Carboniferous–Permian Stratigraphy and Sedimentary Environment of Southeastern Inner Mongolia, China: Constraints on Final Closure of the Paleo-Asian Ocean

ZHU Junbin and REN Jishun*

Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

Abstract: In this paper we discuss the timing of final closure of the Paleo-Asian Ocean based on the field investigations of the Carboniferous–Permian stratigraphic sequences and sedimentary environments in southeastern Inner Mongolia combined with the geology of its neighboring areas. Studies show that during the Carboniferous–Permian in the eastern segment of the Tianshan-Hinggan Orogenic System, there was a giant ENE–NE-trending littoral-neritic to continental sedimentary basin, starting in the west from Ejining eastwards through southeastern Inner Mongolia into Jilin and Heilongjiang. The distribution of the Lower Carboniferous in the vast area is sparse. The Late Carboniferous or Permian volcanic-sedimentary rocks always unconformably overlie the Devonian or older units. The Upper Carboniferous–Middle Permian is dominated by littoral-neritic deposits and the Upper Permian, by continental deposits. The Late Carboniferous–Permian has no trace of subduction-collision orogeny, implying the basin gradually disappeared by shrinking and shallowing. In addition, it is of interest to note that the Ondor Sum and Hegenshan ophiolitic mélanges were formed in the pre-Late Silurian and pre-Late Devonian respectively, and the Solonker ophiolitic mélanges formed in the pre-Late Carboniferous. All the evidence indicates that the eastern segment of the Paleo-Asian Ocean had closed before the Late Carboniferous, and most likely before the latest Devonian (Famennian).

Key words: Carboniferous–Permian, stratigraphic sequences, southeastern Inner Mongolia, Paleo-Asian Ocean

1 Introduction

Southeastern Inner Mongolia that lies on the eastern segment of the Tianshan–Hinggan Orogenic System (Ren Jishun et al., 1980, 1999) is regarded as the finally closed place of the Paleo-Asian Ocean. However, the timing of its closure in this region has long been controversial, and there are two prominent views on it: (1) some geologists consider that the Paleo-Asian Ocean finally closed before the Carboniferous or earlier, and that it entered the post-closure evolution stage in the Late Carboniferous or Late Devonian (Guo Shengzhe, 1986; Tang, 1990; Shao J’ian, 1991; Tang Kedong and Zhang Yumping, 1991; Xu Bei et al., 1997; Shao Ji’an et al., 2015b; Tong et al., 2015; Xu et al., 2015; Zhao et al., 2016); and (2) others hold that the opposing margins of the Siberian Craton and the Sino-Korean Craton accreted to each other, suturing into one continent in the latest Late Paleozoic or earliest Mesozoic (Wang and Liu, 1986; Xiao et al., 2003, 2009, 2015; Li, 2006; Li Jinyi et al., 2007; Miao et al., 2008; Chen et al., 2009; Zhang et al., 2007, 2009a,b; Jian et al., 2010; Eizenhöf er et al., 2014; Wilde et al., 2015; Zhang et al., 2015; Li Shan et al., 2016). Hence, research on the Late Paleozoic tectonic evolution of southeastern Inner Mongolia, especially its Carboniferous–Permian depositional and tectonic settings, is key to answering this subject.

Previous studies of Late Paleozoic tectonic evolution were focused on petrology, geochronology, and geochemistry (Jahn et al., 2000; Zhang et al., 2008; Chen et al., 2009; Hu et al., 2015; Tong et al., 2015). The relationship of stratigraphic systems and sedimentary characteristics to structural features is poorly understood. Research of temporal and spatial variations in stratigraphic sequences and sedimentary environments has been
lacking. Therefore, between 2013 and 2015 we carried out detailed field work and indoor integrated studies of Carboniferous–Permian strata in southeastern Inner Mongolia, with the emphasis on its stratigraphic sequences and sedimentary environments, to deepen our knowledge of the tectonic setting of the region, and explore the closure time of the Paleo-Asian Ocean.

2 Stratigraphic Systems and Sedimentary Environments

2.1 Stratigraphic systems

Carboniferous–Permian strata are widely distributed in southeastern Inner Mongolia north of the Sino-Korean Craton. According to lithostratigraphic sequences, paleontologic fossils, tectonic settings and sedimentary types, the region can be divided into three stratigraphic subregions from north to south: Dong Ujimqini (bounded by the China–Mongolia border on the north, and the Erenhot–Hegenshan line on the south), Inner Mongolia Grassland (bounded by the Erenhot–Hegenshan line on the north, and the Xar Moron River on the south), and Chifeng (bounded by the Xar Moron River on the north, and the Chifeng–Bayan Obo fault on the south) (Fig. 1).

2.1.1 Dong Ujimqini stratigraphic subregion

The Carboniferous–Permian in this region is distinguished into the Upper Carboniferous Baoligaomiao Formation, the Lower Permian Gegen Obo Formation, and the Middle Permian Zhesi Formation.

The Baoligaomiao Formation lies unconformably upon the Upper Devonian Angeeryinwula Formation or older strata. It is a suite of terrestrial intermediate-acidic volcanics, volcanioclastics, and terrigenous clastics, with andesite, andesitic basalt, dacite, tuff, tuffaceous sandstone, siltstone, and sandy conglomerate included. The fossil is represented by the plant *Noeggerathiopsis–Angaropteridium* assemblage, which is the most common element of the Late Carboniferous terrestrial strata in northern Heilongjiang and eastern and western Junggar of Xinjiang in China, as well as the Kuznet Basin in Russia (Li Wenguo et al., 1981). Considering that volcanics have U-Pb zircon ages of 320 to 300 Ma (Xin Houtian et al., 2011; He Shusai et al., 2014; Li Ke et al., 2015) in combination with the fossil plant evidence, the Baoligaomiao Formation can be determined as Late Carboniferous in age.

The Gegen Obo Formation is exposed in the southwestern Dong Ujimqini area, and can be divided

![Diagram of stratigraphic distribution](image-url)
into two parts according to its lithology. The lower part of it consists of volcanics, volcanioclastics and terrigenous clastic rocks, including andesite, dacite, volcanic breccia, tuff, sandstone, and conglomerate. The upper part consists of conglomerate and sandstone intercalated with limestone lenses, grading upwards into silty mudstone, siltstone, and shale. Parallel beddings are common in sandstone. This formation contains Early Permian (Chishian) brachiopods *Kochi productus* sp., *Linoproductus simensis*, *Rhyynchopora inconstans*, and *Licharewia greeningi* within limestone (Tazawa, 2011); and fossil plant fragments are found in silty mudstone at the top (Fig. 2a). Zircon U–Pb dating of volcanics yields a Late Carboniferous age (ca. 312 Ma) for the lower part (Zhu Junbin et al., 2015), but the Chishian brachiopods for the upper part suggest a late Early Permian age. Obviously, there is a depositional break between the volcanics and sedimentary strata, lacking the earliest Permian deposition. The facts lead to a more appropriate subdivision: the upper sedimentary strata belong to the Gegen Obo Formation, and the lower volcanic rocks, to the Baoliaoqiaomiao Formation.

The Middle Permian Zhesi Formation crops out in Xiaobaliang in the southern Dong Ujimqinqi area. It consists of conglomerate, arkose, muddy siltstone, and limestone, with the Wordian-age brachiopod *Spiriferella–Kochi productus* assemblage (Wang Chengwen and Zhang Songmei, 2003; Shen et al., 2006). This formation is usually directly covered by Quaternary deposits and lies unconformably upon the Devonian Hegenshan holoilithic mélange (Wang Quan et al., 1991; Ren Jishun et al., 1992).

2.1.2 Inner Mongolia Grassland stratigraphic subregion

This area encompasses the grasslands east of Sonidzuqoi, i.e. Xinlinhot, Xi Ujimqinqi, and Linxi. Here, the Carboniferous–Permian is well developed. It comprises the Lower Carboniferous Aomugenhuudge Formation, the Upper Carboniferous Benbatu Formation, the Upper Carboniferous–Lower Permian Amusam Formation, the Lower Permian Shoushangou and Dashzhai formations, the Middle Permian Zhesi Formation, and the Upper Permian Linxi Formation, in ascending order (Fig. 3).

The Aomugenhuudge Formation, which is exposed in the southern Sonidzuqoi and Abagaqi areas, consists of conglomerate, sandstone, siltstone, feldspar-quartz sandstone, quartz sandstone, and volcanioclastics intercalated with shale, thin-bedded limestone, and limestone lenses. This formation is more than 1000 m-thick and overlies the Upper Devonian Seribayan Obo Formation. The coral *Sugiyamaeella–Siphonophyllia* assemblage and the brachiopod *Syringothyris–Spirifer* assemblage in sandstone imply that the Aomugenhuudge Formation is of Early Carboniferous (Tournaisian to Viséan) (BGMRNM, 1996).

The Benbatu Formation is distributed in Xi Ujimqinqi, Sonidzuqoi, and Sonidyouqi, and consists of terrigenous clastic rocks interbedded with intermediate-basic volcanics, volcanioclastics, and limestone. This formation is 2000 m-thick and is overlain by the Amusam Formation with conformity, and is inferred to be in unconformable contact with the Lower Carboniferous below. Fossils herein are abundant, such as the fusulinid *Fusulina–Fusulinella* zone and the *Pseudostaffella–Profusulinella* zone; *Lithostrotionella* sp., *Amygdalophyllum* sp., and *Caninia* sp. corals; and the brachiopod *Char计ites mosquensis*. Therefore, the age of the Benbatu Formation is Bashkirian to Moscovian of Late Carboniferous (Guo Shengzhe et al., 1986; BGMRNM, 1996).

The Amusam Formation is widespread in Xinlinhot to Xi Ujimqinqi. It is about 1000 m-thick and dominated by thick-bedded limestone and bioclastic limestone intercalated with some siltstone, calcareous sandstone, and sandy conglomerate (Fig. 3e). Fusulinids and corals are of frequent occurrence: the lower part of the formation contains the fusulinid *Tritites*, suggesting a latest Carboniferous (Kasimovian to Gzhelian) age, whereas the upper part yields the fusulinid *Pseudoschwagerina* and coral *Carinithiophyllum–Akagophyllum* and *Empodesma–Ufimia* assemblages, which have been assigned to Asselian to Artinskian (Early Permian) (BGMRNM, 1996; Shen et al., 2006; Wang et al., 2006; Bu Jianjun et al., 2012). So the Amusam Formation ranges from latest Carboniferous to Early Permian in age.

The Shoushangou Formation is distributed chiefly in Xi Ujimqinqi, Linxi, and Balinzuoqi, and overlies the Amusam Formation with conformity. This formation exhibits considerable lateral variations in lithofacies. For example, in the Xi Ujimqinqi area it consists of slate, feldspar sandstone, and sandstone interbedded with some volcanics, but in the Balinzuoqi area the rocks change to more fine-grained siltstone, sandstone, and slate. The formation contains a few brachiopods, bryozoans, and fossil plants (BGMRNM, 1996). The youngest detrital zircon age is ca. 285 Ma for the sandstone in Xi Ujimqinqi (Zheng Yuejuan et al., 2013). On the basis of these data and regional geology, the Shoushangou Formation is probably of Early Permian age.

The Dashzhai Formation extends from Xinlinhot to southern Da Hinggan Mountains, and overlies the Shoushangou Formation. The main rock types are intermediate-acidic volcanics, volcanioclastics intercalated with sandstone, and sedimentary clastics (Fig. 3c, d). The brachiopod *Anidanthus–Yakovlevia–Permundaria* assemblage is present (BGMRNM, 1996; Shen et al., 2006). Geochronological data reveal the volcanics of the Dashzhai Formation range in age from 298 to 272 Ma, with the peak age of 288 Ma (Gao Dezhen et al., 1998;
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Fig. 2. Stratigraphic sequences of Carboniferous-Permian strata in the Dong Ujimqinqi stratigraphic subregion (fossil data from BGMRNM, 1996).
The position of each photograph is marked next to column. Photos: (a) fossil plant fragment; (b) parallel bedding; (c) brachiopods; (d) tuff; sandstone; (e) fossil plant fragment.
Fig. 3. Stratigraphic sequences of Carboniferous–Permian strata in the Inner Mongolia Grassland stratigraphic subregion (fossil data from BGMRNM, 1991, 1996).

The position of each photograph is marked next to the column. Photos: (a) bivalve; (b) cross bedding; (c) volcanic rocks from the Dashizhai Formation; (d) sedimentary sequence of the Shoushangou Formation; (e) limestone from the Amushan Formation.
Zhu et al., 2001; Zhang et al., 2008; Zhang Jian, 2012). Undoubtedly, the Dashizhai Formation is middle to late Early Permian in age.

The Zheshi Formation crops out widely in the Xilingol and northern Hinggan League areas. Its contact with the Dashizhai Formation is not exposed. This formation exhibits considerably lateral variations in both lithofacies and biofacies. Unlike that of the Zheshi Obo area in central Inner Mongolia, the Zheshi Formation in southeastern Inner Mongolia has less carbonatite and biological species, but more clastics and volcanics. This formation yields the famous Zheshi fauna, dominated by brachiopods and corals. The former is represented by the Spiriferella–Kochioproduc–Yakovlevia assemblage, and the latter by the Pterophyllum–Tachylasma assemblage, both being of a Middle Permian (Wordian) age (Ding Yunjie et al., 1985; Wang Chengwen and Zhang Songmei, 2003).

The Linxi Formation is distributed in Xilinhot, Xi Ujimqinqi, Linxi, and Balinyouqi, especially at Guandi of Linxi. This formation unconformably overlies the Zheshi Formation and is conformably overlain by the Lower Triassic Xingfuzhu Formation. The main rock types are sandstone, conglomerate, black slate, and shale. Primary sedimentary structures, such as cross beddings (Fig. 3b), ripples, and muddy cracks, have been found (Qin et al., 2001). The fossils are represented by the freshwater bivalve Palaeomutela–Palaeonodonata assemblage (Fig. 3a) and the Angaran flora Noeggerathiopsis–Schizoneura assemblage, indicating a Late Permian age (Huang Benhong, 1993; Zhang Yongsheng et al., 2012).

2.1.3. Chifeng stratigraphic subregion

The Chifeng stratigraphic subregion is situated north of the Sino-Korean Cronut, and embraces Xianghuangqi, Zhengxianghaiqi, Duolun, Chifeng, and Aohanqi. The Carboniferous is well developed around Aohanqi, including the Lower Carboniferous Baijiadian Formation, and the Upper Carboniferous Jiaodaogou and Jiujizi formations. The Permian is widely distributed in the region, including the Lower Permian Sanmianjing Formation, the Lower–Middle Permian Elitu Formation, the Middle Permian Yujiaobeigou Formation, and the Upper Permian Tiegynzi Formation (Fig. 4).

The Baijiadian Formation is hundreds to thousands of meters thick and exposed in Baijiadian, Houfangshengou, and western Xiawa of the Aohanqi area. Its lower part consists of slate, siltstone, and sandstone intercalated with limestone lenses, and the upper part is composed of siltstone with a little calcareous sandstone. The fossils are dominated by brachiopods such as Gigantoproductus edelburgensis, and G.submaxims and corals such as Dibunophyllum bipartitum, Yuanophyllum kansuense, Palaeosmilia murchisoni, and Kueichophyllum sinense, with a few fossil plants in slate. These shallow marine fossils are the most common elements of Early Carboniferous strata (Visean to Serpukhovian) in Europe and South China (BGMRMN, 1991, 1996; Huang Benhong, 1993; Lin et al., 2012; Qiao et al., 2015).

The Jiaodaogou Formation, overlaying the Baijiadian Formation, is distributed in Baijiadian and Jiaodaogou. This formation consists of sandy slate, muddy slate, limestone, and sandstone, more than 1000 m-thick, yielding brachiopods, corals, fusulinids, and the fossil plant Neuropteris gigantea–Linopteris bronniarti assemblage (BGMRMN, 1991, 1996; Huang Benhong, 1993). Tazawa (2010) has reported that the brachiopod Choristites cf. mosquensis is of a Late Carboniferous (Moscovian to Kasimovian) age. According to Wang Juntao (2011) the fusulinid Pseudostaffella and Profusulinella zones belong to Bashkirian to Moscovian. So, the Jiaodaogou Formation may be of early to middle Late Carboniferous.

The Jiujizi Formation is exposed in Jiaodaogou and Fanjiazhangzi of Aohanqi, and in conformable contact with the Jiaodaogou Formation. It is coal bearing and composed mainly of sandstone, conglomerate, and slate, about 235 m-thick. The Cathaysian flora Neuropteris pseudovata–Lepidodendron tachingshanense assemblage has been recognized, suggesting a Late Carboniferous (Gzhelian) age (BGMRMN, 1996; Huang Benhong, 1993).

In the west of the Chifeng subregion, the Lower Permian Sanmianjing Formation is distributed in an E–W trend throughout Xianghuangqi, Kangbao, Zhengxianghaiqi, and Duolun. It lies unconformably upon the Ordovician gneisses tonalite (462.7 ± 4.3 Ma, Zhu Junbin and He Zhengjun, 2017). Lithologically, this formation can be divided into a sedimentary section and a volcanic section. The lowest part of the sedimentary section is about 20 to 50 m-thick and consists of yellowish gritstone and pebbly sandstone, which is followed by 30 m of limestone and cherty limestone containing a Misellina–Parafusulina fusulimid zone. The upper part of it is composed of tawny shale and sandstone intercalated with limestone lenses, more than 150 m-thick. The fusulinid Parafusulina splendens occurs frequently in the Early Permian (Chihsian) strata in Ziyun of Guizhou, Yishan of Guangxi, and Baimimiao of Inner Mongolia (Zhang Zhicun et al., 1987). Besides, Misellina claudiae and M. ovalis have been recorded from the middle to late Chihsian in southeastern Hunan (Zhou Zuren, 1984). The youngest detrital zircon U–Pb age from the sandstone is 280 Ma (Zhu Junbin and He Zhengjun, 2017), which constrains the age of the sedimentary section. The volcanic section is more than 100 m-thick and includes
Fig. 4. Stratigraphic sequences of Carboniferous-Permian strata in Chifeng stratigraphic subregion (fossil data from BGMRNM, 1991, 1996). The position of each photograph is marked next to the column. Photos: (a) fossil from the Yujiaobeigou Formation; (b) ripple marks; (c) conglomerate; (d) fossil plant; (e) fusulinids; (f) sedimentary sequence of the Sanmianjing Formation.
andesite, andesitic breccia, and tuff. The U–Pb age of the andesite is 283.7±2.3 Ma (unpublished data). All of these manifests that the Sanmianjing Formation should belong to middle to late Early Permian.

The Elitu Formation is widely distributed south of the Xar Moron River, particularly at Elitu of southeastern Zhengxiangbaiqi. The rock types are quite different from bottom to top. The lower part of it consists of more than 1000 m of siltstone, conglomerate, quartz sandstone, and pebbly arkose intercalated with mudstone and shale, yielding a few layers of fossil plants (Fig. 4d) that suggest an Early Permian age (Huang Benhong, 1993). The upper part is composed of more than 500 m of intermediate-acidic volcanics such as grey dacite, black tuffaceous breccia, and andesite. Geochronological data reveal that the youngest detrital zircon U–Pb age of arkose from the Zhengxiangbaiqi area (the Elitu Formation standard profile) is 271 Ma (Zhu Junbin and He Zhengjun, 2017), while the U–Pb age of dacite from the upper part is 268.7±2.0 Ma (unpublished data). From these data, it is considered that the Elitu Formation ranges from late Early Permian to early Middle Permian.

The approximately 580 m-thick Yujiabeigou Formation is widely exposed south of the Xar Moron River. Its lower part is mainly composed of fine-grained conglomerate, sandy conglomerate, and tuffaceous sandstone intercalated with andesite, basaltic andesite, and tuff, with ripples and parallel beddings being present (China University of Geosciences, 2007). Both brachiopods, fusulinids, freshwater bivalves and plant fossils are abundant within the sandstone (BGRMNM, 1996). The upper part is characterized by gigantic conglomerate intercalated with sandstone. The presence of fusulinids Pseudodiolina and Pararafialina and brachiopods Permundaria, Yakovlevia mammatiformis, and Spirigerellina allows this formation to be ascribed to early Maokouan (Ding Yunjie et al., 1985; Shen et al., 2006).

The Upper Permian Tieyingzi Formation is distributed in Tieyingzi and Jiangyingzi of Hexigenqi. Its lower part is composed of red conglomerate intercalated with lentoid sandstone, while the upper part consists of greyish-green muddy siltstone, feldspar-quartz sandstone, and some sandy conglomerate lenses, yielding fossil plants Sohonophyllum thonii, Lobatannulora enisoflia, Gigantopecten nicotianaefolia, and Taeniopites taiyuenensis (China University of Geosciences, 2007). In the Jiangyingzi area, this formation unconformably overlies the Yujiabeigou Formation and is unconformably covered by Mesozoic volcanic rocks.

2.2 Sedimentary environments and paleogeography

From the Carboniferous–Permian rock types and palentological characteristics mentioned above, it is known that what is now southeastern Inner Mongolia used to be part of an ENE-NE trending littoral-neritic to continental sedimentary basin, with the Carboniferous and Upper–Middle Permian depositional regime being of a littoral-neritic facies, and the Upper Permian regime being of a continental facies.

2.2.1 Northern part of the basin: Dong Ujimqinqi subregion

The absence of Early Carboniferous deposits in Dong Ujimqinqi implies that the northern part of the basin was involved in the development of a continental environment. This is supported by the unconformable relationship between the Upper Carboniferous Baoligaomiao Formation and the Ordovician or Upper Devonian strata below in Wulan Obo of northern Abagqi and in southeastern Dong Ujimqinqi. The Baoligaomiao Formation characterized by rift-related continental deposits and volcanioclastic rocks is widely exposed from Erenhot to Dong Ujimqinqi. The Angaran flora is common in this formation, and there are coal lenses (Li Wenguo, 1981; Huang Benhong, 1993). In southwestern Dong Ujimqinqi, there is a distinctive succession named the Gegen Obo Formation, which ranges in age from latest Carboniferous to Early Permian. Its lower part is probably equivalent to the Baoligaomiao Formation. The upper part is a sequence of alternating marine–continental facies deposits containing Chihsian brachiopods and fossil plants, disconformably overlying the volcanic rocks below. The existence of the distinctive succession probably proves that a limited transgressive event took place in the northern part of the basin, while other places would be dominated by a continental environment, for example Manduhuobaolage in northeastern Dong Ujimqinqi, where Zhou Zhiguang et al. (2010) has found Early–Middle Permian Cathaysian floras. However, the Middle Permian shallow marine deposits of the Zhesi Formation in Xiaobaliang, which unconformably overlie the Hegenshan ophiolitic mélangé, probably mark the northernmost extent of another transgressive event. The lack of Late Permian strata perhaps indicates that the conditions of deposition in the northern basin gave way to a continental environment once again.

2.2.2 Central part of the basin: Inner Mongolia Grassland subregion

In the Early Carboniferous, there was an E–W-trending narrow seaway from southern Sonidzuqi to Abagqi, while other areas of the central basin would be in a denuded condition. The Lower Carboniferous Aomugenhuduge Formation consists of conglomerate,
shale, siltstone, feldspar-quartz sandstone, quartz sandstone, and sandstone intercalated with thin-bedded limestone, yielding Early Carboniferous (Tournaisian–Viscian) brachiopods and corals. The lithologic diversity suggests a nearshore environment. The Late Carboniferous deposits are quite different from bottom to top. The Upper Carboniferous Benbatu Formation is dominated by continental clastic rocks intercalated with volcanics. The younger Amushan Formation is characterized by thick-bedded carbonates and lies unconformably upon the Upper Silurian–Lower Devonian Xibiehe Formation in Mandula in central Inner Mongolia. The manifestations of clastics grading upwards into carbonate rocks indicate that the scope of the transgression was expanding. The lack of Visian to Bashkirian deposits in the region further suggests that there appeared an erosion stage between the Early and Late Carboniferous.

The fusulind Pseudoschwagerina occurs in the upper part of the Amushan Formation, confirming that the age is Early Permian. The Early Permian Shoushangou Formation in Xilinhhot and Xi Ujimqinqi consists of slate, arkose, calcareous sandstone, and sandstone intercalated with a few volcanic rocks. Fossils are poorly developed in this formation, and only a few brachiopods, corals, and bryozoans have been reported (Bao Qingzhong et al., 2005). The Early Permian deposits in the region exhibit considerably lateral variations in both lithofacies and biofacies, implying a variety of depositional environments. A succession of volcanic-sedimentary rocks consisting of intermediate-acidic volcanics and volcanioclastic rocks intercalated with continental clastic rocks is common in the late Early Permian. Some of the volcanics have typical bimodal features, and the eruption environment would be littoral-neritic. The thickness of the volcanic deposits increases from west to east, especially at Dashizhai of eastern Inner Mongolia (BGMRMN, 1996).

The Middle Permian strata represented by the Zhensi Formation are widely exposed in the region. However, they are quite different in lithological associations, thicknesses and biological assemblages owing to different hydrodynamic and aqueous medium conditions. The Zhensi Formation consists of massive limestone and yields a great variety of the Zhensi fauna in the west, such as in the Zhensi Obo area. Clastic rocks and volcanic rocks increase, but sedimentary thickness and biological taxa decrease in the east, such as in Xilinhut and Xi Ujimqinqi (BGMRMN, 1991, 1996). The frequent variations of lithofacies and thickness reflect a shallow marine environment where slight eustasy would result in large-scale transgressions and regressions. In the late Middle Permian, a lack of the Capitanian deposits may suggest that this region used to be in a continental environment.

In the late Late Permian, a continental environment developed in the entire region. Accordingly, carbon and oxygen isotope data for limestone from the lower part of the Upper Permian Linxi Formation show freshening seawater or semi-saline water characteristics (He Zhengjun et al., 1997). The upper part of this formation contains fossil plants, freshwater bivalves, and conchostracans (Zhang Yongsheng et al., 2012), with abundant cross bedding, ripples, rain marks, and muddy cracks. It means that with the uplift of the crust, the residual shallow marine basin disappeared and river or lacustrine deposits were dominant.

2.2.3 Southern part of the basin: Chifeng subregion

Carboniferous deposits are well developed in the Chifeng area, with a total thickness of 3 to 4 km. The Lower Carboniferous Baijadian Formation around Aohanqi consists of littoral-neritic slate, sandstone, and calcareous sandstone intercalated with limestone, yielding abundant brachiopods, corals, and a few fossil plants. The sedimentary and paleontological characteristics of this formation suggest a nearshore environment. The Upper Carboniferous Jiadaogou Formation is a succession of clastic rocks and limestone of nearshore and continental origin, yielding abundant brachiopods and corals. However, the uppermost Carboniferous is dominated by sandy and muddy deposits, with coal beds and abundant fossil plants, suggesting that the conditions of this region gave way to continental lacustrine and paludal environments.

The Lower Permian Sanmianjing Formation is represented by the initial Permian sediments in Xianghuangqi, Zhengxianbaqi, and Duolun. It consists of continental clastic rocks, limestone, and volcanics. The sedimentary and paleontological characteristics indicate a high energy littoral-neritic environment. The coeval sediments in northern Chifeng have abundant volcanic matter, with little fossils. The overlying Elitu Formation is widely distributed south of the Xar Moron River. This is a volcanic-sedimentary sequence of predominantly continental to alternating marine-continental facies with abundant fossil plants. Paleontological and chronological data manifest that the formation ranges in age from Early to Middle Permian. Accordingly, the widespread Yujiabiegu Formation consists of sandstone, coarse sandstone, and conglomerate, containing abundant brachiopods, fusulinids, bivalves, and some fossil plants. Primary sedimentary structures, such as ripples and parallel beddings, have been found. This evidence demonstrates that the Yujiabiegu Formation is the result of alternating marine–continental facies. The depocenter should be located on the south bank of the Xar Moron.
River. The sediments coarsen in ascending order, indicating that the Chifeng subregion underwent a regression in the late Middle Permian. In the early Late Permian, this subregion probably became a landmass as a result of uplifting. At Tieyingzi in southeastern Heixigengqi, the Tieyingzi Formation is dominated by red conglomerate, sandy mudstone, greyish-green sandstone, and siltstone, containing abundant fossil plants, implying a fluvial to lacustrine sedimentary environment.

3 Carboniferous–Permian Stratigraphic Sequences and Sedimentary Environments in the Neighboring Areas

In order to further explore Carboniferous–Permian environments of the study area, we have consulted and analyzed a lot of source material and data, on the eastern segment of the Tianshan–Hinggan Orogenic System, covering Ejini, South Mongolia, Jilin, eastern Heilongjiang etc. (Fig. 5). The research result shows that the whole region used to be a littoral–neritic to continental sedimentary basin during the Carboniferous–Permian times.

3.1 Ejini, Zhesi Obo and adjacent South Mongolia

The Carboniferous–Permian has a wide distribution along the China–Mongolia border (Fig. 5), particularly in the Ejini and Zhesi Obo areas (Grabau, 1931; Ding Yunjie et al., 1985; BGRMN, 1991, 1996). The strata in Ejini comprise the Upper Carboniferous–Lower Permian Ganquan Formation, the Lower middle Permian Shuangputang Formation, the middle Permian Jushitan Formation, and the Upper Permian Fangshankou Formation. And the strata in Zhesi Obo comprise the Upper Carboniferous–Lower Permian Amushan Formation, and the Middle Permian Baotege, Zhesi, and Yihewusu formations.

In Ejini of western Inner Mongolia (Figs. 5 and 6), the Ganquan Formation lies unconformably upon the Middle Devonian Queershan Group volcanic rocks. It is a suite of shallow marine arkose, siltstone, pebbly conglomerate, limestone, rhyolite, and dacite, yielding some ammonoids, brachiopods, and corals (BGRMN, 1991, 1996). The ammonoids in limestone include Gastrioceras listeria and Branneroceras sp., suggesting a Bashkirian age (Niu Yafu et al., 2014). In addition, U–Pb ages of volcanic rocks are focused on 315 to 297 Ma (Lu Jinchai et al., 2013). Therefore, the age of this formation is generally considered to be from Late Carboniferous to Early Permian. The Shuangputang Formation overlying the Ganquan Formation is composed of shallow marine sandy conglomerate, sandstone, shale, limestone, and basalt. The
occurrence of the brachiopod *Spiriferella–Kochiproductus–Yakovlevia* and *Streptorhynchus–Uncinammina* assemblages and the coral *Plerophyllum–Tachylysma* assemblage in this formation indicates that its age probably ranges from Early to Middle Permian (Lu Jincui et al., 2013; Bu Jianjun et al., 2011). The Jushitan Formation resting on the Shuangputang Formation is composed of shallow marine basalt, sandstone, and shale intercalated with limestone lenses, with infrequent ammonoids and brachiopods (BGRMRN, 1991). The age of this formation hasn’t be precisely identified because of the lack of biostratigraphically diagnostic species. However, by its correlation with the Lower–Middle Permian Shuangputang Formation below, the Jushitan Formation is probably equivalent to the Yihewusu Formation. As the uppermost Permian unit in this region, the Fangshankou Formation consists of continental sandstone, siltstone, feldspar-quartz sandstone, sandy mudstone, and some limestone lenses, yielding fossil plants *Pecopteris* sp., *Callipterus* sp., and *Paracalamites* sp. (BGRMRN, 1996). So, this formation is probably of Late Permian age.

In Zhesi Obo (Figs. 5 and 6), the Amushan Formation lies unconformably upon the Upper Silurian–Lower Devonian Xibiehe Formation. This formation consists mainly of shallow marine limestone, biological limestone, sandstone, and sandy conglomerate intercalated with some tuff, containing Late Carboniferous *Triticites* and Early Permian *Pseudoschwagerina* fusulinids, with *Cariniphyllyum–Akagophyllum* and *Empodesma–Ufima* coral assemblages (BGRMRN, 1996; Shen et al., 2006; Wang et al., 2006; Bu Jianjun et al., 2012). The Middle Permian Baotiege Formation overlying unconformably the Amushan Formation consists of littoral-neritic conglomerate, sandy conglomerate, and calcareous sandstone intercalated with some limestone. The fusulimid *Monodiexodina* zone and some brachiopods such as *Yakovlevia, Waagenoconcha*, and
Anidanthus have been recorded from calcareous sandstone of this formation, which can be assigned to the Roadian (Ding Yunjie et al., 1985; BGMRMN, 1996). The Middle Permian Zhesi Formation resting on the Baotege Formation consists of littoral-neritic carbonate and clastic rocks. This formation yields the famous Zhesi fauna, which is dominated by fusulinids, brachiopods, and corals, such as the Schwagerina quasiregularis–Codonofusiella simplicata fusulinid subzone, the brachiopod Spiriferella–Kochiopoductus–Yakovlevia assemblage, and the coral Plerophllum–Tachylasma assemblage, indicating the age of the Zhesi Formation is most likely Wordian (Ding Yunjie et al., 1985; Wang Chengwen and Zhang Songmei, 2003). The Yihewu Formation lying on the Zhesi Formation is subdivided into two parts. The lower part of it is dominated by massive limestone, yielding the Schwagerina ulangabensis–Codonofusiella pseudoextensa fusulinid subzone; corals Wentzelella, Zhesipora, and Waagenophyllum; and the brachiopod Streptorhynchus–Hemiptychina–Richthofenia assemblage, and the upper part mainly consists of sandstone and sandy conglomerate. Therefore, this formation is probably Capitanian in age (Leven et al., 2001; Shen et al., 2006).

In South Mongolia north of Ejinqi, the Upper Carboniferous–Lower Permian shallow marine volcanic-sedimentary sequence is equivalent to the Ganquan Formation. However, unlike that of Ejinqi, the Permian in the region is dominated by continental deposits. It can be divided into three parts: the lower part, equivalent to the Early Permian, consists of continental sandstone and conglomerate; the middle part is composed of fluvial-paludal mudstone, siltstone, sandstone, and conglomerate intercalated with some coal beds and volcanic rocks; and the upper part is represented by fluvial facies fuchisia mudstone, siltstone, and conglomerate (Lu Jincai et al., 2014). In South Mongolia north of Zhesi Obo, the Carboniferous–Permian strata are well developed. The Upper Carboniferous–Lower Permian sequence, which is almost 2500 m-thick and consists of carbonate, clastic and volcanic rocks, is equivalent to the Amushan Formation. The Lower Permian is represented by a sequence of shallow marine sandstone, siltstone, and limestone, yielding abundant foraminifers and few brachiopods, bryozoans, and corals. The foraminifers suggest an age of Asselian to Lower Sakmarian (Manankov, 1998). The middle-late Early Permian strata are composed of sandstone, calcareous sandstone, mudstone, and siltstone intercalated with limestone, yielding abundant brachiopods, bryozoans, bivalves, and foraminifers (Nassichuk, 1995; Ueno et al., 2007). The Middle Permian is a succession of shallow marine sandstone, calcareous sandstone, conglomerate, and limestone. Its lithofacies and biofacies are quite similar to those of the Baotege Formation and the Zhesi Formation in the Zhesi Obo area (Manankov et al., 2006). The uppermost Middle Permian, equivalent to the Yihewu Formation in Zhesi Obo, is composed of limestone, calcareous mudstone, siltstone, and sandstone, with abundant brachiopods (Manankov et al., 1998; Shen et al., 2006). Late Permian strata are not exposed in South Mongolia.

3.2 Central-eastern Jilin

The Carboniferous–Permian is well developed in Yongji–Panshi of central Jilin and in Yanbian of eastern Jilin. The strata in the central part include the Lower Carboniferous Tongqigu Formation, the Lower–Upper Carboniferous Luquantun Formation, the Upper Carboniferous Mopanshan Formation, the Upper Carboniferous–Lower Permian Shizhuzi Formation, the Lower Permian Shoushangou Formation, the Lower–Middle Permian Daheshen Formation, the Middle Permian Fanjiatun Formation, and the Upper Permian Yangjiaogou Formation. Those which crop out in the eastern part are composed of the Upper Carboniferous–Lower Permian Shanxiuling Formation, the Lower–Middle Permian Dasuangou Formation, the Middle Permian Miaoling Formation, the Middle Permian Kedaogou Formation, and the Upper Permian Kaishantun Formation.

In central Jilin (Figs. 5 and 7), the Lower Carboniferous Tongqigu Formation, which unconformably overlies the Upper Silurian–Lower Devonian limestone, is characterized by shallow marine siltstone, sandstone, and quartz sandstone. Fossils within the siltstone are represented by the brachiopod Fusella–Syringothyris assemblage and few bryozoans and bivalves, indicating a probable Tournaisian age (BGMRP, 1988, 1997; Liu Fa, 1988). The Luquantun Formation rests on the Tongqigu Formation, and the main rock types are alternating marine–continental facies siltstone, sandstone, feldspar-quartz sandstone, shale, and limestone. The lower part of the formation contains brachiopods Gigantopoductus irregularis, Linopoductus cf. temistriatus, and Productus dognensis, corals Yunophyllum sp. and Ganganophyllum latum, and fossil plants Angaridium panisiense, Mesocalamites jilinensis, and Neuropteris pseudogigantea, suggesting an age of Viséan (Zhang Shanzhen et al., 1987). The upper part yields conodonts Declinognathodus noduliferus and D. praenoduliferus, indicating an age of Bashkirian (Li Dongjin et al., 2012). Therefore, the Luquantun Formation is a shallow marine sequence that ranges from Early to Late Carboniferous. The Mopanshan Formation overlying the Luquantun Formation is dominated by shallow marine carbonate rocks. This formation contains the coral Opiphyllum–Cystolonsdaleia assemblage and the Fusulina–
Fusulinella, Eostaffella–Pseudostaffella, and Eostaffella–Pseudostaffella fusulinid zones, which suggest a Late Carboniferous (Bashkirian) age (BGMJP, 1988; Huang Zhuxi, 1988). The Shizuish Formation overlying the Mopanshan Formation is more than 1000 m-thick. The lower part of it is composed of sandstone, shale, and limestone, while the upper part is represented by intermediate-acidic volcanic rocks intercalated with sandstone and limestone. The occurrence of the fusulinid Triticites–Pseudoschwagerina assemblage in limestone indicates a Late Carboniferous to Early Permian age (BGMJP, 1997).

The Lower Permian Shoushangou Formation consists mainly of sandy slate, siltstone, sandstone, and a little limestone. It contains abundant fusulinids, corals, and brachiopods, which suggest a late Early Permian age (Yu Jianzhang et al., 1981; Ding Yunjie et al., 1985; Shen et al., 2006; Kim et al., 2012). The Daeshen Formation overlying the Shoushangou Formation is characterized by intermediate-acidic volcanic and volcaniclastic rocks.
intercalated with tuffaceous sandstone, siltstone, sandy conglomerate, and limestone. The lower part of this formation contains the fusulinids Monodiezodina sp. and Parafusulina sp., coral Szechuanophyllum szechuanense, and fossil plant Cardionewa, suggesting an age of Chihsian (Mi Jiarong and Liu Maoqiang, 1985; Su Yangzheng, 1996; Shen et al., 2006; Guo Shengzhe, 2012). The upper part yields the conodont Mesogondolella aserrata, indicating an age of Wordian (Zhou Xiaodong et al., 2013). In addition, the U–Pb ages of volcanic rocks are concentrated on 293 to 279 Ma (Cao Huahua et al., 2012).

Thus, the age of this formation ranges from Chihsian to Wordian. The Fanjitian Formation overlying the Daheshen Formation is composed of slate, siltstone, sandstone, and limestone, with some volcanic and volcanioclastic rocks, yielding abundant fusulinids and brachiopods (BGMJP, 1997; Leven, 2001), and a few fossil plants as well (Kim et al., 2012). The lithologic association and biofacies of the formation indicate a nearshore littoral-neritic environment. The Yangjiagou Formation disconformably overlying the Fanjitian Formation is composed of continental siltstone, sandstone, and conglomerate, with cross beddings and imbricate sedimentary structures (Yang Baozhong et al., 2006). It contains the freshwater bivalve Paeleonodontia–Palaenomutella assemblage and some fossil plants such as Noeggerathiopsis and Paracalamites, which suggest a Late Permian age (Guo Shengzhe et al., 1992).

In the Yambian area of eastern Jilin (Figs. 5 and 7), the Upper Carboniferous–Lower Permian Shanxiuling Formation is characterized by shallow marine carbonate rocks, locally intercalated with some volcanic rocks. Fossils are abundant, such as the fusulinid Triticites–Pseudoschwagerina assemblage and some brachiopods (Li Li et al., 1980; Sun Hengyuan, 1988; BGMJP, 1997). The Dasangou Formation unconformably overlying the Shanxiuling Formation is characterized by massive conglomerate intercalated with pebbly sandstone, siltstone, calcareous sandstone, and limestone lenses. The marine bivalves and Cathaysian flora from the siltstone in the lower part of this formation not only suggest a late Early Permian age, but also show an alternating marine–continental facies environment (Yin Changjian et al., 2003). The fusulinids and brachiopods from the limestone in the upper part would belong to a Middle Permian (Wordian) age (BGMJP, 1988; Shen et al., 2006). On the above evidence, it is clear that the Early–Middle Permian Dasangou Formation is a sequence of alternating marine–continental facies deposits. The Miaoling Formation disconformably overlying the Dasangou Formation consists of shallow marine arkose, sandstone, siltstone, sandy conglomerate, and limestone. This formation contains abundant fusulinids and brachiopods, suggesting a Middle Permian age (BGMJP, 1988; Shen et al., 2006). The Kedao Formation has been informally subdivided into the Lower Kedao Formation and the Upper Kedao Formation by the Bureau of Geology and Mineral Resources of Jilin Province (BGMJP) (1988, 1997). The Lower Kedao Formation is composed of conglomerate, pebbly sandstone, sandstone, siltstone, and arkose, commonly intercalated with allochthonous limestone blocks containing the Late Guadalupian fusulinids Verbeekina, Neoschwagerina, Yabeina, and Schwagerina (Shen et al., 2006). The Upper Kedao Formation consists of slate, siltstone, silty mudstone, and sandstone, exhibiting parallel beddings and small cross beddings. The age of the Kedao Formation is probably late Middle Permian. The Kaishantun Formation disconformably overlying the Kedao Formation is a sequence of continental slate, siltstone, sandstone, and conglomerate. The pebbles within the conglomerate are derived from Proterozoic granite and various volcanic rocks, except for those from the underlying strata (Jia et al., 2004). The flora in this formation is dominated by Angaran flora species mixed with some Cathaysian elements, which suggest a Late Permian age (Sun Hengyuan, 1988; BGMJP, 1997).

3.3 The Da Hinggan and Xiao Hinggan Mountains

The Da Hinggan and Xiao Hinggan Mountains region described in this paper embraces the western and northeastern margin of the Songliao Basin and south of the Dong Ujimqinji–Huma line. The Carboniferous–Permian strata which are present in the Zhalantun, Longjiang, and Heihe areas fall into the Lower Carboniferous Huadaqi Formation and Chaergelahe Formation, the Upper Carboniferous Xinghuo Formation, the Lower Permian Gaojiawopeng Formation, the Middle Permian Sijiashan and Liutiaogou formations, and the Upper Permian Linxi Formation.

In the Zhalantun–Longjiang area (Figs. 5 and 8), the Lower Permian Gaojiawopeng Formation is characterized by intermediate-acidic and volcanioclastic rocks intercalated with carbonate rocks and sandstone. No isotopic ages or fossil data are reported. Given its associations, this formation would be deposited in a shallow marine environment. The Sijiashan Formation overlying the Gaojiawopeng Formation is mainly composed of shallow marine limestone, sandstone, and siltstone. Upwards, its clastic rocks are progressively decreasing, while carbonate rocks increasing. This formation contains the brachiopods Yakovlevia and Spiriferella, the corals Tachylasma and Calophyllum, and the fusulinids Monodiezodina and Parafusulina,
indicating a Roadian–Wordian age. The Liutiaogou Formation overlying the Sijuashan Formation is a suite of shallow marine carbonate rocks, and yields the corals *Liangshanophyllum* and *Waggenophyllum*, the brachiopods *Richthofenia* and *Neospirifer*, and the fusulinid *Parafusulina*, indicating a Capitanian age (BGMRHP, 1993, 1997; Shen et al., 2006). The Linxi Formation overlying the Liutiaogou Formation consists of continental siltstone, sandstone, and slate, locally intercalated with some intermediate-acidic volcanic rocks. Fossils include the freshwater bivalve *Palaeomutela–Palaeamodonta* assemblage and Angaran flora, which are the most common elements in the Late Permian continental deposits of Northeast China.

In the Heihe area of Heilongjiang (Figs. 5 and 8), the Lower Carboniferous Huaqia Formation, which overlies the Upper Devonian Xiaohelihe Formation, is a sequence of fluvial-lacustrine conglomerate, sandstone, siltstone, and slate. It contains abundant fossil plants and a few freshwater zoolites, indicating a continental sedimentary setting. The Lower Carboniferous Chaergelaha Formation overlying the Huaqia Formation is composed of fluvial-lacustrine sandstone, conglomerate, and slate intercalated siltstone, containing some fragments of fossil plants. Cross beddings and wave beddings have been observed, which suggest a continental depositional environment. The Upper Carboniferous in the Heihe area is characterized by intermediate-acidic volcanic and volcanioclastic rocks intercalated with sedimentary rocks, and is equivalent to the Baoligaomiao Formation in the Dong Ujimqinqi area of Inner Mongolia. Fossil plants such as *Noeggerathiopsis* sp. were found within sedimentary rocks (BGMRHP, 1993, 1997), indicating a continental environment. Permian strata in this region are similar to those of the Zhalantum–Longjiang area on the northwestern margin of the Songliao Basin.
3.4 Eastern Heilongjiang

The eastern Heilongjiang area encompasses the Zhangguangcai Range and its eastern surroundings, such as Yichun–Shangzhi and Mishan–Dongning. Here, the Carboniferous strata can be divided into the Lower Carboniferous Beixing Formation and the Upper Carboniferous Guangqin, Zhenzishan and Yangmugang formations. The Permian is represented by the Lower Permian Erlongshan and Qinglongtun formations, the Middle Permian Tumenling and Pingyangzhen formations, and the Upper Permian Hongshan and Chengshan formations.

In the Yichun–Shangzhi area (Figs. 5 and 9), the Upper Carboniferous–Lower Permian Yangmugang Formation is composed of continental slate, sandstone, siltstone, and arkose, containing the Angaran flora, which is represented by Angaridium. This formation is overlain by the Lower Permian Qinglongtun Formation, which is mainly composed of andesite, basaltic andesite, tuffaceous breccia, sandstone, and slate. The Middle Permian Tumenling Formation is a sequence of shallow marine to alternating marine–continental facies sandstone, slate, and limestone. Its contact relationship with the strata below is unknown. Brachiopods from this formation include Spiriferella sp., Yakovlevia sp., Kochioproductus porrectus, Leptodus nobilis, and Spinomarginifera sp., which suggest a Wordian–Capitanian age (Tazawa et al., 2006). In addition, bivalves, gastropods, bryozoans, and fossil plants are also common in the formation (BGMRHP, 1993, 1997), indicating a nearshore shallow marine environment. The Tumenling Formation is overlain by the Upper Permian...
Hongshan Formation which is composed of continental conglomerate, sandstone, and slate intercalated with infrequent volcanic and volcanioclastic rocks. Fossil plants are represented by the *Callipteris–Comia–Inoipteris* assemblage (Huang Benhong et al., 1998).

In the Mishan—Dongning area (Figs. 5 and 9), the Lower Carboniferous Beixing Formation is dominated by shallow marine tuff, slate, and sandstone. It is conformable with the Upper Devonian Qilikashan Formation below, but the contact relationship with the strata above is not exposed. The fossil record is represented by the brachiopod *Hemipleurathorhynchus*, suggesting a Tournaian age (BGMRHP, 1993, 1997). The Upper Carboniferous Guangqing Formation is characterized by a sequence of continental deposits. The lower part of it consists of sandstone and layers of slate intercalated with tuff, while the upper part is represented by slate intercalated with infrequent sandstone. Fossil plants such as *Angaridium* sp. were reported (BGMRHP, 1997). The Guangqing Formation is followed by the Zhenzishan Formation, which consists of continental sandstone, siltstone, and sandy silt. Furthermore, a 10- to 16 m-thick coal bed was reported (BGMRHP, 1997), suggesting an organic-rich paludal facies. The Lower Permian Erlongshan Formation, which lies upon the Zhenzishan Formation, is dominated by shallow marine andesite, basaltic andesite, tuff, siltstone, and slate, containing few brachiopods and corals (BGMRHP, 1993, 1997). The overlying Middle Permian Pingyangzhen Formation is a suite of metamorphosed shallow marine mudstone and limestone, which have become phyllite and marble as a result of regional metamorphism. Fossils are found from the marble, such as the corals *Tachylasma* cf. *pseudoche, T. magnum*, and *Lophophyllidium acostatum*; and the brachiopods *Spiriferella* cf. *persaranea, S. keilhavi*, and *Neospirifer* sp., which are common elements in the Middle Permian strata of Inner Mongolia and Northeast China (Li Li et al., 1985; BGMRHP, 1997; Cui Junping et al., 2013). The Upper Permian Chengshan Formation is composed of conglomerate, sandstone, arkose, and slate, yielding abundant fossil plants such as *Comia* sp., *Noeggerathioptis* sp., and *Cladophlebis* sp. (BGMRHP, 1993). The contact relationship with the strata below is not exposed.

![Fig. 10 Distribution of Late Carboniferous–Middle Permian extension-related magmatism in southeastern Inner Mongolia (data from Hong Dawei et al., 1994; Shi Guanghui et al., 2004; Zhang et al., 2008, 2011, 2015; Zhang Yueqing et al., 2009, Chen et al., 2012, 2014, 2015; Xue Huimin et al., 2010; Shen Xiaoli et al., 2012; Xu Jiaying et al., 2012; Wang Zhihua et al., 2013; Chen Yan et al., 2014; Li Ke et al., 2014, 2015; Tong et al., 2015). The inset map shows the distribution of the Late Paleozoic rift system in the Paleo-Asian Ocean Tectonic Domain (after Hong Dawei et al., 1995; Jahn et al., 2009; Yarmolyuk et al., 2013, 2014).](image-url)
4 Discussion

After dealing with the Carboniferous–Permian stratigraphic systems and sedimentary environments of southeastern Inner Mongolia and its neighboring areas, we will go into the magmatic activity and tectonic movement in the study area.

4.1 Alkaline granites and bimodal volcanic rocks

The wide distribution of Paleozoic granitoids is one of the most prominent features of the Paleozoic–Asian Ocean Tectonic Domain (Hong Dawei et al., 2000). In the vast area from the southern margin of the Siberian Craton, through North Mongolia–Transbaikal, to Erenhot–Dong Ujimqinqi on the China–Mongolia border, several gigantic belts of alkaline granites and genetically related bimodal volcanics have been recognized, suggesting a regional-scale crustal extension during the Late Carboniferous to Permian (Hong Dawei et al., 1994; Jahn et al., 2009; Yarmolyuk et al., 2013, 2014; Tong et al., 2015) (Fig. 10).

The Erenhot–Dong Ujimqinqi alkaline granite belt extends westward through South Mongolia to northern Xinjiang, and eastwards occurs in the Heihe area of Heilongjiang as an eastern extension. The emplacement of alkaline granites happened in a short time, from 292 to 273 Ma (Wu et al., 2002; Zhang Yuqing et al., 2009; Shen Xiaoli et al., 2012; Wang Zhihua et al., 2013; Chen Yan et al., 2014; Tong et al., 2015; Zhang et al., 2015). The myrmekitic and miarolitic textures indicate the granites were formed by magmatic volatile exsolution (Hong Dawei et al., 1994). Additionally, a large number of coeval bimodal volcanics and A-type granitoids crop out along with the alkaline granite belt (Li Ke et al., 2014, 2015; Zhang et al., 2011). Widespread extension-related magmatism has been recognized in the interval between the alkaline granite belt in the north and the Sino-Korean Craton in the south (Fig. 10). For example, the Late Carboniferous high-Mg basalt (319 to 315 Ma) appear in the Daqing area of southern Xi Ujimqinqi (Shao Ji’an et al., 2015a), the bimodal volcanic of the Early Permian Dashizhai Formation in Xi Ujimqinqi (Zhang et al., 2008; Chen Yan et al., 2014), the Late Carboniferous to Early Permian post-orogenic granites (Xue Huaimin et al., 2010; Xu Jiajia et al., 2012) and A-type granite around Xilinhhot (Shi Guanghai et al., 2004), Late Carboniferous Baoliao granites in Sonidzuooqi (Hu et al., 2015), and the Early Permian bimodal volcanics in Damaoqi (Chen et al., 2012, 2015). Furthermore, the Late Carboniferous–Permian granite belt on the northern margin of the Sino-Korean Craton may also exhibit bimodal characteristics (Shao Ji’an et al., 2015b).

Our analysis leads to the interpretation that the Late Carboniferous–Middle Permian extension-related magmatism in southeastern Inner Mongolia and its neighboring areas is the result of regional crustal extension, probably linked to post-collisional extension following closure of the Paleo-Asian Ocean, rather than to subduction plate or back-arc origin.

4.2 Ophiolitic mélangé belts of southeastern Inner Mongolia

Several NE–trending ophiolitic mélangé belts occur in southeastern Inner Mongolia, which record the complex evolution of the Paleo-Asian Ocean. Among these ophiolitic mélangé belts, the Onod Sum–Xar Moron, Erenhot–Hegenshan, and Solonker belts near the China–Mongolia border are the best exposed and studied (He Guoqi et al., 1983; Cao Congzhou et al., 1986; Wang Quan et al., 1991; Liang Rixuan, 1994; Miao et al., 2007, 2008; Jian et al., 2008, 2010, 2012).

Geologists have reached a consensus about the age of the Onod Sum ophiolitic mélangé. The Late Cambrian radiolarians in siliceous rocks and the ages of corresponding mafic rocks (497 to 477 Ma) probably suggest that the ophiolite was formed in the Late Cambrian (Wang Quan et al., 1991; Jian et al., 2008). Additionally, the ages of blueschist and adakite (467 to 427 Ma) imply a continued subduction of oceanic crust until the Late Silurian (Wang and Liu, 1986; Liu Dunyi et al., 2003; Miao et al., 2007). In the eastern segment of the Onod Sum ophiolitic mélangé belt, the bedanshan, Wudaoshimen, Erbadi, and Xingshuwa ophiolites are scattered along the northern Xar Moron River. Li Jinyi (1987) detailed the petrology of this belt and interpreted it as a relic of the Early Paleozoic oceanic lithosphere that had been subducted southward under the Sino-Korean Craton. This interpretation was based mainly on Ordovician microfossils, such as Ecopristis sp. ostracods, Ammodiscus sp. foraminifers, Acrotretidae brachiopods, Sphaerellari radiolarians, and Panderodus sp. conodonts (He Guoqi et al., 1983). Considering the fact that the Onod Sum–Xar Moron ophiolitic mélangé belt is unconformably overlain by the Upper Silurian Xibihe Formation, it can be confirmed that this belt represents a Caledonian Orogeny in southeastern Inner Mongolia. It is worth mentioning that Wang Yujing et al. (1997) reported Permian radiolarian fossils within associated silaceous rocks, which were thought to be an important evidence for the existence of the Paleo-Asian Ocean during the Middle Permian. However, abundant gastropods and bivalves have been found with radiolarian fossils at Maodeng of the Xi Ujimqinqi area and Zhesi Obo of the Mandula area, indicating the radiolarian fossils had no direct connection to a deep-sea environment (Fang
Junqin et al., 2014).

The Erenhot–Hegenshan ophiolitic mélangé belt is well developed in northern Inner Mongolia, especially in the Hegenshan area. It intruded tectonically into a Devonian marine volcanic-sedimentary sequence and is overlain unconformably by the Permian Zhezi Formation or the Gegen Obo Formation (Ren Jishun et al., 1992; Bao Qingzhong et al., 2011). The siliceous rocks contain Devonian radiolarian fossils, while the limestone contains Middle-Late Devonian corals (Cao Congzhou et al., 1986; Shao Jian, 1991; Wang Quan et al., 1991). Therefore, the Hegenshan ophiolitic mélangé may be Early to Middle Devonian in age.

The Solonker ophiolitic mélangé, exposed with the Upper Carboniferous Benbatu Formation along the China–Mongolia border, has been considered the youngest of the Paleo-Asian Ocean Tectonic Domain, and a part of the Solonker suture zone marking the final closure of the Paleo-Asian Ocean (Xiao et al., 2003; Jian et al., 2010). However, these ophiolitic mélanges that emplaced tectonically the Benbatu Formation have common fault contacts with the surrounding sedimentary rocks, which are unconformably overlain by the Middle Permian marine terrigenous elastic clastics (Wang and Liu, 1986; Wang Quan et al., 1991; Li, 2006). The Benbatu Formation in this region is a littoral-territic volcanic-sedimentary sequence, which is quite similar to that of other areas of central-eastern Inner Mongolia. In our opinion, the Solonker ophiolitic mélangé was formed at least before the Late Carboniferous. Recently the Mongolian geologists have discovered the 367 to 344 Ma ophiolitic mélangé in Solonker on the Mongolia side (Ochir and Baatar, 2015), which is a definite proof for this. As to Early Permian mafic rocks of this ophiolitic mélangé reported by Jian et al. (2010), they should represent the record of a magmatic event taking place after the formation of the Solonker ophiolitic mélangé. According to Luo et al. (2016), in the Solonker area there occurred a small newly-emerging oceanic basin during the Late Permian. It seems to be impossible, because the continental deposits of the Late Permian occupy the entire region.

4.3 Paleozoic tectonic events

Published data show that before the Late Carboniferous three important orogenies occurred in southeastern Inner Mongolia: (1) Pre-Late Silurian orogeny. This is supported by evidence that the Upper Silurian–Lower Devonian Xibiehe Formation unconformably lies upon the Ordovician strata, ophiolite mélangé, Xilinhot complex, and Caledonian granites (BGMRNM, 1991, 1996; Tang, 1990; Zhang Yunping et al., 2010). The Ondor Sum–Xar Monron ophiolitic mélangé could be related to this orogeny. (2) Pre-Late Devonian (Famennian) orogeny. The Upper Devonian–Lower Carboniferous Aomugenhuduge Formation unconformably lies upon the Xibiehe Formation or the Early–Middle Silurian complex from Wulanhuduge to Wuguietu in southern Sonidzuqi (Tang Kedong and Zhang Yunping, 1991). The Erenhot–Hegenshan ophiolitic mélangé may be related to this orogeny. (3) Pre-Late Carboniferous orogeny. The eastern segment of the Tianshan–Hinggan Orogenic System generally lacks Early Carboniferous deposits, and the Late Carboniferous or Permian volcanic-sedimentary rocks always directly unconformably overlie the Devonian or older units. For example, the Amushan Formation unconformably rests on the Xibiehe Formation of central Inner Mongolia, the Baoligaomiao Formation unconformably, on the Late Devonian Angeryinwula Formation at Dong Ujimiqini, and the Sannianjing Formation unconformably, on the Ordovician gneissose tonalite. The Suolunshan ophiolitic mélangé is probably related to this orogeny.

During the Late Carboniferous–Early Permian, southeastern Inner Mongolia and its neighboring areas entered a post-orogenic extensional stage following abundant extension-related tectonic magmatism, evidenced by the bimodal volcanics, and alkaline granites. Although there are a few depositional breaks or slight unconformities in the Late Carboniferous and Permian strata, no obviously regional unconformities are discovered, and corresponding post-orogenic molasse deposits are absent. These features indicate that in the eastern segment of the Tianshan–Hinggan Orogenic System there was no strong subduction or collision orogenic process at this time, and the basin disappeared by gradual shrinking and shallowing.

The western segment of the orogenic system such as Kazakhstan and the Junggar Basin also exhibits the pre-Late Silurian, pre-Late Devonian, and Early Carboniferous (Visean) orogenic events. Here, post-orogenic extension began in middle–late Early Carboniferous times, and marine deposits disappeared at the end of Late Carboniferous. During the Late Carboniferous–Early Permian, in this region was developed a post-collision extensional setting accompanied by intense intermediate-acid magmatic events (BGRMRX, 1993; Xia Linqi et al., 2002; Xia et al., 2004, 2008; Xu Xueyi et al., 2014).

5 Conclusions

The Carboniferous–Permian stratigraphic sequences and sedimentary environments in southeastern Inner Mongolia and its neighboring areas manifest that the vast area used to be an ENE–NE-trending littoral-territic-continental basin. Most of the area lacks Early Carboniferous deposits, and
the Late Carboniferous or Permian volcanic-sedimentary rocks always directly unconformably overlie the Devonian or older units. The Upper Carboniferous–Middle Permian is marked by littoral-neritic deposition and the Upper Permian by continental sedimentation. Although there are some disconformities in the Late Carboniferous and Permian strata, obviously regional unconformities are not seen, and corresponding molasse sediments are lacking. It means that no strong subduction or collision orogeny process took place at this time, and the basin disappeared by gradual shrinking and shallowing.

The Ondor Sum and Hegenshan ophiolitic mélanges in the eastern segment of the Tianshan–Hinggan Orogenic System were formed in pre-Late Silurian and pre-Late Devonian, respectively, while the Solonker ophiolitic mélangé formed at least in pre-Late Carboniferous. In addition, the Late Carboniferous to Early Permian strata in this region are characterized by widespread and thick volcanic and volcaniclastic successions, some of which show predominantly bimodal characteristics. The appearance of the bimodal volcanic rocks in combination with the alkaline granites clearly indicates a post-orogenic extensional environment.

In the light of the above statement, it is obvious that the eastern segment of the Paleo-Asian Ocean closed before the Late Carboniferous, and most likely before the latest Devonian (Famennian), rather than at the end of the Permian or in the Early Triassic.

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**About the first author**

ZHJU Junbin, born in 1984, received his Ph.D degree from the China University of Geosciences (Beijing) in 2015. He is currently a postdoctor at Institute of Geology, Chinese Academy of Geological Sciences, Beijing. His current research interest focuses on the Late Paleozoic tectonic evolution of southeastern Inner Mongolia. E-mail: zhujunbin0819@163.com.