Early Paleozoic Ocean Plate Stratigraphy of the Beishan Orogenic Zone, NW China: Implications for Regional Tectonic Evolution

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Abstract: The Beishan orogenic zone is a key area to understand evolution of the Central Asian Orogenic Belt that is an accretionary factory well-enough preserved in the Paleozoic. In early Paleozoic, the tectonic mélangé zone containing the coherent unit and mélangé unit is triggered by the complicated accretionary process of the Beishan area. The early Paleozoic tectonic evolution of the Beishan orogenic zone is investigated in this study using sedimentology and stratigraphic correlations of the lowe Paleozoic deposits. From the Cambrian to the Middle Ordovician, this region was characterized by geographically extensive, flat-bedded siliceous mudstone, indicating the existence of a large ocean basin. The oceanic plate entered the convergence phase in terms of the Wilson Circle during the Middle Ordovician, when numerous magmatic arcs formed along two opposite sides of the ocean. The magmatic arcs became the widest during the Silurian, suggesting that the Hongliuhe-Niujianzi-Xichangjing Ocean (HNX; a southern branch of the Paleo Asian Ocean) was reduced to a small residual ocean in the central Beishan region by that time, and probably lasted till the Carboniferous or later by newly published data.

Key words: sedimentology, tectono-paleogeography, Beishan orogenic zone, ocean plate stratigraphy


1 Introduction

The formation of the Central Asian Orogenic Belts (CAOB) was closely associated with the evolution of the Paleo-Asian Ocean, represented by a well-preserved suite of rock and fossils record. Their study, therefore, can provide much insight into the processes of accretionary orogenesis and crustal growth (Şengör et al., 1993, 2014; Jahn et al., 2000, 2014; Wakita et al., 2005; Kusky et al., 2013; Zhang et al., 2012, 2016; Song et al., 2013, 2014, 2015, 2016; Zheng et al., 2013, 2018, 2019; Guo et al., 2014; Tian et al., 2014, 2016; Wang et al., 2014, 2016; Hu et al., 2015, 2017, 2018; Shi et al., 2018; Wang X Y et al., 2018; Wang et al., 2020).

In previous studies, ophiolite occurrences have been used for major paleogeographic elements for dividing oceanic basins within the ancient oceanic realm. With the development of ocean plate stratigraphy (OPS; Isozaki et al., 1990; Wakita et al., 2005; Kusky et al., 2013; Zhang et al., 2016; Wakabayashi, 2017; Raymond, 2019), the sedimentological characteristics in different parts of a given oceanic crustal “unit” have become increasingly important constraints for deciphering complicated accretionary processes. Movement of the oceanic lithosphere commonly results in preservation of its remnants in active margins and particularly along subduction zones, providing key lithological and paleontological information for paleogeographic reconstruction of ancient oceans.

As part of the Paleo-Asian ocean during the early Paleozoic, the Beishan area was situated in among the...
larger tectonic plates of Siberia, North China, and Kazakhstan terranes (Fig. 1a). Tectonically this region was intensely active at that time, making it difficult to determine the paleogeographic positions of the numerous micro-plates and micro-terrane.

The lower Paleozoic of the Beishan orogenic zone were not recognized and their sedimentary characteristics were overlooked. This has hampered our understanding the paleo-oceanic evolution in the Beishan area. The main objective of this study is to reconstruct the accretionary processes and paleogeography of the Beishan area in the early Paleozoic, based on the extensive sedimentological and paleontological data accumulated in recent field investigations.

2 Geological Settings

The Beishan area today is situated in a triangular zone, surrounded by Tarim Craton, North China Craton and Kazakhstan terranes (Fig. 1b). In the early Paleozoic, this area was part of the Paleo-Asian Ocean.

In the idealized model for Ocean Plate Stratigraphy, complete stratigraphic sections are used to reconstruct the evolutionary history of ocean floor transported from birth at a mid-ocean ridge to death at the trench (Isozaki et al., 1990; Wakita et al., 2005, 2012; Kusky et al., 2013; Safonova et al., 2014; Zhang et al., 2016; Feng et al., 2018; Raymond, 2019). The presence of various OPS were reported in the Gorny Altai region (Ota et al., 2007) and the Khangai-Khentei belt of Central Mongolia (Kurihara et al., 2009), as well as in the systematic description of the Central Asian Orogenic Belt by Safonova et al. (2014). The Beishan orogenic zone consists of several tectonic units that are separated by four ophiolite zones. Within the four mainly ophiolite zones, there are numerous ophiolitic blocks with variable ages, from north to south, namely the Hongshishan ophiolite zone, the Jijitai-Xiaohuanshan ophiolite zone, the Hongluhe-Niujunzi-Xichanging tectonic mélanage zone and the Liuyuan ophiolite zone (Fig. 1c; Xiao et al., 2010; Zhang et al., 2018; Wang et al., 2020).

In the far north, the Hongshishan-Baiheshan ophiolite zone, sandwiched between the Queershan arc unit to the north and the Mingshi-Hanshan massif unit to the south, is represented by outcrops mainly in the Hongshishan Mountain (Mao, 2008; Chen et al., 2018). The Hongshishan ophiolite mélanage contains tectonic blocks of serpentinitized ultramafic rocks, gabbros with minor diabase dikes, massive basalts, cherts, and mudstones. The gabbros in the ophiolite suite have a high-resolution U-Pb age of 346.6 ± 2.8 Ma, with lithological and geochemical characteristics of an embryonic ocean crust (Wang et al., 2014). However, the tectonic setting of the Hongshishan ophiolite zone is debated, and it has been variously correlated with delamination after the Baiheshan ophiolite mélanage. The Baiheshan complex and surrounding strata

![Fig. 1. Location of the study area in the Central Asian Orogenic Belt (after Xiao et al., 2003; Zhang et al., 2018).](image-url)
show that the Hongshishan-Baibeheshan zone represent the remnant of the south-dipping oceanic crust, and that a northern branch of the Paleo-Asian ocean exists in the northern Hongshishan-Baibeheshan area (Chen et al., 2018). The Queershan arc, extending from north of the Hongshishan Mountain in the west, to the Xiaohulishan area in the east, includes several Ordovician to Permian arcs composed of mafic to intermediate volcanic and volcanoclastic rocks (Mao et al., 2008; Chen et al., 2018). In the south side of the Hongshishan ophiolite zone, the basement of the Mingshui-Hanshan massif has been recognized (Zuo et al., 1991; Chen et al., 2018).

To the north, the Jijitaizi-Xiaohuanshan ophiolite zone was overthrust onto the Precambrian basement rocks in the Mingshui-Hanshan massif, including schist and mylonite of the matrix and harzburgite, gabbro and basalt of the mafic and ultramafic rocks, which contact each other by faults (Zuo et al., 1991; Li et al., 2012; Zheng et al., 2013). The geochemical characteristics of the mafic rocks and adjacent geological bodies suggest that this ophiolite suite originated in a back-arc setting (Li et al., 2012).

The longest, E-W trending Hongliuhe-Niujuanzhi-Mazongshan-Xichangjing (HNMX) tectonic mélangé zone is exposed in the central part of the Beishan orogenic zone, which is fault-bounded with two neighboring tectonic units: the Hongpanguo arc unit to the north (Wang X Y et al., 2018; Zheng et al., 2018, 2019) and the Huanushan arc unit to the south (Liu et al., 2011; Mao et al., 2012; Guo et al., 2014, 2017). The HNMX is composed mainly of several geological units, such as fragments of island arcs, crustal debris, trench slope turbidites, and pelagic and forearc sediments (Zhang et al., 2008; Hu et al., Ao et al., 2012; Tian et al., 2014; Sun et al., 2017; Wang S D et al., 2017, 2018; Wang et al., 2020). All these units were likely formed from Late Neoproterozoic to Paleozoic, through convergent tectonics that took place off the southern margin of the southern Altaiids. The associated northern Gongpoquan arc unit consists of Middle/Late Ordovician to Silurian volcanic rocks, metamorphic rocks and siliciclastic rocks (Xiao et al., 2010; Zheng et al., 2018, 2019; Wang X Y et al., 2018). The associated southern Huanushan arc unit contains packages of Paleozoic arc-related volcanic rocks and clastic sedimentary rocks (Xiao et al., 2010; Mao et al., 2010, 2012; Lv et al., 2012; Guo et al., 2014, 2017).

Farther south, a newly termed Liuyuan ophiolite zone is recognized to mark the terminal closure of the Beishan area in the Permian based on U-Pb dating (Xiao et al., 2010; Mao et al., 2011). The associated southern Shibanshan arc unit is interpreted as subduction products connecting the Dunhuang massif to the south (Mao et al., 2011).

3 Timing and Sedimentary Characteristics of the OPS in the Beishan Orogenic Zone

The strata of the Beishan area range from the Archean to the Quaterary, and the stratigraphic distributions of the lower Paleozoic sequence show great variations locally (as shown in Fig. 2). The lower Paleozoic consist mainly of the Shuangyingshan Formation, Xishuangyingshan Formation, Pochengshan Formation, Xiaolinkebo Formation, Luoyachushan Formation, Baiyunshan Formation, Gongpoquan Group., and Heijianshan Formation (Gansu Survey Institute, 2001; Zhang et al., 2017).

3.1 Coherent units in the Beishan orogenic zone

The belt is characterized by a coherent sequence comprising Lower Cambrian to Lower Silurian bedded chert and Upper Ordovician to Upper Silurian magmatic rocks (Gansu Survey Institute, 2001; Zhang et al., 2017). The Shuangyingshan Formation is distributed mainly along the south of HNMX, consisting of argillaceous rocks and bioclastic limestones. This formation disconformably overlies the Sinian Xichangjing Group, marked by a lower boundary of gray-purple grit-bearing ferruginous limestones or cherts. Fossilliferous bioclastic limestones of the Shuangyingshan Formation crop out sporadically in the Beishan area. Benthic trilobites including the lower Cambrian (provisional Cambrian Series 2) Serrodiscus, Tannudiscus, Calodiscus, Pagetides, Kootenia, Edelsteinaspis, Ptmagmanoides,?, Politinella, Dinesus and Subeia were recovered from section 2, 3 (Fig. 3), together with cephalopods and brachiopods (Bergström et al., 2014). The composition of the fauna suggests that the Cambrian Series 2 faunas described herein and from elsewhere in the Siberian palaeocontinent are seem to be the slope molecules (Zhu et al., 2018). Lithology and fossil assemblages suggest that this formation was deposited in an abyssal-bathyal environment.

The distribution of the Xishuangyingshan Formation is similar to that of the Shuangyingshan Formation, dominated by black pelagic cherts with horizontal bedding within thin stinkstone (Zhang et al., 2017). This formation, varying in thickness from 110–134 m, conformably overlies the Shuangyingshan Formation The trilobites and brachiopods in the limestone facies of this formation, include Agonostis, Gyptagnostus, Homagnostus, Corynecocchus, Pseudagnostus, Proceratapyyge, and Cycliclogoreynella etc. It suggest a Cambrian Series 3 (Furongian) age. Recrystallized radiolarian occurs in the siliceous mudstones of section S1, pointing to an abyssal-bathyal depositional environment.

Outcrops of the Pochengshan Formation are geographically limited, found only on the north side of the Pochenshan Mountain (Fig. 2). The formation is characterized by clastic rocks within cherts and limestones. Trilobites and brachiopods from Pochenshan section S8 (see Figs. 3, 4) indicate an early Cambrian age (Zhang et al., 2017). The stratigraphic nomenclature of the formation, however, is controversial. The bioclastic limestones contain lower Cambrian trilobita Subeia/bashamensis, suggesting that it corresponds to the Shuangyingshan Formation (Zhou, 2003; Fig. 4a, c). In this study, the interlayer of limestone is made a preliminary division of the Ordovician. In the Dapingnian, the Scolopodopus euspinus biozone is based on Scolopodopus euspinus and Drepanoistodus arecatus morphotype. In the Sandbian, the Pygodus anserinus Zone and Baltoniodus variabilis Zone are described herein indirectly based on Pygodus anserinus and Baltoniodus variabilis as reference markers (An et al., 1987; Bergström et al., 2017). The
Fig. 2. Geological map and section location of the Beishan orogenic zone (modified from Zhang et al., 2018).

S1, The Suhaigaole Section, Subei county, Gansu; S2, The northeastern Dahuloukou (Dahuoluo Well) Section, Subei county, Gansu; S3, The Shuangyingshan Section, Subei county, Gansu; S4, The southern Shuangyingshan Section, Subei county, Gansu; S5, The Zelumu Section, Subei county, Gansu; S6, The Hongshan Section, Subei county, Gansu; S7, The Fangshankou Section, Dunhuang city, Gansu; S8, The Pochenshan Section, Subei county, Gansu; S9, The Luoyachushan Section, Subei county, Gansu; S10, The Shajing Section, Guazhou county, Gansu; S11, The Zelumu Section, Subei county, Gansu; S12, The Xilinkebo Section, Subei county, Gansu; S13, The Xishuangyingshan Section, Subei county, Gansu; S14, The Dahulukou Section, Subei county, Gansu; S15, The southern Dahulukou Section, Subei county, Gansu; S16, The northwestern Suhaigaole Section, Subei county, Gansu; S17, The southern Suhaigaole Section, Subei county, Gansu; S18, The Hulunbasike Section, Ejin Banner city, Inner Mongolia; S19, The Fluorite Mine Section, Ejin Banner city, Inner Mongolia; S20, The Baiyunshan section, Ejin Banner city, Inner Mongolia; S21, The Gongpoquan Copper Mine Section, Subei county, Gansu; S22, The Changpingliang Section, Subei county, Gansu; S23, The Heijianshan Section, Subei county, Gansu; S24, The Xichangjing ophiolite mé lange Section, Ejin Banner city, Inner Mongolia; S25, The Yueyashan ophiolite mé lange Section, Ejin Banner city, Inner Mongolia; S26, The Baiyunshan ophiolite mé lange Section, Ejin Banner city, Inner Mongolia; S27-S29, The Mazongshang accretion complex Section, Subei county, Gansu; S30, The Niujuanzi ophiolite mé lange Section, Subei county, Gansu.
Fig. 3. Cambrian strata (Section S1-S8) comparison and characteristics in the Beishan orogenic zone. Depositional environment: MC, abyssal environment; BA, bathyal environment; ss, shallow-sea environment; VG, volcanogenitic sedimentary environment; CP, carbonate platform environment.
conodonts from the interlayer of limestone in the basal part of section S8 imply that the northern HNMX contains middle-upper Ordovician (Fig. 4b).

The Luoyachushan Formation is exposed mainly in the western portion of the central Beishan orogenic zone, and conformably overlies the middle-late Cambrian Xishuangyingsha Formation. The Luoyachushan Formation is characterized by interbedded feldspatic sandstone and siliceous slates, forming partly a thinning-upward sequence (Zhang et al., 2017). Graptolite and brachiopod fossils from the formation in the section S9 (Fig. 5) indicate that the Luoyachushan Formation is largely early Ordovician in age. The Luoyachushan Formation is interpreted to have accumulated in a

Fig. 4. Cambrian stratigraphic column of the Pochengshan Section (S8).
(a) Trilobite fauna Subeiabeishannensis from the basal of S8 constrains the Pochengshan Formation to the lower Cambrian (We are grateful to Wang Guoqiang from the Xi’an Geological Survey Centers of China Geological Survey for these materials); (b) Conodonts fauna of the interlayer of limestone from the S8 constrains the Pochenshan Formation containing Ordovician. A-B, Scolopodus euspinus, A, outer lateral view, B, inner lateral view; C, Drepanoistodus arcatus, outer lateral view, D, Protopanderodus varicosus, outer lateral view, E-G, Erraticodon balticus, E,G, lateral view, F, posterior view; H-I, Pygodus anserinus, lateral view; (c) and (d) lithologies characteristics of the bioclastic limestone from the basal S8
Fig. 5. Ordovician strata (Section S9-S18) comparison and characteristics in the Beishan orogenic zone.
succession of non-marine to shallow-marine and then to deeper marine environments.

The Xilinkebo Formation is dominated by black pelagic cherts (see in Fig. 5) with lense of limestones, with large, middle Ordovician siphonopods and trilobites found in the limestone lithofacies (Zhang et al., 2017). The formation conformably overlies the Cambrian Xishuangyingshan Formation, but the stratigraphic correlation between the Xilinkebo Formation and Luoyachushan Formation is unclear. The intense tectonic movement dominate this kind of formation as evidenced by the presence of a series of tight folds (Fig. 6a, b). Based on its fossil content, the Xilinkebo Formation belong to the Middle Ordovician. In the interlayer of limestone the typical trilobites was collected: *Xenocyclopyge* sp. (Gansu Survey Institute, 2001). This index trilobite approximately corresponds to the following cephalopoda. Some samples are collected in section with a degree of recrystallization and have no clear shell structure. It roughly suggests this formation formed in the Ordovician (Wang et al., 2018). Based on the previous study, we suggest that the Xilinkebo Formation coeval to the upper part of The Luoyachushan Formation, representing abyssal environment from lateral and vertical facies changes.

The Baiyunshan Formation is composed mainly of sandstone, siltstone, conglomerate, partially intercalated with siliceous rocks and limestones (Zhang et al., 2017) (see in Figs. 5, 6c-e, 7a–d). The distribution of the Baiyunshan Formation is similar to the Xilinkebo Formation in the south side of the HNMX. Based on the relationship between The Baiyunshan Formation and Xilinkebo Formation, the Baiyunshan Formation is assigned a Late Ordovician age. Lithology shows that The Baiyunshan Formation was deposited in the hemipelagic environment.

The Xianshuihu Formation, corresponding to the Baiyunshan Formation on the north side of the Hongshishan ophiolite belt, comprises sandstone, siltstone, and conglomerate, partly intercalated with siliceous rocks and limestones (Zhang et al., 2017). Brachiopods are the most abundant fossils at the section S18, containing *Howellites* sp., *Onniella* sp., *Plectorthis* sp., *Lingulla* sp., *Bicuspina* cf. *trapezoida* Fu, *Eospirigerina* sp., *Tetraphalerella* coopeii, etc. In addition, this formation contains a great diversity of fossils, including trilobites (*Encrinuroides* cf. *yanheensis*) and cephalopod (*Rizosceras* cf. *orientale* Lai). Based on the fossiliferous beds in the Xiaohuli Mountain, the Xianshuihu Formation vest in a Late Ordovician age. Lithology and fossils suggest the Xianshuihu Formation was deposited in the shallow marine environment.

The Gongpouquan Group is the main component of the Gongpouquan arc unit with various thickness from 1000–3000 m, extending from the Hongliuhe to the Dongqiyi.
The rock assemblages of the Gongpoquan Group include basic volcanic rocks, medium-acidic volcanic rocks, volcanic clastic rocks, associated with crystalline limestone, clastic rocks and cherts (Fig. 8). High-resolution geochronology and biostratigraphy suggest that the Gongpoquan Group has a range from the Late Ordovician to late Silurian (Zuo et al., 1991; Song et al., 2015; Wang X Y et al., 2018). The depositional environment of the Gongpoquan Group includes shallow marine and volcanic arc settings.

The Huaniushan Group is characterized by meta-sandstones, phyllites, limestones, marbles and basic-acid volcanic rocks (Zhang et al., 2017). The group contains trilobites (i.e., Pliomera Encrinuridae Calymenidae Encrinurella (cf)) and corals (i.e., Chaetetes ? sp., Crinoid stemy, Heliatites Lichenaria, Cryptol ichenaria), etc., indicating an Middle Ordovician to Silurian age (Zuo et al., 1991; Liu et al., 1995). The volcanic rocks have a calc-alkaline geochemical signature, suggesting the Huanuoshan Group formed shallow marine and volcanic arc settings accompanied by the southward subduction of the HNX oceanic crust.

The Heijianshan Formation is confined to the Luoyachunshan Mountain area, characterized by black shale and cherts, and containing Silurian graptolites (Zhang et al., 2017) (section S23 in the Fig. 8), faulted against the underlying Luoyachushan Formation. The lithology indicates an abyssal-bathyal environment.

3.2 Mélangé units in the Beishan orogenic zone

The HNMX tectonic mélangé zone, extending from the Hongluhe in the west, easterly through Niujuanzi-Mazongshan, to the Baiyunshan-Xichangjing in the east, contains numerous dismembered ophiolite mélangé with variable ages in its western, central, and eastern portions. Detailed datas were collected from the Beishan orogenic...

zone in the central portion (Wang et al., 2020). In this paper, we reconstruct the Xichangjing-Yueyashan ophiolite mélange (data from Hu et al., 2016), the Mazongshan accretion complex (data from Wang et al., 2020; shown in Fig. 9), the Niujuanzi ophiolite mélange (data from Wang et al., 2017; shown in Figure 8) and the Lebaquan forearc-arc complex in the central part of HNMX (data from Song et al., 2014; shown in Fig. 9).

The Baiyunshan-Xichangjing area contains several ophiolite blocks, such as the Baiyunshan, Yueyashan and Xichangjing blocks. The Yueyashan ophiolite mélange extends for 27 km NW-SE, and has a similar Cambrian tectonic and depositional history to the Hongliuhe part of the Mingshui-Hanshan continental margin. The Yueyashan ophiolite consists of a series of deep-water Cambrian cherts unconformably overlying an ophiolite suit. The published ages of these ophiolite mélanges span most of the Cambrian, suggesting that the oceanic expansion initiated during the Cambrian (Hu X Z et al., 2015; Hu X M et al., 2016). The Baiyunshanophiolite mélange is structurally dismembered and composed of gabbro, iherzolite, serpentinite and pelagic-hemipelagic sediments. Mafic-ultramafic bodies of the ophiolite mélange are generally 2–3 km (Sun et al., 2017), and faulted bound by the volcanic rocks and clastic rocks (Tian et al., 2020). The numerous studies of this complex span from Cambrian to Silurian indicating that the oceanic crust experienced the trip from the forming age to the emplacement age.

The Mazongshan accretion complex occurs widely to the south of Mazongshan town, composed mostly of unmetamorphosed to weakly metamorphosed ultramafic-basic rocks, andesites, marbles, sandstones with amount of tuffaceous slates (Wang et al., 2020). At outcrop scale, these blocks occur as several fault-bounded slices. Within individual areas, basaltic rocks are directly overlain by marbles with sedimentary contact (as shown in Fig. 6f). The basaltic rocks are mainly massive basalts, and often contain thin limestone intercalations. By analogy to modern and ancient examples, these lithological assemblages are interpreted to correspond to those of the sediments on and around a mid-oceanic seamount, particularly those of the slope facies transient to the deep-sea floor facies (Uchio et al., 2004). Blocks from various

Fig. 8. Silurian strata (Section S19-S23) comparison and characteristics in the Beishan orogenic zone.
Fig. 9. Formation process of the ocean plate stratigraphy (OPS) in the Beishan orogenic zone.
settings are in contact with surrounding sediments as lenses, suggesting a block-in-matrix relationship for the mingling of the mid-oceanic rocks and continent-derived terrigenous clastics, probably in an active trench (Isozaki, 1997).

The Niujianzi ophiolite mélangé is tectonically faulted by the northern Lebaquan fore-arc complex and connected with the Mazongshan accretion complex. The Niujianzi ophiolite mélangé is composed mainly, in ascending order, of layered gabbros, plagio-granites, sheeted dikes, massive basalts, and trench-fill sedimentary rocks. Thus this portion is a dismembered ophiolite that lacks several parts of the standard definition of an ophiolite, such as peridotites and bedded chert. The MOR ophiolite blocks are in fault contact with the sandstone, suggesting a segment of mid-ocean ridge incorporated in an active trench (Wang et al., 2017). Compared to the block in the HNMX, the high precision chronology of the matrix is obviously deficient. The youngest detrital zircon U-Pb ages and microfossils can be devoted to determine the turbidites upper depositional age limit (Brown et al., 2007; Dickinson et al., 2009). Meanwhile, making analogy with adjacent areas of depositional ages known independently from biostratigraphy can reconstruct the sequences of mélangé unit. The Ordovician ages yielded from Niujianzi ophiolite mélangé (Wang S D et al., 2018) and the Carboniferous ages yielded from Beishan orogenic zone and Niujianzi ophiolite mélangé (Wang S D et al., 2018; Wang et al., 2020) suggest that the northward accretion process is continuous from Late Ordovician to Early Carboniferous (Fig. 9). The fossils are preserved hard-enough in the orogen. Several acritarchs (Buedinisphaeridium cf. balticum, Lophosphaeridium sp., Multiplicisphaeridium sp. and Adorfia firma) and spore fossils (Leiotriletes spp.) of the matrix are presented in previous study (Wang et al., 2018). In this study, a few highly carbonated acritarchs fossils (as shown in Fig. 10) of the matrix from the Beishan orogenic zone suggest the
accretion process continuing from the Ordovician to the Carboniferous, and support the idea that the initial age of the accretion process is Ordovician.

The Lobaquan forearc-arc complex are exposed in the northwest part of the Mazongshan accretion complex, characterized by metasedimentary quartzite, phyllite, chlorite–quartz schist, sericite–quartz schist, chert, marble, metavolcanic metabasites, plus gneissic granitic plutons and later intrusions of leucogranite–pegmatites and mafic dykes. The primary structures of the protoliths of the metasedimentary rocks have been extensively obliterated by intense deformation and metamorphism, but residual bedding such as graded bedding or rhythmic bedding can still be observed. The lithological characteristics indicate that the sediments of the Lobaquan complex accumulated in a fore-arc basin (Song et al., 2014).

4 Discussion

4.1 The correlation of the coherent units and mélangé units

The OPS, generally including upper plate oceanic assemblages and accretion complex, are difficulty distinguished from one another in Beishan area owing to complicated tectonic movement. The variation in Beishan OPS packages and their relationship to the architecture of the accretion complex contribute to evolution of early Paleozoic in the Beishan orogenic zone. The earliest mélangé units of the OPS in the Beishan comprises MORB (mid-ocean-ridge basalt) progressively over lain by chert and siliciclastic rocks (Zhang et al., 2008; Hu et al., 2015; Sun et al., 2017). The contemporaneous coherent units of the OPS in the Beishan are characterized by pelagic-hemipelagic sediments that represented the oceanic basin. These rocks may have formed before subduction that initiated during 475–450 Ma within oceanic crust, in an environment lacking clastic sediment input.

Following subduction initiation and accretion of island arc; subsequent oceanic igneous rocks subducted and accreted were of subduction zone (SSZ) affinity with lesser amounts of mid-ocean ridge (MOR). The age of the subducted oceanic crust in the mélangé units became progressively younger until termination of subduction and conversion to a transform plate boundary (Wang et al., 2020). The mélangé units in the Beishan OPS packages had significant components of trench fill clastic sedimentary rocks that are composed of variable proportions of turbidites and siliciclastic and serpentinite–matrix olistostromes overlying the pelagic-hemipelagic sedimentary rocks (Fig. 10; Ao et al., 2012; Wang et al., 2018; Wang et al., 2020). In contrast to the age of the subducted oceanic crust, the age of clastic sedimentary rocks in each accretion complex was progressively younger with each successively accreted unit. In addition, the trench fill sedimentary rocks, overlying the pelagic sedimentary rocks, play a significant role of the coherent units of the Beishan OPS packages.

4.2 The paleogeography of the Beishan orogenic zone

In this study, the formation of the coherent units as an accretionary complex is investigated on the basis of ocean plate stratigraphy (Isozaki et al., 1990; Watika et al., 2005). The lowermost part of the reconstructed stratigraphy consists of basaltic rocks and the overlying radiolarian chert (Fig. 10). Such MOR-type basalts described from the Hongluluhe-Niujuanzi-Xichangjing area are interpreted to be the lowest part of the formation corresponding to ocean floor rocks (Zhang et al., 2008; Ao et al., 2012; Hu et al., 2014; Wang et al., 2017, 2020). The southern oceanic sediments span a period of nearly 80 million years from late Cambrian to early Silurian. This implies that the oceanic sediments were likely deposited over a vast and open ocean floor that enabled the continuous sedimentation over a prolonged geological time under a persistent pelagic-hemipelagic environment. The Cambrian trilobites, containing main slope molecules, closely resemble the Siberia terrenes and Kazakhstan terrenes (Ivshin, 1979; Zhou et al., 2008; Zhu et al., 2018). It suggests that the Beishan orogenic zone, the Siberian Craton, the Kazakhstan terrenes and the North China terrenes are adjacent to each other in the Cambrian. However, the Early-Middle Ordovician strata of the Beishan have a greater diversity of fossils, including the South China fauna and Tarim fauna (Bu et al., 2019). It infers that the oceanic basin was expanding in the Early-Middle Ordovician. Previous studies show that the Mazongshan trench developed in late Middle Ordovician, consisting of ancient arc or oceanic plateau, and coeval fore-arc basin and arc were formed along the southern Mingshui-Hanshan massif (Song et al., 2014, 2015; Wang et al., 2020). This implies that the features of late Middle Ordovician active continental margin were present in the southern Mingshui-Hanshan massif.

With subsequent movement into the trench region, the pelagic-hemipelagic sequence was replaced by trench-fill turbidite (e.g. the Baiyunshan Formation) before being accreted to an active continental margin or arc. Tectonic stacking of the oceanic sediments, turbidite, and other lithologies, as well as the formation of clast-bearing mudstone with block-in-matrix structure, occurred during these subduction and accretion stages. Paleomagnetic analysis of the southernmost Tarim terrenes or Dunhuang massif indicates that the study area drifted to low paleolatitudes by the early Paleozoic, based on the succession of interpreted depositional environments (Zuo et al., 1993). Data from this study suggests that the oceanic plate of the study area had a close paleogeographic affinity with the Siberian Craton, and was surrounded by the Tarim, Kazakhstan and Mongolian terrenes.

4.3 Evolution of the Paleo-Asian Ocean in the Beishan area

Field studies in four localities in the Mazongshan town and Xiaohulishan Mountain, paleogeographically located in the central part of the Beishan orogenic zone from south to north, revealed that HNMX in this area consists of early pelagic and semi-pelagic sedimentary sequences and common magmatic rocks (Gansu survey Institute, 2001). Previous biostratigraphic work on the upper lower Cambrian carbonate deposits of the southern side of the
Fig. 11. Early Paleozoic tectono-paleogeography evolution chart of the Beishan orogenic zone.

(a) In the Cambrian to Early Ordovician the Paleo-Asian Ocean was expanding, as indicated by sedimentary of the OPS; age of ophiolites by Hou et al., (2012), Hu et al., (2015) and Shi et al. (2018). (b) The Paleo-Asian oceanic crust experienced bidirectional subduction since the Middle Ordovician (after Guo et al., 2014; Song et al., 2015; Tian et al., 2014; Wang et al., 2020). (c) Magmatic activity peaked in the Late Ordovician-Late Silurian on the two sides of the HNMX, shrinkage of the HNX ocean (a southern branch of the Paleo-Asian Ocean; Liu et al., 2011; Mao et al., 2012; Zheng et al. 2018, 2019).
central Beishan orogenic zone (Bergström et al., 2014) suggests the existence of a shallow sea in the central Beishan area at that time. The reducing deep-ocean expanded from the Hongliuhe to the Xichangjing areas, as defined by the coherent units and mélange units of the Hongliuhe-Xichangjing area (Zhang et al., 2008; Ao et al., 2012; Hu et al., 2016). The paleogeography of the central Beishan orogenic zone within the Paleo-Asian Ocean can be constrained by the dimensions of the continental terranes bearing bathyal – abyssal environment deposits (see Fig. 11a).

The paleogeographic pattern of the Beishan area remained similar from middle to late Cambrian, dominated by a large ocean that accumulated widespread pelagic oceanic sediments, characterized by bedded cherts. The extent of the oceanic basins at that time between the tectonic blocks can be estimated on the basis of both lateral (paleogeographic) and vertical (stratigraphic) distributions of the tectonic units as well as their bedded cherts in the southern HNMX, which can be used as a proxy for the minimum geographic extend and geological duration of a basin. Such estimate is further supported by high-resolution geochronological ages obtained from the ophiolite suite in the Hongliuhe, Xichangjing and Yueyashan area.

Compared with the early Middle Ordovician, the paleogeographic pattern of the late Middle Ordovician changed significantly. The paleogeographic extent of the HNX ocean (a southern branch of the Paleo-Asian Ocean) reached its maximum in the Beishan area by the Middle Ordovician, followed by the initial phase of reduction by late Middle Ordovician, as indicated by the intense crustal activity in the southern margin of the Mingshan-Hanshan margin. The lithological succession in the Hongliuhe–Luoyachuanshan Mountain area is characterized by bedded cherts, shale and sandstone with graptolites of relatively deep-water origin. The succession in the Lebaquan area is dominated by a suite of clastic rocks and cherts accompanied by turbidites, which shown a pelagic-hemipelagic fore-are settings. In contrast, the lithological package in the northern Gongpoquan–Dongqivishan Mountain area and Huanishan Mountain area comprise volcanic assemblages with interbeds of bioclastic limestone with corals and brachiopods, suggesting a shallow water depositional environment (Liu et al., 2011; Mao et al., 2012; Wang X Y et al., 2018; Zheng et al., 2018, 2019). The lithology in the Xiaohulishan area on the north side of the Mingshui-Hanshan area is similar to that of the Gongpoquan area, originated from the Zoolen ocean (a northern branch of the Paleo-Asian Ocean) south-dipping (Chen et al., 2018). These lithological packages in the Beishan area generally point to an active margin with typical ‘trench-arc-basin’ depositional systems (see Fig. 11b).

In the Silurian, the basic paleogeographic pattern of the Late Ordovician persisted. The dimensions of the oceanic basin in the central Beishan area shrank further, as a result of a bidirectional subduction in central Beishan. Sedimentological and paleontological data suggest that depositional settings evolved from a deep-water pelagic-hemipelagic basin to a shallow water shelf. Meanwhile, the uplift of the Mingshui-Hanshan massif generated large amounts of terrigenous material, providing sediments for the trench (Fig. 11c). The accretion process of the HNX ocean continued well into the Carboniferous based on the youngest age of the trench-fill turbidites (Wang et al., 2018, 2020).

5 Conclusions

The tectonostratigraphic analysis of the Hongliuhe-Niujuanzi-Mazongshan-Xichangjing tectonic mélange zone (HNMX), based on geological mapping and stratigraphy of typical outcrops for individual constituent terranes, showed a successive emplacement, with increasingly older age along the subduction-accretion belt in the central Beishan orogenic zone. The HNMX terrane paleogeography is characterized by a segment of the Paleo-Asian Ocean comprising a number of oceanic sub-basins separated by northerly drifting continental terranes of Siberian origin. This general geodynamic process implies a relatively long duration of the open oceanic basins, followed by northward subduction and final accretion and basin closure by the Late Ordovician. This intra-Paleo-Asian plate tectonic process may have resulted in the co-existence of the MOR and SSZ ophiolites in the oceanic terranes of the HNMX. Thus, drifting of continental terranes and opening of oceanic basins is followed by multi-island arc terrane accretion and subduction of oceanic basins, leading to the final closure of the oceanic basins and the subsequent subduction-accretion belt. The subduction-accretion model is shown to apply to two units of the HNMX with ophiolites, related pelagic-hemipelagic sediments and arc-related magmatic rocks.

This study of the coherent units and mélange units of oceanic basin within the Beishan accretionary belt provided strong evidence for the existence of a regionally extensive oceanic basin during the early Paleozoic in the Beishan area, surrounded by such tectonicall significant terranes as the Tarim, Mongolia, and Kazakhstan blocks. The newly published data infer that the residual oceanic basin in the Beishan area probably last till the Carboniferous or later.

Acknowledgments

We are grateful to WANG Guoqiang from the Xi'an Center of China Geological Survey for partial materials (figures of trilobite). This research is funded by the National Natural Science Foundation (No. 41772107), the Geological Survey Program (No. DD20190370 and No. DD20190812) of the People’s Republic of China, and the National Key Research, Development Program of China (No. 2016YFC0601005).

References


Mao, Q.Q., Xiao, W.J., Fang, T.H., Wang, J.B., Han, C.M., Sun, M., and Yuan, C., 2012. Late Ordovician to early Devonian adakites and Nb-enriched basalts in the Liuyuan area, Beishan, NW China: Implications for early Paleozoic slab-


Xiao, W.J., Mao, Q.G., Windley, B.F., Han, C.M., and Li, J.L., 2010. Paleozoic multiple accretionary and collisional

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