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Chapter 1
An Overview

1.1 Introduction

Orogenic gold deposits account for over a quarter of the World's gold resources (Goldfarb et al. 2005), and a widely accepted genetic model proposes that metamorphic fluids are responsible for gold mineralization (Goldfarb et al. 2005; Chen 2006; Phillips and Powell 2010; Tomkins 2010; Zhong et al. 2015a). Traditionally, orogenic-type deposits are believed to be gold-only, which means that base metals such as Cu, Pb and Zn are believed to be immobile in the metamorphic ore-fluids. Some researchers proposed that gold is highly soluble in low salinity S-rich metamorphic fluids, because it forms strong complexes with reduced S in the fluids. In contrast, base metals are believed to be predominated by chloride complexes, and are thus of sub-economic quantities in low salinity metamorphic fluids (Phillips and Powell 2010).

However, case studies have demonstrated the presence of base metal deposits that share broad geological and geochemical similarities with orogenic gold, and they are defined as orogenic-type base metal deposits by some researchers (Chen 2006; Bierlein et al. 2009; Pirajno 2008). Typical cases include the Coeur d'Alene Ag–Pb–Zn–Cu–Au deposit in the US (Leach et al. 1988), the Tieluping Ag–Pb deposit in central China (Chen et al. 2004), the Tiemuertie Pb–Zn–Cu (Zhang et al. 2012) and Wulasigou Cu deposits (Zheng et al. 2012) in Xinjiang of northwest China, Au–Cu mineralization in the Kautokein greenstone belt in Norway (Ettner et al. 1993), CSA Cu–Pb–Zn (Giles and Marshall 2004) and Elura Ag–Pb–Zn deposits (De Roo 1989) in the Cobar basin in Australia and Omitiomire Cu deposit in Namibia (see http://www.interbasemetals.com).

On one hand, recent thermodynamic and experimental studies revealed that base metal hydrosulfide complexes are stable in high temperature fluids (e.g., Etschmann et al. 2010, 2019; Mei et al. 2013; Zhong et al. 2015a, b), and therefore the transport of base metals in the low-salinity metamorphic fluids is theoretically plausible. On the other hand, field-based cases studies can provide insights in understanding why base metals can be enriched in orogenic-type deposits.

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In his book, we synthesized our researches on four base metal deposit in the northern margin of the North China Plate, namely the Bainaimiao Cu–Mo–Au, the Huogeqi Cu–Pb–Zn, the Dongshengmiao Zn–Pb–Cu and the Jiashengpan Zn–Pb deposits. These four deposits are all characterized by affinities of orogenic-type deposits: shear zone-controlled mineralization, carbon-rich low-salinities ore-fluids, and close temporal and spatial relationships with orogenesis. Furthermore, all of these deposits have multistage ore-forming histories, including the pre-enrichment of ore-forming metals in porphyry magmatic (Bainaimiao) or submarine exhalative systems (Huogeqi, Dongshengmiao, and Jiashengpan), and later remobilization and upgrading of the metals during orogenesis and accompanied tectonism and metamorphism.

Geographically, these four deposits are located in the western and central parts of Inner Mongolia, northern China. Tectonically, these deposits are distributed in two different tectonic units. The Huogeqi, Dongshengmiao and Jiashengpan deposits are in the Langshan-Zhaertai area, which is a part of the northern margin of the North China Craton (NCC). The Bainaimiao deposit is located in the Bainaimiao area, which is a terrane composed of early Paleozoic intra-oceanic island arc and associated accretionary wedge within the Paleo-Asian Ocean, and accreted to the NCC (Fig. 1.1). In the following sections, the geological settings of these two areas will be introduced separately. All these two areas were subject to intensive tectonism, metamorphism and magmatism during Phanerozoic times, as responses to the multistage orogenesis, including the development of accretionary orogeny and the collision between the North China Plate and the South Mongolian Microcontinent during Paleozoic-early Mesozoic times, and intraplate orogeny during late Mesozoic. The shear zone-controlled mineralization of these deposits took place as responses to these multistage orogenesis.

1.2 Regional Geology

The ore deposits introduced in this book are located in the Langshan-Zhaertai and Bainaimiao areas (Fig. 1.1). These two areas have different tectonic affinities. The former belongs the northern margin of NCC, while the latter is a subduction-accretion terrane within the Central Asian Orogenic Belt (CAOB) (Fig. 1.1). During pre-Cambrian times, the most prominent tectonic events are the development of Proterozoic rifts in the Langshan-Zhaertai area, which formed the ore-hosting rift sequences in this area. Since early Paleozoic, both of these two areas were subjected to the long-term tectonism related to the formation of CAOB, and underwent multistage tectonic events. Among them, the final closure of Paleo-Asian Ocean is a key point of the tectonic evolution of CAOB, but its timing is still under debate. In this section, we will firstly introduce the geological settings of the Langshan-Zhaertai area and Bainaimiao areas separately, and then a special focus will be paid on the tectonic evolution of CAOB.

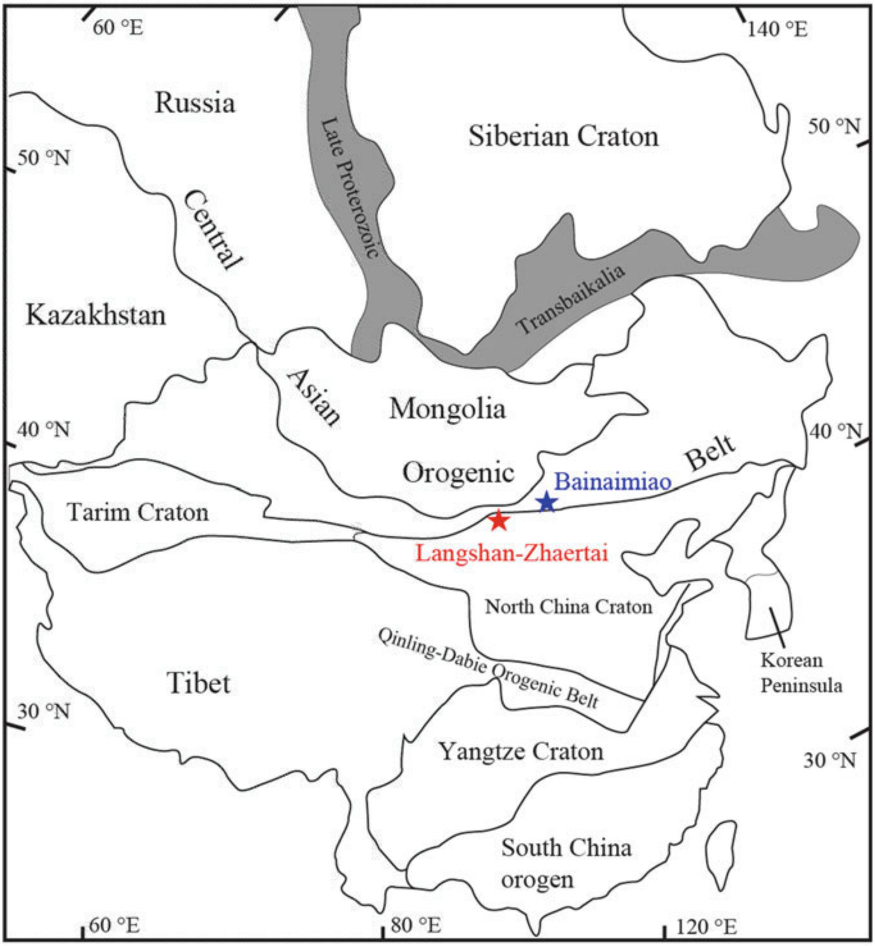

Fig. 1.1 The locations of Langshan-Zhaertai and Bainaimiao areas (Modified after Jahn 2004)

1.2.1 Langshan-Zhaertai Area

1.2.1.1 Pre-cambrian

The Langshan-Zhaertai area is composed of the western Langshan and the eastern Zhaertai districts. The Wulashan Group, an Archean metamorphic complex which was regarded as part of the NCC basement, is locally exposed in the Langshan-Zhaertai area (Fig. 1.2; Zhai et al. 2008). In the west, it is covered by the Proterozoic Langshan Group, which mainly consist of greenschist to amphibolite facies rift sequences, including metasedimentary shale, schist, marble and quartzite, intercalated with mafic and felsic metavolcanic rocks (Peng et al. 2007a; Zhai et al. 2008). To

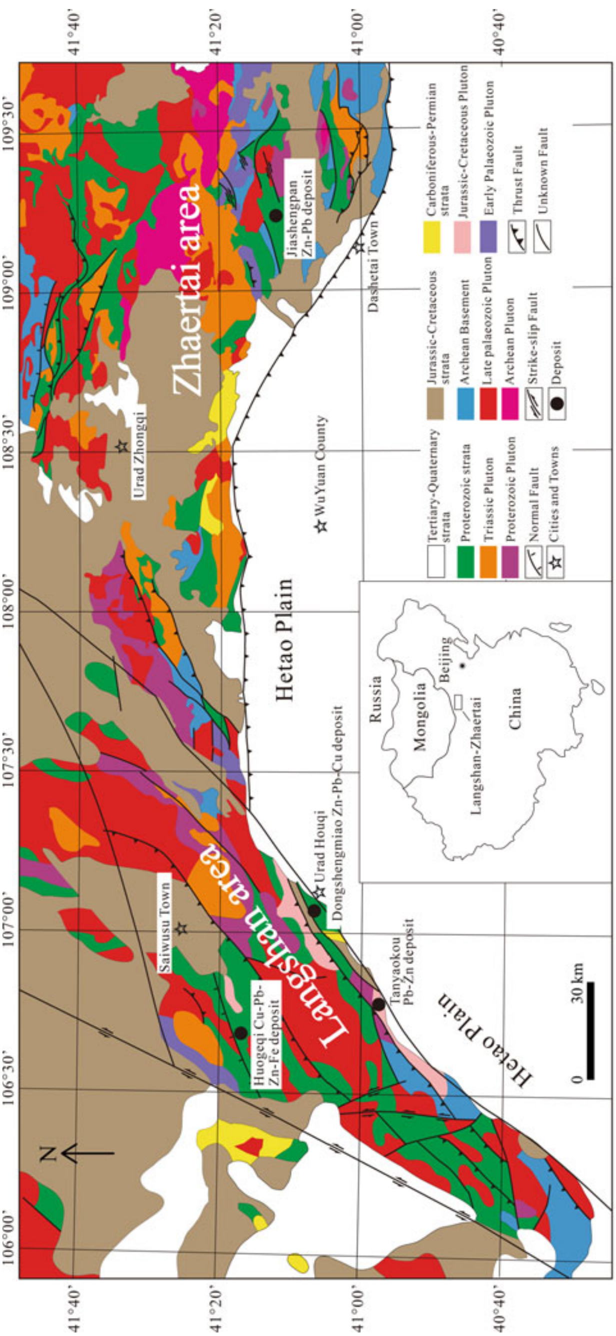

Fig. 1.2 Regional geology of Langshan-Zhaertai district (Modified after 1:500,000 regional geological map provided by the Bureau Geological Mineral Exploration and Development in Inner Mongolia, cited from Yu et al. 2019)

the northeast, the Proterozoic rift sequence is known as the Zhaertai Group. These rift sequences were deposited on Archean basement in the NCC during Meso- to Neoproterozoic rifting events (Lu et al. 2002; Zhai and Santosh 2013; Li et al. 2007; Zhai et al. 2008).

In earlier literatures, the Langshan and Zhaertai Groups were regarded as deposited synchronously in different parts of a single rift (e.g., Lu et al. 2002; Zhai et al. 2008). However, more recent geochronological works indicate that the Zhaertai Group was deposited during Paleoproterozoic, whereas the Langshan Group is Mesoproterozoic to Neoproterozoic (Peng et al. 2010; Gong 2014), implying that they might have different tectonic affinities during the Proterozoic. Based on U–Pb dating on detrital zircons separated from Proterozoic quartzite, the depositional age of metasedimentary rocks of Langshan Group was constrained to be younger than 1426 Ma (Sun et al. 2013). The geochronological studies of intercalated volcanic rocks of the Langshan Group obtain the zircon U–Pb ages of 867 ± 10 to 805 ± 5 Ma (Peng et al. 2010) and 804 ± 3.5 Ma (Gong 2014), constraining its depositional age to be Neoproterozoic. In addition, another work on the U–Pb dating of detrital zircons from metasedimentary rocks of the Langshan Group constrains them to be younger than 1100 Ma (Gong 2014). In the northeast, the emplacement of the Zhaertai Group is constrained to be Paleoproterozoic in age, based on the ages of detrital zircon from metasedimentary rocks that range from 2.5 to 1.8 Ga (Gong 2014) and the 1743 ± 7 Ma U–Pb dating result that is obtained by a single zircon grain separated from a basaltic metavolcanic rock (Li et al. 2007)

1.2.1.2 Phanerozoic

Paleozoic sedimentary strata are almost absent in the Langshan-Zhaertai area, except for some Carboniferous-Permian marine strata (Fig. 1.2), and all strata are overlain by Jurassic–Quaternary terrestrial sediments (Fig. 1.2). However, contemporaneous intrusive rocks are abundant. Carboniferous to Triassic (321–228 Ma) intermediate to granitic plutons were developed in this area (Fig. 1.2; Pi et al. 2010; Liu 2012; Wang et al. 2012; Wu et al. 2013). During this period, the northern margin of the NCC was reactivated during tectonic activity along the Paleo-Asian Ocean to the north. This reactivation was marked by widespread magmatism, metamorphism, and deformation. Paleozoic igneous rocks in the Langshan district are dominated by Late Paleozoic biotite granite, granodiorite, and intermediate intrusive rocks (Fig. 1.2), mostly dated at Late Carboniferous to Early Permian (Pi et al. 2010; Han et al. 2010). These intrusive rocks were interpreted as formed in an Andean-style continental-margin arc that was related to the subduction of the paleo-Asian oceanic plate beneath the NCC in the Late Paleozoic (Zhang et al. 2009b, 2009). On the other hand, an alternative model proposed that the final closure of the Paleo-Asian ocean was earlier than Late Devonian, and the Late Paleozoic plutons were formed in a post collisional tectonic setting (e.g., Xu et al. 2013). Except for the Late Paleozoic plutons, minor Proterozoic gabbro, amphibololite, diorite and granite, Early Paleozoic diorite and granite, and Mesozoic granite also occur in this area (Fig. 1.2; Peng et al. 2007b).

During the Late Jurassic-Early Cretaceous, intraplate deformations took place in large areas from far east Russian to eastern China, known as the Yanshanian tectonism (Dong et al. 2008; Yakubchuk 2004). In the northern margin of the North China Plate, although the geodynamic background is not well understood, far-field interaction of several convergent tectonic systems might have resulted in the intraplate deformation, i.e. the southward propagation of the Siberia Craton in conjunction with the opening of the Amerasian basin; final closure of Mongol-Okhotsk Oceans; subduction of Pacific beneath Eurasian plates; and collision between the Lhasa and Qiangtang blocks (Davis et al. 1998; Zheng et al. 1998; Xu et al. 2001; Dong et al. 2008; Darby and Ritts 2007; Yakubchuk 2004). The pattern of deformation varies in different areas. Large-scale strike-slip faults with offsets of several hundreds of kilometers are developed in Central Asia, Mongolia, and northeast China (Yakubchuk 2004). Metamorphic core complexes and contemporary magmatic activities are locally observed in Daqinshan (Wang et al. 2004; Qi et al. 2007; Davis and Darby 2010) and eastern Mongolia (Daoudene et al. 2013). Large-scale thrust faults and related molasse-filled basins are developed in a 1200 km-long east-west-trending intraplate orogenic belt in northern China, known as Yanshan in the east and Daqingshan in the west (Davis et al. 1998; Zheng et al. 1998; He et al. 1998; Dong et al. 2008; Zhang et al. 2009a). Accompanying the development of intraplate orogeny and the activity of thrust faults, regional metamorphism locally took place in this belt (Dong et al. 2008).

For the Langshan area, Darby and Ritts (2007) proposed two phases of Late Jurassic-Early Cretaceous tectonism: (1) a Late Jurassic-Early Cretaceous northwest-southeast crustal shortening, with development of thrust faults and widespread foreland basin sedimentation; (2) a Late Cretaceous east-west extension, with development of a 12 km^2 basin bordered by normal faults. Most of the widespread Cretaceous strata in the Langshan area (Fig. 1.2) are interpreted as foreland basin sediments that formed during crustal shortening (Darby and Ritts 2007). Combined with the widespread northwest-dipping Late Jurassic-Early Cretaceous thrust faults (Darby and Ritts 2007; Li and Liu 2009; Gao 2010; Fig. 1.2) and the absence of metamorphic core complexes in the Langshan district, the deformation during convergence seems to have been much stronger than the subsequent regional extension.

1.2.2 The Bainaimiao Area

The Bainaimiao area is located in the accretionary orogen, related to the evolution of CAOB (Hart et al. 2002). This area consists of the Bainaimiao arc and Mid-Ordovician-Early Silurian Ondor Sum subduction-accretion complex (Fig. 1.3; Xiao et al. 2003). This area is bounded by two E-W-trending regional faults, the Chifeng-Bayan Obo fault to the south and the Xar Moron fault to the north (Fig. 1.3). The Solonker suture, which is regarded as the suture between the NCC and Siberian Craton, is located to the far north of this area (Fig. 1.3; Xiao et al. 2003).

The strata in Bainaimiao area consist of the Bayan Obo Group, Baiyinduxi Group, Ondor Sum Group and Bainaimiao Group. The Mesoproterozoic Bayan Obo Group

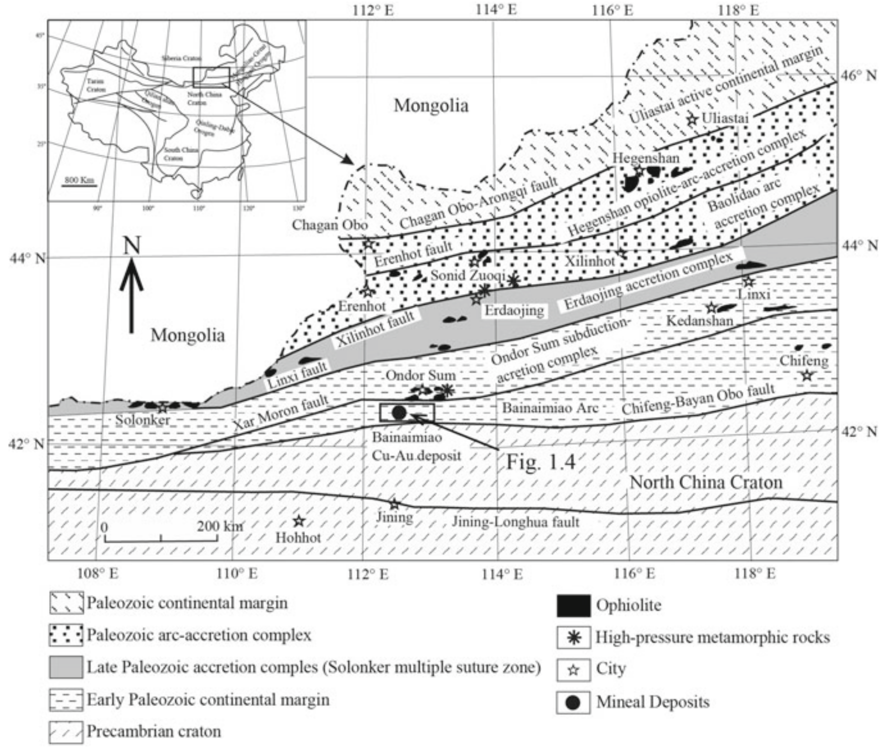

Fig. 1.3 Regional geological map of the northern margin of the North China Plate (Modified after Xiao et al. 2003, cited from Li et al. 2012)

is composed of slate and phyllite, occurs southwest of Bainaimiao area (Fig. 1.4). The Baiyinduxi Group, composed of sillimanite biotite schist and fine-grained biotite gneiss, determined as Mesoproterozoic based on Sm–Nd isochron data (Bureau of Geology and Mineral Resources of Inner Mongolia Autonomous Region 1991; Nie et al 1993; Zhang and Wu 1999), occurs northeast of the Bainaimiao deposit and shows a faulted contact with the Bainaimiao Group (Fig. 1.4). The Ondor Sum Group is composed of greenschist and exposed in the north of the Bainaimiao area (Nie et al. 1993; Fig. 1.4). Its metamorphic age is determined as 509 Ma by Rb–Sr whole rock isochron age and 538.8 Ma and 636 Ma by two K–Ar hornblende ages, respectively (Nie et al. 1993). The Bainaimiao Group, consists of sericite-altered felsic schist and greenschist, intruded by some Paleozoic granite (Fig. 1.4), is the host rock of the Bainaimiao Cu–Mo–Au deposit. Middle–Late Silurian Xuniwusu Formation, consisting of phyllite and slate, occurs to southwest of the Bainaimiao Group. In addition, Late Carboniferous greywacke and tuff, Early Permian sandstone and tuffaceous sandstone, and Jurassic intermediate and felsic volcanic rocks are exposed near the Bainaimiao Group (Fig. 1.4).

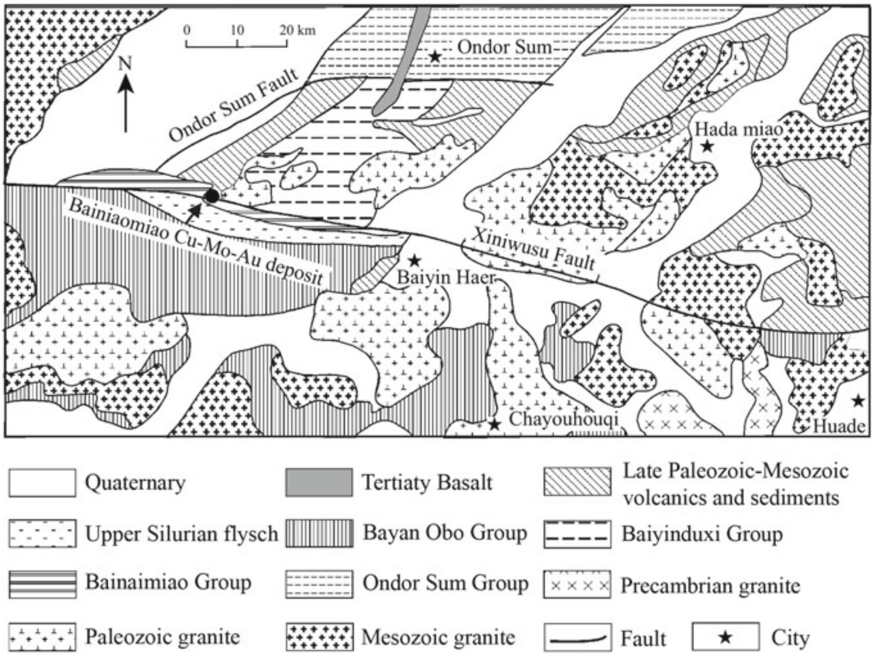

Fig. 1.4 Geological map of the Bainaimiao area (Modified after Nie et al. 1993, cited from Li et al. 2012)

1.2.3 A Special Focus on the Paleozoic Orogenesis

The eastern part of CAOB is located between the Siberian Craton to the north and the NCC to the south (Fig. 1.1), and it is a complex orogenic belt with successive accretion of arc complexes, accompanied by the emplacement of intrusions during Late Paleozoic to early Mesozoic (Davis et al. 2001; Xiao et al. 2003; Zhang et al. 2010; Xu et al. 2014).

The CAOB is the product the evolution of the long-lasting Paleo-Asian Ocean, and the time and location of the final closure of the ocean have been under debate for a long time. One viewpoint suggestes that two opposite subductions and collisions occurred during the late Devonian to early Carboniferous (Xu et al. 2013; Zhao et al. 2013; Shao et al. 2014), based on evolution of magmatic rocks, field geological mapping, regional structural and stratigraphical investigations (Tang 1990; Shao 1991; Xu and Chen 1993, 1997; Xu et al. 2001). Six tectonic units, namely the Southern margin of Ergun Block, South Mongolia microcontinent, Northern Orogenic Belt, Hunshandake Block, Southern Orogenic Belt and the North China Craton from north to south, were proposed by these researchers in central and western Inner Mongolia (Xu et al. 2013). The Northern Orogenic Belt is composed of arc–pluton belt, mélange, foreland molasse basin, and fold belt, from north to south, indicating a northern subduction–collision system between the Hunshandake Block and South Mongolia microcontinent during 500–380 Ma (Xu et al. 2013). The Southern Orogenic Belt consists also of four units from north to south: fold belt, mélange, arc–pluton belt, and retro-arc foreland basin, indicating a southern subduction–collision system between the NCC and Hunshandake Block during 500–440 Ma. In conclusion, a double subduction–collision accretionary process occurred in western Inner Mongolia during the early to mid-Paleozoic, resulting in the formation of the Northern Orogenic Belt and the Southern Orogenic Belt in 380 Ma and 410 Ma, respectively (Xu et al. 2013).

Some researchers propose another viewpoint that the collision between the NCC and the South Mongolia microcontinent occurred in the late Permian to early Triassic (Sengör and Natal'in 1996; Chen et al. 2000; Xiao et al. 2003; Zhang et al. 2007, 2009b; Chen et al. 2007, 2009; Wang et al. 2015). For example, Jian et al. (2008, 2010) argued that an early to mid-Paleozoic paired orogen was followed by a Permian intra-oceanic arc-trench system and a sequence of tectono-magmatic events from 299 Ma to 260 Ma, based on SHRIMP U–Pb ages and geochemical results of magmatic rocks. A geological framework and tectonic model of the western and central Inner Mongolia was proposed by Xiao et al. (2003). The northern accretionary zone which is located on the northmost China and southern Mongolia represents an active continental margin that was active till Permian, due to the northward subduction of the Paleo-Asian Ocean. The southern accretionary zone, which is located to the north of NCC, is a collage of mid-Ordovician–early Silurian Ulan island arc, the Ondor Sum subduction–accretionary complex and the Bainaimiao arc. These units were finally accreted to the NCC during late Ordovician, and became a part of the North China Plate, and then evolved into an active continental margin due to the southward subduction of the Paleo-Asian Ocean during the Carboniferous–Permian. This model proposes that the final closure of the Paleo-Asian Ocean caused the collision of the two opposing active continental margins, resulting in the formation of the Solonker suture in the late Permian.

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