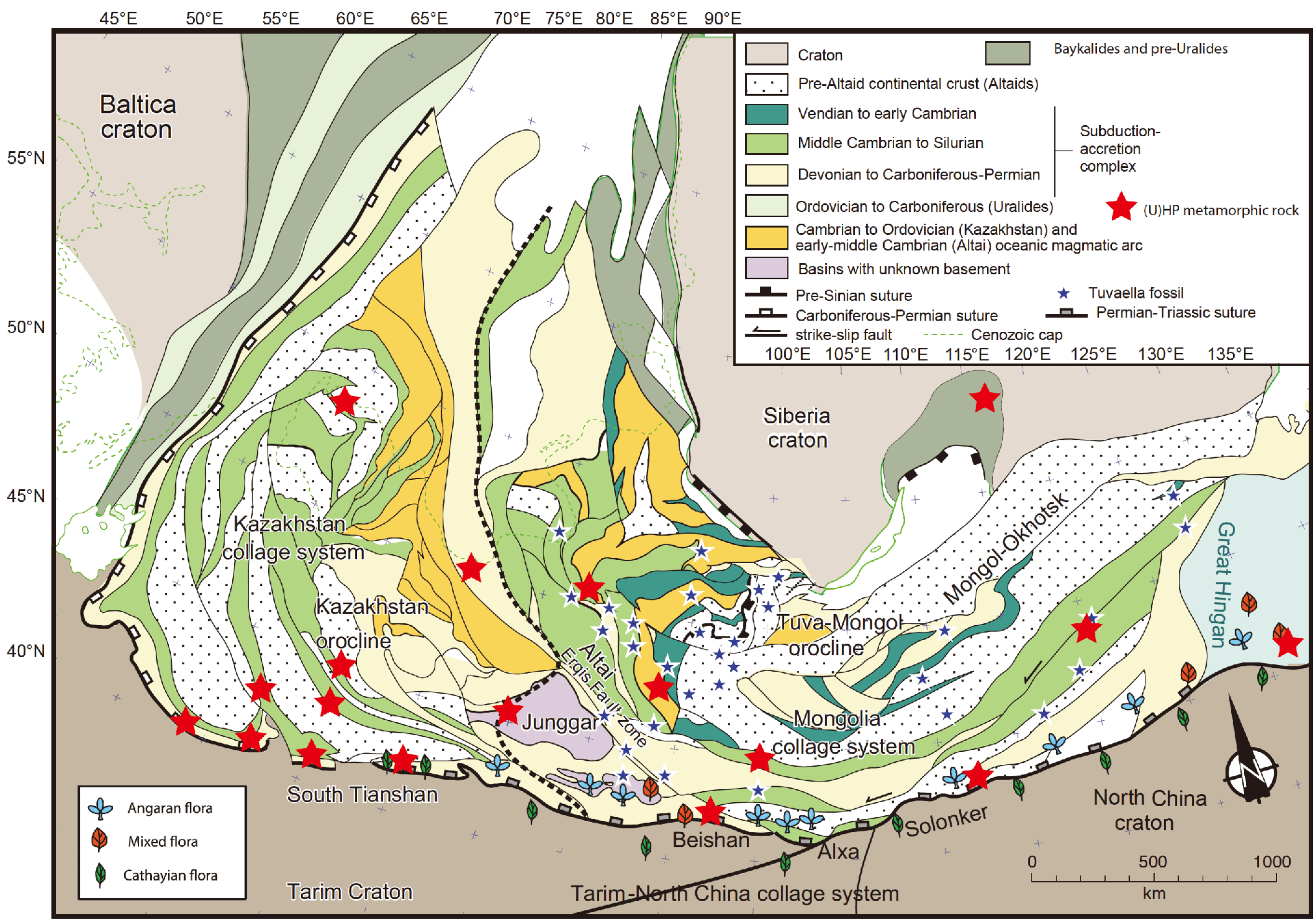

Figure 7 A sketch map showing the distribution of (U)HP metamorphic rocks in the Central Asian Orogenic Belt. Modified after Liu et al. (2012), Xiao et al. (2015) and Gao et al. (2018).

processes (Klemd et al., 2015). Ages of the HP/UHP metamorphism are late Paleozoic by and large. Gao and Klemd (2003) obtained an eclogite Sm-Nd isochron age of 343±44 Ma, and two ages of ~344 Ma and 331 Ma by Ar-Ar dating of crossite and phengite. An eclogite Lu-Hf isochron age of 315 ±3 Ma was reported by Klemd et al. (2015). Su et al. (2010) published a 319±3 Ma U-Pb age from zircon rims that experienced eclogite-facies metamorphism. Another zircon U-Pb age of ~233–226 Ma for the eclogite was also reported, representing a Triassic UHP metamorphic event (Zhang L et al., 2007). However, de Jong et al. (2009) argued that the Triassic zircons might have undergone recrystallization affected by later fluids or tectonic thermal events.

The Gubaoquan eclogites in the Beishan Orogen are distributed about 5 km long and 1 km wide, and the eclogites occur as tectonic lenses in gneisses (Liu et al., 2002). The protoliths of the eclogites show geochemical characteristics similar to that of mid-ocean ridge basalt (Qu et al., 2011). However, other studies suggest that the protoliths are Neoproterozoic mafic dykes that intruded into the continental crust (Saktura et al., 2017). The eclogite P-T pseudosection yields a steep clockwise P-T path with peak P-T conditions of >15.5 kPa and 700–800°C (Qu et al., 2011). Different geologists have provided relatively consistent peak metamorphic ages of 465±10 Ma (Liu et al., 2010), 467±16 Ma (Qu et al., 2011), or 466±27 Ma (Saktura et al., 2017).

Blueschist-facies metamorphic rocks are exposed in the Ondor Sum accretionary complex in Inner Mongolia. Blueschists are characterized by the occurrence of riebeckite, epidote, albite, chlorite and calcic hornblende. The metamorphic P-T conditions of the blueschist-facies were estimated at 3.2–4.2 kPa/355–415°C, 8.2–9.0 kPa/455–495°C, 6.6–8.1 kPa/420–470°C, indicating that the blueschist-facies metamorphism occurred with a relatively high geothermal gradient (Zhang et al., 2015b). de Jong et al. (2006) obtained phengite Ar/Ar ages of 453±2 and 449±2 Ma for the blueschist-facies quartzite mylonites. Zircon U-Pb dating revealed that the protolith ages of the blueschists is late Paleozoic-Triassic (Zhang et al., 2015b), indicating that the Ondor Sum accretionary complex recorded multiple subduction processes of the oceanic crust.

The Toudaoqiao blueschists in the Great Khingan Range outcrop between the Erguna and Xing'an terranes, and mark the suture between them. The protoliths of the blueschists are mainly alkalic basalts (OIB), and a few of them are N-MORB to IAT transitional tholeiites (Miao et al., 2015). Zhou et al. (2015) considered that the protoliths were similar to those in intra-oceanic subduction accretionary complex in the Philippines, and calculated the blueschist-facies peak P-T conditions as 0.9–1.1 GPa and 320–450°C. Miao et al. (2015) obtained the blueschist-facies peak metamorphic P-T conditions of ~7 kPa/450–480°C, the protoliths age of ~516 Ma, and the blueschist-facies metamorphic age of ~436 Ma.

In addition, recent studies have reported lherzolite, garnet pyroxenite, quartz magnesitite and retrograde eclogite related to UHP metamorphism in the Zhaheba-Armantai ophiolitic mélange in East Junggar (Niu et al., 2007). Phengite Ar/Ar age in the quartz magnesitite is 282±3 Ma, interpreted as the exhumation age of the UHP metamorphic rocks (Niu et al., 2007).

4.7 Mid-ocean ridge subduction

Zhao et al. (2006) proposed a slab window caused by mid-ocean ridge subduction to explain the formation of adakites, Nb-enriched basalts and high-Mg andesites in the Chinese Altai. Windley et al. (2007) further pointed out that the petrogenesis of adakites, Alaskan-type basic-ultrabasic rocks, near-trench intrusions and HP metamorphism in the CAOB could be explained by mid-ocean ridge subduction. Geological evidence for Paleozoic ridge subduction of the Paleo-Asian Ocean has been reported in Altai, West Junggar, East Junggar, Beishan, Alxa, and Inner Mongolia (Liu et al., 2007; Sun et al., 2009; Geng et al., 2009; Jian et al., 2010; Windley and Xiao, 2018).

The magmatic records related to Devonian ridge subduction in the Altai include adakites, boninitic pillow lavas, high TiO_2 and low TiO_2 basalts (Niu et al., 2006), and a large amount of garnet-bearing crust-derived granites (Liu et al., 2012). The peaks of the ridge subduction occurred in the Early Devonian (400–390 Ma) and the Late Devonian (380–365 Ma) (Sun et al., 2009; Cai et al., 2010; Shen et al., 2011). The abrupt change from enrichment to depletion of Hf isotopic compositions for the Altai magmatic rocks at 400 Ma was considered as a hallmark of ridge subduction (Sun et al., 2009). Meanwhile, the asthenosphere upwelling due to ridge subduction generated HT metamorphism in the Early Devonian (~390 Ma) (Jiang et al., 2010).

A large number of adakites related to ridge subduction in West Junggar were developed from Ordovician to early Permian (Geng et al., 2009; Zhang et al., 2011b; Yin et al., 2013; Shen et al., 2014). The Ordovician magmatism include both island-arc to calc-alkaline basalts, andesites and Nb-enriched basalts, which were considered as products of an intra-oceanic subduction process along with ridge subduction (Shen et al., 2014). The slab window induced by mid-ocean ridge subduction in the late Carboniferous led to intensive eruptions of diverse magma. Partial melting occurred widely in various areas such as the subducted oceanic crust, the juvenile lower crust, and the mantle wedge, generating adakitic rocks, charnockite and syenogranite, and basic rocks, respectively (Figure 8; Geng et al., 2009; Tang et al., 2012; Yin et al., 2015). According to the spatial relationship of the late Carboniferous adakitic diorite dykes, Ma et al. (2012) reconstructed the geometrical structure of the mid-ocean ridge subduction in West Junggar. According to the geochemical characteristics, Yin et al. (2015) distinguished two types of sanukites formed at different depths during the ridge subduction in the Early Permian. Two types of basic volcanic rocks exist in the Karamaili ophiolite in East Junggar. The first type holds the characteristics of both MORB and IAB (island-arc basalt), while the second type is normal IAB with relatively depleted Nd isotopic composition. This ophiolite was formed in an island-arc or forearc extension environment affected by the subduction of mid-ocean ridge (Liu et al., 2007; Liu X et al., 2017).

In the Beishan Orogen, the existence of high-Mg diorites, adakites, Nb-enriched basalts, N-MORB and E-MORB basalts, island-arc tholeiites and high-K calc-alkaline granites indicate that mid-ocean ridge subduction and slab window formation might occur in the Late Ordovician to Early Devonian (Mao et al., 2012a; Zheng et al., 2018). The subduction of mid-ocean ridge in the late Carboniferous-late Permian in the Alxa area formed peridotites, pyroxenes and high-Mg gabbros (Feng et al., 2013). In Inner Mongolia, bipolar subduction of the Paleo-Asian Ocean led to the subduction of mid-ocean ridge both in the Southern and the Northern Orogens, resulting in HT metamorphism and near-trench magmatism.

The mid-ocean ridge subduction and slab window in the Southern Orogen of Inner Mongolia generated a HT metamorphic event at 451–436 Ma and adakitic magmatism at 448–438 Ma, while the mid-ocean ridge subduction in the Northern Orogen caused low P/T metamorphism at 440–434 Ma (Jian et al., 2008). The doleritic dykes with N-MORB geochemical signatures intruding into the Permian Mandula forearc complex were considered to be a product of ridge-trench interaction (Jian et al., 2010).

4.8 Interaction between mantle plumes and plates

As a long-lived ocean, the Paleo-Asian Ocean possesses large amounts of oceanic plateaus or seamounts formed by mantle plumes. During the subduction of the ocean, the seamounts will migrate from the oceanic basin to the trench (convergent plate margin). Most of the oceanic plateaus or seamounts would enter the subduction zone, where they might be involved in material recycling. However, some of them would emplace into the accretionary wedge, and get accreted to the upper plate. By summarizing the field geo-

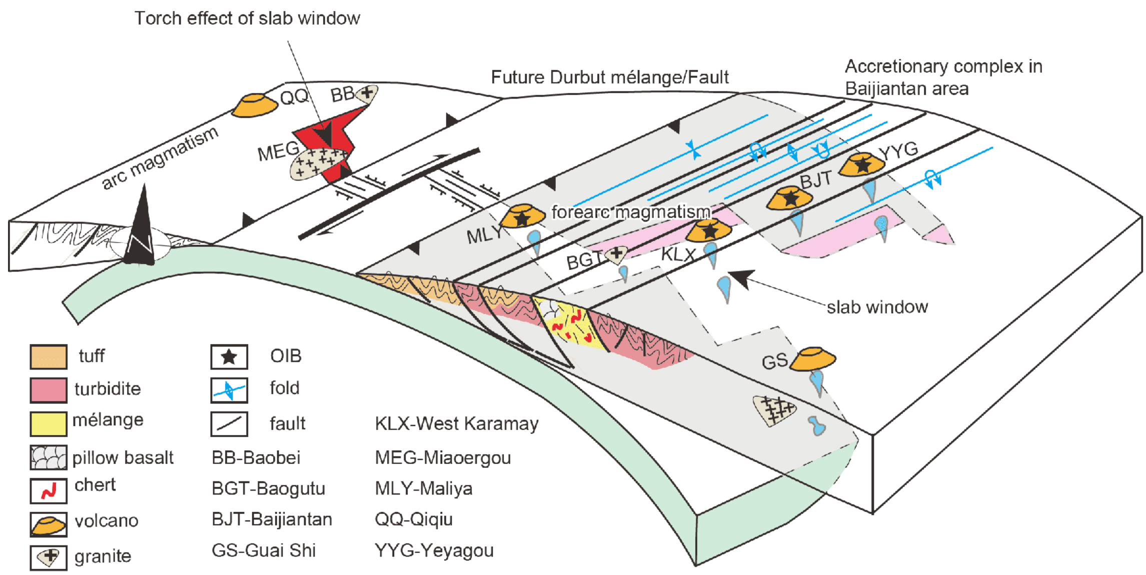

Figure 8 A tectonic model for Paleozoic ridge subduction in West Junggar. Modified after Zhang et al. (2011a) and Yin et al. (2015).

logical and petrogeochemical data of basalts preserved in the accretionary wedges, Safonova and Santosh (2014) identified a mass of OIB-type basalts aged from Neoproterozoic to late Permian. They are mainly distributed in the western Mongolia, Sayan, Tuva-Mongolia, Russian Altai and West Junggar. The OIB-type basalts in the accretionary wedges were considered as the seamounts in the Paleo-Asian Ocean, and were products of mantle plume magmatism (Safonova and Santosh, 2014).

The ophiolites from Tangbale, Mayle, Darbut and Karamay in West Junggar contain alkali basalts. They occur as tectonic blocks in the mélange that consists of pelagic limestones, siliceous mudstones and radiolarian cherts (Zhang et al., 2011a, 2018). These alkaline basalts show enrichment in LREEs, depletion in HREEs, with no or weak Eu anomaly and no distinct Nb, Ta, Ti negative anomaly. They are intra-plate basalts derived from mantle transition zone with geochemical signatures of typical OIB-type basalts (Yang et al., 2015). These basalts, together with the surrounding pelagic limestones, constitute the representative features of seamounts. They either emplaced into accretionary wedges or entered the subduction channel and generated OIB-type volcanic rocks during partial melting (Figure 9; Yang et al., 2015). The Carboniferous Bayingou Ophiolite in North Tianshan contains two types of basalts. One type shows MORB-type geochemical characteristics and the other type shows OIB-type signatures. The OIB-type basalts are generated from low degree (2–3%) partial melting of garnet lherzolites and are considered to be the remnants of seamounts accreted to the North Tianshan accretionary wedge during the subduction of the Junggar ocean beneath the Yili-Central Tianshan arc (Yang et al., 2018). The accretion of seamounts in the forearc is of great significance to the growth of continental crust. As the research further develops, it is believed that more and more seamounts/oceanic plateaus related to the Paleo-Asian Ocean will be identified in the CAOB.

In addition, a Permian large igneous province exists in the Tarim Block. The basalts and doleritic dykes display geochemical characteristics similar to OIB-type basalts. The obvious crustal uplift in the early Permian, together with the noticeable picrites, the voluminous dyke swarms, and the large V-Ti magnetite deposits imply that the Tarim large igneous province is related to mantle plume activities (Yang et al., 2013). It remains a controversial issue about the dynamic linkage between the Tarim mantle plume activities and the Permian magmatism in the CAOB (Zhang et al., 2010).

4.9 Archipelagic paleogeography and multiple accretionary orogeny

It has been a consensus in the international academic society that the CAOB is the largest Phanerozoic accretionary orogen in the world. The spatio-temporal architecture of the CAOB therefore has become a basic theoretical issue in the study of orogenic belts. There have been different thoughts, such as archipelago-multiple blocks (Zonenshain et al., 1990), single island arc-backarc basin (Şengör et al., 1993) for the paleogeographic architecture of the CAOB. In terms of accretionary model, there are multiple continent collision (Zonenshain et al., 1990), back-arc collapse (Hsü et al., 1991) or single arc accretion (Şengör et al., 1993).

As more and more research results have been brought out, the paleogeography, paleotectonics, sedimentology and tectonic facies have synthetically indicated that the CAOB is characterized by complicated paleogeography featuring a

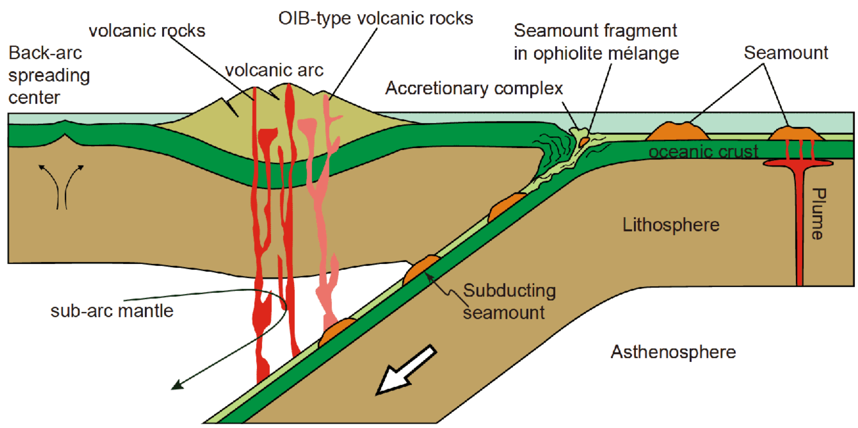

Figure 9 A model for seamount subduction and accretion in West Junggar. Modified after Yang et al. (2015).

archipelagic style (Sun et al., 1991; Hsü et al., 1991; Xiao et al., 2008; Pan et al., 2009, 2016). At the same time, the long chain of arcs were subjected to large-scale oroclinal bending during the accretionary orogeny (Şengör et al., 1993; van der Voo, 2004; Xiao et al., 2015, 2018).

However, it remains debatable that which oceanic basins could represent the main ocean of the Paleo-Asian Ocean in the archipelagic pattern of the CAOB. The paleobiogeographic study plays a key role in solving this dispute. The facts that the Silurian Tuvaella is only widespread in the southwest Siberian Craton and adjacent Mongolia, eastern Kazakhstan, and western China (Rong et al., 1995; Xiao et al., 2015), and the Cathaysia flora in north China form a stark contrast to the northern Angara flora along the South Tianshan-Solonker suture in the Permian (Guo, 2000), indicating that there should be a long distance between the NCC and the Siberia-Kazakhstan accretionary terranes. Therefore, the paleobiogeographic study may make certain that the main oceanic basin of the Paleo-Asian Ocean might be located along the South Tianshan-Solonker suture, and the termination of subduction processes of the main oceanic basin was not earlier than the Permian (Xiao et al., 2008, 2015).

Based on Pb isotopic study of ophiolites in the CAOB, Liu et al. (2015) argued that the mantle domain of the Paleo-Asian Ocean had a long-term low Th/U reservoir compared to that of Tethys, and the diverse magma-tectonic processes in these tectonic domains finally caused the differences in Pb isotopic composition. The results of the isotopic study on oceanic lithospheric mantle support the South Tianshan-Solonker suture as the main basin of the Paleo-Asian Ocean.

According to the facts that the southern Yili-Central Tianshan is an active continental margin and South Tianshan is an accretionary complex, the South Tianshan Ocean is regarded to subduct northward (Chen et al., 1999; Xiao et al., 2008, 2015). Of course, the opinion of southward subduction also exists (Charvet et al., 2011).

Based on the studies of accretionary complexes, ophiolites, magmatic arcs of the Inner Mongolian Orogenic Belt, Xiao et al. (2003) pointed out that the eastern segment of the CAOB was formed by accretionary wedge-wedge amalgamation due to bipolar subduction of the Paleo-Asian Ocean. By the detailed studies of spatio-temporal relationships of the tectonic units including accretionary wedges, magmatic arcs and ophiolites in Altai, East Junggar and East Tianshan, Xiao et al. (2004b, 2010b) proposed a long-lived multiple accretionary process involving multiple oceanic basins, multiple subduction zones, and multiple subduction polarities for the western segment of the CAOB, which is similar to the Meso-Cenozoic Circum-Pacific Orogenic System (Windley et al., 2007). This model is different from previous multi-block collision model (Zonenshain et al., 1990), or single arc accretion model (Şengör et al., 1993), and has been one of the three representative models for the accretionary history of the CAOB (Schulmann and Paterson, 2011).

Based on the paleobiogeographic and paleomagnetic data (Rong and Zhang, 1982; Torsvik and Cocks, 2004; Cocks and Torsvik, 2007; Huang et al., 2008), Xiao et al. (2015) proposed that the entire CAOB was amalgamated during Middle-Late Triassic by the Kazakhstan collage system in the west, the Tuva-Mongolian collage system in the north and the Tarim-North China collage system in the south. The South Tianshan suture, Liuyuan suture and Solonker suture were considered to be the final suture zones of the southern CAOB (Xiao et al., 2003, 2010b, 2013). The late Paleozoic to Early Triassic tectonic evolution of the CAOB was characterized by multiple roll-back and oroclinal bending (Kazakhstan and Tuva-Mongolian oroclines) (Figure 10; Xiao et al., 2018).

There are still considerable controversies on the timing of final amalgamation of the CAOB. Different thoughts have been proposed, including Late Devonian (Xu B et al., 2013), Late Devonian to Early Carboniferous (Charvet et al., 2007), Late Carboniferous (Gao et al., 2006; Gao et al., 2009; Han et al., 2010a, 2010b, 2011), Permian (Li, 2006), and end Permian to Middle Triassic (Xiao et al., 2009a, 2018). Geologists who argued for Devonian or Carboniferous termination are mainly based on the Devonian regional angular unconformity (Xu B et al., 2013), the age of A-type granites (Shi et al., 2010), the age of the oldest stitching pluton in ophiolites and the metamorphic age of the HP metamorphic rocks (Gao et al., 2006; Gao et al., 2011). Geologists who upheld Permian to Middle Triassic termination mainly considered the age of the youngest radiolarian cherts in the accretionary wedge, the youngest angular unconformity involved in the accretionary orogeny, the youngest arc-related basins (Eizenhöfer et al., 2014; Song et al., 2018) and the youngest regional deformation in the arc-related basins (Tian et al., 2015; Xiao et al., 2009a, 2015). In recent years, more and more evidence for the Triassic termination of the accretionary processes of the CAOB have been reported, including Permian ophiolites (Song S et al., 2015), blueschists with Triassic protolith ages (Chu et al., 2013; Zhang et al., 2015b), Permian-Triassic granitic rocks with subduction-related geochemical signatures (Pei et al., 2018), late Paleozoic arc-related sedimentary and volcanic rocks (Li et al., 2015; Eizenhöfer et al., 2014) and Permian cherts (Xie et al., 2014). Obviously, the timing of termination of accretionary process is a difficult issue in the research of accretionary orogenic belts, and further studies are needed.

4.10 Mechanism for continental growth

Paleozoic to Mesozoic granitoids are extensively developed in the CAOB, and they are important records of continental accretion in Central Asia. Based on the Nd isotopic study of granitic rocks in Tianshan, Hu et al. (1995, 1999) pointed out that the Tianshan Orogen underwent extensive continental crustal growth during the Paleozoic.

In October 1996, Jahn Bor-Ming from the University of Rennes and Dobretsov from the Siberian Branch of the Russian Academy of Sciences jointly submitted a project proposal entitled “Phanerozoic continental accretion: Evidence from the east-central Asia” to the UNESCO (United Nations Educational, Scientific and Cultural Organization), which was then officially accepted as IGCP420 project (Yao, 1997).

Jahn et al. (2000c) found that granites in the CAOB had depleted Sr-Nd isotopic compositions, and showed juvenile characteristics. Therefore, Jahn et al. (2000a, 2000c) considered the CAOB as the most important continental crustal growth area during the Phanerozoic. Systematic isotopic study indicates that the Junggar Basin has younger crust than the Altai and Tianshan (Hu et al., 2000).

As the product of oceanic plate subduction, magmatic arcs are of great significance for the growth of the continental crust. There are a lot of arc related magmatic rocks as well as some microcontinents in the CAOB. Studies of Sr-Nd isotopes and zircon Hf isotopes of magmatic rocks can reveal the contributions of magmatic arcs with different properties to crustal growth in Central Asia. Andean-type magmatic arcs, such as the Bainaomiao arc and the North Yili arc, have enriched isotopic compositions in their magmatic rocks, and are characterized by the recycling of ancient crustal materials and the contribution of a small amount of mantle materials (Zhang et al., 2009a; Zhu et al., 2009). Japan-type arcs commonly experienced the transition from a continental arc to an intra-oceanic arc. The arc magmatism generated the majority of juvenile crust. Minor additions of ancient crustal materials may also contribute to arc magmatism, such as the Altai arc (Sun et al., 2008; Wang et al., 2009). The intra-oceanic subduction system of West Junggar is dominated by juvenile crust, which contributes significantly to the continental growth (Tang et al., 2012). Based on Sr-Nd isotopic studies of granites from the Western Tianshan, Long et al. (2011) proposed a two-stage model of continental growth of “syn-subduction lateral accretion of arc complexes” and “post-collisional vertical accretion of underplated mantle material”. Based on the study of zircon Hf isotopes from granites in northeast China, Wu et al. (2007b) and Ma et al. (2018) considered that lateral and vertical accretion are the main mechanisms for the crustal growth in the CAOB.

Besides arc magmatism, the subduction of mid-ocean ridge is another important way of continental growth. Ridge subduction leads to the formation of slab windows. Partial melting of subducted slab edges generates adakites. At the same time, decompression melting of the asthenosphere generates MORB-type magma. These processes will eventually lead to the formation of new continental crust and result in continental growth. For example, ridge subduction in the Chinese Altai and West Junggar generated large amounts of magmatic rocks with positive Nd-Hf isotopic compositions (Sun et al., 2009; Tang et al., 2010). The accretion of seamounts or oceanic plateaus to the continental margin is also an important way of continental growth (Yang et al., 2015). During the accretionary processes of the CAOB, large-scale arc bending, oroclinal bending and oceanic-basin trapping may be important mechanisms of the continental growth (Xiao et al., 2015, 2018; Xiao et al., 2019).

4.11 Metallogenesis during accretionary orogeny

As one of the three major metallogenic domains in the world, the Central Asian Metallogenic Domain contains a variety of important mineral resources, including porphyry-type deposits, massive sulfide-type (VMS) deposits, magmatic Cu-Ni sulfide-type deposits and orogenic gold deposits. There are many large or super-large porphyry copper-(molybdenum)-(gold) deposits in the CAOB, including the Kounrad, the Kal’makyr, the Oyu Tolgoi and the Chalukou deposits. Gao et al. (2018) divided the porphyry metallogenic system

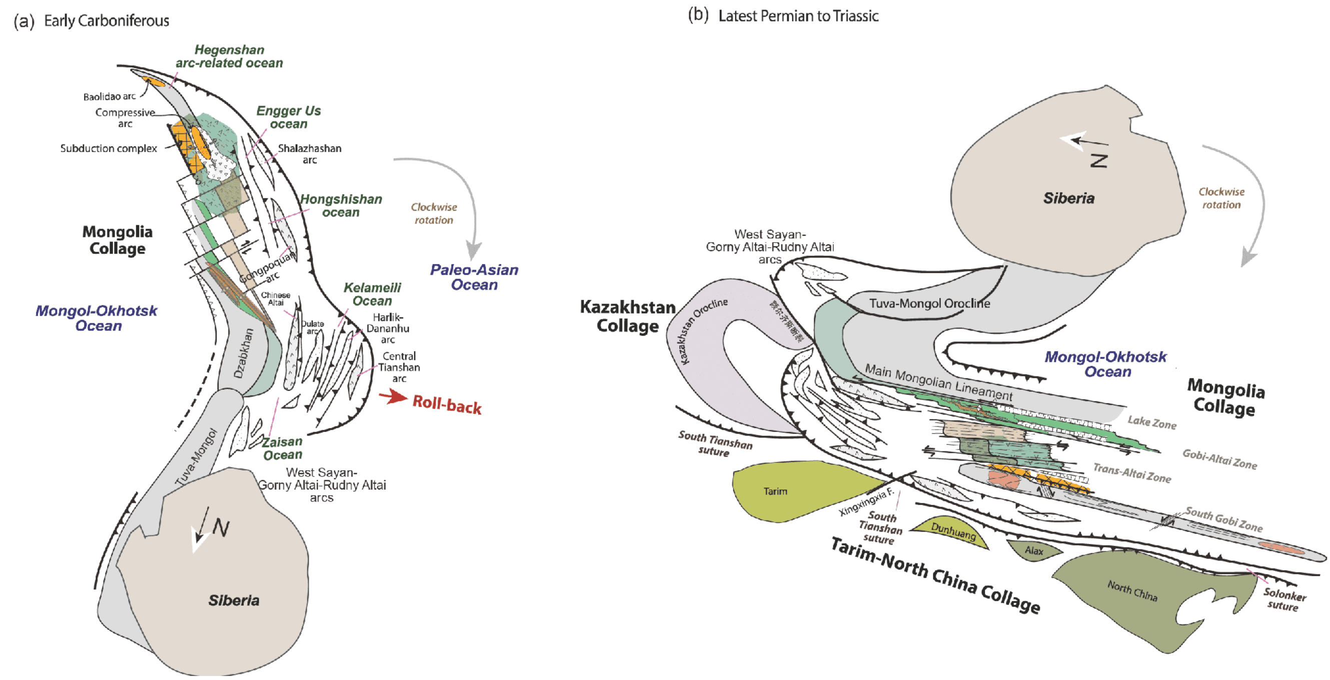

Figure 10 A schematic diagram illustrating the tectonic evolution of the Central Asian Orogenic Belt from Carboniferous to Triassic. Modified after Xiao et al. (2018).

in Central Asia into three metallogenic provinces: The Kazakhstan copper-gold-molybdenum metallogenic province, the Mongolian copper-gold metallogenic province, and the northeast China molybdenum-copper metallogenic province (Figure 11; Gao et al., 2019), based on their geological, metallogenic, geochronological characteristics and tectonic settings. The Kazakhstan metallogenic province has a Paleoarchean-Paleoproterozoic continental basement affected by intensive magmatism related to the assembly and breakup of the Rodinia supercontinent (Gao et al., 2015). It is characterized by concentrated metallogenesis during the Carboniferous-early Permian (339–278 Ma). In contrast, only four large porphyry-type deposits in the early Paleozoic (489–440 Ma) and a few Triassic (228–225 Ma) porphyry molybdenum deposits specifically in the East Tianshan and Beishan have been found. The dominant tectonic background for the metallogenesis was considered to be magmatic arcs in association with the subduction of the Paleo-Asian Ocean (Shen et al., 2016). Rocks of the ore-forming porphyry in these regions mainly include quartz diorite, diorite, granodiorite, monzonite, plagiogranite, monzonitic granite and granites. The Neoarchean-Paleoproterozoic and Mesoproterozoic basements only occur in the Mongolian metallogenic province. Two peaks of the porphyry metallogenesis occurred in the Devonian (~370 Ma) and the Triassic (~240 Ma), which were considered to be associated with the subduction processes of the Paleo-Asian Ocean and the Mongolia-Okhotsk Ocean, respectively (Seltmann et al., 2014). Rocks of ore-forming porphyry in this province mainly include quartz diorite, quartz monzonite, monzonitic granite, granodiorite and trachydacites. The Neoarchean-Paleoproterozoic metamorphic rocks are exposed sporadically in the northeast China metallogenic province, but magmatic records of the Meso-Neoproterozoic and the Pan-African events are extensive. Some Early Paleozoic porphyry deposits (482–440 Ma) were formed during the subduction of the Paleo-Asian Ocean. Several small and medium porphyry deposits (248–204 Ma) were developed under the influence of subduction of the Mongolia-Okhotsk Ocean. During the Mesozoic (240–106 Ma), the porphyry molybdenum metallogenesis densely broke out because of the subduction of the Paleo-Pacific Plate (Zeng et al., 2015). Rocks of the ore-forming porphyry are dominated by monzonite granite, granodiorite and granite.

Massive sulfide deposits are widely distributed in the Altai-East Junggar and East Tianshan metallogenic belts in northwest China. The Ashele Cu-Zn deposit is the largest VMS deposit in the Chinese Altai. This deposit dveloped in the contact zones of the arc basalt, dacite and rhyolite. Recycling of oceanic sediments occured in the source area. Geochemical and isotopic data indicate that the deposit was formed in an arc rifting environment (Wan et al., 2010). The VMS deposits in East Tianshan include the Xiaorequanzi, Honghai, Hongyuan and Yamansu deposits. The Honghai VMS deposit is located in the southeast part of the Kalatage ore cluster, with its ore body placed in the marine strata of the Daliugou Formation.

The karatongke Cu-Ni deposit in the northernmost part of East Junggar and the Huangshan-Jingerquan Cu-Ni metallogenic belt (including Huangshan, Huangshan east,

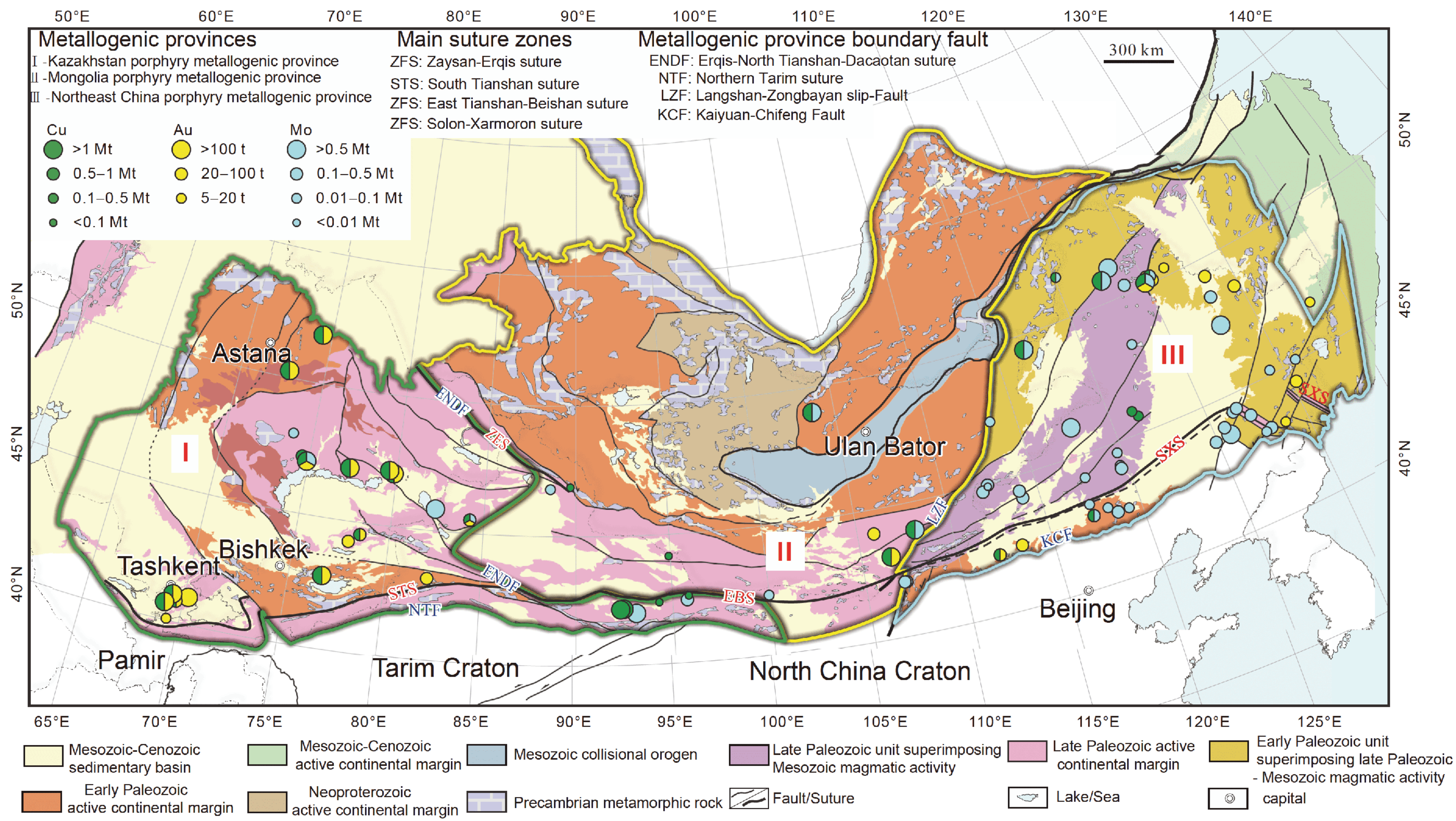

Figure 11 A tectonic map of the Central Asian Metallogenic Domain showing the distribution of porphyry deposit and the three porphyry metallogenic provinces. Modified after Gao et al. (2019).

Xiangshan, Turaergen and Hongling Cu-Ni deposits) in the East Tianshan are important magmatic Cu-Ni sulfide deposits in the CAOB. The Karatongke Cu-Ni deposit was formed in the late Carboniferous to early Permian, intruding into the slate and tuff of the Nanmingshui Formation. The Huangshan-Jingerquan Cu-Ni metallogenic belt is the largest metallogenic belt in Xinjiang, which extends more than 200 km along the Kanggurtag Fault. The Huangshan East ore deposit is the largest and most representative one in the belt. The mafic, ultramafic rocks and veins align as lenses along an east-west direction, surrounded by the country rocks of Carboniferous turbidites interbedded with subordinate limestone, basalt, andesite, spilite, tuff and glutenite.

In addition, Cu-Ni sulfide deposits related to mafic-ultramafic rocks also exist in the Baishiquan and Pobei areas (Mao et al., 2008). Geochemistry studies show that the ore-bearing magma in the Altai-East Tianshan is similar to Alaska-type complex formed in a subduction environment (Ao et al., 2010; Han et al., 2007). However, some studies suggest that it may be derived from partial melting of the metasomatic mantle wedge in the tectonic background of post-subduction (Mao et al., 2015) or post-collision (Song and Li, 2009).

Orogenic gold deposits in the CAOB are mainly distributed along large ductile shear zones (Chen et al., 2012; Zhang et al., 2012). For example, the Tokuzibayi and Dunbasitao gold deposits are distributed in the Irtysh shear zone between the Altai and East Junggar. Kanggur, and the Hongshan and Jinshan gold deposits are distributed along the Kanggur-Huangshan shear zone.

4.12 Tectonic superposition and transformation

Since the Mesozoic, the CAOB had been strongly influenced by the tectonic superposition of the surrounding tectonic domains (Yin and Nie, 1996; Wilde et al., 2003; Zuza and Yin, 2017; Şengör et al., 2018). A series of landmasses in the Tethyan Ocean drifted northward and accreted to the southern margin of the Eurasian continent (Roger et al., 2003; Ding et al., 2005; Xu Z et al., 2013). The compressional stress transmitted northward to Tianshan and the areas in the north through the Tarim Craton, forming numerous mountain peaks and related intermontane basins (Yin et al., 1998; Jia and Wei, 2002; Wang et al., 2014). Yin (2010) argued that the interaction between the Indo-Asia collision and the Arabia-Asia convergence controlled the Cenozoic deformation in Asia and formed the strike-slip fault system across Zagros, Tianshan, Altai and Mongolia.

Based on provenance analysis of the Meso-Cenozoic strata of the south and north foots of Tianshan (Tarim Basin and Junggar Basin), Li and Peng (2013) proposed four stages for the basin-range evolution of Tianshan: Weak tectonic activities with main watershed located in South Tianshan in the Middle-Late Triassic to Middle Jurassic, remarkable uplifting of the whole Tianshan resulting in northward migration of the watershed in the Late Jurassic-Early Cretaceous, relative tectonic-tranquility in the Late Cretaceous-Paleogene, and the most violent uplifting causing separate watershed systems in the north and south individually in the Neogene. The intensive intracontinental orogeny and crustal shortening in the Cenozoic are manifested by fold-thrust structures and syntectonic faults in the foreland basins of Tianshan inland region (Sun and Zhang, 2009).

The receiver function image shows that the lithosphere of Junggar Basin is decoupled along the Moho, and its mantle subducts southward beneath the northern margin of Tianshan, resulting in thickening of the overlying crust. Li et al. (2016) called it M-type subduction, and considered it a common process in intracontinental orogenesis.

The eastern part of the CAOB was mainly superimposed by the subduction of the Mongolia-Okhotsk Ocean and the (Paleo-)Pacific Ocean in the Meso-Cenozoic (Zuza and Yin, 2017). The subduction of the Mongolia-Okhotsk Ocean and the collapse of the orogenic belt produced a large number of Jurassic-Cretaceous magmatic rocks in the Xingmeng orogenic belt (Li et al., 2018; Wang et al., 2015). The timing of initial subduction of the Paleo-Pacific Plate beneath the eastern margin of Eurasian Plate is or have been estimated in the Permian (Li, 2006), the end of the Triassic (Ma et al., 2017; Zhou et al., 2009), or the Early Jurassic (Xu W L et al., 2013).

5. Prospects for future research

Orogenic belt is the frontier of basic research in the international academia. The orogeny and its mechanisms have been principal focuses, and also been solid foundations for understanding the continental accretion and the supercontinent cycle (Şengör et al., 1993; Zhang et al., 2001; Cawood and Buchan, 2007). The unique accretionary process of the CAOB makes it one of the best field laboratories for studying the mechanisms of orogeny (Şengör et al., 1993; Jahn et al., 2000a, 2000b, 2000c; Xiao et al., 2008; Liu Y et al., 2017). Since the founding of the People's Republic of China, especially after the reform and opening-up, fruitful achievements have been made in fundamental geology and metallogenesis of the CAOB. As the research further develops, some new scientific issues arise, which could be summarized in the following aspects.

5.1 The early evolution of the Paleo-Asian Ocean and its subduction initiation mechanism

The present studies have mainly focused on the subduction-closure process of the Paleo-Asian Ocean and the accretionary process of the CAOB during Phanerozoic. However, relatively little attention has been paid to the early history of the Paleo-Asian Ocean. How did the Paleo-Asian Ocean open? What was the geodynamic process for its opening? What was the relationship between the Paleo-Asian Ocean and other oceans? How long did it take from the formation of the Paleo-Asian Ocean to its initial subduction? How did the subduction initiate?

5.2 Mechanism for extroversion closure of the Paleo-Asian Ocean

Studies on the supercontinent cycle show that there are basically two types of orogenesis through earth history, namely introversion and extroversion (Collins et al., 2011). Different from the introversion closure of the Tethys, the Paleo-Asian Ocean experienced a long-lived subduction period. Numerous studies have indicated that it was an extroversion ocean similar to the Circum-Pacific Ocean, and both introversion and extroversion closure might have taken place in the Paleo-Asian Ocean. How to understand the complex mechanism for the extroversion closure of the Paleo-Asian Ocean?

5.3 Mantle properties of the Paleo-Asian Ocean and their spatio-temporal distribution

There are a large number of ophiolitic mélanges in the CAOB. Some of them represent the residual oceanic crust, and some represent the root of island arcs. Ophiolites have different geochemical properties, especially isotopic compositions, which indicate the existence of different oceanic lithosphere. So what information on deep mantle can we get from the ophiolites? What are the mantle properties of the Paleo-Asian Ocean and how are they distributed in space and time?

5.4 Interaction between the Paleo-Asian Ocean and the Tethys Ocean

The subduction and closure of the Paleo-Asian Ocean gave birth to the Laurasia, and the evolution of the Tethys Ocean was closely related to the assemblage and fragmentation of the Gondwana. The collision of the Laurasia and Gondwana created the Pangea. What are the relationships between the Paleo-Asian Ocean and the Tethys Ocean?

5.5 The mechanism of Phanerozoic continental growth and global comparison

The mechanism of continental growth is one of the fundamental issues in earth sciences. Many geologists believe that the growth of the earth's continental crust had basically completed in the Precambrian, and the exchange and cycling of crust and mantle materials occurred during the Phanerozoic subduction. At present, crustal growth happens in the Circum-Pacific subduction zone. Meanwhile, large amounts of crust from the upper plate is delivered into the deep mantle through subduction erosion. The overall effect of these processes is to maintain the balance of the continental crust of the Earth. However, it is argued that considerable continental crustal growth has taken place in the CAOB in the Phanerozoic, which is of great significance for the growth of global continental crust. What is the mechanism for the continental growth in Central Asia? Was there any similar continental growth at the same time in other places around the world?

In addition, there are some concealed terranes within the CAOB, such as the Junggar Basin, the Tacheng Basin and the Songliao Basin. Due to a lack of direct geological evidence and reliable isotopic age data, it is still an open question whether the basements of these basins are Precambrian microcontinents, Phanerozoic orogenic belts or remnant oceanic basins.

5.6 Metallogenic mechanism for the Central Asian Metallogenic Domain

The Central Asian Metallogenic Domain, the Circum-Pacific Metallogenic Domain and the Tethyan Metallogenic Domain are the three largest metallogenic domains in the world. Different from the subduction-related metallogenesis in the Circum-Pacific and collision-related metallogenesis in the Tethys, the Central Asian Metallogenic Domain underwent a long-lived accretionary process and experienced complex tectonic evolution of oceanic subduction, continental margin accretion and intracontinental transformation. What is the mechanism for the accretionary metallogenesis? Is there any special metallogenic process in the CAOB compared to the Circum-Pacific and the Tethys metallogenic domains?

5.7 Continental transformation and reworking mechanism

After the Paleo-Asian Ocean closed, the CAOB was strongly reworked and transformed by activities of the surrounding plates. What is the mechanism for continental transformation and reworking? How do pre-existing and latter structures interact? As regards the reworking mechanism, previous studies have attributed it to the far-field effect of the Tethys orogenesis in the south. However, how did the southward subduction of the Mongolia-Okhotsk Ocean affect the CAOB?

Acknowledgements *The tectonic evolution of the CAOB is very complex, and it is impossible to give a detailed review of all the research advances of the accretionary process and metallogenesis in Central Asia.*

This paper is only a preliminary summary based on a large number of research results from domestic and international research groups. We apologize for inevitably missing references due to space limitation. Sun S gave careful instructions to the study of the accretionary process in Central Asia. Xiao X C, Li T D, Zhang G W, Xu Z Q, Jin Z M, Wang C S, Zheng Y F, Wu F Y, Ge X H, Xu W L, Xu J F, Liu Y J, Zhang J J, Zhou J B, Liu W, A M C Şengör, K Schulmann, T Kusky, and R Seltmann offered great guidance and help to the authors in accretionary tectonic research, which is greatly acknowledged. The Editor-in-Chief and two reviewers gave detailed and constructive suggestions on the manuscript. This work was supported by the National Key R & D Program of China (Grant No. 2017YFC0601201), the National Natural Science Foundation of China (Grant Nos. 41888101, 41730210, 41672219), and the IGCP662 Project.

References

Ai Y, Zhang L, Li X, Qu J. 2006. Geochemical characteristics and tectonic implications of HP-UHP eclogites and blueschists in Southwestern Tianshan, China. Prog Nat Sci, 16: 624–632

Ao S J, Xiao W J, Han C M, Li X H, Qu J F, Zhang J E, Guo Q Q, Tian Z H. 2012. Cambrian to early Silurian ophiolite and accretionary processes in the Beishan collage, NW China: Implications for the architecture of the Southern Altaids. Geol Mag, 149: 606–625

Ao S J, Xiao W J, Han C M, Mao Q G, Zhang J E. 2010. Geochronology and geochemistry of Early Permian mafic-ultramafic complexes in the Beishan area, Xinjiang, NW China: Implications for late Paleozoic tectonic evolution of the southern Altaids. Gondwana Res, 18: 466–478

Banerjee S, Matin A. 2013. Evolution of microstructures in Precambrian shear zones: An example from eastern India. J Struct Geol, 50: 199–208

Beinlich A, Klemd R, John T, Gao J. 2010. Trace-element mobilization during Ca-metasomatism along a major fluid conduit: Eclogitization of blueschist as a consequence of fluid-rock interaction. Geochim Cosmochim Acta, 74: 1892–1922

Briggs S M, Yin A, Manning C E, Chen Z L, Wang X F. 2009. Tectonic development of the southern Chinese Altai Range as determined by structural geology, thermobarometry, $^{40}Ar/^{39}Ar$ thermochronology, and Th/Pb ion-microprobe monazite geochronology. Geol Soc Am Bull, 121: 1381–1393

Cai K, Sun M, Yuan C, Zhao G, Xiao W, Long X, Wu F. 2010. Geochronological and geochemical study of mafic dykes from the northwest Chinese Altai: Implications for petrogenesis and tectonic evolution. Gondwana Res, 18: 638–652

Cawood P A, Buchan C. 2007. Linking accretionary orogenesis with supercontinent assembly. Earth-Sci Rev, 82: 217–256

Charvet J, Shu L, Laurent-Charvet S. 2007. Paleozoic structural and geodynamic evolution of eastern Tianshan (NW China): Welding of the Tarim and Junggar plates. Episodes, 30: 162–186

Charvet J, Shu L S, Laurent-Charvet S, Wang B, Faure M, Cluzel D, Chen Y, De Jong K. 2011. Palaeozoic tectonic evolution of the Tianshan belt, NW China. Sci China Earth Sci, 54: 166–184

Chen C M, Lu H F, Jia D, Cai D S, Wu S M. 1999. Closing history of the southern Tianshan oceanic basin, western China: An oblique collisional orogeny. Tectonophysics, 302: 23–40

Chen G D, Chen J C, Wei B L, Xue J M, Liu Y X, Wen S J, Wei Z L, Hu H Y.1975. A brief review on the geotectonics of China (in Chinese). Chin J Geol, 10: 205–219

Chen H Y, Chen Y J, Baker M. 2012. Isotopic geochemistry of the Sawayaerdun orogenic-type gold deposit, Tianshan, northwest China: Implications for ore genesis and mineral exploration. Chem Geol, 310-311: 1–11

Chen X, Shu L, Santosh M, Zhao X. 2013. Island arc-type bimodal magmatism in the eastern Tianshan Belt, Northwest China: Geochemistry, zircon U-Pb geochronology and implications for the Paleozoic crustal evolution in Central Asia. Lithos, 168-169: 48–66

Chen Y, Xiao W, Windley B F, Zhang J, Zhou K, Sang M. 2017. Structures and detrital zircon ages of the Devonian-Permian Tarbagatay accretionary complex in west Junggar, China: Imbricated ocean plate stratigraphy and implications for amalgamation of the CAOB. Int Geol Rev, 59: 1097–1115

Cheng Y, Xiao Q H, Li T D, Guo J l, Li Y, Fan Y X, Luo P Y, Pang J L. 2019. Magmatism and tectonic background of the early Permian intraoceanic arc in the Diyanmiao Subduction Accretion Complex Belt on the eastern margin of the Central Asian Orogenic Belt (in Chinese). Earth Sci, 44: 3454–3468

Cui R W. 1988. Petrochemical characteristics of the ophiolite of Kalameli, Xinjiang and its genetic environment (in Chinese). Xinjiang Geol, 6: 70–82

Chu H, Zhang J R, Wei C J, Wang H C, Ren Y W. 2013. A new interpretation of the tectonic setting and age of meta-basic volcanics in the Ondor Sum Group, Inner Mongolia (in Chinese). Chin Sci Bull, 58: 2958–2965

Cocks L R M, Torsvik T H. 2007. Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. Earth-Sci Rev, 82: 29–74

Collins W J, Belousova E A, Kemp A I S, Murphy J B. 2011. Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. Nat Geosci, 4: 333–337

Cui F H, Zheng C Q, Xu X C, Yao W G, Ding X, Shi L, Li J. 2015. Detrital zircon ages of the Jiageda and Woduhe formations: Constrains on the tectonic attribute of the Xing'an terrane in the central Great Xing'an Range, NE China. J Asian Earth Sci, 113: 427–442

de Jong K, Wang B, Faure M, Shu L, Cluzel D, Charvet J, Ruffet G, Chen Y. 2009. New $^{40}Ar/^{39}Ar$ age constraints on the Late Palaeozoic tectonic evolution of the western Tianshan (Xinjiang, northwestern China), with emphasis on Permian fluid ingress. Int J Earth Sci-Geol Rundsch, 98: 1239–1258

de Jong K, Xiao W, Windley B F, Masago H, Lo C. 2006. Ordovician $^{40}Ar/^{39}Ar$ phengite ages from the blueschist-facies Ondor Sum subduction-accretion complex (Inner Mongolia) and implications for the early Paleozoic history of continental blocks in China and adjacent areas. Am J Sci, 306: 799–845

Ding L, Kapp P, Wan X Q. 2005. Paleocene-Eocene record of ophiolite obduction and initial India-Asia collision, south central Tibet. Tectonics, 24: TC3001

Dobretsov N L, Berzin N A, Buslov M M. 1995. Opening and tectonic evolution of the Paleo-Asian Ocean. Int Geol Rev, 37: 335–360

Dong Y, Zhang G, Neubauer F, Liu X, Hauzenberger C, Zhou D, Li W. 2011. Syn- and post-collisional granitoids in the Central Tianshan orogen: Geochemistry, geochronology and implications for tectonic evolution. Gondwana Res, 20: 568–581

Du J, Zhang L, Lü Z, Chu X. 2011. Lawsonite-bearing chloritoid-glaucophane schist from SW Tianshan, China: Phase equilibria and *P-T* path. J Asian Earth Sci, 42: 684–693

Ducea M N, Saleeby J B, Bergantz G. 2015. The architecture, chemistry, and evolution of continental magmatic arcs. Annu Rev Earth Planet Sci, 43: 299–331

Eizenhöfer P R, Zhao G, Zhang J, Sun M. 2014. Final closure of the Paleo-Asian Ocean along the Solonker Suture Zone: Constraints from geochronological and geochemical data of Permian volcanic and sedimentary rocks. Tectonics, 33: 441–463

Feng J, Xiao W, Windley B, Han C, Wan B, Zhang J, Ao S, Zhang Z, Lin L. 2013. Field geology, geochronology and geochemistry of mafic-ultramafic rocks from Alxa, China: Implications for Late Permian accretionary tectonics in the southern Altaids. J Asian Earth Sci, 78: 114–142

Feng Z Q, Liu Y J, Li Y L, Li W M, Wen Q B, Liu B Q, Zhou J P, Zhao Y L. 2017. Ages, geochemistry and tectonic implications of the Cambrian igneous rocks in the northern Great Xing'an Range, NE China. J Asian Earth Sci, 144: 5–21

Feng Z Q, Liu Y J, Jin W, Jiang L W, Li W M, Wen Q B, Li X Y, Zhang T A, Du B Y, Ma Y F, Zhang L. 2019. Spatiotemporal distribution of ophiolites in the northern Great Xing'an Range and its relationship with the geotectonic evolution of NE China (in Chinese). Earth Sci Front, 26:

120–136
Furnes H, Safonova I. 2019. Ophiolites of the Central Asian Orogenic Belt: Geochemical and petrological characterization and tectonic settings. Geosci Front, 10: 1255–1284
Gao J. 1993. Plate tectonics and orogenic dynamics of northwest Tianshan. Doctoral Dissertation (in Chinese). Beijing: Chinese Academy of Geological Sciences
Gao J. 1997. Discovery of eclogite in northwest Tianshan mountains and its tectonic significance (in Chinese). Chin Sci Bull, 42: 737–740
Gao J, He G Q, Li M S. 1997. Paleozoic orogenic processes of western Tianshan orogeny (in Chinese). Earth Sci, 22: 27–32
Gao J, He G Q, Li M S, Wang X C, Lu S N. 1996. New advances in the study of the tectonics in the south Tianshan mountains, Xinjiang (in Chinese). Geol Bull China, 21: 58–63
Gao J, Klemd R, Zhang M, Wang Q, Xiao X. 1999. *P-T* path of high-pressure/low-temperature rocks and tectonic implications in the western Tianshan Mountains, NW China. J Metamorph Geol, 17: 621–636
Gao J, Klemd R. 2000. Eclogite occurrences in the Southern Tianshan High-Pressure Belt, Xinjiang, Western China. Gondwana Res, 3: 33–38
Gao J, Klemd R. 2003. Formation of HP-LT rocks and their tectonic implications in the western Tianshan Orogen, NW China: Geochemical and age constraints. Lithos, 66: 1–22
Gao J, Klemd R, Qian Q, Zhang X, Li J, Jiang T, Yang Y. 2011. The collision between the Yili and Tarim blocks of the Southwestern Altaids: Geochemical and age constraints of a leucogranite dike crosscutting the HP-LT metamorphic belt in the Chinese Tianshan Orogen. Tectonophysics, 499: 118–131
Gao J, Klemd R, Zhu M, Wang X, Li J, Wan B, Xiao W, Zeng Q, Shen P, Sun J, Qin K, Campos E. 2018. Large-scale porphyry-type mineralization in the Central Asian metallogenic domain: A review. J Asian Earth Sci, 165: 7–36
Gao J, Long L L, Qian Q, Huang D Z, Su W. 2006. South Tianshan: A late Paleozoic or a Triassic orogen? (in Chinese). Acta Petrol Sin, 22: 1049–1061
Gao J, Li M, Xiao X, Tang Y, He G. 1998. Paleozoic tectonic evolution of the Tianshan Orogen, northwestern China. Tectonophysics, 287: 213–231
Gao J, Long L, Klemd R, Qian Q, Liu D, Xiong X, Su W, Liu W, Wang Y, Yang F. 2009. Tectonic evolution of the South Tianshan orogen and adjacent regions, NW China: Geochemical and age constraints of granitoid rocks. Int J Earth Sci-Geol Rundsch, 98: 1221–1238
Gao J, Wang X S, Klemd R, Jiang T, Qian Q, Mu L X, Ma Y Z. 2015. Record of assembly and breakup of Rodinia in the Southwestern Altaids: Evidence from Neoproterozoic magmatism in the Chinese Western Tianshan Orogen. J Asian Earth Sci, 113: 173–193
Gao J, Xiao X C. 1994. The metamorphic *pTDt* path of blueschists and tectonic evolution in the southwestern Tianshan mountains Xinjian (in Chinese). Geol Rev, 40: 544–553
Gao J, Xiao X C., Tang Y Q, Zhao M, Wang J, Wu H Q. 1993. The discovery of blueschist in Kumux of the south Tianshan mountains and its tectonic significance (in Chinese). Geol Bull China, 40: 344–347
Gao J, Zhu M T, Wang X S, Hong T, Li G M , Li J L, Xiao W J, Qin K Z, Zeng Q D, Shen P, Xu X W, Zhang Z C, Zhou J B, Lai Y, Zhang X H, Sun J G, Wan B, Wang B. 2019. Large-scale porphyry-type metallogenesis in the Central Asian metallogenic domain: Tectonic background, fluid feature and metallogenic deep dynamic mechanism (in Chinese). Acta Geol Sin, 93: 24–71
Geng H, Sun M, Yuan C, Xiao W, Xian W, Zhao G, Zhang L, Wong K, Wu F. 2009. Geochemical, Sr-Nd and zircon U-Pb-Hf isotopic studies of Late Carboniferous magmatism in the West Junggar, Xinjiang: Implications for ridge subduction? Chem Geol, 266: 364–389
Gordienko I V, Bulgatov A N, Lastochkin N I, Sitnikova V S. 2009. Composition and U-Pb isotopic age determinations (SHRIMP II) of the ophiolitic assemblage from the Shaman paleospreading zone and the conditions of its formation (North Transbaikalia). Dokl Earth Sci, 429: 1420–1425
Gu P, Li Y, Zhang B. 2009. LA-ICP-MS zircon U-Pb dating of gabbro in the Darbut ophiolite, western Junggar, China. Acta Petrol Sin, 25: 1364–1372
Guo F X. 2000. Affinity between Paleozoic blocks of Xinjiang and their suturing ages (in Chinese with English abstarct). Acta Geol Sin, 74: 1–6
Han B F, Guo Z J, He G Q. 2010a. Timing of major suture zones in North Xinjiang, China: Constraints from stitching plutons (in Chinese). Acta Petrol Sin, 26: 2233–2246
Han B F, Guo Z J, Zhang Z C, Zhang L, Chen J F, Song B. 2010b. Age, geochemistry, and tectonic implications of a late Paleozoic stitching pluton in the North Tian Shan suture zone, western China. Geol Soc Am Bull, 122: 627–640
Han B F, He G Q, Wang X C, Guo Z J. 2011. Late Carboniferous collision between the Tarim and Kazakhstan-Yili terranes in the western segment of the South Tian Shan Orogen, Central Asia, and implications for the Northern Xinjiang, western China. Earth-Sci Rev, 109: 74–93
Han C, Xiao W, Zhao G, Qu W, Du A. 2007. Re-Os dating of the Kalatongke Cu-Ni deposit, Altay Shan, NW China, and resulting geodynamic implications. Ore Geol Rev, 32: 452–468
Han G Q, Liu Y J, Neubauer F, Bartel E, Genser J, Feng Z Q, Zhang L, Yang M C. 2015. U-Pb age and Hf isotopic data of detrital zircons from the Devonian and Carboniferous sandstones in Yimin area, NE China: New evidences to the collision timing between the Xing'an and Erguna blocks in eastern segment of Central Asian Orogenic Belt. J Asian Earth Sci, 97: 211–228
He G Q, Liu J B, Zhang Y Q, Xu X. 2007. Keramay ophiolite mélange formed during Early Paleozoic in western Junggar basin (in Chinese). Acta Petrol Sin, 23: 1573–1576
He Z C. 1956. The boundary of Tianshan geosyncline and Qilian geosyncline (in Chinese). Geol China, (10): 21–23
He Z Y, Klemd R, Yan L L, Lu T Y, Zhang Z M. 2018a. Mesoproterozoic juvenile crust in microcontinents of the Central Asian Orogenic Belt: Evidence from oxygen and hafnium isotopes in zircon. Sci Rep, 8: 5054
He Z Y, Klemd R, Yan L L, Zhang Z M. 2018b. The origin and crustal evolution of microcontinents in the Beishan orogen of the southern Central Asian Orogenic Belt. Earth-Sci Rev, 185: 1–14
Hegner E, Klemd R, Kroner A, Corsini M, Alexeiev D V, Iaccheri L M, Zack T, Dulski P, Xia X, Windley B F. 2010. Mineral ages and *P-T* conditions of Late Paleozoic high-pressure eclogite and provenance of melange sediments from Atbashi in the south Tianshan orogen of Kyrgyzstan. Am J Sci, 310: 916–950
Hsü K J, Wang Q C, Li J L, Hao J. 1991. Geologic evolution of the Neimonides: A working hypothesis. Ecl Geol Hel, 84: 1–35
Hu A, Jahn B, Zhang G, Chen Y, Zhang Q. 2000. Crustal evolution and Phanerozoic crustal growth in northern Xinjiang: Nd isotopic evidence. Part I. Isotopic characterization of basement rocks. Tectonophysics, 328: 15–51
Hu A Q, Zhang G X, Li X Q, Zhang Q F, Hu S R, Fan S K, Guo T Z. 1995. The isotopic chronological scale of major geological events in northern Xinjiang, China (in Chinese). Geochimica, 24: 20–31
Hu A Q, Zhang G X, Zhang Q F, Chen Y B. 1999. Constraints on the age of basement and crustal growth in Tianshan Orogen by Nd isotopic composition. Sci China Ser D-Earth Sci, 41: 648–657
Hu B, Wang J B, Gao Z J, Lu Q, Fang X D. 1964. Some problems of Xinjiang geotectonics (in Chinese). Acta Geol Sin, (2): 28–42
Huang B C, Zhou Y X, Zhu R X. 2008. Discussions on Phanerozoic evolution and formation of continental China, based on paleo-magnetic studies. Earth Sci Front, 15: 348–359
Huang J Q, eds. 1959. A preliminary discussion on the basic characteristics of geological structure in China (in Chinese). Geology in China, (7): 24–34
Huang J Q, Ren J S, Jiang C F, Zhang Z M, Zhang Z K. 1974. New understanding of some characteristics of Chinese tectonic structure (in Chinese). Acta Geol Sin, 48: 38–54
Jahn B, Wu F, Chen B. 2000a. Massive granitoid generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic. Episodes, 23: 82–92
Jahn B M, Griffin W L, Windley B. 2000b. Continental growth in the

Phanerozoic: Evidence from Central Asia. Tectonophysics, 328: vii–x
Jahn B, Wu F, Chen B. 2000c. Granitoids of the Central Asian Orogenic Belt and continental growth in the Phanerozoic. Earth Environ Sci Trans R Soc Edinburgh, 91: 181–193
Jia C Z, Wei G Q. 2002. Structural characteristics and oil-gas bearing in Tarim basin (in Chinese). Chin Sci Bull, 47: 1–8
Jian P, Kröner A, Jahn B, Windley B F, Shi Y, Zhang W, Zhang F, Miao L, Tomurhuu D, Liu D. 2014. Zircon dating of Neoproterozoic and Cambrian ophiolites in West Mongolia and implications for the timing of orogenic processes in the central part of the Central Asian Orogenic Belt. Earth-Sci Rev, 133: 62–93
Jian P, Liu D, Kröner A, Windley B F, Shi Y, Zhang F, Shi G, Miao L, Zhang W, Zhang Q, Zhang L, Ren J. 2008. Time scale of an early to mid-Paleozoic orogenic cycle of the long-lived Central Asian Orogenic Belt, Inner Mongolia of China: Implications for continental growth. Lithos, 101: 233–259
Jian P, Liu D, Kröner A, Windley B F, Shi Y, Zhang W, Zhang F, Miao L, Zhang L, Tomurhuu D. 2010. Evolution of a Permian intraoceanic arc-trench system in the Solonker suture zone, Central Asian Orogenic Belt, China and Mongolia. Lithos, 118: 169–190
Jiang T, Gao J, Klemd R, Qian Q, Zhang X, Xiong X, Wang X, Tan Z, Chen B. 2014. Paleozoic ophiolitic mélanges from the South Tianshan Orogen, NW China: Geological, geochemical and geochronological implications for the geodynamic setting. Tectonophysics, 612-613: 106–127
Jiang Y, Sun M, Zhao G, Yuan C, Xiao W, Xia X, Long X, Wu F. 2010. The 390 Ma high-*T* metamorphic event in the Chinese Altai: A consequence of ridge-subduction? Am J Sci, 310: 1421–1452
Jiang Y D, Schulmann K, Sun M, Weinberg R F, Štípská P, Li P F, Zhang J, Chopin F, Wang S, Xia X P, Xiao W J. 2019. Structural and geochronological constraints on Devonian suprasubduction tectonic switching and Permian collisional dynamics in the Chinese Altai, Central Asia. Tectonics, 38: 253–280
Khain E V, Bibikova E V, Kröner A, Zhuravlev D Z, Sklyarov E V, Fedotova A A, Kravchenko-Berezhnoy I R. 2002. The most ancient ophiolite of the Central Asian fold belt: U-Pb and Pb-Pb zircon ages for the Dunzhugur Complex, Eastern Sayan, Siberia, and geodynamic implications. Earth Planet Sci Lett, 199: 311–325
Klemd R, Gao J, Li J L, Meyer M. 2015. Metamorphic evolution of (ultra)-high-pressure subduction-related transient crust in the South Tianshan Orogen (Central Asian Orogenic Belt): Geodynamic implications. Gondwana Res, 28: 1–25
Klemd R, Hegner E, Bergmann H, Pfänder J A, Li J L, Hentschel F. 2014. Eclogitization of transient crust of the Aktyuz Complex during Late Palaeozoic plate collisions in the Northern Tianshan of Kyrgyzstan. Gondwana Res, 26: 925–941
Konopelko D, Kullerud K, Apayarov F, Sakiev K, Baruleva O, Ravna E, Lepekhina E. 2012. SHRIMP zircon chronology of HP-UHP rocks of the Makbal metamorphic complex in the Northern Tien Shan, Kyrgyzstan. Gondwana Res, 22: 300–309
Kovalenko V I, Yarmolyuk V V, Kovach V P, Kotov A B, Kozakov I K, Salnikova E B, Larin A M. 2004. Isotope provinces, mechanisms of generation and sources of the continental crust in the Central Asian mobile belt: Geological and isotopic evidence. J Asian Earth Sci, 23: 605–627
Kröner A, Alexeiev D V, Kovach V P, Rojas-Agramonte Y, Tretyakov A A, Mikolaichuk A V, Xie H, Sobel E R. 2017. Zircon ages, geochemistry and Nd isotopic systematics for the Palaeoproterozoic 2.3–1.8 Ga Kuilyu Complex, East Kyrgyzstan—The oldest continental basement fragment in the Tianshan orogenic belt. J Asian Earth Sci, 135: 122–135
Kröner A, Alexeiev D V, Rojas-Agramonte Y, Hegner E, Wong J, Xia X, Belousova E, Mikolaichuk A V, Seltmann R, Liu D, Kiselev V V. 2013. Mesoproterozoic (Grenville-age) terranes in the Kyrgyz North Tianshan: Zircon ages and Nd-Hf isotopic constraints on the origin and evolution of basement blocks in the southern Central Asian Orogen. Gondwana Res, 23: 272–295
Kusky T M, Windley B F, Safonova I, Wakita K, Wakabayashi J, Polat A, Santosh M. 2013. Recognition of ocean plate stratigraphy in accretionary orogens through Earth history: A record of 3.8 billion years of sea floor spreading, subduction, and accretion. Gondwana Res, 24: 501–547
Lei R X, Wu C Z, Gu L X, Zhang Z Z, Chi G X, Jiang Y H. 2011. Zircon U-Pb chronology and Hf isotope of the Xingxingxia granodiorite from the Central Tianshan zone (NW China): Implications for the tectonic evolution of the southern Altaids. Gondwana Res, 20: 582–593
Lei Z, He G. 2014. Geochronology and geochemistry of the Cambrian (~518 Ma) Chagantaolegai ophiolite in northern West Junggar (NW China): Constraints on spatiotemporal characteristics of the Chingiz-Tarbagatai megazone. Int Geol Rev, 56: 1181–1196
Levashova N M, Meert J G, Gibsher A S, Grice W C, Bazhenov M L. 2011. The origin of microcontinents in the Central Asian Orogenic Belt: Constraints from paleomagnetism and geochronology. Precambrian Res, 185: 37–54
Li C Y. 1980. The outline of Chinese plate tectonics (in Chinese). Geol Soc China, 2: 11–19
Li C Y, Tang Y Q. 1983. Asian paleo plate division and related issues (in Chinese). Acta Geol Sin, (1): 3–12
Li C Y, Wang Q, Liu X Y, Tang Y Q. 1984. Tectonic evolution of Asia (in Chinese). Acta Geosci Sin, (3): 9–17
Li D P, Jin Y, Hou K J, Chen Y L, Lu Z. 2015. Late Paleozoic final closure of the Paleo-Asian Ocean in the eastern part of the Xing-Meng Orogenic Belt: Constrains from Carboniferous-Permian (meta-) sedimentary strata and (meta-) igneous rocks. Tectonophysics, 665: 251–262
Li H J, He G Q, Wu T R, Wu B. 2006. Confirmation of Altai-Mongolia and its implications (in Chinese). Acta Petrol Sin, 22: 803–809
Li J Y. 2006. Permian geodynamic setting of Northeast China and adjacent regions: Closure of the Paleo-Asian Ocean and subduction of the Paleo-Pacific Plate. J Asian Earth Sci, 26: 207–224
Li J, Zhang J, Zhao X, Jiang M, Li Y, Zhu Z, Feng Q, Wang L, Sun G, Liu J, Yang T. 2016. Mantle subduction and uplift of intracontinental mountains: A case study from the Chinese Tianshan Mountains within Eurasia. Sci Rep, 6: 28831
Li J T, eds. 1998. Some new ideas on tectonics of NE China and its neighboring areas (in Chinese). Geol Rev, 44: 339–347
Li J T, Xiao X C, Tang Y Q, Zhao M, Feng Y M, Zhu B Q. 1992. Metal deposits and plate tectonics in northern Xinjiang (in Chinese). Xinjiang Geol, (2):138–146
Li S L, Ouyang Z Y. 1998. Tectonic framework and evolution of Xing'anling-Mongolian orogenic belt (XMOB) and its adjacent region (in Chinese). Mar Geol Quat Geol, 18: 45–54
Li S G. 1962. Introduction to Geomechanics (in Chinese). Beijing: Science Press
Li T D, Xiao Q H, Pan G T, Lu S N, Ding X Z, Liu Y. 2019. A consideration about the development of ocean plate geology (in Chinese). Earth Sci, 44: 1441–1451
Li Y, Xu W L, Tang J, Pei F P, Wang F, Sun C Y. 2018. Geochronology and geochemistry of Mesozoic intrusive rocks in the Xing'an Massif of NE China: Implications for the evolution and spatial extent of the Mongol-Okhotsk tectonic regime. Lithos, 304-307: 57–73
Li Y, Zhou H, Brouwer F M, Wijbrans J R, Zhong Z, Liu H. 2011. Tectonic significance of the Xilin Gol Complex, Inner Mongolia, China: Petrological, geochemical and U-Pb zircon age constraints. J Asian Earth Sci, 42: 1018–1029
Li Z, Peng S T. 2013. U-Pb geochronological records and provenance system analysis of the Mesozoic-Cenozoic sandstone detrital zircons in the northern and southern piedmonts of Tianshan, Northwest China Respomses to intracontinental basin-range evolution (in Chinese). Acta Petrol Sin, 29: 739–755
Liu W, Liu X J, Xiao W J. 2012. Massive granitoid production without massive continental-crust growth in the Chinese Altay: Insight into the source rock of granitoids using integrated zircon U-Pb age, Hf-Nd-Sr isotopes and geochemistry. Am J Sci, 312: 629–684
Liu X, Chen B, Jahn B, Wu G, Liu Y. 2010. Early Paleozoic (ca. 465 Ma) eclogites from Beishan (NW China) and their bearing on the tectonic evolution of the southern Central Asian Orogenic Belt. J Asian Earth

Sci, 42: 715–731
Liu X, Wang Q. 1995. Tectonics of orogenic belts in Beishan Mts., western China and their evolution. Geosci Res, 28: 37–48
Liu X, Wu G, Chen B, Shu B. 2002. Metamorphic history of eclogites from Beishan, Gansu Province. Acta Geosci Sin, 23: 25–29
Liu X, Xiao W, Xu J, Castillo P R, Shi Y. 2017. Geochemical signature and rock associations of ocean ridge-subduction: Evidence from the Karamaili Paleo-Asian ophiolite in east Junggar, NW China. Gondwana Res, 48: 34–49
Liu X, Xu J, Xiao W, Castillo P R, Shi Y, Wang S, Huo Q, Feng Z. 2015. The boundary between the Central Asian Orogenic belt and Tethyan tectonic domain deduced from Pb isotopic data. J Asian Earth Sci, 113: 7–15
Liu X, Xu J, Hou Q, Bai Z, Lei M. 2007. Geochemical characteristics of Karamaili ophiolite in east Junggar, Xingjiang: Products of ridge subduction. Acta Petrol Sin, 23: 1591–1602
Liu Y, Li W, Feng Z, Wen Q, Neubauer F, Liang C. 2017. A review of the paleozoic tectonics in the eastern part of central asian orogenic belt. Gondwana Res, 43: 123–148
Long L, Gao J, Klemd R, Beier C, Qian Q, Zhang X, Wang J, Jiang T. 2011. Geochemical and geochronological studies of granitoid rocks from the Western Tianshan Orogen: Implications for continental growth in the southwestern Central Asian Orogenic Belt. Lithos, 126: 321–340
Long X, Sun M, Yuan C, Xiao W, Cai K. 2008. Early Paleozoic sedimentary record of the Chinese Altai: Implications for its tectonic evolution. Sediment Geol, 208: 88–100
Long X, Sun M, Yuan C, Xiao W, Lin S, Wu F, Xia X, Cai K. 2007. Detrital zircon age and Hf isotopic studies for metasedimentary rocks from the Chinese Altai: Implications for the Early Paleozoic tectonic evolution of the Central Asian Orogenic Belt. Tectonics, 26: TC5015
Long X, Yuan C, Sun M, Xiao W, Zhao G, Wang Y, Cai K, Xia X, Xie L. 2010. Detrital zircon ages and Hf isotopes of the early Paleozoic flysch sequence in the Chinese Altai, NW China: New constrains on depositional age, provenance and tectonic evolution. Tectonophysics, 480: 213–231
Luo Z W, Xu B, Shi G Z, Zhao P, Faure M, Chen Y. 2016. Solonker ophiolite in Inner Mongolia, China: A late Permian continental margin-type ophiolite. Lithos, 261: 72–91
Lü Z, Zhang L F. 2012. Coesite in the eclogite and schist of the Atantayi Valley, southwestern Tianshan, China. Chin Sci Bull, 57: 1467–1472
Lü Z, Zhang L, Du J, Bucher K. 2008. Coesite inclusions in garnet from eclogitic rocks in western Tianshan, northwest China: Convincing proof of UHP metamorphism. Am Miner, 93: 1845–1850
Lü Z, Zhang L, Du J, Bucher K. 2009. Petrology of coesite-bearing eclogite from Habutengsu Valley, western Tianshan, NW China and its tectonometamorphic implication. J Metamorph Geol, 27: 773–787
Lü Z, Zhang L, Du J, Yang X, Tian Z, Xia B. 2012. Petrology of HP metamorphic veins in coesite-bearing eclogite from western Tianshan, China: Fluid processes and elemental mobility during exhumation in a cold subduction zone. Lithos, 136–139: 168–186
Ma C, Xiao W, Windley B F, Zhao G, Han C, Zhang J, Luo J, Li C. 2012. Tracing a subducted ridge-transform system in a late Carboniferous accretionary prism of the southern Altaids: Orthogonal sanukitoid dyke swarms in Western Junggar, NW China. Lithos, 140-141: 152–165
Ma X, Shu L, Meert J G, Li J. 2014. The Paleozoic evolution of Central Tianshan: Geochemical and geochronological evidence. Gondwana Res, 25: 797–819
Ma X H, Zhu W P, Zhou Z H, Qiao S L. 2017. Transformation from Paleo-Asian Ocean closure to Paleo-Pacific subduction: New constraints from granitoids in the eastern Jilin-Heilongjiang Belt, NE China. J Asian Earth Sci, 144: 261–286
Ma Y F, Liu Y J, Qin T, Sun W, Zang Y Q. 2018. Carboniferous granites in the Jalaid Banner area, middle Great Xing'an Range, NE China: Petrogenesis, tectonic background and orogeny accretionary implications (in Chinese). Acta Petrol Sin, 34: 2931–2955
Mao J W, Pirajno F, Zhang Z H, Chai F M, Wu H, Chen S P, Cheng L S, Yang J M, Zhang C Q. 2008. A review of the Cu-Ni sulphide deposits in the Chinese Tianshan and Altay orogens (Xinjiang Autonomous Region, NW China): Principal characteristics and ore-forming processes. J Asian Earth Sci, 32: 184–203
Mao Q, Xiao W, Fang T, Wang J, Han C, Sun M, Yuan C. 2012a. Late Ordovician to early Devonian adakites and Nb-enriched basalts in the Liuyuan area, Beishan, NW China: Implications for early Paleozoic slab-melting and crustal growth in the southern Altaids. Gondwana Res, 22: 534–553
Mao Q, Xiao W, Windley B F, Han C, Qu J, Ao S, Zhang J E, Guo Q. 2012b. The Liuyuan complex in the Beishan, NW China: A Carboniferous-Permian ophiolitic fore-arc sliver in the southern Altaids. Geol Mag, 149: 483–506
Mao Q G, Xiao W J, Han C M, Sun M, Yuan C, Yan Z, Li J L, Yong Y, Zhang J E. 2006. Zircon U-Pb age and the geochemistry of the Baishuiquan mafic-ultramafic complex in the Eastern Tianshan, Xinjiang province: Constraints on the closure of the Paleo-Asian Ocean (in Chinese). Acta Petrol Sin, 22: 153–162
Mao Y J, Qin K Z, Li C, Tang D M. 2015. A modified genetic model for the Huangshandong magmatic sulfide deposit in the Central Asian Orogenic Belt, Xinjiang, western China. Miner Depos, 50: 65–82
Meyer M, Klemd R, Hegner E, Konopelko D. 2014. Subduction and exhumation mechanisms of ultra-high and high-pressure oceanic and continental crust at Makbal (Tianshan, Kazakhstan and Kyrgyzstan). J Meta Geol, 32: 861–884
Meyer M, Klemd R, Konopelko D. 2013. High-pressure mafic oceanic rocks from the Makbal Complex, Tianshan Mountains (Kazakhstan & Kyrgyzstan): Implications for the metamorphic evolution of a fossil subduction zone. Lithos, 177: 207–225
Miao L, Fan W, Liu D, Zhang F, Shi Y, Guo F. 2008. Geochronology and geochemistry of the Hegenshan ophiolitic complex: Implications for late-stage tectonic evolution of the Inner Mongolia-Daxinganling Orogenic Belt, China. J Asian Earth Sci, 32: 348–370
Miao L, Zhang F, Jiao S. 2015. Age, protoliths and tectonic implications of the Toudaoqiao blueschist, Inner Mongolia, China. J Asian Earth Sci, 105: 360–373
Miao L, Zhang F, Fan W M, Liu D. 2007. Phanerozoic evolution of the Inner Mongolia-Daxinganling orogenic belt in North China: Constraints from geochronology of ophiolites and associated formations. Geol Soc Lond Spec Publ, 280: 223–237
Niu H, Sato H, Zhang H, Ito J, Yu X, Nagao T, Terada K, Zhang Q. 2006. Juxtaposition of adakite, boninite, high-TiO_2 and low-TiO_2 basalts in the Devonian southern Altay, Xinjiang, NW China. J Asian Earth Sci, 28: 439–456
Niu H, Shan Q, Zhang H, Yu X. 2007. $^{40}Ar/^{39}Ar$ geochronology of the ultrahigh-pressure metamorphic quartz-magnesitite in Zaheba, eastern Junggar, Xinjiang. Acta Petrol Sin, 23: 1627–1634
Niu S Y, Hu X, Sun A Q. 1993. Evolution of the paleoplate tectonics on north side of north China platform (in Chinese). Geol Sci Technol Inform, (1): 17–21
Pan G T, Xiao Q H, Zhang K X, et al. 2019. Recognition of the Oceanic Subduction-Accretion Zones from the Orogenic Belt in Continents and Its Important Scientific Significance (in Chinese). Earth Sci, 44: 1544–1561
Pan G F, Xiao Q H, Lu S N, Deng J F, Feng Y M, Zhang K X, Zhang Z Y, Wang F G, Xing G F, Hao G J, Feng Y F. 2009. Subdivision of tectonic units in China (in Chinese). Geol China, 36: 1–28
Pan G T, Lu S N, Xiao Q H, Zhang K X, Yin F G, Hao G J. 2016. Division of tectonic stages and tectonic evolution in China (in Chinese). Earth Sci Front, 23: 1–23
Pei Q M, Zhang S T, Hayashi K, Cao H W, Li D, Tang L, Hu X K, Li H X, Fang D R. 2018. Permo-Triassic granitoids of the Xing'an-Mongolia segment of the Central Asian Orogenic Belt, Northeast China: Age, composition, and tectonic implications. Int Geol Rev, 60: 1172–1194
Qu J F, Xiao W J, Windley B F, Han C M, Mao Q G, Ao S J, Zhang J E. 2011. Ordovician eclogites from the Chinese Beishan: Implications for the tectonic evolution of the southern Altaids. J Metamorph Geol, 29: 803–820

Ren R, Han B F, Xu Z, Zhou Y Z, Liu B, Zhang L, Chen J F, Su L, Li J, Li X H, Li Q L. 2014. When did the subduction first initiate in the southern Paleo-Asian Ocean: New constraints from a Cambrian intra-oceanic arc system in West Junggar, NW China. Earth Planet Sci Lett, 388: 222–236

Roger F, Arnaud N, Gilder S, Tapponnier P, Jolivet M, Brunel M, Malavieille J, Xu Z, Yang J. 2003. Geochronological and geochemical constraints on Mesozoic suturing in east Central Tibet. Tectonics, 22: 1037

Rojas-Agramonte Y, Herwartz D, García-Casco A, Kröner A, Alexeiev D V, Klemd R, Buhre S, Barth M. 2013. Early Palaeozoic deep subduction of continental crust in the Kyrgyz North Tianshan: Evidence from Lu-Hf garnet geochronology and petrology of mafic dikes. Contrib Mineral Petrol, 166: 525–543

Rong J Y, Zhang Z X. 1982. A southward extension of the Silurian Tuvaella brachiopod fauna. Lethaia, 15: 133–147

Rong J Y, Boucot A J, Su Y Z, Strusz D. L1995. Biogeographical analysis of Late Silurian brachiopod faunas, chiefly from Asia and Australia. Lethaia, 28: 39–60

Safonova I, Biske G, Romer R L, Seltmann R, Simonov V, Maruyama S. 2016. Middle Paleozoic mafic magmatism and ocean plate stratigraphy of the South Tianshan, Kyrgyzstan. Gondwana Res, 30: 236–256

Safonova I, Kotlyarov A, Krivonogov S, Xiao W. 2017. Intra-oceanic arcs of the Paleo-Asian Ocean. Gondwana Res, 50: 167–194

Safonova I Y, Santosh M. 2014. Accretionary complexes in the Asia-Pacific region: Tracing archives of ocean plate stratigraphy and tracking mantle plumes. Gondwana Res, 25: 126–158

Saktura W M, Buckman S, Nutman A P, Belousova E A, Yan Z, Aitchison J C. 2017. Continental origin of the Gubaoquan eclogite and implications for evolution of the Beishan Orogen, Central Asian Orogenic Belt, NW China. Lithos, 294-295: 20–38

Salnikova E B, Kozakov I K, Kotov A B, Kröner A, Todt W, Bibikova E V, Nutman A, Yakovleva S Z, Kovach V P. 2001. Age of Palaeozoic granites and metamorphism in the Tuvino-Mongolian Massif of the Central Asian Mobile Belt: Loss of a Precambrian microcontinent. Precambrian Res, 110: 143–164

Sang M, Xiao W, Bakirov A, Orozbaev R, Sakiev K, Zhou K. 2017. Oblique wedge extrusion of UHP/HP complexes in the Late Triassic: Structural analysis and zircon ages of the Atbashi Complex, South Tianshan, Kyrgyzstan. Int Geol Rev, 59: 1369–1389

Schulmann K, Paterson S. 2011. Asian continental growth. Nat Geosci, 4: 827–829

Seltmann R, Porter T M, Pirajno F. 2014. Geodynamics and metallogeny of the central Eurasian porphyry and related epithermal mineral systems: A review. J Asian Earth Sci, 79: 810–841

Şengör A M C, Natal'in B A. 1996. Turkic-type orogeny and its role in the making of the continental crust. Annu Rev Earth Planet Sci, 24: 263–337

Şengör A M C, Natal'in B A, Burtman V S. 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature, 364: 299–307

Şengör A M C, Natal'in B A, Sunal G, van der Voo R. 2018. The tectonics of the Altaids: Crustal growth during the construction of the continental lithosphere of Central Asia between ~750 and ~130 Ma ago. Annu Rev Earth Planet Sci, 46: 439–494

Shen P, Pan M D, Eleonora S. 2016. Characteristics of the porphyry Cu deposits in the Central Asia Metallogenic Domain (in Chinese). Dissertation for Doctoral Degree. Beijing: Institute of Geology and Geophysics, Chinese Academy of Sciences

Shen P, Pan H, Xiao W, Shen Y. 2014. An Ordovician intra-oceanic subduction system influenced by ridge subduction in the West Junggar, Northwest China. Int Geol Rev, 56: 206–223

Shen X, Zhang H, Wang Q, Wyman D A, Yang Y. 2011. Late Devonian-Early Permian A-type granites in the southern Altay Range, Northwest China: Petrogenesis and implications for tectonic setting of "A2-type" granites. J Asian Earth Sci, 42: 986–1007

Shen X M, Zhang H X, Wang Q, Saha A, Ma L, Santosh M. 2018. Zircon U-Pb geochronology and geochemistry of Devonian plagiogranites in the Kuerti area of southern Chinese Altay, northwest China: Petrogenesis and tectonic evolution of late Paleozoic ophiolites. Geol J, 53: 1886–1905

Shi G H, Liu D Y, Zhang F Q, Jian P, Miao L C, Shi Y R, Tao H. 2003. SHRIMP zircon U-Pb chronology and its significance in Xilin Gol complex, Inner Mongolia, China (in Chinese). Chin Sci Bull, 48: 2187–2192

Shi Y, Liu D, Miao L, Zhang F, Jian P, Zhang W, Hou K, Xu J. 2010. Devonian A-type granitic magmatism on the northern margin of the North China Craton: SHRIMP U-Pb zircon dating and Hf-isotopes of the Hongshan granite at Chifeng, Inner Mongolia, China. Gondwana Res, 17: 632–641

Shu L, Charvet J, Lu H, Laurent S C. 2002. Paleozoic acretion-collision events and kinematics of ductile deformation in the eastern part of the southern-central Tianshan belt, China. Acta Geol Sin, 76: 308–323

Simonov V A, Sakiev K S, Volkova N I, Stupakov S I, Travin A V. 2008. Conditions of formation of the Atbashi Ridge eclogites (South Tien Shan). Rus Geol Geophys, 49: 803–815

Song D, Xiao W, Collins A S, Glorie S, Han C, Li Y. 2018. Final subduction processes of the Paleo-Asian Ocean in the Alxa Tectonic Belt (NW China): Constraints from field and chronological data of Permian arc-related volcano-sedimentary rocks. Tectonics, 37: 1658–1687

Song D, Xiao W, Han C, Li J, Qu J, Guo Q, Lin L, Wang Z. 2013. Progressive accretionary tectonics of the Beishan orogenic collage, southern Altaids: Insights from zircon U-Pb and Hf isotopic data of high-grade complexes. Precambrian Res, 227: 368–388

Song D, Xiao W, Han C, Tian Z. 2014. Polyphase deformation of a Paleozoic forearc-arc complex in the Beishan orogen, NW China. Tectonophysics, 632: 224–243

Song D, Xiao W, Windley B F, Han C, Tian Z. 2015. A Paleozoic Japan-type subduction-accretion system in the Beishan orogenic collage, southern Central Asian Orogenic Belt. Lithos, 224-225: 195–213

Song D, Xiao W, Windley B F, Han C, Yang L. 2016. Metamorphic complexes in accretionary orogens: Insights from the Beishan collage, southern Central Asian Orogenic Belt. Tectonophysics, 688: 135–147

Song S, Wang M M, Xu X, Wang C, Niu Y, Allen M B, Su L. 2015. Ophiolites in the Xing'an-Inner Mongolia accretionary belt of the CAOB: Implications for two cycles of seafloor spreading and accretionary orogenic events. Tectonics, 34: 2221–2248

Song X Y, Li X R. 2009. Geochemistry of the Kalatongke Ni-Cu-(PGE) sulfide deposit, NW China: Implications for the formation of magmatic sulfide mineralization in a postcollisional environment. Miner Depos, 44: 303–327

Su W, Gao J, Klemd R, Li J L, Zhang X, Li X H, Chen N S, Zhang L. 2010. U-Pb zircon geochronology of Tianshan eclogites in NW China: Implication for the collision between the YiLi and Tarim blocks of the southwestern Altaids. Eur J Mineral, 22: 473–478

Sun J, Zhang Z. 2009. Syntectonic growth strata and implications for late Cenozoic tectonic uplift in the northern Tian Shan, China. Tectonophysics, 463: 60–68

Sun M, Long X P, Cai K D, Jiang Y D, Wang B Y, Yuan C, Zhao G C, Xiao W J, Wu F Y. 2009. Early Paleozoic ridge subduction in the Chinese Altai: Insight from the abrupt change in zircon Hf isotopic compositions. Sci China Ser D-Earth Sci, 52: 1345–1358

Sun M, Yuan C, Xiao W, Long X, Xia X, Zhao G, Lin S, Wu F, Kröner A. 2008. Zircon U-Pb and Hf isotopic study of gneissic rocks from the Chinese Altai: Progressive accretionary history in the early to middle Palaeozoic. Chem Geol, 247: 352–383

Sun S, Li J L, Lin J L, Wang Q C, Chen H H. 1991. Indosinides in China and the consumption of Eastern Paleotethys. In: Muller D W, McKenzie J A, Weissert H, eds. Controversies in Modern Geology. London: Academic Press. 363–384

Sun W, Chi X G, Zhao Z, Pan S Y, Liu J F, Zhang R, Quan J Y. 2014. Zircon geochronology constraints on the age and nature of "Precambrian metamorphic rocks" in the Xing'an block of Northeast China. Int Geol Rev, 56: 672–694

Sun X C, Zhang H J, Wei Z J, Huang Z B, Gao N. 2005. Time of definition and geological meaning for metamorphic intrusive rock body in Xiao-

hongshan region, Beishan area of Gansu and Inner Mongolia (in Chinese). Northwestern Geol, 38: 61–67
Tang G, Wang Q, Wyman D A, Li Z X, Zhao Z H, Jia X H, Jiang Z Q. 2010. Ridge subduction and crustal growth in the Central Asian Orogenic Belt: Evidence from Late Carboniferous adakites and high-Mg diorites in the western Junggar region, northern Xinjiang (west China). Chem Geol, 277: 281–300
Tang G J, Wang Q, Wyman D A, Li Z X, Zhao Z H, Yang Y H. 2012. Late Carboniferous high $\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$ granitoids, enclaves and dikes in western Junggar, NW China: Ridge-subduction-related magmatism and crustal growth. Lithos, 140-141: 86–102
Tang K D, Wang Y, He G Q, Shao J A. 1995. Continental-margin structure of northeast China and its adjacent areas (in Chinese). Acta Geol Sin, 69: 16–30
Tang Y Q. 1989. Introduction to IGCP283 (tectonic evolution of Paleo-Asian Ocean) (in Chinese). Chin Geol, 11: 32
Tang Y Q. 1990. Project 283 of the international geological comparison program (IGCP) and 1989 work brief (in Chinese). Adv Earth Sci, (1): 89–90
Tao J Z, Lu Z, Zhu C S. 1982. Primary outline of plate tectonics in Xinjiang (in Chinese). J Xinjiang Univ-Nat Sci Ed, (1): 3–20
Tectonic Map Compiling Group, Institute of Geology, Academia Sinica. 1974. A preliminary note on the basic tectonic features and their developments in China (in Chinese). Chin J Geol-Sci Geol Sin, 9: 1–17
Tian C L, Yang F L. 1983. Petrological features of ophiolite in northeast China (in Chinese). Shenyang Inst Geol Miner Res, 6: 34–56
Tian Z, Xiao W, Shan Y, Windley B, Han C, Zhang J, Song D. 2013. Mega-fold interference patterns in the Beishan orogen (NW China) created by change in plate configuration during Permo-Triassic termination of the Altaids. J Struct Geol, 52: 119–135
Tian Z, Xiao W, Sun J, Windley B F, Glen R, Han C, Zhang Z, Zhang J, Wan B, Ao S, Song D. 2015. Triassic deformation of Permian Early Triassic arc-related sediments in the Beishan (NW China): Last pulse of the accretionary orogenesis in the southernmost Altaids. Tectonophysics, 662: 363–384
Tian Z, Xiao W, Windley B F, Lin L, Han C, Zhang J, Wan B, Ao S, Song D, Feng J. 2014. Structure, age, and tectonic development of the Huoshishan-Niujuanzi ophiolitic mélange, Beishan, southernmost Altaids. Gondwana Res, 25: 820–841
Tian Z L, Wei C J. 2014. Coexistence of garnet blueschist and eclogite in South Tianshan, NW China: Dependence of *P-T* evolution and bulk-rock composition. J Meta Geol, 32: 743–764
Torsvik T H, Cocks L R M. 2004. Earth geography from 400 to 250 Ma: A palaeomagnetic, faunal and facies review. J Geol Soc, 161: 555–572
Tu G Z. 1999. On the Central Asia metallogenic province (in Chinese). Chin J Geol-Sci Geol Sin, 34: 397–404
van der Straaten F, Schenk V, John T, Gao J. 2008. Blueschist-facies rehydration of eclogites (Tian Shan, NW-China): Implications for fluid-rock interaction in the subduction channel. Chem Geol, 255: 195–219
van der Voo R. 2004. Presidential address: Paleomagnetism, oroclines, and growth of the continental crust. GSA Today, 14: 4–9
Wakita K, Metcalfe I. 2005. Ocean plate stratigraphy in East and Southeast Asia. J Asian Earth Sci, 24: 679–702
Wan B, Li S, Xiao W, Windley B F. 2018. Where and when did the Paleo-Asian ocean form? Precambrian Res, 317: 241–252
Wan B, Zhang L, Xiang P. 2010. The Ashele VMS-type Cu-Zn deposit in Xinjiang, NW China formed in a rifted arc setting. Resour Geol, 60: 150–164
Wang B, Shu L, Faure M, Jahn B, Cluzel D, Charvet J, Chung S, Meffre S. 2011. Paleozoic tectonics of the southern Chinese Tianshan: Insights from structural, chronological and geochemical studies of the Heiyingshan ophiolitic mélange (NW China). Tectonophysics, 497: 85–104
Wang C S, Dai J G, Zhao X X, Li Y, Graham S A, He D, Ran B, Meng J. 2014. Outward-growth of the Tibetan Plateau during the Cenozoic: A review. Tectonophysics, 621: 1–43
Wang T, Guo L, Zhang L, Yang Q, Zhang J, Tong Y, Ye K. 2015. Timing and evolution of Jurassic-Cretaceous granitoid magmatisms in the Mongol-Okhotsk belt and adjacent areas, NE Asia: Implications for transition from contractional crustal thickening to extensional thinning and geodynamic settings. J Asian Earth Sci, 97: 365–392
Wang T, Jahn B M, Kovach V P, Tong Y, Hong D W, Han B F. 2009. Nd-Sr isotopic mapping of the Chinese Altai and implications for continental growth in the Central Asian Orogenic Belt. Lithos, 110: 359–372
Wang Q, Liu X Y, Li J T. 1991. Paleoplate tectonics in Nei Monggol of China (in Chinese). Acta Geosci Sin, (1): 1–12
Wang Z X, Wu J Y, Lv X Z, Liu C D, Zhang J G. 1989. The plate tectonics of Tianshan in China (in Chinese). J Hebei Geo Univ, (1): 54–58
Wei C J, Powell R, Zhang L F. 2003. Eclogites from the south Tianshan, NW China: Petrological characteristic and calculated mineral equilibria in the Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2-H_2O system. J Metamorph Geol, 21: 163–179
Wilde S A, Wu F Y, Zhang X Z. 2003. Late Pan-African magmatism in northeastern China: SHRIMP U-Pb zircon evidence from granitoids in the Jiamusi Massif. Precambrian Res, 122: 311–327
Windley B F, Allen M B, Zhang C, Zhao Z Y, Wang G R. 1990. Paleozoic accretion and Cenozoic redeformation of the Chinese Tien Shan range, central Asia. Geology, 18: 128–131
Windley B F, Alexeiev D, Xiao W, Kröner A, Badarch G. 2007. Tectonic models for accretion of the Central Asian orogenic belt. J Geol Soc, 164: 31–47
Windley B F, Xiao W. 2018. Ridge subduction and slab windows in the Central Asian Orogenic Belt: Tectonic implications for the evolution of an accretionary orogen. Gondwana Res, 61: 73–87
Wu F Y, Sun D Y, Ge W C, Zhang Y B, Grant M L, Wilde S A, Jahn B M. 2011. Geochronology of the Phanerozoic granitoids in northeastern China. J Asian Earth Sci, 41: 1–30
Wu F Y, Yang J H, Lo C H, Wilde S A, Sun D Y, Jahn B M. 2007a. The Heilongjiang Group: A Jurassic accretionary complex in the Jiamusi Massif at the western Pacific margin of northeastern China. Isl Arc, 16: 156–172
Wu F Y, Li X H, Yang J H, Zheng Y F. 2007b. Discussions on the petrogenesis of granite (in Chinese). Acta Petrol Sin, 23: 1217–1238
Wu H, Li H Q, Mo X H, Chen F W, Lu Y F, Mei Y P, Deng G. 2005. Age of the Baishiqun Mafic-Ultramafic Complex, Hami, Xinjiang and Its Geological Significance (in Chinese). Acta Geol Sin, 79: 498–502
Xiao W, Han C, Yuan C, Sun M, Lin S, Chen H, Li Z, Li J, Sun S. 2008. Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: Implications for the tectonic evolution of central Asia. J Asian Earth Sci, 32: 102–117
Xiao W, Han C, Yuan C, Sun M, Zhao G, Shan Y. 2010a. Transitions among Mariana-, Japan-, Cordillera- and Alaska-type arc systems and their final juxtapositions leading to accretionary and collisional orogenesis. Geol Soc Lond Spec Publ, 338: 35–53
Xiao W, Windley B F, Badarch G, Sun S, Li J, Qin K, Wang Z. 2004a. Palaeozoic accretionary and convergent tectonics of the southern Altaids: Implications for the growth of Central Asia. J Geol Soc, 161: 339–342
Xiao W, Windley B F, Allen M B, Han C. 2013. Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage. Gondwana Res, 23: 1316–1341
Xiao W, Windley B F, Han C, Liu W, Wan B, Zhang J, Ao S, Zhang Z, Song D. 2018. Late Paleozoic to early Triassic multiple roll-back and oroclinal bending of the Mongolia collage in Central Asia. Earth-Sci Rev, 186: 94–128
Xiao W, Windley B F, Hao J, Zhai M. 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. Tectonics, 22: 1069
Xiao W, Windley B F, Sun S, Li J, Huang B, Han C, Yuan C, Sun M, Chen H. 2015. A tale of amalgamation of three Permo-Triassic collage systems in Central Asia: Oroclines, sutures, and terminal accretion. Annu Rev Earth Planet Sci, 43: 477–507
Xiao W, Zhang L, Qin K, Sun S, Li J. 2004b. Paleozoic accretionary and collisional tectonics of the eastern Tianshan (China): Implications for

the continental growth of central Asia. Am J Sci, 304: 370–395
Xiao W J, Li J L, Song D F, Han C M, Wan B, Zhang J E, Ao S J, Zhang Z Y.2019. Structural analyses and spatio-temporal constraints of accretionary orogens (in Chinese). Earth Sci, 44: 1661–1687
Xiao W J, Mao Q G, Windley B F, Han C M, Qu J F, Zhang J E, Ao S J, Guo Q Q, Cleven N R, Lin S F, Shan Y H, Li J L. 2010b. Paleozoic multiple accretionary and collisional processes of the Beishan orogenic collage. Am J Sci, 310: 1553–1594
Xiao W J, Windley B F, Huang B C, Han C M, Yuan C, Chen H L, Sun M, Sun S, Li J L. 2009a. End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaids: Implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia. Int J Earth Sci-Geol Rundsch, 98: 1189–1217
Xiao W J, Windley B F, Yuan C, Sun M, Han C M, Lin S F, Chen H L, Yan Q R, Liu D Y, Qin K Z, Li J L, Sun S. 2009b. Paleozoic multiple subduction-accretion processes of the southern Altaids. Am J Sci, 309: 221–270
Xiao X C, Liu Y Q. 1962. Some new understanding of Inner Mongolia geology (in Chinese). Acta Geol Sin, (4): 29–96
Xiao X C, Tang Y Q, Wang J, Gao J, Zhao M. 1994. Blueschist Belts and their tectonic implications of the S. Tianshan Mts., N. W. China (in Chinese). Acta Geosci Sin, (Z2): 54–64
Xingmeng-north Xinjiang research group. 1991. Important progress has been made in the study of Paleozoic lithosphere in Xingmeng-northern Xinjiang and adjacent areas of China (in Chinese). Adv Earth Sci, (4): 89–90
Xie W, Xu Y G, Chen Y B, Luo Z Y, Hong L B, Ma L, Liu H Q. 2016. High-alumina basalts from the Bogda Mountains suggest an arc setting for Chinese Northern Tianshan during the Late Carboniferous. Lithos, 256-257: 165–181
Xie L, Yin H Q, Zhou H R, Zhang W J. 2014. Permian radiolarians from the Engeerwusu suture zone in Alxa area of Inner Mongoliaand its geological significance (in Chinese). Geol Bull China, (5): 691–697
Xu B, Charvet J, Chen Y, Zhao P, Shi G. 2013. Middle Paleozoic convergent orogenic belts in western Inner Mongolia (China): Framework, kinematics, geochronology and implications for tectonic evolution of the Central Asian Orogenic Belt. Gondwana Res, 23: 1342–1364
Xu B, Wang Z W, Zhang L Y, Wang Z H, Yang Z N, He Y. 2018. The Xing-Meng Intracontinent Orogenic Belt (in Chinese). Acta Petrol Sin, 34: 2819–284
Xu G X. 1963. Preliminary opinions on classification and identification of ultrabasic rocks in Inner Mongolia (in Chinese). Geol China, (5): 17–21
Xu M, Xu W, Wang F, Gao F. 2012. Age, association and provenance of the “Neoproterozoic” Fengshuigouhe Group in the Northwestern Lesser Xing’an Range, NE China: Constraints from zircon U-Pb geochronology. J Earth Sci, 23: 786–801
Xu W L, Pei F P, Wang F, Meng E, Ji W Q, Yang D B, Wang W. 2013. Spatial-temporal relationships of Mesozoic volcanic rocks in NE China: Constraints on tectonic overprinting and transformations between multiple tectonic regimes. J Asian Earth Sci, 74: 167–193
Xu W L, Sun C Y, Tang J, Luan J P, Wang F. 2019. Basement nature and tectonic evolution of the Xing’an-Mongolian Orogenic Belt (in Chinese). Earth Sci, 44: 1620–1646
Xu X, Li X, Zhongping M, Xia L, Xia Z. 2006. LA-ICPMS zircon U-Pb dating of gabbro from the bayingou ophiolite in the Northern Tianshan Mountains. Acta Geol Sin, 80: 1168–1176
Xu X. 1979. A new compilation of 1:100000 geological maps (first draft) for the Xinjiang region has been successfully completed (in Chinese). Northwestern Geol, (3): 72
Xu Z, Wang Q, Pêcher A, Liang F, Qi X, Cai Z, Li H, Zeng L, Cao H. 2013. Orogen-parallel ductile extension and extrusion of the Greater Himalaya in the late Oligocene and Miocene. Tectonics, 32: 191–215
Xue H M, Guo L J, Hou Z X, Zhou X W, Tong Y, Pan X F. 2009. The Xilingele complex from the eastern part of the Central Asian-Mongolia Orogenic Belt, China: Products of early variscan orogeny other than ancient block: Evidence from zircon SHRIMP U-Pb ages (in Chinese). Acta Petrol Sin, 25: 640–650
Yang G, Li Y, Kerr A C, Tong L. 2018. Accreted seamounts in North Tianshan, NW China: Implications for the evolution of the Central Asian Orogenic Belt. J Asian Earth Sci, 153: 223–237
Yang G, Li Y, Xiao W, Tong L. 2015. OIB-type rocks within West Junggar ophiolitic mélanges: Evidence for the accretion of seamounts. Earth-Sci Rev, 150: 477–496
Yang J S, Xu X Z, Li T F, Chen S Y, Ren Y F, Li J Y, Liu Z. 2011. U-Pb ages of zircons from ophiolite and related rocks in the Kumishi region at the southern margin of Middle Tianshan, Xinjiang: Evidence of Early Paleozoic oceanic basin (in Chinese). Acta Petrol Sin, 27: 77–95
Yang J, Zhang Z, Chen Y, Yu H, Qian X. 2017. Ages and origin of felsic rocks from the Eastern Erenhot ophiolitic complex, southeastern Central Asian Orogenic Belt, Inner Mongolia China. J Asian Earth Sci, 144: 126–140
Yang S F, Chen H L, Li Z L, Li Y Q, Yu X, Li D X, Meng L F. 2013. Early Permian Tarim Large Igneous Province in northwest China. Sci China Earth Sci, 56: 2015–2026
Yao Y P. 1997. Introduction to project IGCP420—“Phanerozoic continental accretion: Evidence for east-central Asia” (in Chinese). Chin Sci Bull, 42: 1119–1120
Ye X T, Zhang C L, Zou H B, Yao C Y, Dong Y G. 2017. Age and geochemistry of the Zhaheba ophiolite complex in eastern Junggar of the Central Asian Orogenic Belt (CAOB): Implications for the accretion process of the Junggar terrane. Geol Mag, 154: 419–440
Yin A. 2010. Cenozoic tectonic evolution of Asia: A preliminary synthesis. Tectonophysics, 488: 293–325
Yin A, Nie S. 1996. A Phanerozoic palinspastic reconstruction of China and its neighboring regions. In: Yin A, Harrison T M, eds. The Tectonic Evolution of Asia. Cambridge: Cambridge University Press. 442–485
Yin A, Nie S, Craig P, Harrison T M, Ryerson F J, Xianglin Q, Geng Y. 1998. Late Cenozoic tectonic evolution of the southern Chinese Tian Shan. Tectonics, 17: 1–27
Yin J, Chen W, Xiao W, Yuan C, Sun M, Tang G, Yu S, Long X, Cai K, Geng H, Zhang Y, Liu X. 2015. Petrogenesis of Early-Permian sanukitoids from West Junggar, Northwest China: Implications for Late Paleozoic crustal growth in Central Asia. Tectonophysics, 662: 385–397
Yin J, Long X, Yuan C, Sun M, Zhao G, Geng H. 2013. A Late Carboniferous-Early Permian slab window in the West Junggar of NW China: Geochronological and geochemical evidence from mafic to intermediate dikes. Lithos, 175-176: 146–162
Yuan F L. 1956. Preliminary report on continental geology of piedmont depression belt and Junggar basin in northern Tianshan, Xinjiang (in Chinese). Acta Geol Sin, (2): 23–144
Zeng Q, Qin K, Liu J, Li G, Zhai M, Chu S, Guo Y. 2015. Porphyry molybdenum deposits in the Tianshan-Xingmeng orogenic belt, northern China. Int J Earth Sci-Geol Rundsch, 104: 991–1023
Zhang B S, Wu W K. 1975. The corrugated bank structure in the crust of Xinjiang (in Chinese). J Northwest Univ-Nat Sci Ed, (3): 80–91
Zhang C. 1981. Some geologacal features of the ophiolites in Xinjiang (in Chinese). Geol Rev, 27: 307–314
Zhang C L, Li Z X, Li X H, Xu Y G, Zhou G, Ye H M. 2010. A Permian large igneous province in Tarim and Central Asian orogenic belt, NW China: Results of a ca. 275 Ma mantle plume? Geol Soc Am Bull, 122: 2020–2040
Zhang C, Wu T. 2001. Crack and assembly events of Meso-Neoproterozoic-Palaeozoic continental blocks in the sourthern area of Suzuoqi, Inner Mongolia (in Chinese). Acta Petrol Sin, 17: 199–205
Zhang J, Cunningham D. 2012. Kilometer-scale refolded folds caused by strike-slip reversal and intraplate shortening in the Beishan region, China. Tectonics, 31: TC3009
Zhang J, Sun M, Schulmann K, Zhao G, Wu Q, Jiang Y, Guy A, Wang Y. 2015a. Distinct deformational history of two contrasting tectonic domains in the Chinese Altai: Their significance in understanding accretionary orogenic process. J Struct Geol, 73: 64–82
Zhang J, Wei C, Chu H. 2015b. Blueschist metamorphism and its tectonic implication of Late Paleozoic-Early Mesozoic metabasites in the mél-

ange zones, central Inner Mongolia, China. J Asian Earth Sci, 97: 352–364

Zhang J E, Xiao W J, Han C M, Ao S J, Yuan C, Sun M, Geng H Y, Zhao G C, Guo Q Q, Ma C. 2011a. Kinematics and age constraints of deformation in a Late Carboniferous accretionary complex in Western Junggar, NW China. Gondwana Res, 19: 958–974

Zhang J E, Xiao W J, Han C M, Mao Q G, Ao S J, Guo Q Q, Ma C. 2011b. A Devonian to Carboniferous intra-oceanic subduction system in Western Junggar, NW China. Lithos, 125: 592–606

Zhang J E, Xiao W J, Luo J, Chen Y C, Windley B F, Song D F, Han C M, Safonova I. 2018. Collision of the Tacheng block with the Mayile-Barleik-Tangbale accretionary complex in Western Junggar, NW China: Implication for Early-Middle Paleozoic architecture of the western Altaids. J Asian Earth Sci, 159: 259–278

Zhang G W, Dong Y P, Yao A P. 2001. Review on the development of studies on the tectonic and orogen process of orogenic belt, and discussing on some new key problems (in Chinese). Northwestern Geol, 34: 1–9

Zhang L, Liu Y J, Li W M, Han G Q, Zhang J D, Guo Q Y, Li C H. 2013. Discussion on basement property and eastern boundary of Erguna block (in Chinese). Chin J Geol-Sci Geol Sin, 48: 227–244

Zhang L, Jin Z. 2016. High-temperature metamorphism of the Yushugou ophiolitic slice: Late Devonian subduction of seamount and mid-oceanic ridge in the South Tianshan orogen. J Asian Earth Sci, 132: 75–93

Zhang L, Ellis D J, Jiang W. 2002a. Ultrahigh-pressure metamorphism in western Tianshan, China: Part I. Evidence from inclusions of coesite pseudomorphs in garnet and from quartz exsolution lamellae in omphacite in eclogites. Am Miner, 87: 853–860

Zhang L, Ellis D J, Williams S, Jiang W. 2002b. Ultra-high pressure metamorphism in western Tianshan, China: Part II. Evidence from magnesite in eclogite. Am Miner, 87: 861–866

Zhang L, Ai Y, Li X, Rubatto D, Song B, Williams S, Song S, Ellis D, Liou J G. 2007. Triassic collision of western Tianshan orogenic belt, China: Evidence from SHRIMP U-Pb dating of zircon from HP/UHP eclogitic rocks. Lithos, 96: 266–280

Zhang L, Chen H, Chen Y, Qin Y, Liu C, Zheng Y, Jansen N H. 2012. Geology and fluid evolution of the Wangfeng orogenic-type gold deposit, Western Tian Shan, China. Ore Geol Rev, 49: 85–95

Zhang M S, Peng X D, Sun X M. 1998. Paleozoic tectonic paleogeographic pattern in northeast China (in Chinese). Land Res, 2: 91–96

Zhang S H, Zhao Y. 2013. Mid-crustal emplacement and deformation of plutons in an Andean-style continental arc along the northern margin of the North China Block and tectonic implications. Tectonophysics, 608: 176–195

Zhang S H, Zhao Y, Kröner A, Liu X M, Xie L W, Chen F K. 2009a. Early Permian plutons from the northern North China Block: Constraints on continental arc evolution and convergent margin magmatism related to the Central Asian Orogenic Belt. Int J Earth Sci-Geol Rundsch, 98: 1441–1467

Zhang S H, Zhao Y, Song B, Hu J M, Liu S W, Yang Y H, Chen F K, Liu X M, Liu J. 2009b. Contrasting Late Carboniferous and Late Permian-Middle Triassic intrusive suites from the northern margin of the North China craton: Geochronology, petrogenesis, and tectonic implications. Geol Soc Am Bull, 121: 181–200

Zhang S H, Zhao Y, Song B, Yang Z Y, Hu J M, Wu H. 2007. Carboniferous granitic plutons from the northern margin of the North China block: Implications for a late Palaeozoic active continental margin. J Geol Soc, 164: 451–463

Zhang W Y, Cao Y C, Jiang C C, Ning Q S, Sun S, Wang X Z, Li T D, Gao F Y. 1959. Based on the division and nomenclature of geotectonic units in China, this paper discusses the characteristics of geotectonic units in the northern part of northeast China (in Chinese). Chin J Geol-Sci Geol Sin, 2: 99–103

Zhang Y, He G Q. 1988. Characteristics and evolution of early Paleozoic ophiolite belt in Beishan, Gansu (in Chinese). Shanghai Land Res, 27: 10–23

Zhang Y Y, Guo Z J. 2008. Accurate constraint on formation and emplacement age of Hongliuhe ophiolite, boundary region between Xinjiang and Gansu Province and its tectonic implications (in Chinese). Acta Petrol Sin, 24: 803–809

Zhao Z H, Wang Q, Xiong X L, Zhang H X, Niu H C, Xu J F, Bai Z H, Qiao Y L. 2006. Two types of adakites in north Xinjiang, China (in Chinese). Acta Petrol Sin, 22: 1249–1265

Zhao Z, Chi X G, Liu J F, Wang T F, Hu Z C. 2010. Late Paleozoic arc-related magmatism in Yakeshi region, Inner Mongolia: Chronological and geochemical evidence (in Chinese). Acta Petrol Sin, 26: 3245–3258

Zheng R, Wu T, Zhang W, Xu C, Meng Q. 2013. Late Paleozoic subduction system in the southern Central Asian Orogenic Belt: Evidences from geochronology and geochemistry of the Xiaohuangshan ophiolite in the Beishan orogenic belt. J Asian Earth Sci, 62: 463–475

Zheng R, Wu T, Zhang W, Xu C, Meng Q, Zhang Z. 2014. Late Paleozoic subduction system in the northern margin of the Alxa block, Altaids: Geochronological and geochemical evidences from ophiolites. Gondwana Res, 25: 842–858

Zheng R, Xiao W, Li J, Wu T, Zhang W. 2018. A Silurian-early Devonian slab window in the southern Central Asian Orogenic Belt: Evidence from high-Mg diorites, adakites and granitoids in the western Central Beishan region, NW China. J Asian Earth Sci, 153: 75–99

Zhou J B, Cao J L, Wilde S A, Zhao G C, Zhang J J, Wang B. 2014. Paleo-Pacific subduction-accretion: Evidence from Geochemical and U-Pb zircon dating of the Nadanhada accretionary complex, NE China. Tectonics, 33: 2444–2466

Zhou J B, Li L. 2017. The Mesozoic accretionary complex in Northeast China: Evidence for the accretion history of Paleo-Pacific subduction. J Asian Earth Sci, 145: 91–100

Zhou J B, Wang B, Wilde S A, Zhao G C, Cao J L, Zheng C Q, Zeng W S. 2015. Geochemistry and U-Pb zircon dating of the Toudaoqiao blueschists in the Great Xing'an Range, northeast China, and tectonic implications. J Asian Earth Sci, 97: 197–210

Zhou J B, Wilde S A, Zhang X Z, Zhao G C, Liu F L, Qiao D W, Ren S M, Liu J H. 2011. A >1300 km late Pan-African metamorphic belt in NE China: New evidence from the Xing'an block and its tectonic implications. Tectonophysics, 509: 280–292

Zhou J B, Wilde S A, Zhang X Z, Zhao G C, Zheng C Q, Wang Y J, Zhang X H. 2009. The onset of Pacific margin accretion in NE China: Evidence from the Heilongjiang high-pressure metamorphic belt. Tectonophysics, 478: 230–246

Zhou J B, Wilde S A, Zhao G C, Han J. 2018. Nature and assembly of microcontinental blocks within the Paleo-Asian Ocean. Earth-Sci Rev, 186: 76–93

Zhu B Q, Wang L S, Wang L X. 1987. Paleozoic era ophiolite of southwest part in western Junggar, Xinjiang, China (in Chinese). Bull Xi'an Inst Geo Min Res Chin Acad Geol Sci, 17: 3–64

Zhu Y, Guo X, Song B, Zhang L, Gu L. 2009. Petrology, Sr-Nd-Hf isotopic geochemistry and zircon chronology of the Late Palaeozoic volcanic rocks in the southwestern Tianshan Mountains, Xinjiang, NW China. J Geol Soc, 166: 1085–1099

Zonenshain L P, Kuz'min M I, Natapov L M, Page B M. 1990. Geology of the USSR: A plate-tectonic synthesis. Geodynamics Series 21. Washington DC: AGU. 242

Zuo G C, He G Q. 1990. Beishan Plate Tectonics and Metallogenic Regularity (in Chinese). Beijing: Peking University Press. 226

Zuo G C, Zhang S L, He G Q, Zhang Y. 1990. Early Paleozoic plate tectonics in Beishan area (in Chinese). Chin J Geol-Sci Geol Sin, 25: 305–314

Zuza A V, Yin A. 2017. Balkatach hypothesis: A new model for the evolution of the Pacific, Tethyan, and Paleo-Asian oceanic domains. Geosphere, 13: 1664–1712

(Responsible editor: Maoyan ZHU)