Chapter 9

Tectonic evolution of the eastern Central Asian Orogenic Belt

The Central Asian Orogenic Belt (CAOB) is a large accretionary orogen (Sengör et al., 1993; Jahn et al., 2004a; Windley et al., 2007; Xiao et al., 2009) that separates the Siberia Craton to the North from the Tarim and North China cratons to the South (see Fig. 1-2 in Chapter 1; Xiao et al., 2003). Its major tectonic components include ophiolites, island arcs, oceanic islands, accretionary wedges and microcontinents (Khain et al., 2002, 2003; Xiao et al., 2003). It is a Precambrian through Early Mesozoic orogenic belt that provides excellent information on accretionary processes and continental growth (Sengör et al., 1993; Jahn et al., 2000; Jahn et al., 2004b; Xiao et al., 2009). Many studies have attempted to unravel the architecture of the CAOB and to reconstruct its history (e.g., Tang, 1990; Chen et al., 2000; Badarch et al., 2002; Xiao et al., 2003; Jahn et al., 2004a; Miao et al., 2008). However, the tectonic evolution of the CAOB is complicated because of the allochthonous nature of many terranes and their complex amalgamation. The evolution of the CAOB is subject to discussion; in particular the tectonic style, the position of the suture line, the timing of final suturing and the processes responsible for collision. It has been widely recognized that the Solonker suture zone, extending from Solonker, via Sonidyouqi, to Linxi, records the terminal evolution of the CAOB in Inner Mongolia (Tang, 1990; Sengör et al., 1993; Xiao et al., 2003).

The Xilinhhot-Linxi area is located in the Solonker suture zone between the Siberia
Craton and the North China Craton, in the eastern section of the CAOB. The process of collision and suturing between the cratons is related to the subduction and closure of the Paleo-Asian Ocean. After summarizing existing research findings, we carried out detailed geological fieldwork in the Xilinhot-Linxi area. We chose the Xilin Gol Complex (Chapter 3) and the Shuangjing Complex (Chapter 6 and 7) as the main research targets (Fig. 1-3), together with some dynamic metamorphic rocks (Chapter 5) and intrusives (Chapter 4 and 8), to study their mineralogy, petrology, geochemistry and geochronology. This forms the basis for the reconstruction of the evolution of the Xilin Gol and Shuangjing complexes, which underpins new models for the tectonic evolution of the eastern Central Asian Orogenic Belt.

§9.1 Evolution of the Xilin Gol Complex

(1) The protolith of the biotite-plagioclase gneiss from the Xilin Gol Complex is a sedimentary rock. Its source ages are older than 800 Ma. The protolith was deposited at the southern active continental margin of the Siberia Craton (Fig. 9-1a). This study resolves the debate regarding the age of the Xilin Gol Complex by conclusively showing that it is a Middle-Late Proterozoic terrane. The Xilin Gol Complex recorded the Middle-Late Proterozoic amalgamation of the Rodinia supercontinent on the southern margin of the Siberia Craton. The breakup of Rodinia induced the separation of the South Mongolia microcontinent from the southern margin of the Siberia Craton and the opening of the Paleo-Asian Ocean at the southern margin of the South Mongolia microcontinent, just south of the Xilin Gol Complex (Fig. 9-1b).

(2) The Xilin Gol Complex underwent partial melting and migmatization at 452 ± 5 Ma because of north-dipping oceanic subduction in the Sonidzuoqi-Xilinhot area (Fig. 9-1c). Many new magmatic materials were formed during this time and preserved in the complex, reflecting the presence of a continental marginal arc. Subduction of the Paleo-Asian Ocean started around 490 ± 8 Ma and lasted at least until 440 ± 4 Ma. The Xilin Gol Complex, Precambrian basement at the southern margin of the South Mongolia microcontinent, underwent strong deformation and recorded Early Paleozoic oceanic subduction, as well as accretion of the CAOB along the Xilinhot-Sonidzuoji north-dipping thrust belt. It was not a continental block that was rifted off the margin of Gondwana, but recorded the successive accretion of a long-lived, single accretionary arc at the southern margin of the South Mongolia microcontinent. Continued subduction of oceanic crust ended in collision between the accretion zones of the North China Craton and the South Mongolia microcontinent. The continental crust in the area then entered a
cycle of tectonic uplift, weathering, erosion and sedimentation (Fig. 9-1d).

Fig. 9-1 Tectonic evolution of the Xilin Gol Complex during the Proterozoic to Mesozoic

(3) The protolith of the plagioclase-amphibolite exposed in the Xilin Gol Complex is a basic rock that intruded into the base of the Xilin Gol Complex at 318 ± 5 Ma, as determined by LA-ICPMS U-Pb zircon dating. The biotite $^{40}$Ar/$^{39}$Ar age 312.2 ± 1.5 Ma of the biotite-plagioclase gneiss in Xilin Gol Complex also recorded this thermal event. Amphibolite facies metamorphism at 0.31-0.39 GPa and 620-660°C occurred at 263.4 ± 1.4 Ma, as indicated by the hornblende $^{40}$Ar/$^{39}$Ar age of this rock. The magma of the basic
Zircon U-Pb dating and geochemistry of the Shuangjing Complex

intrusion was not a primary magma but experienced crystal fractionation. Slab-derived fluids admixed into the magma source, which formed during early Paleozoic oceanic subduction along the Sonidzuqi-Xilinhaot north-dipping subduction zone.

(4) After Early Paleozoic oceanic subduction and collision, transient extension occurred during 320-280 Ma in the Sonidzuqi-Xilinhaot area (Fig. 9-1e). Extension induced widespread magmatic activity and thinning of the overriding continental crust in the Xilinhao area but did not lead to oceanization in the Xilin Gol Complex. However, there were oceanic basins around the Xilin Gol Complex during this time, which may reflect the loci of oceanization in response to this stage of extension. Extension may have been caused by collapse of the thickened crust after the collision of the oceanic and continental arcs.

(5) Final collision of the Solonker suture zone occurred during 265-228 Ma (Fig. 9-1f). The closure of the residual and young oceanic basins around the Xilin Gol Complex induced amphibolite facies metamorphism of the base of the complex. The Xilinhao-Sonidzuqi area entered a post-orogenic regime after 222 ± 4 Ma.

§9.2 Evolution of the Shuangjing Complex

(1) The Shuangjing Complex carries evidence for Paleoproterozoic basement in the Linxi area, which is therefore thought to be a part of the North China Craton. During amalgamation of the Rodinia supercontinent, the Linxi area was located at the northern margin of the craton (Fig. 9-2a). Upon breakup of Rodinia, widespread extensional stress induced rifting of the Shuangjing microcontinent off the North China Craton (Fig. 9-2b).

(2) During the Early Paleozoic, stresses related to southward subduction of the Paleo-Asian Oceanic crust concentrated in the Shuangjing microcontinent and led to the formation of a series of south-dipping thrust faults at its northern margin (Fig. 9-2c). The microcontinent approached the North China Craton upon southward subduction of oceanic crust, while small scale and south-dipping thrusts developed in the southern margin of the Shuangjing microcontinent. Continuous subduction induced accretion of Ordovician-Silurian oceanic sedimentary strata to the Shuangjing microcontinent and was followed by collision of the microcontinent with the craton (Fig. 9-2d).

(3) Transient extension during the Late Carboniferous to Middle Permian in central Inner Mongolia led to oceanization in the Linxi area (Fig. 9-2e). In response to extension, volcanics (298 ± 2 Ma) and intermediate intrusions (286 ± 1 Ma) developed in the continental margin of the Shuangjing microcontinent at Lianhuashan. The closure of the young oceanic basin induced the final collision between the North China Craton and the
South Mongolia microcontinent (Fig. 9-2f). Collision induced widespread magmatic activity in Linxi from 272 ± 2 to 231 ± 2 Ma.

Fig. 9-2 Tectonic evolution of the Shuangjing Complex during the Proterozoic to Mesozoic

§9.3 Tectonic evolution of the eastern CAOB

On the basis of our study of the metamorphic rock series in the Xilinhot and Linxi areas, we divide the tectonic evolution of the eastern Central Asian Orogenic Belt into
Zircon U-Pb dating and geochemistry of the Shuangjing Complex

Fig. 9-3 The Proterozoic to Mesozoic tectonic evolution of the Xilinhot-Linxi area
four stages: Precambrian basement evolution, Early Paleozoic arc-continent convergence, Late Paleozoic to Early Triassic opening and closure of a marginal ocean basin and Mesozoic active continental margin development (Fig. 9-3).

9.3.1 Precambrian basement evolution

There are two exposures of ancient metamorphic rocks in the research area: the northern Xilin Gol Complex in the Xilinhot area and the southern Shuangjing Complex in the Linxi area.

The Xilin Gol Complex, composed of gneisses, schists, and lenticular or quasi-layered amphibolites occurs in the Xilinhot-Bayanhushuo-Baiyinchagan area. Its protolith is a clastic sedimentary rock, deposited at the southern active continental margin of the Siberia Craton. Magmatic source materials formed mainly from 1150 to 900 Ma and some Archean sediments were added to the source. Diagenesis of the protolith predated 800 Ma. The Xilin Gol Complex recorded the Middle-Late Proterozoic amalgamation of the Rodinia supercontinent at the southern margin of the Siberia Craton.

The Shuangjing Complex, composed of granitic gneiss and schists, is represented in Linxi County. The protolith of the schist is a volcanic-sedimentary rock series, with a few lenticular marbles. The schists in the Shuangjing Complex were thought to be Archean metamorphic rocks that form the basement of the area (SRGST-IMAR, 1997). Our research indicates that the schist is not an Archean terrane but has a Late Carboniferous U-Pb zircon formation age of 298 ± 2 Ma. A concentration of crustal xenoliths occurs at the edge of the marginal facies of the granitic gneiss in the Shuangjing Complex. The presence of Paleoproterozoic intermediate magmatic rocks below the schist is suggested by detrital zircon ages of 2190 ± 8 to 1804 ± 25 Ma from the xenoliths. A xenolith zircon core age of 3377 ± 7 Ma indicates Paleoarchean basement may also exist in the source area. The Paleoproterozoic age is consistent with the widespread Luliang and Fuping orogenic stages in the North China Craton, suggesting the Linxi area is underlain by the same basement as the North China Craton. Therefore, we suggest that the Shuangjing schist is not Archean basement, but part of a Paleoproterozoic geological terrane that rifted away from the northern margin of the North China Craton to form the Shuangjing microcontinent.

The North China Craton formed during Jinning orogeny (1000-800 Ma), which had crucial impact on the tectonic evolution of China (Ren et al., 1980; Yang and Wang, 1991). After Jinning orogeny, the North China and Tarim cratons merged to form the so-called “Asian axial structure” (Wang et al., 1990). Combining the tectonic evolution of the
research area and adjacent areas, Gao et al. (2001) suggested that the North China Craton split during Middle to Late Proterozoic and developed a series of EW directional rifts. Ren et al. (1999; 2002) suggested that the Ancient China Continental Segments rifted away from the main North China Craton during the Late Neoproterozoic to Early Cambrian. Wu et al. (1998) studied ancient continental units at the northern margin of the North China Craton by comparison of rock assemblages and P-T-t paths of different continental blocks. The blocks showing amphibolite facies metamorphism were thought to be extensional products, reflecting long-lived extension. This prolonged extension is the root cause of the formation of many microcontinents at the northern margin of the North China Craton during the Neoproterozoic.

The evolution of the Xilinhot-Linxi area during the Precambrian can be summarized as follows:

(1) In the Paleoproterozoic, the Shuangjing area in the south of Linxi County was part of the northern margin of the North China Craton.

(2) In the Mesoproterozoic to middle Neoproterozoic, associated with the assembly of the Rodinia supercontinent, the southern margin of the Siberia Craton developed into an active continental margin, which resulted in extensive magmatism during this time. Following collision with another continental block, the southern margin of the Siberia Craton experienced rapid uplift and erosion. Erosion materials were deposited in the Xilinhot area and became the protolith of the Xilin Gol Complex. The major components of the protolith are magmatic materials formed at 1150-900 Ma during amalgamation of the Rodinia supercontinent, augmented with some ancient sedimentary materials.

(3) From the Middle to Late Neoproterozoic, Rodinia started to break up, leading to extension at the northern margin of the North China Craton and the southern margin of the Siberia Craton, and eventual break-up and oceanization to form the Paleo-Asian Ocean. The South Mongolia microcontinent separated from the southern margin of the Siberia Craton at this time. A number of continental rifts developed near the northern margin of the North China Craton, inducing the development of several microcontinents, including Shuangjing. Oceanization occurred in at least some of the intervening basins.

(4) From Late Neoproterozoic to Early Paleozoic times, the microcontinents at the northern margin of the North China Craton may locally have experienced convergence or overthrusting, but the central-eastern section of Inner Mongolia, including the study area, experienced continuous ocean spreading. At this stage, some microcontinents and islands of various sizes and shapes existed in the ocean. The biggest in the research area was the South Mongolia microcontinent, the Shuangjing microcontinent was another. The wide oceanic basin, together with small-scale microcontinents and arcs formed during
convergent stages, forms the tectonic framework of the Paleo-Asian Ocean in the Xilinhot-Linxi and adjacent areas.

9.3.2 Early Paleoozoic arc-continent convergence

During the Early Paleoozoic, the Paleo-Asian Oceanic crust, the North China Craton, the Siberia Craton and the microcontinents in the ocean endured a complex tectonic evolution, leading to long-term disputes regarding the tectonic framework and evolution of the area.

At the beginning of the Early Paleoozoic, the Shuangjing microcontinent was located near the northern margin of the North China Craton. There is no material with accurate Cambrian ages in the area. It is speculated that the tectonic regime of the area at this stage was inherited from the Precambrian extensional evolution and the northern margin of the North China Craton remained a stable passive continental margin. During the Middle-Late stages of the Early Paleoozoic, subduction roll-back occurred at the northern margin of the North China Craton. In the Ordovician and Silurian the part of the Paleo-Asian Ocean in the study area underwent bilateral subduction: to the north below the South Mongolia microcontinent and to the south below the North China Craton. With continued convergence, the Xilinhot-Linxi area became the suture zone. Upon closure of the oceanic basin, fragments of oceanic crust were included in the Early Paleoozoic Ondor Sum orogenic belt, which is part of the lateral accretion belt at the northern margin of the North China Craton (Ren et al., 1999; 2002). The structure of the suture zone is very complex and in the research area it can be divided into three belts from north to south.

9.3.2.1 Northern section of the suture zone

The main part of the Xilinhot island arc belt crops out in the Xilinhot-Bayanhusuo-Baiyinchagan area as basement of the strongly deformed and metamorphosed Xilin Gol Complex. It forms sequences of thrust slices with opposite inclination at the northern and southern edges of the belt, in the center of which ultrabasic-basic and granitoid melts intruded. Some granites developed a gneissic structure. In the south of the Xilinhot island arc belt, the Xilin Gol Complex overlies the Ordovician-Silurian tectonic slice of the Xuniwusu group with marine volcanic and flysch protoliths, along a brittle-ductile fault belt (GS-CUG, 2008). The fault plane dips to NW 330-345° with dips between 45 and 75°. Stretching lineations on the fault plane have the same trends, which together with the fault plane indicates SSE-directed thrust-sense movement of the Xilin Gol Complex over the Silurian tectonic slice of the Xuniwusu group, probably in a subduction setting. In response, the Xilin Gol Complex hanging wall
and the Xuniwusu tectonic slice in the footwall suffered identical top-to-southeast ductile shear deformation. Northward subduction of the Silurian tectonic slice below the Xilin Gol Complex was a prolonged process accompanied by deformation and metamorphism.

Subduction below the Xilin Gol Complex brought about uplift and thickening of the Xilin Gol Complex, inducing intense melting at $452 \pm 5$ Ma with strong ductile deformation under shear stress. Northward subduction of the Xuniwusu group led to its accretion at the southern margin of the Xilin Gol Complex. Continued subduction resulted in collision of the Xilinhhot island arc with the southern active margin of the South Mongolia microcontinent, reflected by the formation of a $416 \pm 3$ Ma granite in the southern branch of the early Paleozoic subduction-accretion zone. After early Paleozoic collision, widespread magmatic activity occurred at $316 \pm 2$ to $302 \pm 2$ Ma due to transient extension at the southern margin of the South Mongolia microcontinent. There were deep marine basins at the southern margin of the $416 \pm 3$ Ma granite during the Permian. Late Paleozoic-Early Triassic north-dipping subduction led to the closure of these oceanic basins and final suturing of the CAOB.

**9.3.2.2 Central section of the suture zone**

In response to North-South compression caused by the contraction of the Paleo-Asian Ocean, an East-West striking fold belt formed between the northern Xilinhhot island arc and the southern Xar Moron fault belt (Fig. 10-3). The axis of this Early Paleozoic fold belt was nearly obliterated by weathering, erosion and the opening and closure of oceanic basins during the Late Paleozoic to Early Triassic. A few remnants of the belt survived at the margins of the Permo-triassic oceanic basins.

**9.3.2.3 Southern section of the suture zone**

The main part of the southern Xar Moron fault belt occurs along the Xar Moron River in the south of Linxi County. During southward subduction of Paleo-Asian Oceanic crust, stress concentrated in the area of the Shuangjing microcontinent and led to the formation of two south-inclined fault belts, at the northern and southern margins of the microcontinent. As a result, the Shuangjing microcontinent broke into several fragments of various sizes. This resulted in a wedge-shaped, SW-NE striking fault belt with a broad eastern section and a narrow western section across the Kedanshan-Jiushenmiao-Shuangjianshan area in the south of Linxi (Fig. 1-3 in Chapter 1).

Ordovician-Silurian strata are exposed along the Xar Moron River in Linxi County, including the Ordovician Baoerhantu group near Kedanshan and the Silurian Xibiehe formation in the Shangganggangkundui-Nadaga-Xiaoweiitang-Xinshuwa area. The protoliths of the Baoerhantu group and the Xibiehe formation are marine volcanics-flysch composites and represent an oceanic basin depositional sequence (GS-CUG, 2008). The
Bainaimiao Ordovician arc rock series in the study area and the Xuniwusu Silurian back-arc basin deposits to the west of the study area in the Ondor Sum area may correspond to the Baoerhantu group and the Xibiehe formation, respectively (Hu, 1990; Shao, 1991; Tang, 1992). Southward subduction of the Paleo-Asian Ocean below the North China Craton in the Ondor Sum-Xar Moron area in the Early Paleozoic led to the similarity in age and the spatial continuity between the units, and marked the transition from a passive to an active accretionary northern margin of the North China Craton.

Comprehensive analysis of the formation and ages of the main geological terranes in the Xar Moron area suggests that the main part of this belt is a residual Early Paleozoic orogenic belt that underwent intense deformation in the Late Paleozoic-Early Triassic. Compared to the northern Xilinhot island arc belt, the Xar Moron units developed in a similar regime of oceanic subduction below a continent, but the scale of tectonic terranes in this belt, the degree of accretion and the evolution are quite different. This suggests a more complex sequence of subduction and accretion: (a) Initial subduction of the Paleo-Asian Oceanic crust at the northern margin of the North China Craton was located far south of the Xar Moron fault and consumed the oceanic basin between the Shuangjing microcontinent and the North China Craton. (b) When the Xar Moron area reached the continental margin, the Shuangjing microcontinent accreted onto the margin of the North China Craton and the Early Paleozoic Ondor Sum Orogeny developed parallel to the Xar Moron fault. (c) After accretion of the Shuangjing microcontinent, the section of the Paleo-Asian Ocean located to its north, started to subduct towards the south below the new cratonic margin. The Paleo-Asian Oceanic crust between the South Mongolia microcontinent and the North China Craton subducted towards both south and north, and terranes were accreted to the northern margin of the North China Craton. Convergence between the microcontinents and the North China Craton resulted in many geological units in the suture zone, reflecting long-lived intense deformation and multiple stages of convergence, subduction and accretion.

9.3.3 Late Paleozoic-Early Triassic opening and closure of a marginal ocean basin

Early Paleozoic orogenesis brought about the consumption of most of the Paleo-Asian Ocean. North-South compression, recorded by the composite of the East-West striking orogenic belt and the North China Craton, dominated the study area during Late Paleozoic. Devonian-Early Carboniferous sediments are absent in the study area, but numerous old zircons with detrital cores were found in an Upper Jurassic
Zircon U-Pb dating and geochemistry of the Shuangjing Complex

andesite of the Manitu volcanic formation (J3m) in the Qihetang area of Linxi County (GS-CUG, 2008). These detrital cores yield U-Pb ages of 1938-400 Ma, reflecting the presence of Proterozoic basement, Ordovician-Silurian subducted oceanic crust and Late Paleozoic magmatic products in the units eroded during orogenesis. Therefore, the Linxi area may have been subaerial continent around 400 Ma, when the Early Paleozoic orogenic belt had accreted to the North China Craton after the closure of the Paleo-Asian Ocean.

From the Late Carboniferous, the Xilinhot-Linxi area entered a North-South extensional regime that induced the development of East-West striking intracontinental rifts and widespread magmatic activity along the Early Paleozoic orogenic belt. Various intrusions occur along the northern Xilinhot island arc belt with a narrow range of ages, such as LA-ICPMS U-Pb zircon ages of 316 ± 2 to 302 ± 2 Ma from granodiorite in Yuejin Township (Chapter 5), a SHRIMP U-Pb zircon age of 309 ± 8 Ma from quartz-diorite in Sonidzuqi (Chen et al., 2001), a LA-ICPMS U-Pb zircon age of 319 ± 4 Ma from diorite in Xilinhot (Chapter 4), a SHRIMP U-Pb zircon age of 316 ± 3 Ma from garnet-bearing granite in Xilinhot (Shi et al., 2003), and SHRIMP U-Pb zircon ages of 323 ± 4 to 313 ± 5 Ma from quartz-diorite in Xilinhot (Bao et al., 2007). Meanwhile, extrusive rocks were widely developed in the southern Xar Moron fault belt. A typical extrusive is the volcanic part of the Shuangjing schist in Linxi, whose protolith is a volcanic with a LA-ICPMS U-Pb zircon age of 298 ± 2 Ma (Chapter 7). The widespread Late Carboniferous magmatic rocks reflect to the initial stages of rifting. Further development of the rift induced continued magma activity in both the northern Xilinhot island arc belt and the southern Xar Moron fault belt, resulting in volcanic rocks of 299 ± 3 to 267 ± 3 Ma at Bayanhushuo in the northern belt (Chapter 5) and a diorite of 286 ± 6 Ma at Shuangjing in the southern belt (Chapter 8). Hong et al. (1994) reported an alkali granite with a Rb-Sr age of 286-276 Ma from the Baiynwula-East Ujimqinq area, which also reflects the extensional tectonic regime that affected the research area at this time.

Middle Permian radiolarian fossils from the Zhesi sedimentary formation (P2z) were found in Yuejin (Shang, 2004), just ~10 km south of the Xilin Gol Complex. Along the Solonker suture zone, Jian et al. (2010) dated zircons from an N-MORB-like diabase (274.4 ± 2.5 Ma), an E-MORB-like diabase (252.5 ± 2.3 Ma), a transitional sanukitoid/adakite (andesite, 250.2 ± 2.4 Ma), a sanukitoid (high-Mg diorite; 251.8 ± 1.1 Ma) and an anorthosite (252.2 ± 1.7 Ma). The N-MORB-like diabase contains ca. 301-394 Ma zircon xenocrysts that were interpreted to reflect assimilation of trench sediments when a spreading ridge passed the trench (Jian et al., 2010). Their young formation ages are thought to constrain a magmatic episode in response to slab break-off.
beneath a fossil forearc, and the youngest xenocryst ages (ca. 269-273 Ma) may define the maximum depositional age of the trench sediments. A diorite of the Baolidao arc was dated at 310 ± 5 Ma and the Halatu granite was dated at 234 ± 7 Ma (SHRIMP U-Pb; Chen et al., 2008). The combined data suggest the existence of one or more oceanic basins between the Shuangjing microcontinent, accreted to the northern margin of the North China Craton, and the South Mongolia microcontinent in the Middle Permian.

The rifts in the research area were closed again when the extensional regime was followed by compression. The geochemistry of a granodiorite of 274 ± 2 Ma (LA-ICPMS U-Pb zircon age) at Buliemiao in the Xilinhot island arc belt (Chapter 5) and a granite of 272 ± 2 Ma (LA-ICPMS U-Pb zircon age) at Fangkuangzi in the southern Xar Moron fault belt (Chapter 7) indicates that they are I-type granite and S-type granite, respectively, reflecting active compression in both the southern and the northern belt. In terms of volume, the Fangkuangzi granite, emplaced dominantly at 265 ± 2 Ma in response to continued compression. At this time, the oceanic basins are thought to be closing again. Compression and collision induced extensive magmatic activity, as well as variable degrees of metamorphism and deformation, as is supported by a variety of age data from the research area. A hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ age of 263.4 ± 1.4 Ma and LA-ICPMS U-Pb zircon ages of 260 ± 3 and 231 ± 3 Ma from plagioclase-amphibolite in the Xilin Gol Complex (Chapter 4), a LA-ICPMS U-Pb zircon age of 263 ± 3 Ma that reflects mylonitization of a granodiorite at Buliemiao (Chapter 5), a whole rock Rb-Sr isochron age of 228 ± 21 Ma and a SHRIMP U-Pb zircon age of 254 ± 4 Ma from a collisional granite in the south of Sonidzuqi (Chen et al., 2001), LA-ICPMS U-Pb zircon ages of 262 to 231 Ma on recrystallized rims of zircon grains from a S-type granite at Fangkuangzi (Chapter 7), SHRIMP U-Pb zircon ages of 229.2 ± 4.1 and 237.5 ± 2.7 Ma from a granite in the west of Shuangjing (Li et al., 2007), and finally muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 224.6 ± 1.1 and 223.1 ± 1.8 Ma from mylonites in Shangganggangkundui in the east of Shuangjing (Ma, 2009) all reflect compression and collision. The Late Permian to Middle Triassic final collision of the eastern section of the Solonker suture zone led to the accretion of all microcontinents in the Paleo-Asian Ocean, as well as the trailing South Mongolia microcontinent to the northern margin of the North China Craton, marking final closure of this ocean (Chapter 8). Shi et al. (2007) obtained a SHRIMP U-Pb zircon age of 222 ± 4 Ma from an A-type granite in Sonidzuqi, marking full collision and the complete closure of the oceanic basins. At this point, the Mongol-North China block had formed, after which the Xilinhot-Linxxi area entered a post-orogenic regime.

Sedimentary sequences from the Early Permian to Early Triassic in the Linxi area include flysch of the Shoushangou formation (P$_1$s), intermediate to basic volcanic rocks
and flysch of the Dashizhai formation (P₁ds), marine flysch and carbonate rocks of the Zhesi formation (P₂z) and inland fluvial and lacustrine sediments with some turbidite and marine sediments of the Linxi formation (P₃-T₁l; GS-CUG, 2008). This sequence reflects pediplanation of an orogenic belt (P₁s), initial development of a continental rift (P₁ds), oceanization and deep water sedimentation (P₂z) and closure of an oceanic basin (P₃-T₁l), which summarizes the complete evolution of an oceanic basin from continental extension to closure. Considering the hiatus of Devonian-Carboniferous strata in Linxi-Xilinhot area (GS-CUG, 2008), the marginal ocean basin that existed from Late Carboniferous to Permian times had probably been newly formed. In summary, the magmatic and sedimentary events in the area are consistent and reflect opening and closure of an oceanic basin.

9.3.4 Mesozoic active continental margin development

The tectonic framework of the study area was established by Late Paleozoic-Early Triassic orogenesis. The Late Permian to Middle Triassic final collision of the eastern section of the Solonker suture zone led to the accretion of the microcontinents of Central Mongolia, South Mongolia, Ergun, Jiamus etc. (Fig. 8-15 in Chapter 8) to the northern margin of the North China Craton, indicating the final closure of the Paleo-Asian Ocean. After this time, the Mongolian-Okhotsk Ocean, a branch of the Paleo-Pacific Ocean, was oriented SW-NE between the Siberia Craton and the amalgamated Mongol-North China block (Fig. 9-3, 4th panel from top; Li, 2006).

Previous work suggested that the contraction and closure of the Mongolian-Okhotsk Ocean resulted from northward subduction of the oceanic lithosphere below the Siberia Craton, and that the Ergun and Central Mongolian margins of the ocean were Atlantic-type passive margins (Zonenshain et al., 1990; Parfenov et al., 1995; Zorin, 1999). However, recent studies on the magmatic rocks in Heilongjiang (Sorokin et al., 2002; Zhang et al., 2002; Zhang et al., 2003; Li, 2004) and volcano-sedimentary sequences and granitoids in the northern segment of Changbai Mountains (Li et al., 1999a, b) imply that a long-lived active margin existed at the northern margins of the Ergun and Jiamusi blocks, that were already accreted to the North China Craton at this time. Therefore, there was simultaneous southward subduction of the Mongolian-Okhotsk oceanic plate below the northern margin of the Ergun and Jiamusi blocks during its northward subduction into the Siberia Craton (Li, 2006). Continued subduction of oceanic plate resulted in closure of the Mongolian-Okhotsk Ocean. On the basis of magmatic, paleobiogeographical and paleomagnetic studies, it has been suggested that the
Mongol-Okhotsk Ocean closed with a scissor-like movement from the Late Carboniferous to Permian in central Mongolia, to Triassic or Early Jurassic in NE Mongolia (Zorin, 1999; Kravchinsky et al., 2002; Cogné et al., 2005; Tomurtogoo et al., 2005). The Mongol-Okhotsk Ocean closed completely with the collision of Mongol-North China block and Siberia Craton in the Late Jurassic in the Far East of Russia (Ying et al., 2010). Considering the low closure temperature for the hornblende K-Ar isotopic system (~510°C; Dodson and McClelland-Brown, 1985), the 188.7 ± 1.4 Ma hornblende 40Ar-39Ar age from the gneissose diorite in the Xar Moron fault belt in Linxi County (Chapter 8) represents the last tectonometamorphic event recorded by the diorite: continent-continent collision after the Triassic-Early Jurassic closure of the Mongol-Okhotsk Ocean in NE Mongolia. After this, NE Mongolia entered a regime of post-orogenic extension.

At the end of the Jurassic, subduction of the Paleo-Pacific plate beneath the Eurasian plate changed from flat and westward to north- or northwest-vergent (Maruyama et al., 1997; Sagong et al., 2005). This caused a change from compressional to extensional tectonics across the region, resulting in large-scale delamination of thickened crust, elevation of the geotherm, and steepening of subduction (Zhang et al., 2009a). The diabase dyke swarms in the Linxi area were divided into three types, which formed in the Lower Jurassic (199 Ma), Middle Jurassic (170 Ma) and Lower Cretaceous (100 Ma), with strikes of NW330°, NW350° and NE20°, respectively (Shao et al., 1998), suggesting multiple alternations between compression and extension during the Jurassic. In a comprehensive analysis of research data and the literature, Zhou et al. (2006; 2009) concluded that the transition towards extension started from 160-140 Ma, that another period of extension occurred around 120 Ma and that extension finally took over at 110-100 Ma.

The frequent alternation of tectonic regimes during the Jurassic suggests more than one controlling process. The research area underwent post-orogenic extension after the Early Jurassic closure of the Mongol-Okhotsk Ocean in NE Mongolia. Therefore, there was NS extensional stress during this time in the research area. Considering that westward subduction of the Paleo-Pacific plate below the North China Craton lasted until the Late Jurassic, the research area experienced EW compressional stress during the Jurassic. The combined action of the two stress fields led to the Jurassic alternation of tectonic regime. It was suggested that the alternation of tectonic regimes was also affected by far-field stresses related to the collision between the South China Craton and the North China Craton (Xu, 2001).

At the end of the Jurassic, a change in the subduction direction of the Paleo-Pacific
plate led to a switch in the regional tectonic setting from compression to extension. Regional extension induced widespread magma activity in northeastern China during this time (Shao et al., 2001b; Hong et al., 2000; Wu et al., 1999; Zhang et al., 2006). The intermediate dyke swarms documented in Chapter 8 resulted from this stage of extension. There have been many discussions on the geodynamic background of lithospheric thinning in eastern China (Wu et al., 2003; Xu, 2006; Deng et al., 2006). Thinning was thought to be related to subduction of the Pacific plate, which initially induced thickening of the lithosphere, followed by delamination. Global seismic tomography reveals a high-speed anomaly horizontally distributed in the mantle transition zone in the east of China, which is thought to represent the subducted Pacific plate (Fukao, et al., 1992; Zhao, 2004). Thinning of the lithosphere in the northeastern China could therefore also be related to intensive mantle convection induced by the subduction of the Pacific plate.