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Sedimentation and mineralization of the Late Paleozoic extensional basin in the western Kunlun Mountains, China

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Abstract

In the western Kunlun Mountain region, due to the convergence of the Paleotethys Ocean in the Late Paleozoic, through northward subduction towards the West Kunlun Block, forming the Kangxiwa−Waqia arc magmatism and back-arc extensional basins, including the Tamu−Kalangu and Oytag−Kurliang basins. This study explores the relationship between basin evolution and mineralization. First, the Late Paleozoic back-arc and far-field continental back-arc basins were distinguished by analyzing sediment constructions in the basins. The former was continuously deposited in the Middle Devonian−Late Permian above the Precambrian basement due to the existence of the depressions. The latter were intermittently deposited in the Middle Devonian−Late Permian due to rifting above the Caledonian orogenic belt. Although the two settings were separated by the Tiekelike fault, their formations were subject to mantle upwelling caused by the subduction of the Kangxiwa oceanic crust. We also divided the Hercynian and Indosinian magmatic activities related to the basin; the former of which included the formation of bimodal magmatic rocks (339−291 Ma) as the basin expanded, which resulted in hydrothermal sediments and hydrothermal−magmatic mineralization, mainly including volcanic massive copper sulfide, Cu and Ni sulfide, and hydrothermal deposits. During the Indosinian orogeny, intermediate acidic magmatic rocks (265−206 Ma) associated with the closure of the basin was formed, leading to the development of hydrothermal Cu−polymetallic and porphyritic copper deposits. The relationship between basin evolution and mineralization was determined. Based on the findings, we concluded that the basin extended between the Middle Devonian and Early Permian. Syngenetic sedimentary deposits formed in the closed basins and anoxic environments of local depressions and mainly included sedimentary rock-hosted stratiform Cu deposits, exhalation-sedimentary Pb−Zn deposits, and sedimentary Mn deposits. Between the Middle Permian and Early Triassic, the basin began to close and the transformation from a basin to a mountain range finally occurred. The sedimentary basement was transformed by folding and faulting, thus forming tectonic deposits, including hydrothermal vein-type Pb−Zn deposits and Cu−Pb deposits within tectonically altered rocks. The results of this work show that the Late Paleozoic extensional tectonic environment formed both the back-arc basin and the far-field continental basin simultaneously. Periods of magmatism related to rifting and convergence could be distinguished by the corresponding mineralization. The metallogenic types related to the basin could also be divided into sedimentary, magmatic hydrothermal and tectonic hydrothermal deposits.

Keywords: Late Paleozoic basin; Extensional back-arc environment; Pb−Zn−Cu−Mn deposits; Magmatic activity; Western Kunlun Mountains

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1. Introduction

In a broad sense, the western Kunlun Mountain region is a composite orogenic belt and its basal belt is roughly composed of the Tianshuihai Block, West Kunlun Block, and the southern margin of the Tarim block (Fig. 1 a). These started to convergent in the Early Paleozoic, forming the West Kunlun Block via the convergence of multiple blocks or micro-blocks in the Proto-Tethys Ocean (also known as the Kudi Ocean). Accordingly, it converged with the southern margin of the Tarim massif, leading to the development of the Caledonian orogenic belt (Cui et al., 2006; Xu et al., 2011). The Paleotethys Ocean (a.k.a., the Kangxiwa Ocean) converged during the Late Paleozoic and the Tianshuihai Block pointed toward the subduction of the West Kunlun Block (Li et al., 1996; Mattern and Schneider, 2000; Xiao et al., 2005; Zhang et al., 2018). In addition to arc magmatism (Li et al., 2006), several back-arc basins and far-field intracontinental back-arc basins were also formed in back-arc settings (Liu et al., 2014; Zhang et al., 2014). After the closure of the Paleotethys Ocean at the end of the Late Paleozoic, it was intruded by a large number of Indochinese granites (Gao et al., 2013; Kang et al., 2015).

In terms of tectonic evolution, sediment formation in the Late Paleozoic basin of the West Kunlun Basin was based on tectonic changes during the Caledonian orogeny and sediments were later transformed by subsequent tectonic activities during the Indosinian orogeny. Therefore, a detailed analysis of this regional interval of extension is of great geological importance for understanding the tectonic evolution of the West Kunlun Block. It is an extensional tectonic event in the evolution of the West Kunlun complex orogenic belt. Additionally, many ore deposits of economic value have been found in the basin, including strata-bound Pb−Zn deposits, sandstone Cu deposits, sedimentary Mn deposits, massive volcanic−hydrothermal sulfide deposits, and Cu−Ni sulfide deposits (Fig. 1b). Therefore, studying this basin is of economic importance for determining the relationship between different tectonic events and ore mineralization.

There remain some disputes regarding the tectonic environments of the Late Paleozoic sedimentary basins in the western Kunlun Mountain region. Many researchers have concluded that the Tamu−Kalangu Basin formed along an active continental margin (Chen et al., 2010; Yin et al., 2003a), while others have suggested that it formed in a belt of

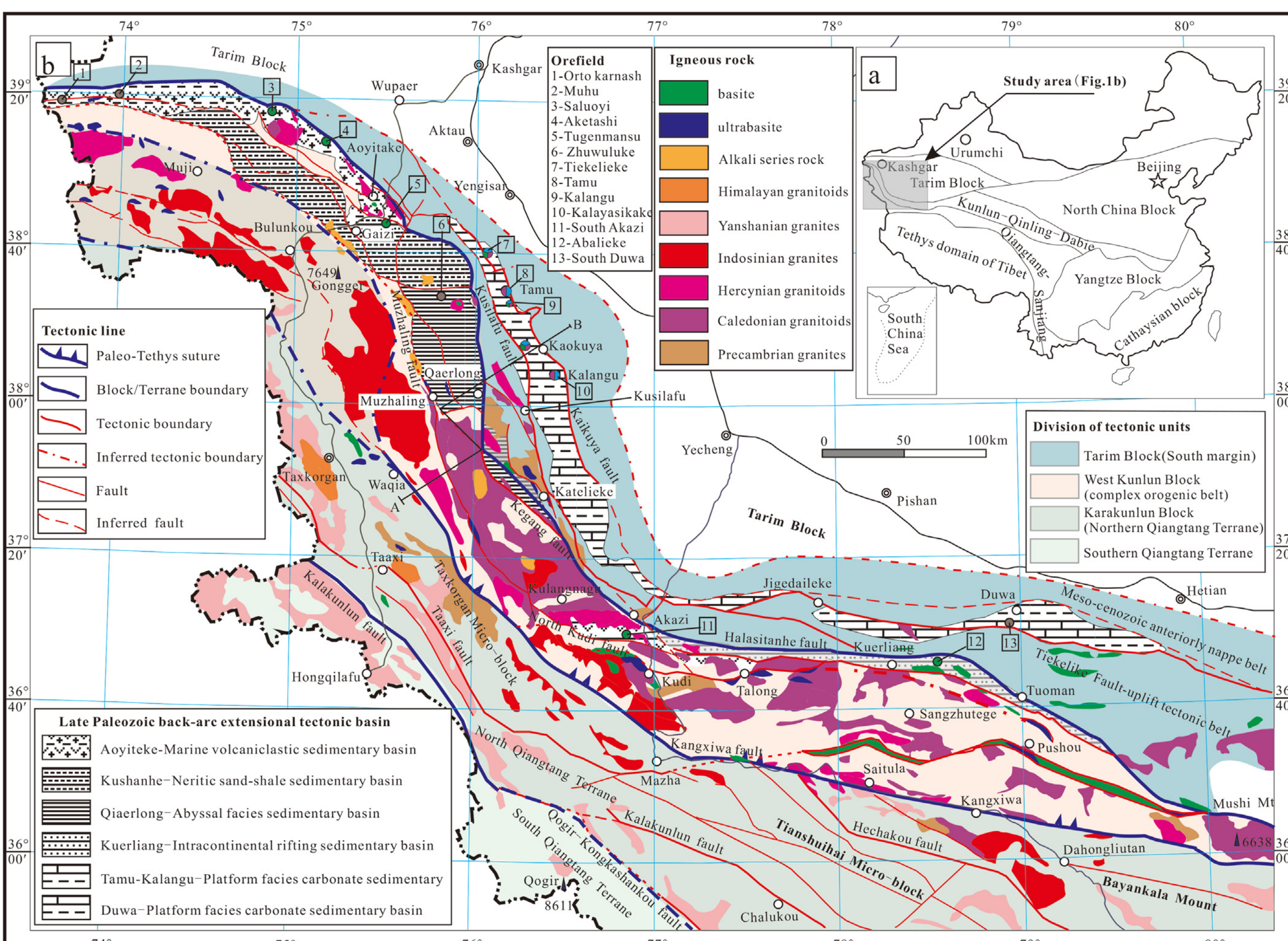

Fig. 1. Geological map of the Late Paleozoic extensional basin and associated mineralization in the western Kunlun Mountains, China (modified after Henan Institute of the Geological Survey, 2006; Zhang et al., 2014).

extensional depressions on the continental margin (Tian and Hu, 2010) or in a marginal cratonic basin (Yang, 1994; Liu, 2001). Meanwhile, the Oytag–Qiaerlong back-arc basin is located on the northern rim of the West Kunlun massif (Liu et al., 2014) and the Talmud–Callan tensional basin is located on the southern margin of the Tarim massif (Zhang et al., 2014). Although these two tectonic blocks are separated by the Tiekelike fault zone (Fig. 2), they are believed to have formed at the same time and from the same magmatic source, suggesting that they have a shared genetic origin, so that it is necessary to study their sedimentary characteristics, magmatic histories, and tectonic environments (Fig. 3).

The Late Paleozoic extension that resulted in the formation of the West Kunlun Basin is not only an important tectonic environment, but it is also closely related to Cu–Pb–Zn–Mn mineralization (Dong et al., 2007). Although many deposits have been reported on (Jia et al., 1999; Zhao et al., 2002; Tian and Hu, 2010; Zhang et al., 2014, 2018; Chen et al., 2018), a holistic analysis of the relationships between the evolution of the sedimentary basin and mineralization remains lacking, especially with respect to the mineralization of these deposits based on a unified extensional tectonic setting. Therefore, in this study, we mainly summarized sediment formation, magmatic activity, and deposit characteristics in the Late Paleozoic basins and analyzed the relationships among the geological background, evolutionary processes, and mineralization in the basins.

2. Geological setting

2.1. Connective zones between tectonic blocks

In the study area, the tectonic framework is generally composed of the belts of the Karakunlun Block, West Kunlun Block, and the southern margin of the Tarim Block (Fig. 1a), with the jointed zones between them being the Kangxiwa–Mazha belt (i.e., the Kangxiwa fault zone) and the Kegang fault zone, respectively.

(1) The Kangxiwa–Mazha mélange belt is distributed along the Kangxiwa–Mazha–Waqia line (Fig. 1b), and its rock formations mainly include an arc magmatic complex, sedimentary formations closely related to the arc, and exotic rock blocks mixed with the structure (Cui et al., 2013; Ji et al., 2013). The arc magmatic complex is mainly composed of diabase porphyrite, altered andesite mixed with dacite, quartz diorite, dacite, andesite, tuffaceous andesite, and moderately crystalline monzonitic granite. The Mazha mélange belt is dominated by andesite, while a complete calc-alkaline series rocks from high-

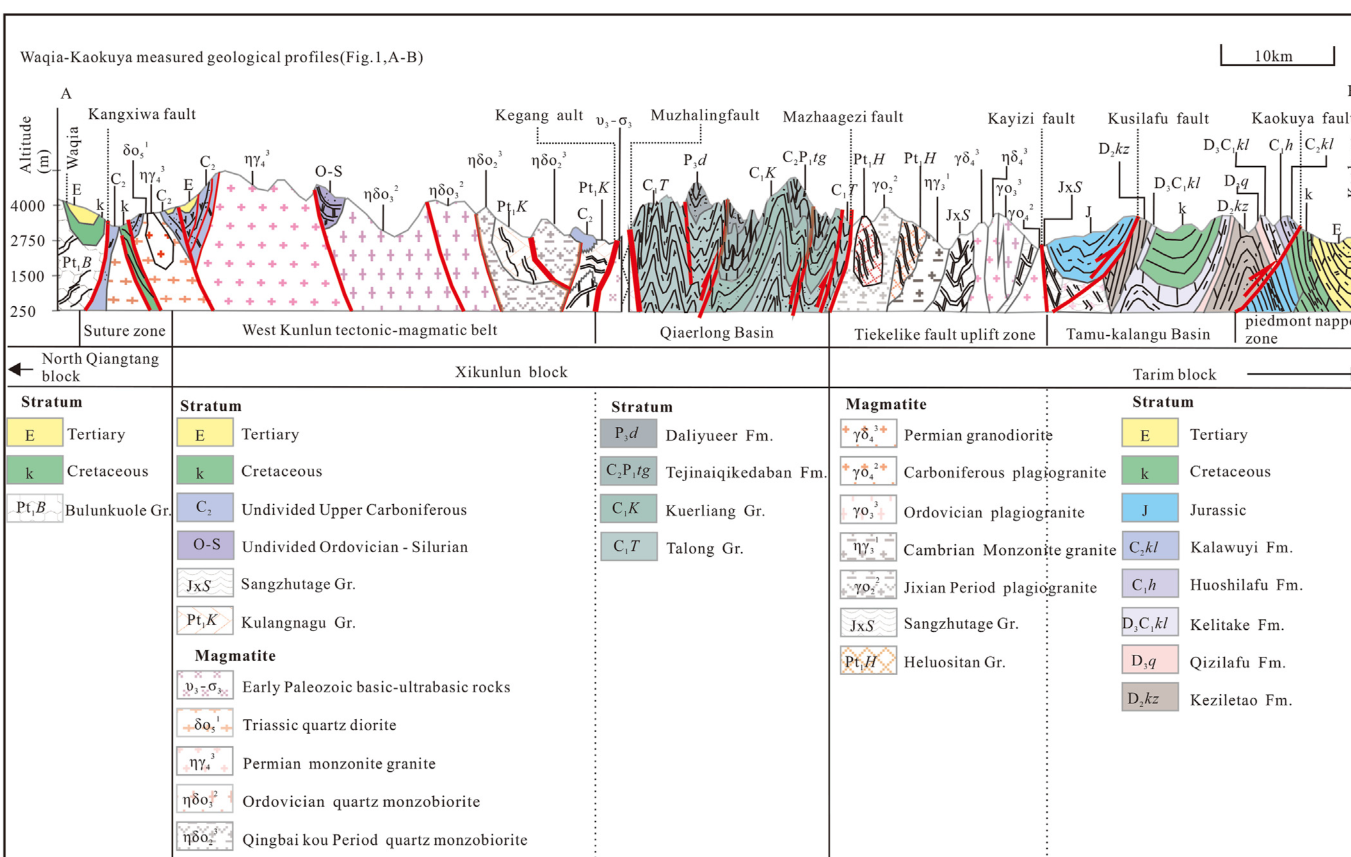

Fig. 2. Geological profile of Waqia-Kaokuya in the western Kunlun Mountains, China (modified after Henan Institute of the Geological Survey, 2006).

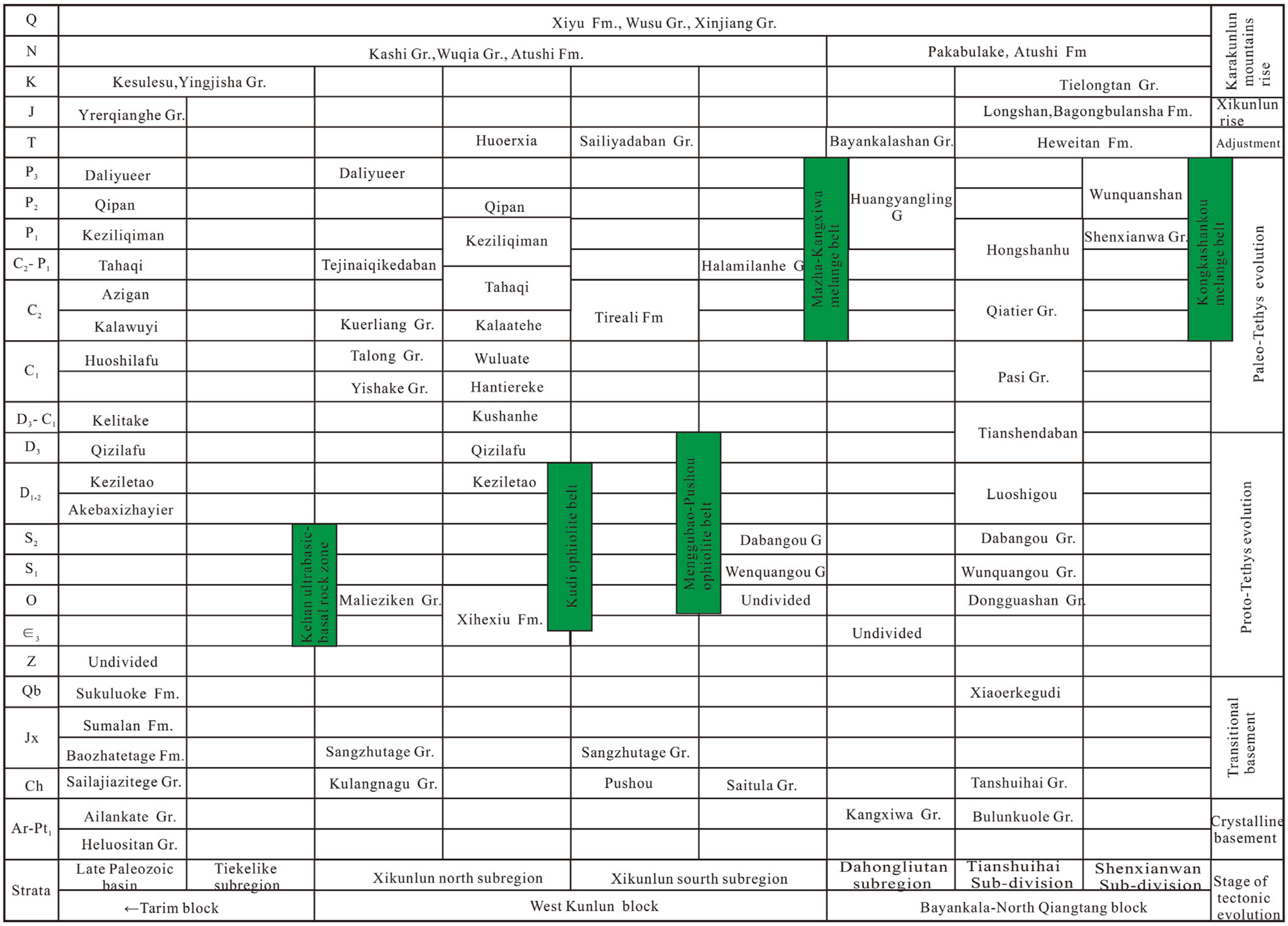

Fig. 3. Comprehensive table of stratigraphic division in the western Kunlun Mountains, China (modified after Lu et al., 2013).

alumina basalt to dacite and rhyolite can also be seen and display island-arc characteristics (Fig. 2).

Petrogeochemical characteristics indicate that magma was formed in an island arc at the plate boundary. The sedimentary and metamorphic rocks associated with volcanic arcs include variable sandstones intercalated with sericite slate, silty slate, variable sandstones intercalated with greenschist, marble, limestone, sandstone, silty sandstone, mudstone intercalated with pebbly sandstone, and silty rocks. The sedimentary rock assemblage in the study area includes neritic and bathyal facies, and bryophyte fossils in a conglomerate further confirmed a neritic sedimentary environment. In addition, there were many greenschists and andesites in the clastic rocks, suggesting that these successions formed in relation to the arc. Exogenous rocks include silty slate mixed Carboniferous dolomitic limestone and coarse marble. A diabase dike intruded into the wallrock in the coarse-grained marble, and some calcite was heavily recrystallized, indicating that these layers have undergone intense deformation and metamorphism.

(2) The Kegang ophiolite belt consists of basic–ultrabasic rocks (Fig. 1b), such as those along the Kateleke (Kegang) and Kuokejilega faults. The lithology consists of altered peridotite, pyroxenite, and altered gabbro (Wang et al., 2013). These rocks have displayed an island-arc tholeiitic nature, with features of an island-arc ophiolite, and have intruded into the Ordovician Malieziken Group to produce plutonic xenolites in the Tarr intrusion that occurred during the later period of the Hercynian (Variscan) orogeny. Therefore, we concluded that the formation age of the ophiolite suite should be later than the Middle Ordovician while preceding the emplacement of the late Variscan granite.

The Kegang fault zone is distributed to the northwest in the Katelieke (Also called Kegang)–southern Taer area. It is connected to the Heluositan River fault zone at the south end, forks toward the northwest, where it is connected to the Muzhaling and Oytag faults, respectively (Fig. 1b). The fault is composed of a ductile shear zone and a series of fault zones distributed parallel to it. At the interface of the main structure, there are exotic rocks mixed with the structure and the calcrete in the Maliekenzi Gr. is a disorderly mass. In addition to the exposed Kogan ophiolite, they also divide the Tarim and Kunlun stratigraphic areas there is abundant quartz diorite in the sides of their structural belts (Fig. 2). The petrochemical data show that they formed on the continental margin of a volcanic arc environment through invasion during the early Caledonian orogeny and intermediate term (zircon U−Pb date: 480.43 ± 5 Ma), respectively, indicating that the Kogan fault zone probably formed early during the Caledonian orogeny and ended later during this event.

2.2. Features of tectonic blocks and sedimentary formations

(1) The Karakunlun Block is divided between the Kangxiwa and the Georgian−Kongkashan fault zones. The secondary tectonic units include the Dahongliutan−Bayankala systems, the Tashkurgan Microcontinental Block, and the Shenxianwan fold zone, and the southern part of the block is connected to the Gangdise system (Fig. 1b). The block base is constructed from the basic volcanic and carbonate rocks of the Paleoproterozoic Bulunkuole Gr. and the depositional environment was similar to an active margin, which was intruded by a Neoproterozoic medium−felsic plutons (Ji et al., 2013).

Only a small amount of carbonate is found in the Late Cambrian, including oolitic limestone and limestone. The Ordovician Dongguashan Gr. is unstable neritic face that contains many clastic, carbonate, and volcanic rocks. The Silurian Wenquangou Gr. is a metamorphic−clastic assemblage with a large sedimentary thickness and a low-refractory greenschist facies, while the Dabangou Gr. contains abundant arkose, quartz sandstone, and greywacke. The shallow marine facies of the Luoshigou and Tianshendaban formations contain Devonian biocarbonate and clastic rocks.

Early Carboniferous deposition of the Pasi Gr. occurred in a neritic, semi-enclosed marine environment consisting of carbonates, clastics with volcanics, and pyroclastic rocks, among others. Late Carboniferous sedimentary facies formed in an epicontinental slope facies (Qiatier Gr.). From the end of the Carboniferous to the Middle Permian, the Mazha mélange belt was formed in a volcanic arc, along with deep-water flysch sedimentation of the Huangyangling and Shenxianwan groups. Late Permian carbonates were deposited in neritic or platform facies (Wenquanshan Formation). During the Triassic, in addition to deep-water facies (Bayankala Gr.) in the Dahongliutan area, a tectonic mélange was also formed in the Mazha−Kangxiwa area, which began to enter a stage of regional tectonic adjustment and uplift (Fig. 3).

(2) The West Kunlun Block is located between the Kangxiwa and the Kegang fault zones. The secondary tectonic units include the Kulangnagu, Sangzhutage, and Setula microcontinental blocks as well as the Gonger Microcontinental Block (Fig. 1). The Kulangnagu Microcontinental Block is

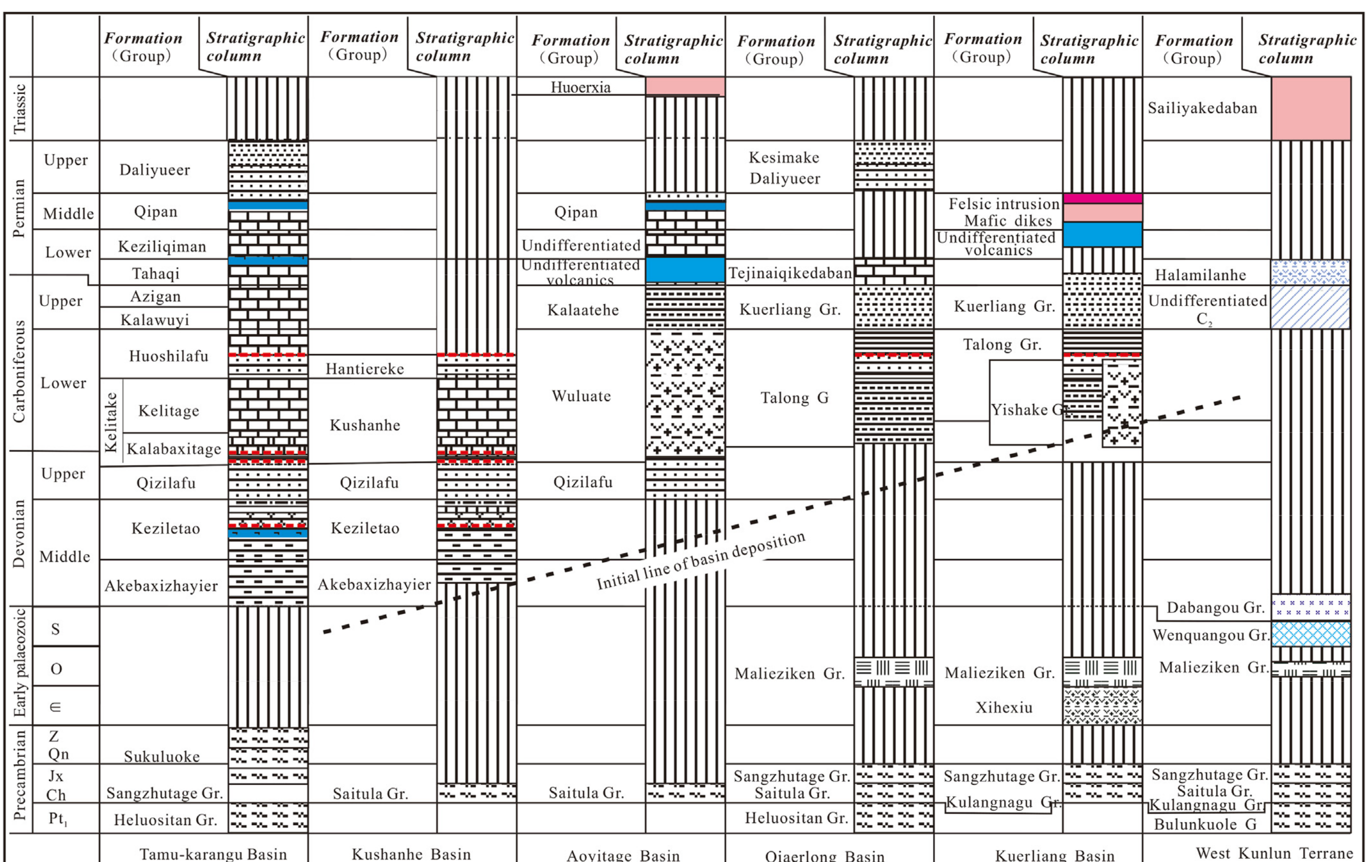

Fig. 4. Stratigraphic column of strata of the Late Paleozoic extensional basin in the western Kunlun Mountains, China (modified after Lu et al., 2013).

Table 1
Brief characteristics of sedimentary strata, lithology and association of the extensional tectonic basin in the Late Paleozoic.

Basin	Strata	Main sedimentary lithology and characteristics	Sedimentary association
Kuerlang Basin	Kuerliang Group C_2K	The main strata are dark-gray to gray conglomerate containing sandstone, carbonaceous siltstone, feldspar-quartz sandstone, limestone, grayish-green thin-to medium- layer calcareous siltstone, sandy crystalline limestone, and tabular microcrystalline schist, quartz schist, actinolite schist containing chlorite and sericite. Coral, Brachiopoda and Crinoid stems fossils can be seen.	Abyssal-neritic shelf, including turbidity deposit
	Talong Group C_1T	The main strata are dark gray carbonaceous sericite slate and a small amount of carbonaceous sandy slate. Peat-bog inferior coal seam occurs occasionally. It can be divided into two layers: lower part consists of black argillaceous-carbonaceous shale with sandstone, limestone, marble, green mica-chlorite schist and fine-grained sandstone; upper part is composed of black, dark gray carbonaceous shale and sandstone.	Abyssal-bathyal deposit
	Yishake Group C_1Y	The lower part is massive basalt, pillow lava, amygdaloidal andesite-basalt cut by a large amount of diabasic dike. The middle part is violet red dominated motley andesite, basaltic-andesitic volcanic rocks. The upper part is volcanic rocks turbidity sediments. Radiolarian assemblage of the Late Devonian to the Early Coniferous indicate a large scale of volcano eruption on the sea floor.	Coast deposit
Qiaerlong Basin	Kesimake Formation P_3k	The main strata are gray thick-layer bioclastic limestone, gray-dark to gray thick-layer bioclastic micrite, grayish-white giant-thick-layer sandy limestone containing bioclast, small amount of micrite, leucitic granular bioclastic limestone, (calcareous) mudstone, minute quantity feldspar-sandstone, and siltstone, which contain coral and bivalve. VMS deposit occurs in this formation (Aktash deposit).	Intertidal - subtidal deposit
	Daliyueer Formation P_3d	The main strata are violet red mudstone, violet red medium-thick layer fine-grained quartz sandstone, violet red thick to thin-layer fine-grained lithoclast feldspathic sandstone, gray to grayish-green medium to thick-layer medium to fine-grained quartz sandstone, and small amount of calcareous quartz siltstone, mudstone, silty mudstone, and dark purple Ferrous silty micrite.	Fluviatile-coastal deposit
	Tegeinaiqikedaban Formation C_2—P_1tg	The main strata are carbonaceous mudstone, calcareous siltstone, (silty) micrite, quartz sandstone, and small amount of silty mudstone, micrite. *Sphenomorphus indicus* and coral fossil can be seen.	Neritic shelf deposit
	Kuerliang Group C_2K	The main strata are gravel-bearing quartz siltstone, argillaceous quartz siltstone, quartz siltstone, fine-grained quartz sandstone, gravel-bearing quartz sandstone, silty mudstone, and sparry gravel-bearing sand (bioclast) limestone. *Sphenomorphus indicus* can be seen in the lower part. It features grave containing, dark gray color, thin layer and fine grain.	Abyssal-neritic shelf, including turbidity deposit
	Talong Group C_1T	The main strata are fine-grained quartz sandstone interbedded with carbonaceous silty mudstone (slate), and interlayer of carbonaceous siltstone, silty shale, which feature dark color, thin layer and small amount of fossil. Sedimentary manganese mineralization host in the Carbonaceous silty mudstone (slate). Marine sedimentary manganese deposit occurs in this group (Zhuwuluke deposit).	Abyssal-bathyal deposit
Wuyitage Basin	Qipan Formation P_2q	The main strata are conglomerate, limestone, lithic feldspar sandstone, calcareous sandstone, lithoclastic sandstone, tuffaceous sandstone with basalt interlayer, pyroxene andesite containing foraminiferan, Atactotoechus, and lamp shells bioclast, about 500-m in thickness. The middle part intercalated with grayish-green altered basalt and diabase vein.	Coast deposit
	Lower Permian (Keziliqiman Formation P_1kz)	The lower part is celandine green basaltic andesite, quartz andesite, andesite, gray violet red andesite tuff lava, crystal debris tuff lava, and small amount of gray violet red basaltic andesitic lump lava. The upper part is composed of red clasolite, carbonate rocks with basalt interlayer, green clasolite, and pyroclastic rock, grayish green clasolite, gray limestone from the bottom to the top.	Open platform deposit
	Upper Permian-Lower Permian (Tahaqi Formation C_2 P_1th)	The lower part is thin-layer conglomerate-sandy conglomerate. The middle part is composed of intermediate-felsic volcanic lava, and pyroclastic rock. The upper part is mainly limestone.	Open platform deposit
	Upper Coniferous C_2 (Kalaatehe Formation C_2kl)	The lower part is giant-thick-layer micrite interbedded with violet red medium- to thick-layer mudstone, dark thick-layer limestone. The middle part is composed of violet red medium-layer mudstone interbedded with gray-yellow medium- to thick-layer marl with micrite interlayer. The upper part mainly contains gray white thick- to giant thick-layer micrite with violet red medium-layer silty mudstone, mudstone and (dark) gray thick-layer limestone. It is called Kalaatehe Formation in Maerkansu region: dark gray thin-layer micrite, gray thick-layer micrite, dark gray thick-layer micrite containing sandy clast, and small amount of limestone containing sand and gravel debris, sparry calcarenite. Marine sedimentary manganese deposit occurs in this formation (Orto Karnash and Muhu deposit).	Open platform deposit
	Wuluate Formation C_1w	The lower part is grayish green metamorphic basalt, amygdaloid basalt with light gray andesite interlayer. The middle part in Taxike west ditch is composed of purplish gray medium- to thick-layer carbonaceous argillaceous limestone with grayish green thin-layer marble interlayer. In contrast, in Ayakekusuoyi south are mainly gray tabular crystalline limestone and thin-layer	Marine volcanic rocks and deep-water siliceous rock

(*continued on next page*)

Table 1 (*continued*)

Basin	Strata	Main sedimentary lithology and characteristics	Sedimentary association
		siliceous rock. The upper part is metamorphic andesite with purplish gray dacite. VMS mineralization occurs in this formation (Saluoyi deposit).	
Kushanhe Basin	Hantiereke Formation C_1*ht*	The lower part is thin-layer mud crystal power limestone, dark gray thick-layer bioclast micrite limestone, dark gray thin-layer bioclast power crystal limestone, and small amount of brown-gray mud power crystal limestone and oolitic limestone. The upper part is composed of gray thick-layer sparry oolitic limestone, tabular silty mudstone and sparry bioclastic limestone containing sandy clast limestone, and small amount of dark gray thin- to thick-layer sparry bioclast limestone and carbonaceous silty mudstone.	Open platform Subtidal deposit
	Kushanhe Formation D_3-C_1*k*	The lower part is dark gray medium- to thick-layer bioclast crystal power limestone, gray thick-layer bioclast crystal power limestone, gray thick-layer sandy fine-grained limestone, and small amount of grayish green thin-layer silty crystal power limestone. The upper part is composed of dark gray thick layer bioclast fine-grained limestone, dark gray medium- to thick-layer bioclast silty fine-grained limestone, and small amount of dark gray medium- to thick-layer bioclastic limestone, dark gray thick-layer bioclastic limestone, and minute quantity of silty limestone with dolomitization.	Upper tidal flat deposit
	Qizilafu Formation D_3*q*	The lower part is gray red gravel-bearing lithic greywacke in thick layer, gray red thick-layer medium-grained lithic greywacke with medium-layer metamorphic argillaceous siltstone and conglomerate. There are Parallel bedding and oblique bedding in the greywacke. The middle part is composed of gray red medium- to thin-layer siltstone, gray red thick-layer fine-grained quartz sandstone, gravel-bearing medium-grained quartz sandstone, gravel-bearing medium- to fine-grained lithic quartz sandstone, calcareous quartz sandstone. The upper part is mainly fine-grained quartz sandstone, calcareous fine-grained quartz sandstone, violet red thick-layer siltstone, violet fine-grained ferruginous quartz sandstone, and gravel-bearing coarse-grained lithic quartz sandstone.	Lower tidal flat deposit
	Keziletao Formation D_2*kz*	The lower part is gray and grayish green basalt, grayish green andesite tuff, grayish green metamorphic medium- to fine-grained sandstone and greywacke, and small amount of light grayish green metamorphic conglomerate. The middle part is composed of gray medium- to thick-layer metamorphic quartz greywacke, light grayish green metamorphic conglomerate, dark gray giant-thick-layer calcareous dolomite, dark gray giant-thick-layer medium- to coarse-grained metamorphic quartz sandstone and gray white giant-thick-layer micrite, and small amount of grayish green medium- to thick-layer metamorphic fine-grained quartz sandstone. The upper part is mainly gray and gray red thick- to giant-thick-layer metamorphic medium- to coarse-grained quartz sandstone and light grayish green metamorphic medium-grained quartz sandstone. Sedimentary rock-hosted stratiform copper deposit occurs in this formation (Tugenmansu deposit).	Offshore deposit
	Akebaximazhaer Formation D_2*a*	The lower part is grey-purple medium-fine quartz sandstone, gray brown medium-layer fine-grained quartz sandstone, and small amount of gravel-bearing quartz greywacke, dark gray sand-bearing mudstone and gray white medium-layer thick-grained quartz sandstone. Large wedge-cross-bedding developed in the quartz greywacke. The upper part is composed of medium- to thick-layer conglomerate, medium-layer coarse- to medium-grained quartz sandstone, and small amount of quartz sandstone, quartz siltstone and limestone.	Estuarine-beach deposit
Tamu-Kalangu Basin	Upper Part of Daliyueer Formation P_3d^2	The main strata are violet red mudstone, violet red medium- to thick-layer fine-grained feldspar quartz sandstone, violet red thick- to thin-layer fine-grained lithic feldspar sandstone, and small amount of calcareous, argillaceous siltstone, silty mudstone, and conglomerate. The tabular and wedge cross bedding developed in the sandstone, and small amount of parallel bedding also can be seen.	Fluvial deposit
	Lower Part of Daliyueer FormationP_3d^1	The main strata are grayish green fine-grained quartz sandstone, gray white gravel-bearing coarse- to fine-grained feldspar quartz sandstone, brown purple lithic quartz sandstone, and small amount of dark gray bioclastic micrite, calcareous siltstone. The Brachiopoda fossils can be seen in the limestone.	Coast deposit
	Qipan Formation P_2*q*	The main strata are grayish green fine-grained sandstone, gray white gravel-bearing coarse- to fine-grained feldspar quartz sandstone, brown purple fine-grained lithic quartz sandstone, and small amount of dark gray bioclast micrite, calcareous siltstone. The Brachiopoda fossils can be seen in the limestone. The grayish green altered basalt and diabase vein intercalated in the middle part of Qipan Formation.	Internal shelf-coast deposit
	Keziliqiman Formation P_1*kz*	The lower part is dark gray medium- to giant-thick-layer micrite containing small amount of bioclast. It features dark color and fine grain. The upper part is composed of dark gray medium- to thick-layer bioclast- and sand-bearing oolitic limestone, gravel- and sand-sized grain-bearing limestone, bioclast-and sand-bearing limestone. There is large amount of bioclast.	Platform-shoal deposit
	Tahaqi Formation C_2 −P_1*th*	The main strata are bioclast-bearing micrite, sand-sized grain micrite, bioclast- and sand-sized grain-bearing micrite, bioclast-bearing micrite, sparry oolitic limestone, sparry bioclastic limestone, micrite, and small amount of grayish green fine- to medium-grained quartz sandstone. There are abundant marine animals' fossils, such as Brachiopoda and coral.	Open platform deposit

	Azigan Formation C_2a	The main strata are gray medium-layer bioclastic micrite, dark gray thick-layer sand-sized grain micrite, gray calcareous quartz siltstone, and small amount of dark gray thick-layer bioclast-and sand-bearing micrite, dark gray argillaceous siltstone. There are abundant sphenomorphus indicus, and gastropods.	Open platform deposit
	Kalawuyi Formation C_2kl	The main strata are bioclast-bearing micrite, sand-sized grain micrite, bioclast- and sand-sized-grain-bearing limestone, bioclastic micrite, sparry oolitic limestone, sparry bioclastic limestone, micrite, and small amount of grayish green fine- to medium-grained quartz sandstone. There are abundant marine animals' fossils, such as Brachiopoda and coral.	Open platform deposit
	Heshilafu Formation C_1h	The lower part is grayish green limestone, gray medium-layer fine-grained quartz sandstone, quartz siltstone. The layer becomes thinner and the grain gets finer from the bottom to the top. There are Brachiopoda fossils in the siltstone. The upper part is composed of bioclast-bearing micrite, sand-sized grain micrite, bioclast- and sand-bearing micrite, bioclastic micrite, sparry oolitic limestone, and bioclastic limestone, micrite, and small amount of grayish green fine-medium-grained quartz sandstone.	Internal shelf-open platform deposit
	Upper Part of Kelitake Formation D_3-C_1kl^2	The main strata are gray thick-layer bioclast- and sand-bearing limestone, dark gray medium-layer medium- to coarse-grained limestone, and small amount of conglomerate-bearing oolitic calcarenite, sand-sized grained oolitic limestone. Coral, Brachiopoda, and gastropods can be seen.	Platform margin deposit
	Lower Part of Kelitake Formation D_3-C_1kl^1	The main strata are dark gray thin-layer bioclastic micrite, bioclastic crystal powder limestone, grayish green silty mudstone, and small amount of brown gray medium-layer fine-grained limestone, light gray thick-layer bioclast-bearing sparry oolitic limestone. The lower part is composed of bioclastic micrite, containing Brachiopoda, coral, and gastropods.	Open platform deposit
	Upper Part of Qizilafu Formation D_3q	The main strata are violet red thin- to medium-layer fine-grained feldspar quartz sandstone, grayish green thin-layer fine-grained feldspar quartz sandstone, and small amount of violet red medium-layer conglomerate, gravel-bearing medium-grained quartz sandstone, quartz siltstone (slate), and minute quantity of grayish green siltstone, silty slate. The wedge cross-bedding developed in the conglomerate-bearing sandstone.	Delta deposit
	Lower Part of Qizilafu Formation D_3q	The main strata are violet red-violet gray−gray violet medium-layer fine-grained quartz sandstone interbedded with grayish green-grayness medium-layer fine-grained quartz sandstone, with grayish green silty mudstone and small amount of violet red silty slate interlayer. The wedge cross- and parallel-bedding developed in the grayish green sandstone. Syngenetic sedimentary Pb−Zn deposit occurs in this formation (Kalayasikake deposit).	Upper tidal flat deposit
	Upper Part of Keziletao Formation D_2kz^2	The main strata are grayish green quartz siltstone, calcareous quartz siltstone, small amount of argillaceous quartz siltstone, bioclastic micrite, calcareous fine-grained quartz sandstone. The trough cross-bedding, wedge cross-bedding, metaripple developed in the sandstone. There are abundant Brachiopoda and coral fossils in the limestone. Sedimentary rock-hosted stratiform copper deposit and syngenetic sedimentary Pb−Zn deposit occur in this formation (Tiekelike and Kalayasikake deposit).	Lower tidal flat deposit
	Lower Part of Keziletao Formation D_2kz^1	The main strata are grayish green medium- to thin-layer argillaceous quartz siltstone, grayish silty mudstone, small amount of brownness thin-layer calcareous quartz siltstone, fine-grained quartz sandstone, minute quantity of sand micrite. There is mass of horizontal burrow in the argillaceous quartz siltstone, showing current bedding and small size wedge cross-bedding.	Offshore deposit
	Akebaximazheer Formation D_2a	The lower part is gray violet medium- to fine-grained quartz greywacke, gray brown medium-layer fine-grained quartz sandstone, and small amount of gravel-bearing quartz greywacke, grayish green fine-grained quartz greywacke, dark gray sand-bearing mudstone, gray white medium-layer medium-grained quartz sandstone. The upper part is composed of gray white medium- to thick-layer conglomerate, medium-grained quartz sandstone. The gravel is mainly quartzite, small amount of quartz sandstone, quartz siltstone, and limestone.	Estuarine-beach deposit
Duwa Basin	Duwa Formation P_2d	The lower part is violet gray thick-layer conglomerate, glutenite with medium- to coarse-grained gravel-bearing quartz sandstone with lithic fragment, gravel-bearing feldspar sandstone with lithic fragment. The conglomerate is thick-layer and massive structure. Most of sandstone is lenticular in distribution. The upper part is composed of grayish green conglomerate, medium-grained gravel-bearing feldspar quartz sandstone. The oblique bedding and graded bedding developed in the sandstone.	Fluvial-lacustrine facies clastic rocks deposit
	Tahaqi Formation C_2 −P_1th	The lower part is gray white sand and bioclast limestone containing large number of fossils. The middle part is composed of gray white to gray yellow medium- to thick-layer gravel-bearing calcareous sandstone. The gravel are mainly quartz and feldspar. The cement is calcite. The upper part contains gray to gray-yellow crystal power limestone, micrite, including minute quantity argillaceous and terrigenous detrital.	Shallow sea carbonate platform facies deposit
	Qizilafu Formation D_3q	The main strata are medium- to fine-grained quartz sandstone, fine-grained calcareous quartz sandstone, fine-grained feldspar quartz sandstone and minute thin-layer siltstone, argillaceous siltstone, and mudstone. The upper part is composed of fine-grained quartz sandstone with gray thin-layer crystal power limestone interlayer. The quartz sandstone in the bottom and middle contains thick-layer gravel.	Tidal flat-coast-shallow sea (retrogradation deposit)

The geologic information are compiled based on Lu et al. (2013); Wang et al. (2013); Ji et al. (2013); Cui et al. (2013).

bounded by the Kegang ophiolite belt and connects with the southern margin of the Tarim Block. The Sangzhutage Microcontinental Block is connected to the Kulanna Microcontinental Block and the southern margin of the Tarim Block through the ophiolitic mélange belt in the reservoir. The Setula Microcontinental Block is connected to the Sangzhutag Microcontinental Block and the southern margin of the Tarim massif through the Purou ophiolitic mélange belt. These land masses coalesced in the Early Paleozoic (Pan et al., 2000; Cui et al., 2006) and evolved into the Caledonian orogenic belt (Xu et al., 2011; Zhang et al., 2019), among which there exists a remnant Ordovician oceanic basin in the Kulangna Microcontinental Block and a remnant Silurian–Devonian oceanic basin in the Gonger Microcontinental Block.

The Middle Proterozoic (Changcheng System) Kulangnagu Gr. is based on volcanic–carbonate–clastic rocks. The Setula Gr. consists of basic volcanic and clastic rocks and were likely deposited on an active continental margin (Wang et al., 2013). The Sangzhutage Gr. in the Jixian System consists of a carbonate–clastic rock formation, which is related to the Tarim Block and was intruded by Neoproterozoic intermediate–felsic plutons (Fig. 2). The Lower Paleozoic–Ordovician (Malieziken Gr.) represents the residual deposition in a marine basin and the Cambrian–Ordovician (Xihexiu Fm.) may belong to a tectonite group between the different blocks. The Upper Paleozoic strata include the Carboniferous–Permian systems, which is mainly indicative of arc continental margin and back-arc basin deposition (Table 1). Glutenites of the Seliyakedaban Gr. belongs to the Mesozoic and are distributed in the Kangxiwa tectonic medullary zone. The rock assemblage is equivalent to intermontane molassite formation (Fig. 3).

(3) The southern boundary of the tectonic belt of the southern margin of the Tarim Block is the Kegang fault zone (known as the Heluositan River fault to the east of Akazi), and the northern boundary is the Kaokuya fault (nappe tectonic front fault). The secondary tectonic units may be subdivided into the Tiekelike fault and the Tamu–Kalangu basin. In the Tiekelike fault (Fig. 1b), the basement of the

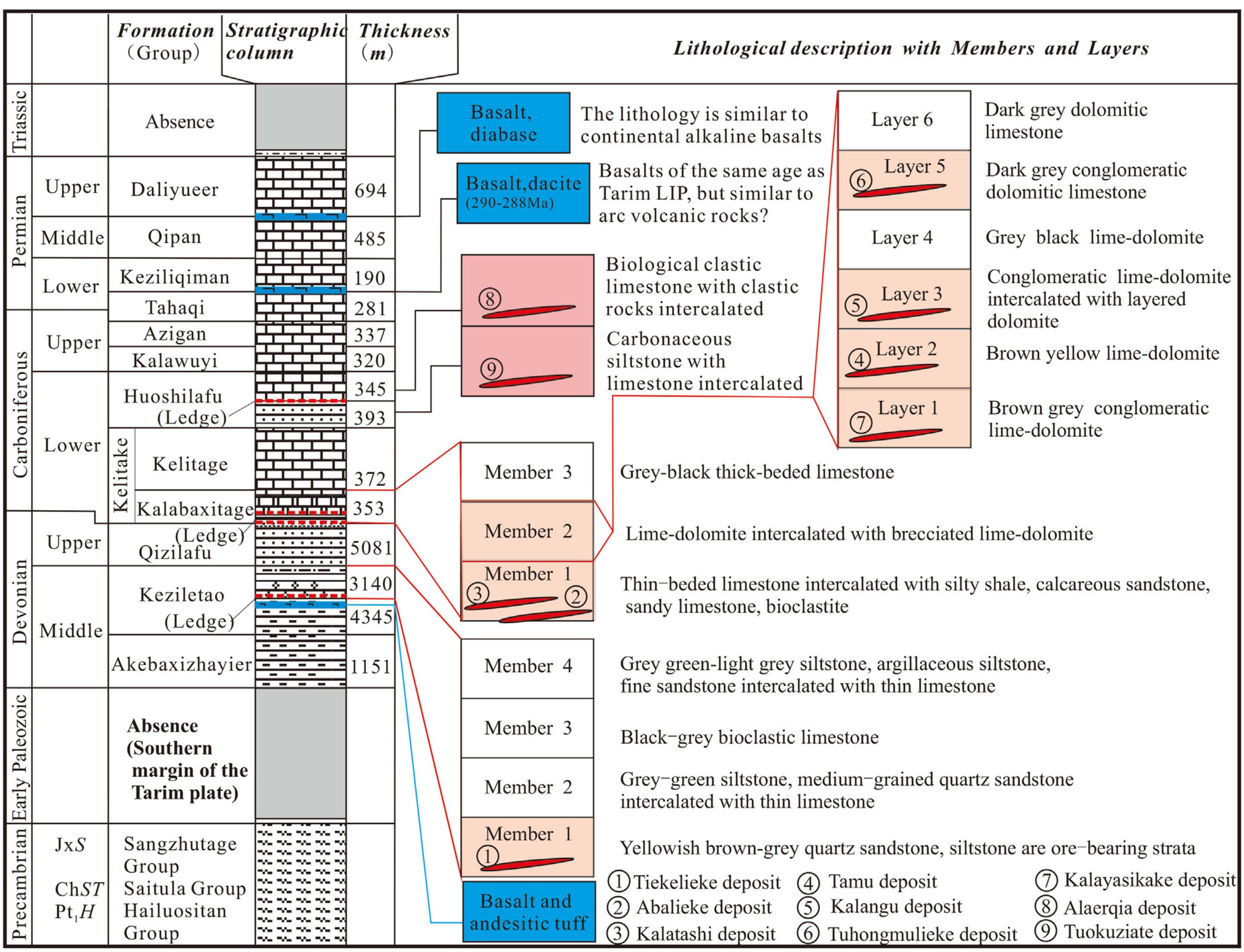

Fig. 5. Stratigraphic column of hosting strata of Pb–Zn–Cu (Co) deposits in the western Kunlun Mountains, China.

block consists of the volcano-sedimentary deposits of the Paleoproterozoic Heluositan Gr. and the clastic deposits of the Ailiankate Gr., representing the material composition of the continental core evolution and marginal hyperplasia, respectively. The formation of clastic and volcanic rocks in the Mesoproterozoic Changcheng Selajazitage Gr. and the carbonate and clastic rocks in the Bochatetage and Sumalan formations in Jixian are products of the sedimentary stage of cap rock formation.

The Qingbaikou System is mainly composed of clastic rocks, while the Sinian System includes Sukuluoke Fm., Qakemakelike Fm., Kuerkake Fm., and Kezihusumu Fm., which consist of clastic rocks with morainic conglomerate. The absence of Lower Paleozoic strata in the region suggests that it was in a state of uplift and denudation for a long time without sedimentation (Henan Institute of the Geological Survey, 2006). From the Middle Devonian to the Late Permian, the outcropping strata were mainly distributed in the Tamu−Kalangu Basin (Fig. 2, Table 1).

The Middle−Late Devonian series in the study area includes the Akebaximazhaer Fm., Keziletao Fm., and Qizilafu Fm. The transitional zone between the Devonian series and the Lower Carboniferous is the Kelitake Fm., where the Carboniferous mainly consists of the Huoshilapu Fm., Kalawuyi Fm., and Azigan Fm., and the transitional strata between the Carboniferous and the Lower Permian is Tahaqi Fm. The Permian consists of the Keziliqiman Fm., Qipan Fm., and Daliyueerr Fm. No deposition occurred during the Triassic, suggesting that the entire region was still in a state of denudation. The occurrence of continental faulted basins in the Jurassic indicates that the environment had begun to change from marine to continental. From the Late Mesozoic to the Early Cenozoic, the pre-sedimentary strata were changed by

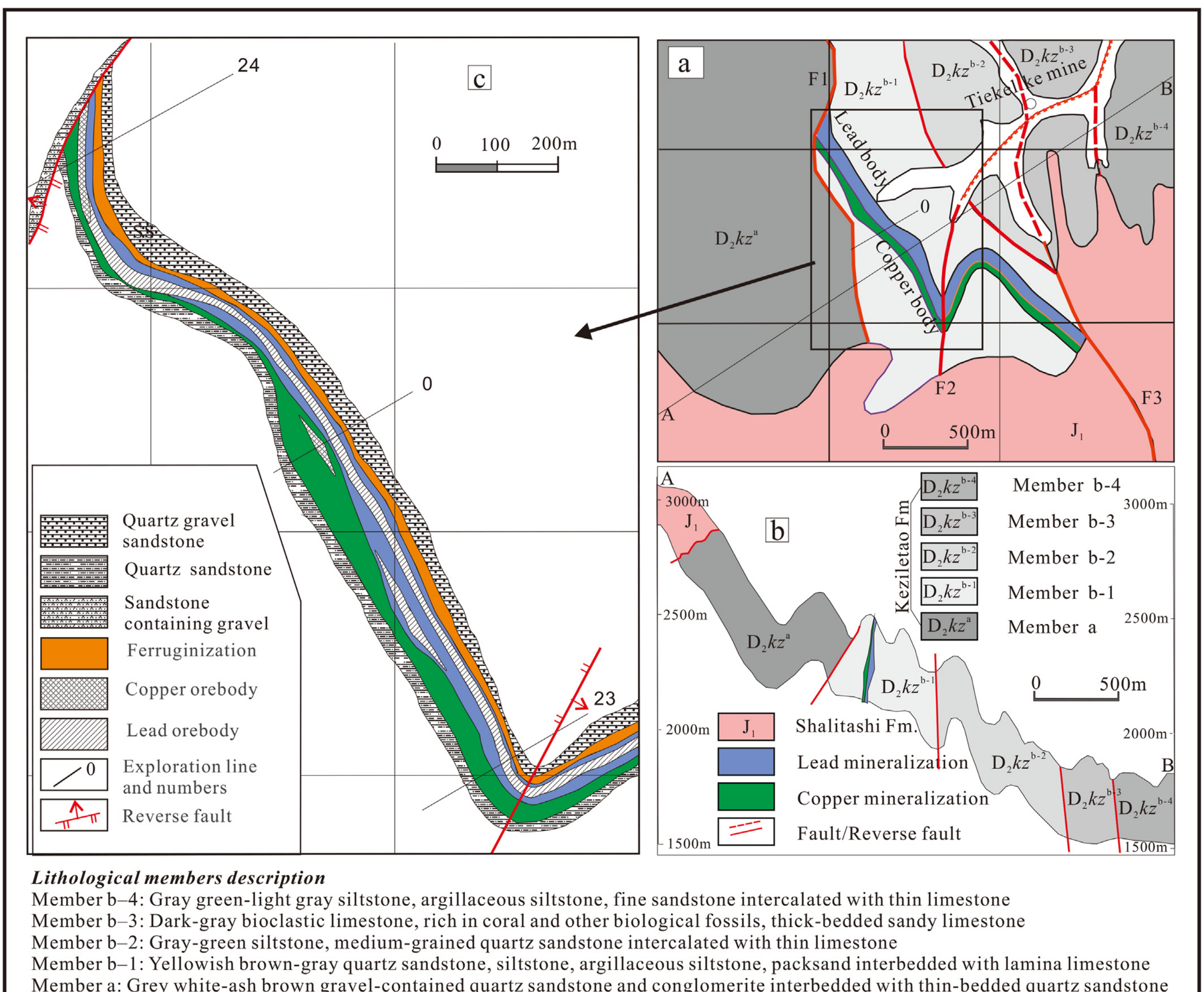

Fig. 6. Geological map (a), stratigraphic section (b) and a sketch showing the orebody zonation (c) in the Tiekelike Cu−Pb deposit (modified after Zhang et al., 2013; 2014).

folding and faulting, and the nappe structure pushed the Late Paleozoic strata over the post-Mesozoic strata (Fig. 2).

2.3. Late Paleozoic back-arc extensional environment and sedimentary basin

According to a study on the structural evolution of the West Kunlun Block and the southern margin of the Tarim Block early in the Late Paleozoic, it is known that the two blocks had been fused to form the Caledonian orogenic belt (Cui et al., 2006; Xu et al., 2011); only in the Late Paleozoic had the tectonic environment begun to extend and a suit of transgressive sequences developed, including the mid-Late Devonian sedimentary Akebaximazhaer and Qizilafu formations, consisting of clastic−carbonate and basalt and volcano-clastic formations (Fig. 4). The characteristics and sediment geochemistries have consistently suggested a tensional environment (Table 1). Based on the tectonic evolution of the Karakunlun Block (Mattern and Schneider, 2000; Xiao et al., 2005), the region was still in a multi-island oceanic environment in the early Late Paleozoic, with the Kangxiwa−Mazha−Waqia forming in the Paleotethys Ocean.

Due to the subduction of the oceanic crust toward the West Kunlun Block, the upwelling of the lithospheric mantle in the front of the subducted plate also resulted in a post-arc extensional tectonic environment and the development of a series of sedimentary basins, in addition to the formation of the Kangxiwa−Mazha belt and arc magmatism (388−324 Ma, Li et al., 2006; Liu et al., 2014; Zhang et al., 2014; Kang et al., 2015). In terms of their regional distribution, these basins can be divided into two subzones: the Tamu−Kalangu Basin belt and the Duwa Basin, located in the southern margin of the Tarim Block, whose sedimentary basement is the Precambrian System (Tian and Hu, 2010). The Oytag−Kurliang back-arc basin belt located along the northern margin of the West Kunlun massif mainly includes the Oytag, Kushanhe, Qiaer-

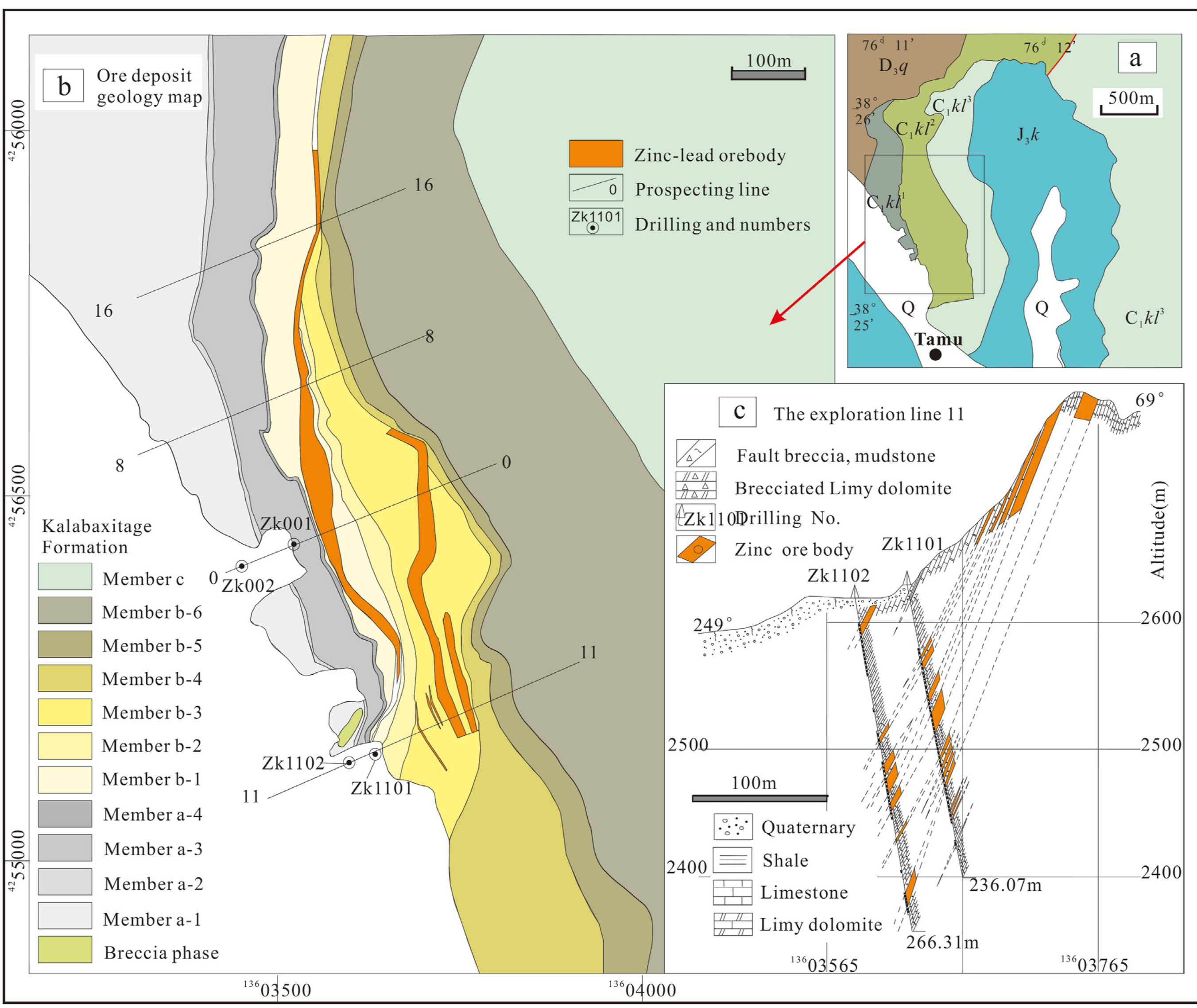

Fig. 7. Geological map (a, b) and geological profile of the no. 11 exploration line (c) in the Tamu Pb−Zn deposit (modified after Zhang et al., 2014).

Table 2
Characteristics of the major deposits in the sedimentary basins of back-arc environment in the Late Paleozoic.

Deposit No , longitude, latitude Minerals and scale	Deposit type and metallogenic epoch (Method/mineral/age)	Ore body morphology and position within host rocks and the grade of metal	Mineral association within ore body Ore structure and texture	Host rock and altered wall rock	Ore−controlling structures	References
No.1 Orto Karnash 73°38′30″,39°21′20″ Mn Large	Marine sedimentary manganese deposit.	The mineralized belt is about 5 km in length and 1 km in width. The occurrence of the stratiform manganese carbonate ore body is accordance with that of the wall rock. The distance between two major ore bodies is 20−40 m. The variation in thickness of the ore body is 0.36−22.32 m, with an average of 4.14 m. The average grade is 37.8%. The primary ore is rhodochrosite. The quartz-rhodochrosite, calcite-rhodochrosite, braunite-rhodochrosite, and alabandite-rhodochrosite can be seen locally.	Mainly rhodochrosite, with minor braunite, alabandite, siderite, sussexite and manganite. Gangue mineral: calcite, minor clay mineral. The manganese carbonate ore is mainly massive. Some ore body show native bedding or lamina.	The manganese ledge is hosted in the third member of Kalaatehe Formation, with carbon-bearing argillaceous limestone with banded thin-layer micrite interlayer of the Upper Carboniferous.	Malkansu compound anticline, Kalaatehe fault developed in the northern axis of the anticline	Zhang et al. (2018)
No.2 Muhu 73°58′18″,39°22′40″ Mn Large	Marine sedimentary manganese deposit. The ledge is in the upper lithologic section of the Upper Carboniferous Kalatehe Formation	Six mineralized belts have been discovered in the mining area; the occurrence of the ore body is accordance with that of the wall rock basically. The mineralized belt I is about 2166 m in length, 1.00−15.30 m in width. The ore body is 3.49 m in width with 341 m. The grade of Mn is 10.38%−45.07%, with an average of 27.66%.	Mainly rhodochrosite, with minor pyrolusite, rhodonite, psilomelane, bixbyite, manganite, and pyrite. The rhodochrosite ore is massive with crystallite. The pyrolusite is xenomorphic granular and is in platy distribution. Ore texture: xenomorphic granular Ore structures: (compact) massive, veinlet, nodular, and earthy	Kalaatehe Formation of the Upper Carboniferous is the main ledge. The ore-bearing rocks are cataclastic, very thin stratified carbon-bearing limestone interbedded with argillaceous limestone. The pyrite, calcite vein and quartz vein developed in the wall rock.	The fault in the late period cut through the fold, cataclasite, tectonic breccia, mylonite, schist developed along the fault belt.	Chen et al. (2018) Xu et al. (2018)
No.3 Saluoyi 74°57′05″,39°15′58″ Cu (Zn, Ag) Small	VMS deposit.	The mineralized belt distributes in NW-direction irregular strip, and is accordance with that of the wall rock basically. It is above 1000 m in length, and 50−150 m in width. The chalcopyrite, malachite, and azurite can be seen on the ground surface. The ore body hosted near the contact interface between lower and middle part of the Wuluate Formation. The occurrence of the ore body is accordance with that of the wall rock, dipping in NW with 50°−75°. The maximum ore body is 220 m in length and 25 m in width. The sulfide content is 60−85%.	Mainly pyrite, chalcopyrite, with minor sphalerite, bornite, magnetite, and specularite. Secondary minerals: limonite, azurite, malachite, covellite, jarosite, and native sulfur. Gangue minerals: mainly quartz, chlorite, minor calcite, epidote, and muscovite. Ore texture: mainly xenomorphic granular, subhedral granular, filling and replacement, intertwining melting and cataclastic texture. Ore structure: sparse and dense disseminated, stockwork, and massive	The lower part of Wuluate Formation of the Upper Carboniferous is spilitic keratophyre rocks with hydrothermal sedimentary rock interlayer. Altered wall rock: obviously, in an order of strongly pyritization, silicification, carbonatation, chloritization, epidotization, pyritization.	Some small extension fracture cut through the strata and ore body in the north wing of the regional anticline. There are granite porphyry and quartz porphyry vein in the periphery of the northern mining area, intruded into the coarse-grained volcanic clastic rocks of Wuluate Formation as dyke or vein.	Jia et al. (1999) Sun et al. (2003) Mao (2019)

(continued on next page)

Table 2 (*continued*)

Deposit No , longitude, latitude Minerals and scale	Deposit type and metallogenic epoch (Method/mineral/age)	Ore body morphology and position within host rocks and the grade of metal	Mineral association within ore body Ore structure and texture	Host rock and altered wall rock	Ore−controlling structures	References
No.4 Aktash 75°35′00″,39°08′52″ Cu (Au,Ag) Small	VMS deposit. It is similar to submarine hydrothermal system in the back-arc environment. The zircon U−Pb age of the ore-bearing quartz-keratophyre is 330.2 ± 3.6 Ma.	The ore body is layer or tabular hosted in the quartz-keratophyre (tuff) on the top of the third lithologic member of the Keziliqiman Formation. The ore body is double-layer structure: the upper part is sulfide ore massive sulfide ore, and the lower part is disseminated sulfide ore. The native sulfide ore is dominated, and small amount of oxide ore. Six ore bodies has been discovered with copper grade 0.63−4.87%, and sulfur grade 8.49% to 48.00%. The longest ore body is 1600 m and 8 m in width.	Mainly pyrite, chalcopyrite, with minor sphalerite, Zn-bearing tetrahedrite, bornite. Gangue minerals: mainly quartz, muscovite, calcite, chlorite, albite. Secondary minerals: malachite, covellite, limonite Ore structures: mainly massive, banding, disseminated, veinlet, brecciated. Ore textures: xenomorphic granular, subhedral-hedral granular, intersertal texture, conjunct edge, sieve, and poikilitic texture	Keziliqiman Formation of the Upper Carboniferou is a marine sedimentary rock series, including basalt, rhyolite, and limestone. Altered wall rock: acidic tuff and quartz-keratophyre, including silicification, sericitization, chloritization, and carbonatation	Jixianian System as nappe exposed on the ground surface, thrusting on the Upper Carboniferous, resulting in strongly foliated, and formed compression and twist and normal fault.	Jia et al. (1999) Sun et al. (2003) Mao (2019)
No.5 Tugenmansu 75°28′50″,38°44′44″ Cu (Pb,Ag) Small	Sedimentary rock-hosted stratiform copper deposit with age of the Middle Devonian.	The mineralized belt is about 10 km in length, 10−230 m in width. The occurrence of the ore body is accordance with that of the wall rock basically. The mineralized belt can be divided into three ore-bearing layers: the upper layer is 60−200 m in length and 20−30 m in length. The middle layer is about 1800 m in length and 8−200 m in width. The lower part is malachite and chalcocite. The ore body is stratiform and lenticular, with 100−300 m in length and 4.05 −16.53 m in width, and extend more than 300 m. The copper grade is 0.4%−3.72%, and the highest is 11.90%.	Mainly chalcopyrite, chalcocite, tetrahedrite, argentite, with minor bornite, galena, sphalerite, pyrite, and magnetite. Copper oxide: malachite, azurite. Gangue minerals: quartz, calcite, and small amount of barite. Metal minerals: mainly xenomorphic-subhedral granular. The copper- and silver-bearing conglomerate is interstitial cement texture. The oxide ore, such as malachite is common. The ore structures are veinlet, disseminated, and massive.	The ore body are conformable with red clastic rock series of Kushanhe Group. The red clastic rocks of the Mesozoic and Cenozoic era also contain Cu −Ag mineralization. The top and bottom are both compact quartz sandstone, quartzite or gray white quartz sandstone interbedded with violet red quartz sandstone. Altered wall rock: slight hydrothermal alteration developed locally.	The red clastic rocks of Kushanhe Group has a fault contact with red clastic rocks of the Craterous and Tertiary systems.	Zhao et al. (2002) Lu et al. (2013)
No.6 Zhuwuluke 74°46′15″,38°28′11″ Mn (Co) Small	The sedimentary manganese mineralization related to black carbonaceous shale of the Early Carboniferous.	Thirteen Fe−Mn ore bodies has been discovered in the black carbonaceous shale with Fe−Mn-bearing carbonate rocks. The ore body is stratiform and parallel with the micrite as wall rock. The bore body I exposed on the ground surface about 630 m, 1.5 −8.5 m in width. Real thickness of ore body controlled by single project is 0.77−4.83 m, with an average of 2.80 m. The average Mn grade is 14.32%.	Mainly rhodochrosite with minor pyrolusite, braunite, pyrite, and chalcopyrite. Nonmetallic minerals: mainly quartz, and calcite. Native manganese carbonate ores texture: microcrystalline, fine grained Ore structures: (compact) massive and nodular	The ledge is the middle member of Talong Group of the Lower Carbonaceous. The micrite is on the top and bottom of the manganese-bearing rock series. Altered wall rock: weak chloritization, ferritization, and magnetite	Small size folds are common in the mining area, resulting in bend and inversion of the manganese ore body. The quartz veinlet developed near the ore body along the joint surface.	Lu et al. (2013) Mao,2019

No.7 Tiekelike 76°04′00″,38°37′00″ Cu −Pb (Zn,Ag,Co) Medium(120,300t)	Synsedimentary SHSC (Medium Devonian) Succeeding transformation (Re−Os isotopic dating/ chalcopyrite/226 Ma)[a]	Disseminated chalcopyrite within the quartz sandstone, with same occurrence to the stratum, length 2000 m, width 70−220 m, grade of metal within 0.5−2.3%. Multilayer galena occurrence to the carbonate, with quasi −lamellar or bedded shape in the breccia zone, grade of metal 0.7 −2.78%, associated with silver than cutoff grade (50 g/t). Partly galena and chalcopyrite occur as veins, with thickness of 1−3 m, and length of 200 m.	Mainly galena, chalcopyrite and pyrite with minor chalcocite. Secondary azurite, malachite, cerusite and jarosite. Gangue minerals: quartz and calcite. Mainly cementation structure, idiomorphic granular texture, replacement texture and poikilitic texture with minor crumpled structure, brecciated and disseminated structure	Ore body within up part of Devonian Keziletao Formation, tawny phyllite and quartzite in sandstones. Altered wall rock: mainly dolomitization and calcitization, with minor silicification	Northeast strike fault cutting inclined fold. Northwest strike growth fault occurrence with tectonic breccia.	Lu et al. (2013) Zhang et al. (2013)
No.8 Tamu 76°11′08″, 38°25′27″ Zn (Pb, Co) Large (893,100t)	Synsedimentary −succeeding transformation (Re−Os isotopic dating/ chalcopyrite/337 Ma)[b] (Ar−Ar isotopic dating of quartz/235 Ma)[c]	Mineralized and breccia zone has the same occurrence with the stratum, length 800 m, maximum thickness 40 m. width 30−70 m. Multilayer ore body occurrence with quasi-tabular or bedded shape in the breccia zone. Single extending vertical 500 m, greater than length 100 m, occurrence with quasi− lamellar, nervation or stockwork within the dolomitite and dolomitic limestone. Zinc grade of metal within 1.28−9.25%	Mainly sphalerite, with minor galena and pyrite. Secondary cerusite, sardinianite and ferrimanganic oxide. Gangue minerals: dolomite, calcite, quartz and muscovite. Spherical strawberry shape structure, exsolution texture. metasomatic relict texture and banded structure, with flow structure, brecciated structure, veiny structure and disseminated structure.	Ore body within thick−layer dolomitite and dolomitic limestone in Lower Carboniferous Kalabaxitage Formation; Altered wall rock mainly dolomitization, silicification and pyritization with minor chloritization	Northeast strike fault cutting overturned fold, growth fault occurrence with tectonic breccia.	Zhang et al. (2014)
No. 9 Kalayasikake 76°13′47″,38°22′44″ Pb−Zn (Ag) Small	Syngenetic sedimentary and epigenetic reform	Mineralized layer has a length of 80 m. Multilayer ore body occurrence with lenticular, quasi −lamellar or bedded shape within dolomitic limestone side in the contact zones of dolomitic limestone and carbonaceous limestone, Lead ore mainly within limestones on the upper wall of fault, nevertheless copper within calcisilicarenite on the foot-wall of fault	Mainly galena and sphalerite with minor pyrite and chalcopyrite. Gangue minerals: quartz and calcite. Secondary minerals: malachite, covellite, azurite, erythrite and iron oxides. Granular, coarse crystal texture, fine crystal texture, metasomatism texture. Massive structure, brecciated structure and dense disseminated structure	Ore body occurs in the inter-contact of Qizilafu Formation and Kelitake Formation Altered wall rock: mainly dolomitization and silicification	The upper wall of fault with dolomitic limestone, and foot-wall of fault with purple fine sandstone-siltstone	Lu et al. (2013) Zhang et al. (2013)
No.10 Kalangu 76°23′12″,38°01′20″ Pb (Zn−Co) Large (630,300t)	Synsedimentary −succeeding transformation (Ar−Ar isotopic dating/sphalerite/ 235 Ma)[c]	Mineralized and breccia zone has the same occurrence to the stratum, length 500 m, maximum thickness 30 m, width 30−60 m. Multilayer occurrence with lenticular or quasi−tabular shape within dolomitic limestone side in the contact zones with quartz gravel carbonate. Lead grade of metal within 0.80−8.90%, zinc grade lower <0.30%, associated with cobalt than cutoff grade (0.02%)	Mainly galena with minor chalcopyrite, pyrite, sphalerite and trace chloanthite. Secondary malachite, covellite, chalcocite, erythrite, cerusitc and ferrimanganic oxide. Gangue minerals: dolomite and calcite. Granular structure, coarse grained texture, skeletal texture and replacement texture, with disseminated and vein structure.	Ore body within limestone, carbonaceous limestone and dolomitic limestone in the Lower Carboniferous Kalabaxitage Formation; Altered wall rock: mainly dolomitization and silicification	Northwest strike fault cutting disharmonic fold, drag fold occurrence with tectonic breccia.	Lu et al. (2013) Zhang et al. (2014)

(continued on next page)

Table 2 (*continued*)

Deposit No , longitude, latitude Minerals and scale	Deposit type and metallogenic epoch (Method/mineral/age)	Ore body morphology and position within host rocks and the grade of metal	Mineral association within ore body Ore structure and texture	Host rock and altered wall rock	Ore−controlling structures	References
No.11 Akazi 76°59′00″,36°58′00″ Cu (Pb) Small	Structural altered rock type Cu deposit. It is inferred to formed at the Middle Permian.	The mineralized belt is hosted in the fault zone, which is longer than 300 m, and the exposed width is 24−30 m, with occurrence of 220°∠55°. The altered medium-grained monzonitic granite and plagioclase biotite quartz schist with strong transformation fill the mineralized belt. The ore bodies occur as lenticular in the fractured altered rocks. The ore structure is disseminated, and the Cu content is more than 0.2%, associated with lead.	Mainly chalcopyrite, pyrite, (limonite). The gangue minerals include muscovite, potassium feldspar, albite, and quartz. The ores are disseminated texture and massive structure.	Structural altered rocks in the contact zone of the Kulangnagu Group and Yishake Group of the Mesoproterozoic Era. Wall rock alteration: silicification, potash feldspathization, pyritization, and sericitization	Structural altered rock in the fault zone	Ji et al. (2013)
No.12 Abaleke 78°30′52″,36°51′10″ Cu (Ni) Small	Magmatic liquated deposit. The copper ore body hosted in the diabase vein intruded into the upper member, indicating it formed after the Late Carboniferous.	Three copper-bearing diabase veins have been discovered, and the copper mineralization concentrate in the footwall of the rock mass. The rocks are fractured and altered strongly. The single ore body is about 1200 m in length and 27 m in width, dipping in 100°. The grade of copper is 0.45%.	Mainly chalcopyrite, bornite, pyrite. The secondary minerals are malachite and azurite. The ores are xenomorphic granular texture, and disseminated, massive structure.	Wall rock alteration: silicification, ferritization Associated with Au, Ag, Cr, Ni, Pt, Pd	The mafic dikes, which is the product of the rifting, intruded into Kuerliang Group of the Carboniferous as vein and lentoid.	Qi et al. (2005) Hou et al. (2007) Cui et al. (2013)
No.13 South Duwa 78°59’ , 36°59′ Mn Small Reserves of calculated 333 + 334 is 23.58 Mt.	Synsedimentary manganese deposit	The mineralized belt is about 4500 m in EW, and 5−6 m in width. The mineralized rock is mainly impure limestone, and quartz siltstone. The morphology of ore body is mainly controlled by occurrence of the wall rock. The ore body and the wall rock are in a layer-by-layer contact. The grade of manganese is 0.5−7%, commonly 2−3%. The ore body is lentoid and lenticular.	Mainly pyrolusite and psilomelane, rhodochrosite is dominated in the biolithite limestone. The gangue minerals are mainly calcite. The ores are mainly subhedral granular texture. The size of the pyrolusite columnar combination is 0.05−0.3 mm. The psilomelane distributes around the pyrolusite. The ores are mainly disseminated and massive structure.	The contact zone of the upper part of Tahaqi Formation of the Carboniferous: calcareous sandstone and biolithite limestone, and biolithite limestone	The SE side of the Duwa Fault	Cui et al. (2013)

The ore deposit characteristics are compiled based on (Zhang et al., 2011); 2014. “a. c. e ”from (Zhang et al., 2011). “b”from Yang (2009). “d”from (Zhang et al., 2011).

long, and Kuerliang basins, where rifting occurred due to the Caledonian orogeny (Chen et al., 2010). Granitic and bimodal volcanic rocks developed in the back-arc spreading environment (339−291 Ma, Ji et al., 2018), correspond to the arc granites developed in the Kangxiwa−Mazha−Waqia area, and constitute a twin magmatic belt in space and time (Fig. 1).

3. Oytag−Kurliang back-arc basin

3.1. Oytag marine pyroclastic basin

3.1.1. Basin distribution

A geological survey (Lu et al., 2013) revealed a NW-trending banded structure in this region. To the south is the western section of the Ayituoyina−Jialagerda Daban fault and to the north is the Kuxiale−Bozidun fault. The Carboniferous System is divided into the Lower Carboniferous Wuluate Fm., undivided Upper Carboniferous, and undivided Lower Permian from the bottom to the top. The upper rock assemblage and thickness of the Wuluate Fm. exhibit little change and are unconformably overlain by the Upper Carboniferous−Lower Permian Tahaqi Fm. (Yun et al., 2015). The bottom of the Upper Carboniferous (not subdivided) has not been detected and the Upper Permian is in conformance with it. The basin is characterized by the occurrence of magmatic activities. The Carboniferous included the eruption of lava from the ocean floor, the construction of pyroclastic rocks with clastic rocks, and the intrusion of granite into the basin. The Permian strata are divided into Lower Permian intermediate acidic volcanic rocks and Middle Permian pyroclastic rocks with basalts. The Triassic oceanic and continental clastics with coeval volcanics are covered by an angular unconformity over the Late Paleozoic strata and the Setula Gr. is superimposed on them by flying peaks; a granite porphyry has intruded into these sediments. The fold axis is mostly NWW−NW, and the only involved stratum is the Wuluate Fm., which should have formed before the Late Carboniferous. The faults are mainly in the NW and NWW directions, followed by the NE, NEE, EW, and NS directions. A series of imbricated thrusted nappe structures formed with posterior spreading characteristics in a compressive−torsion ductile shear zone.

3.1.2. Lithostratigraphic characteristics

The total thickness of the Wuluate Fm. is ~1953 m, and the lower part is a gray−green metamorphosed basalt and lens-

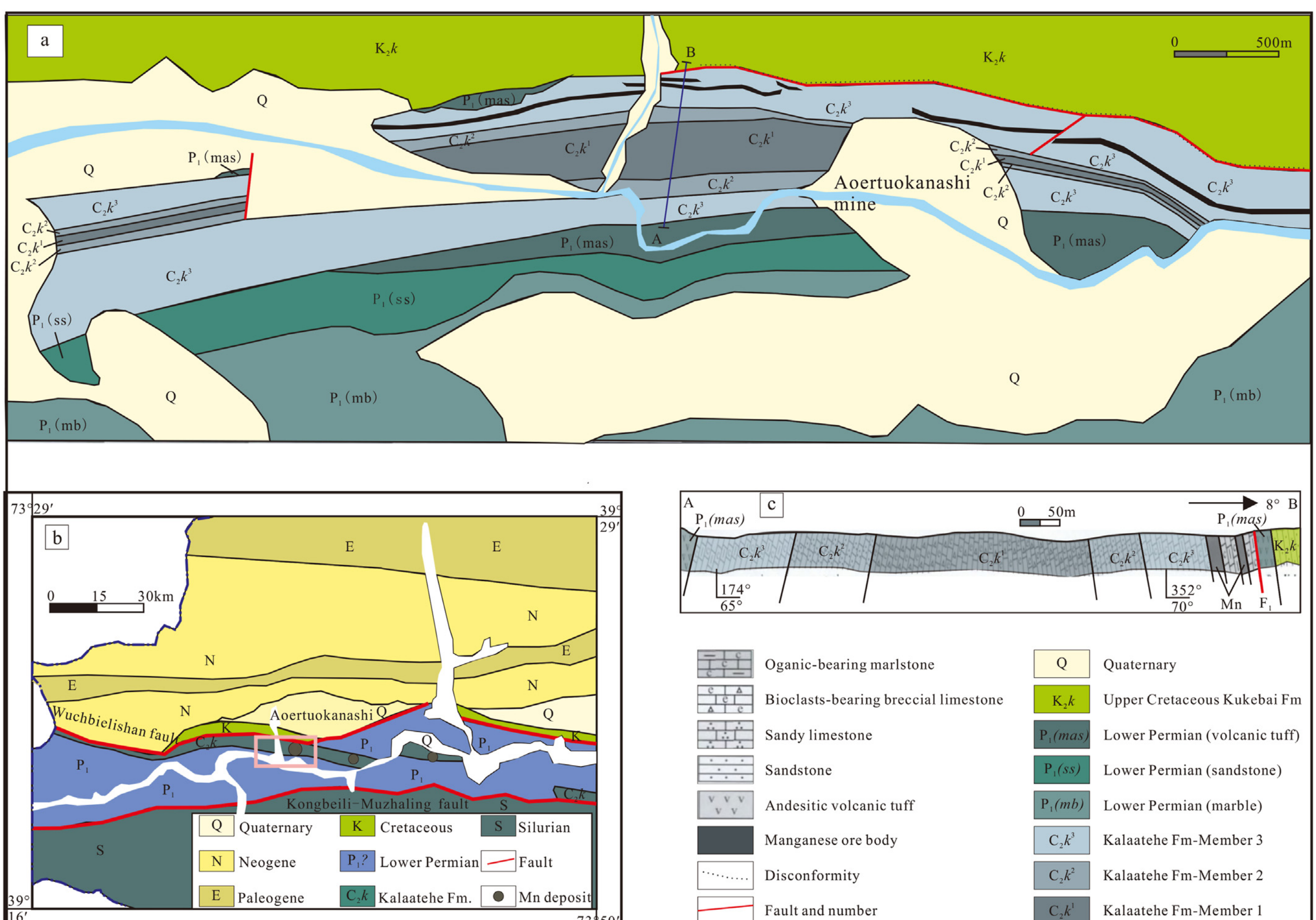

Fig. 8. Geological map (a, b) and stratigraphic section (c) in the Ortokarnash Mn deposit (modified after Zhang et al., 2018; 2020).

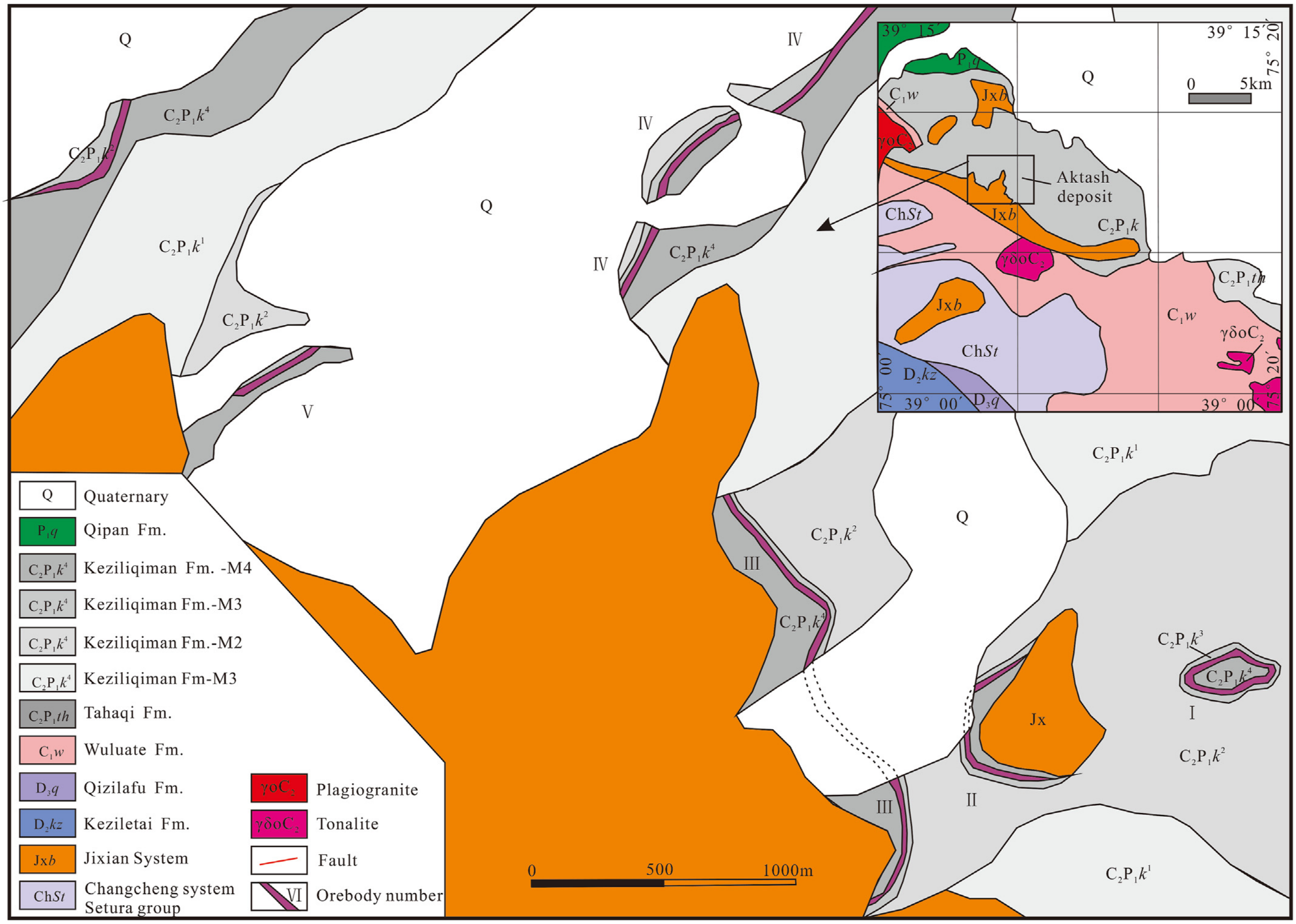

Fig. 9. Geological map of the Aketashi Cu deposit (modified after Jia et al., 1999).

shaped basalt mixed with light gray andesite, which is ~1269-m-thick. In the middle part of Taxikexigou, there is a purple-gray, moderately thick carbonaceous−argillaceous limestone, mixed with thin layers of light gray−green and gray−green marble, which are ~128-m-thick. In the mid-southern part of Ayakusoyi, the rocks are mainly gray, thin crystalline limestones with thin layers of siliceous rock (~113.5-m-thick). The upper part is mainly composed of metamorphosed andesite with purple-gray dacite that is approximately 556-m-thick.

The Upper Carboniferous series has different sedimentary units in different parts of the basin. It is not grouped in the Oytag area and the lower part of the stratigraphic unit is a grayish-white, thick, fine-grained mudstone and dark-gray coarse-grained limestone, containing corals and with a thickness of 2569 m. The middle part is composed of a magenta mudstone and a gray, moderately thick marlstone interbedded with thin, gray, and dark gray micrite, with a thickness of 79 m. The upper part is mainly a grayish white, thickly bedded, fine-grained limestone with purplish red silty mudstone in the middle, mudstone, ash, and dark gray, thickly bedded limestone, containing fossil corals, with a thickness of 1388 m. The area around Malkansu Mountain is called the Kalaatehe Fm. And is mainly composed of thin gray−black micrite, thick gray micrite, and thick gray-black arenaceous micrite, with a small amount of pebbly clastic calcarenite and sparry arenaceous calcarenite and a thickness of ~533 m. The Upper Carboniferous series in the Gaizi River area is subdivided into the Tahaqi and Keziliqiman formations. The lower part of the former is a thin glutenite, the middle part is composed of intermediate acidic lava and pyroclastic rocks, and the upper part is mainly limestone. The lower part of the latter is an intermediate acidic lava, with pyroclastic rocks, and the upper part is limestone.

The Lower Permian is not divided into sub-groups. In the Oytag area, the main lithology is light gray−green basaltic andesite, quartz andesite, andesite, magenta andesitic lava, volcanic crystalline debris, and a small amount of magenta basaltic agglomerate, with a thickness >1182 m. In the Kalaatehe River area, the bottom is a red clastic rock, the lower part is composed of carbonates mixed with basalt, the middle-bottom is composed of red and green clastic and pyroclastic rocks, the middle-upper part is a gray−green clastic rock with gray carbonates, and the upper part is mainly composed of gray−black carbonates, with a total thickness of approximately 4297 m. The Qipan Fm. is sporadically exposed in the basin. The lithology of this formation includes a thick

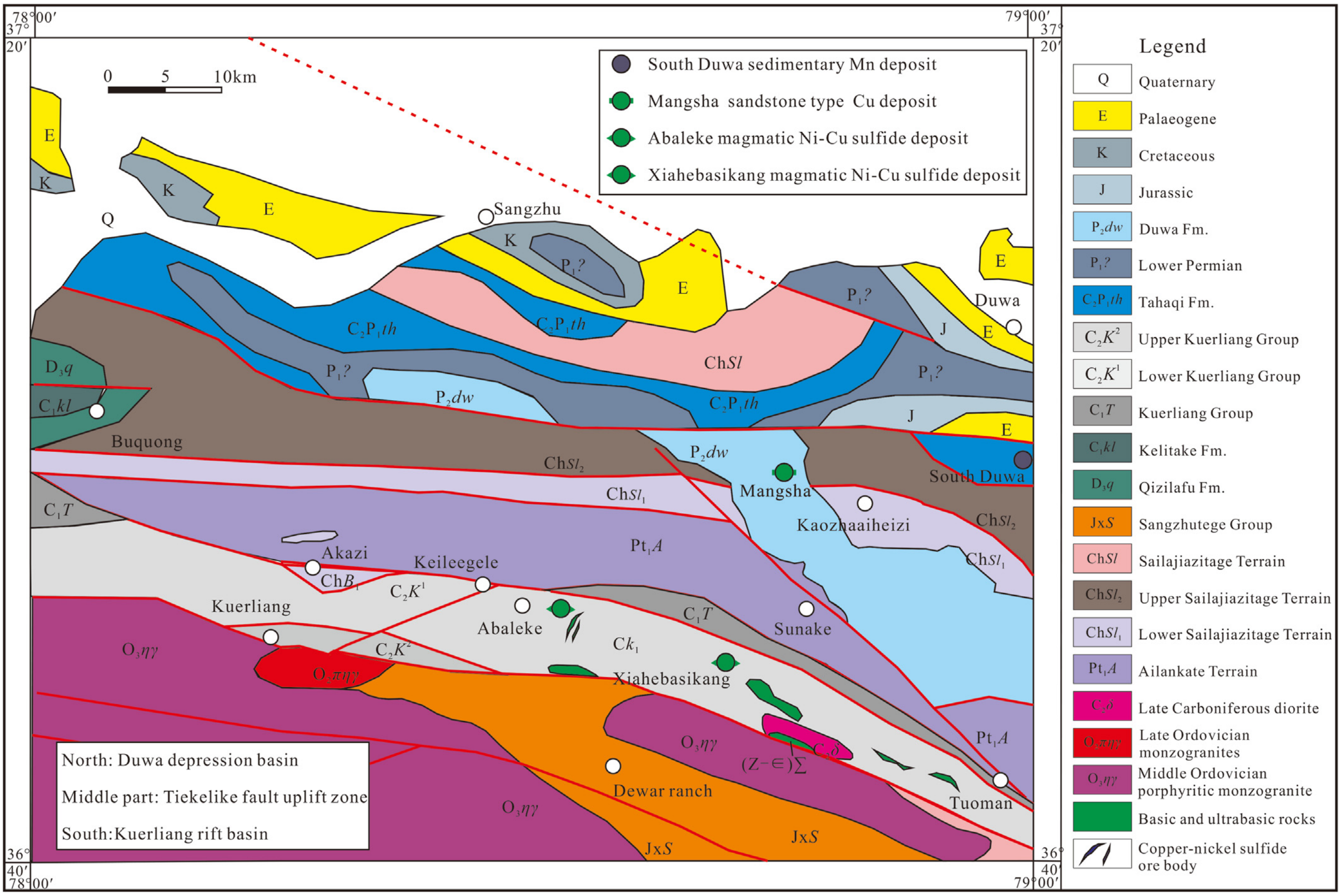

Fig. 10. Geological map of Cu deposits in the Kurliang area (modified after Qi et al., 2005).

layer of gray sparry bioclastic rocks, clastic calcarenite, light ash, and gray−green andesite, containing foraminifera, bryozoa, and brachiopods, with an approximate thickness of 500 m. There are mainly conglomerate, limestone, lithic arkose, calcareous sandstone, lithic sandstone, tuff sandstone sandwiched basalt, and pyroxene andesite, in the Tuoxike area, with a thickness of ~1153 m (Fig. 4).

3.1.3. Sedimentary evolution and mineralization of the basin

The distribution of the Qizilafu Fm. at the edge of the basin suggests that initial rifting was based on a Devonian basin. The Early Carboniferous rock assemblage is dominated by basalt, mixed with gray, sheet-like crystalline limestone and a thin layer of siliceous (radiolarian) rock, representing a deep-water environment and indicating the rapid expansion of the basin and growth via rifting. The Upper Carboniferous is dominated by thick carbonates with a small amount of red mudstone, indicating an open platform sedimentary environment and a stable stage of basin expansion. In the Early Permian, intermediate to acidic volcanic rocks show island-arc affinities, suggesting that the basin began to change from volcano-sedimentary to tectonic.

Although the Middle Permian Qipan Fm. is a set of marine sedimentary rocks with volcanic rocks, the lava of the spillover facies and diabase are equivalent to the compositions of continental alkaline basalts, and the tectonic environment was equivalent to that in which intraplate basalts are formed (Liu et al., 2003), indicating that the basin structure was transformed from a back-arc to an intracontinental environment at this time. The angular unconformity of the Triassic clastic rocks with volcanics that overlie the Late Paleozoic strata and the intruded granite porphyry indicate that the basin structure was completely transformed into an orogenic environment. During the evolution of the basin, the Early Carboniferous experienced intense rifting and a large number of basic−intermediate acidic submarine volcanic eruptions, characterized by typical bimodal volcanic rocks accompanied by the formation for sulfide deposits (Table 1).

Volcanic rocks in Wuluate Fm. are predominantly basic marine volcanics, associated with neutral volcanics, and they belong to a fine green keratophyre series. It has also been found that the Saluoyi Cu deposit occurs in the lower part of the basic volcanic rocks (Wuluate Fm.). Volcanogenic massive sulfide (VMS) mineralization occurred in association with basic volcanic rocks (Jia et al., 1999; Zhang, 2009). The carbonaceous marl of the Upper Carboniferous (Kalaatehe Fm.) produced large Mn deposits (Orto Karnash and Malkansu deposits), whose mineralization may be related to deposition in a back-arc basin/submarine hydrothermal system in an

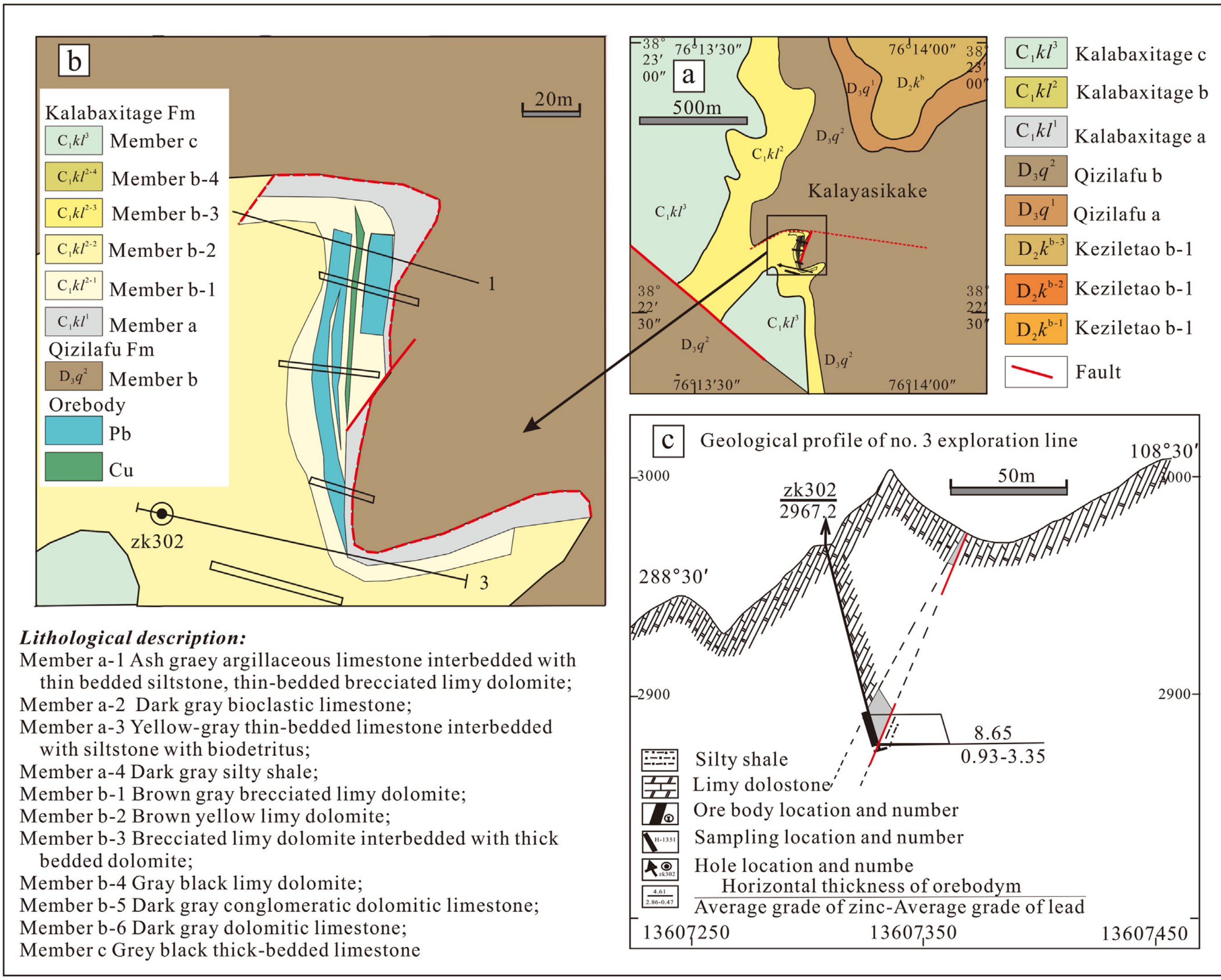

Fig. 11. Geological map (a, b) and geological profile of the no.3 exploration line (c) in the Kalayasikake Pb–Zn deposit (modified after Zhang et al., 2014).

extensional setting (Zhang et al., 2018). As early as the Late Carboniferous to the Permian, the Tahaqi Fm. (subject to a set of marine sedimentary rocks) and Keziliqiman Fm. were deposited; the latter is mainly composed of intermediate acidic volcanic rocks, where the Aketashi Cu deposit was developed in a spilite–keratophyre–quartz keratophyre, whose metallogenic type may be defined as VMS mineralization (Jia et al., 1999; Zhang et al., 2020).

3.2. Kushanhe neritic basin

3.2.1. Basin distribution

The Kushanhe Basin is distributed NWW along the Kushanhe–Gaizi River (Lu et al., 2013). Its southern side is in contact with the West Kunlun massif, with the Kongbeili–Muzhaling fault serving as the boundary. On the northern side, it is directly bounded by the Atuokenake–Jialager Daban fault. On the eastern side, it is connected to the Qiaer-long deep-water basin, with the northern part of the Qiemugan–Aijieke fault as the boundary. Sedimentary formations mainly include Middle and Upper Devonian shallow marine clastics with some carbonates and a small number of volcanic rocks and Carboniferous shallow sea facies. The bottom of the Akbaximazhaer Fm. could not be detected, and the top was in unconformable parallel contact with the Keziletao Fm. The Qizilafu Fm. was separated from the Keziletao Fm. by a large number of magenta rock, while the Kushanhe Fm. is separated from Qizilafu Fm. by limestone, and has an integrated contact with the Upper and Lower Carboniferous Hantiereke Fm. A late Indochinese post-collisional syenogranite intrusion was found along the Kongbeili–Muzhaling fault. Most of the fold axes are in the NW–W direction and were formed in the middle of the Variscan orogeny.

3.2.2. Lithostratigraphic characteristics

The lower part of the Akebaximazhaer Fm. is characterized by green, chlorite-bearing phyllite and schist, while the upper

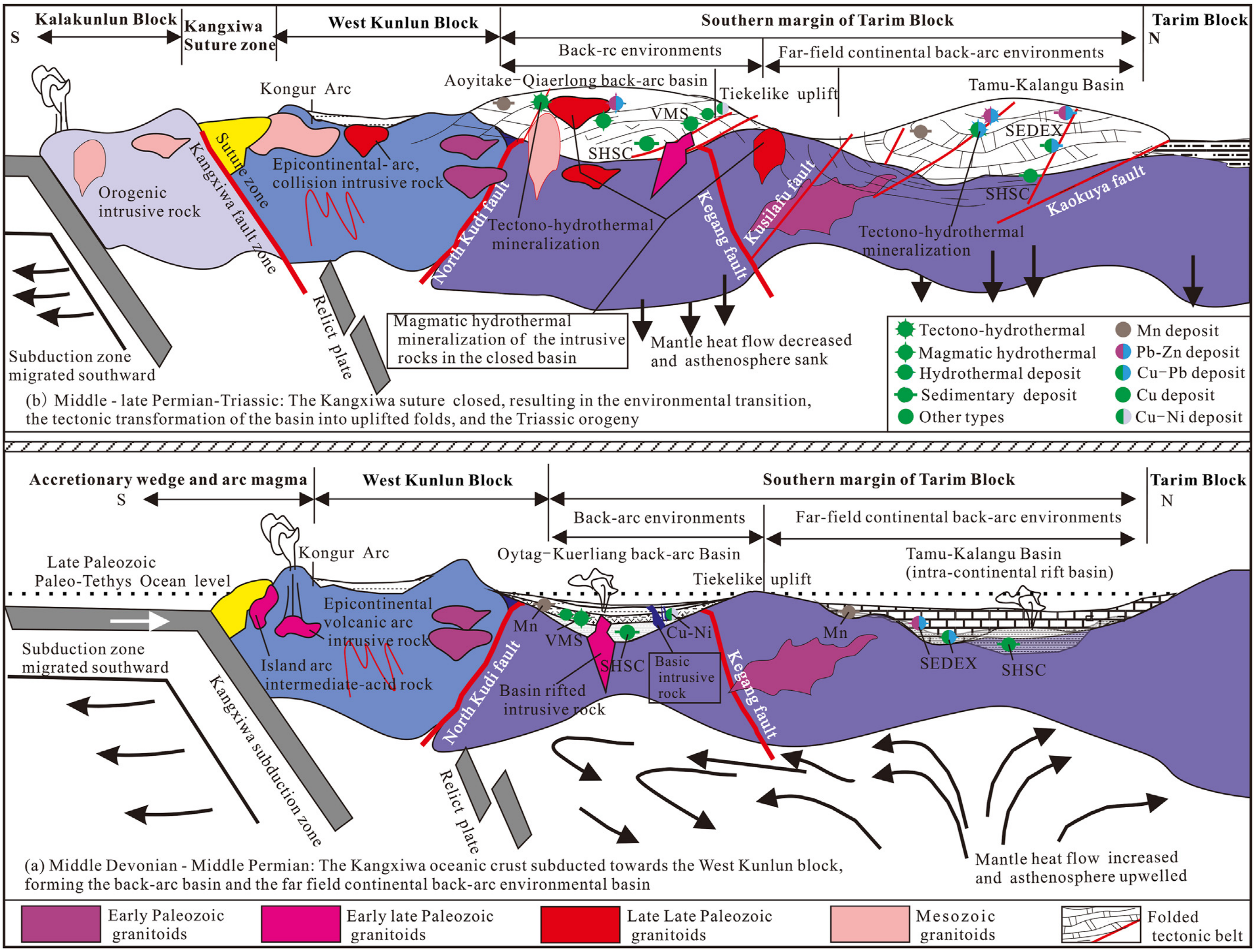

Fig. 12. Tectonic evolution and metallogenic models of the Pb−Zn−Cu (Co) deposits in the western Kunlun Mountains, China.

part is characterized by gray and black carbonaceous slates and microcrystalline dolomitic limestone. In the Miya area, there are mainly thin grayish layers of calcareous, moderately fine-grained quartz sandstone, grayish green and grayish brown moderately fine-grained lithic quartz sandstone, arkose, quartz sandstone, a few grayish white, thickly bedded conglomerates, thin grayish green siltstone, silty mudstone, and chloride-siltstones, with a total thickness of approximately 1348 m. The lower part of Keziletao Fm., is characterized by a gray−green color and the presence of a large number of basalts. The middle part is composed of gray and gray−green clastics with some carbonates. The upper part includes gray-red and gray−green sandstones, as well as a shale assemblage. In the Miya region, it is mainly represented by a grayish green moderately thin layer and moderately fine-grained quartz sandstone, siltstone, arkose, and silty mudstone intercalated with limestone and containing coral and bryozoan fossils and a thickness of ~882 m. In the area of the Kushanhe−Gaizi River, the upper gray-red sandstone, gray−green sandstone, and shale assemblage were divided into the Upper Kushanhe Group based on previous data (Sun et al., 2003), as their stratigraphic distributions and assemblages were the same. Here, we use the term “upper part of the Keziletao Fm.” for these strata (Lu et al., 2013).

The Qizilafu Fm., with a total thickness of up to 5081 m, is mainly composed of massively bedded, grayish red lithics, grayish red and medium-grained lithics, an grayish red thickly bedded layers, sandwiched between the middle argillaceous siltstone and conglomerate, with parallel and oblique bedding in the pebbled sandstone that is ~750-m-thick. The middle part is dominantly composed of moderately thin, gray-red (iron) siltstones, thickly bedded, gray-red (iron), fine-grained quartz sandstone, pebbled medium-grained quartz sandstone, pebbled moderately fine-grained quartz sandstone, calcareous quartz sandstone, with a small amount of Fe-rich fine-grained arkose and pebbled medium-grained quartz sandstone (thickness: ~2248 m). The upper part is mainly a thickly bedded, gray, fine-grained quartz sandstone, with quartz sandstone, thickly bedded, calcareous, fine-grained, purple (Fe-rich) siltstone, purple Fe-rich fine-grained quartz sandstone, and a conglomeratic coarse-grained lithic quartz sandstone; a small amount of celadon occurs in a thin layer of fine-grained quartz sandstone and there is a thick layer of gravel bearing the sandstone in a sage green argillaceous siltstone that is ~2067-m-thick.

The lower part of the Kushanhe Fm. in the Hantiereke area is mainly composed of grayish, moderately thick, bioclastic silty limestone, gray, thickly bedded, fine-grained sandy limestone, a small amount of thin, gray−green silty limestone, and a very small amount of thin black-gray bioclastic oolitic limestone, containing brachiopods and corals, with a thickness of ~787 m. The upper part is a thickly bedded, dark gray, fine-grained bioclastic limestone, with a thick, dark gray layer containing biological fragments, silty fine-grained limestone, a small amount of thick, dark gray bioclastic limestones, and minor thin, dolomitized layers of mudstone and limestone powder. Green and gray green mud powder was also found in the thin limestone, which had a thickness of ~922 m. In the lower part of the Langa area, there are mainly gray dolomitic mudstones, thickly bedded, pale gray silty micritic limestones, light red silty micrite, and a small amount of gray pebbled arenite and a thick layer of light gray micritic dolomite in the middle, with a total thickness of ~210 m. The upper part is mainly a light gray micritic sandstone and bioclastic micritic limestone, with a small amount of thick, gray micritic limestone and medium light gray bioclastic micritic limestone with a thickness of ~222 m. It is mainly composed of a set of carbonate rocks with a small amount of clastics. The limestone contains many animal fossils and is ~1709-m-thick.

The lower part of the Hantiereke Fm. is mainly composed of black and brown ashes, thin green−gray micrite, thickly bedded to massive gray bioclastic micrite, a thin gray layer containing biological debris and micrite, and a small layer of thin brown-gray micrite, silt to fine-grained limestone, and oolitic limestone, with a thickness of ~1356 m. The upper part is mainly a thickly bedded, gray, sparry oolitic limestone, and included a thin layer of gray−black silty mudstone, thick gray sparry bioclastic limestone with arenaceous clasts, and a small amount of thin, gray sparry bioclastic limestone in the middle, with a thin gray layer with carbonaceous silty mudstone containing brachiopods. The total thickness is approximately 880 m (Fig. 4).

3.2.3. Sedimentary evolution and mineralization of the basin

The sedimentary assemblages of the Middle−Late Devonian in this basin range from estuarine, beach, offshore, and tidal flat to deltaic. In the early Middle Devonian, the sedimentary interaction between fine-grained carbonaceous clastics and dolomites was formed in the Akebaximazhaer Fm., in a limited marginal shelf environment. In the late Middle Devonian, with continued transgression, the first layers deposited in the Keziletao Fm. were a pebbly clastic layer and conglomerate. There were followed by volcanic activity and the resulting deposition of basalt and the Anshan tuff, and finally the formation of rapidly filling clastic rocks with a thickness of up to 6000 m.

In the early stage of the Late Devonian, the regressive stage began, forming the red clastic Qizilafu Fm. in a tidal flat environment as the main body, which is up to 5000-m-thick. There are many unstable minerals in these deltaic sediments that were rapidly accumulated. In the Carboniferous, due to the action of Yemutisu fault uplift, the Kushanhe Basin was separated from Tamu−Kalangu Basin and the carbonate rocks of the Kushanhe Fm. were developed, containing a small amount of clastics and limestones from the underlying Hantiereke Fm. This was a subtidal environment, suggesting that the basin structure at this stage was transformed into a back-arc basin (Table 1). In the process of basin evolution, the deposition of the Kezileta Gr. sandy shale formations was favorable for the development of a sandy shale Cu horizon (Upper Kushanhe Fm., Zhao et al., 2002). It has been found that, in the Tugenmansu Cu deposit and Wenjilega and Gaizi Cu mine, its mineralization is defined as a marine sandy shale deposit (Zhao et al., 2002; Wang and Zhao, 2009). In addition, during the late stage of the basin−mountain transformation, the quartz sandstone of the Kezileta Fm. was intruded by the Yuqikapa syenogranite and formed veined hydrothermal Cu deposits (Huang et al., 2011).

3.3. Qiaer-long deep-water sedimentary basin

3.3.1. Basin distribution

The Qiaer-long Basin is mainly distributed in the Aijiekedaban−Qiaer-long area, which is nearly rectangular, with the long axis running from north−south. It is bounded by the Kongbeili−Muzhaling fault and the middle West Kunlun Block to the south, and is adjacent to the Yemutisu fault in the Late Paleozoic extensional trough to the east in the north and center of the basin (Lu et al., 2013). The outcropping strata of the Carboniferous System mainly consist of the Lower Carboniferous Talong Gr., the Upper Carboniferous Kurliang Gr., and the Upper Carboniferous−Lower Permian Tejinaiqikedaban Gr., all of which are in conformable contact; the bottom of the Talong Gr. cannot be seen here. The outlying Permian strata are mainly the Upper Permian Daliyueer Fm. and the Kesimake Fm. The Daliyueer Fm. is in unconformable contact with the Tejinaiqikedaban Fm. and the Daliyueer Fm. is in conformable contact with the Kesimake Fm., without a peak above. Most of the fold axes are NW-trending, which is consistent with the main regional structure. The Qiaer-long anticline is large in scale and the fold is relatively complete and formed early in the middle of the Hercynian orogeny. Early Middle Permian granites intrude into the basin and Permian Taer granites are widely distributed. The southern fault zone was intruded by post-Triassic syenogranite.

3.3.2. Lithostratigraphic characteristics

The Talong Gr. is mainly composed of moderately thick, grayish black, fine-grained quartz sandstone interbedded with thin sheets of grayish black, carbonaceous, silty, argillaceous rocks, which are in-turn interbedded with thin, grayish black, carbonaceous silty sandstones and grayish black silty mudstones. The total thickness of this group is approximately 583 m. The Kurliang Gr. is characterized by gravel bearing a grayish black color and relatively thin layers. A layer of gray calcareous conglomerate at the bottom is approximately 1138-m-thick. The lower part is composed of thick layers of gray and dark gray sparry pebbled bioclastic calcarenite and sparry pebbled clastic calcarenite, thinly bedded, dark gray, pebbled argillaceous quartz siltstone, and a small amount of gray silty mudstone and fine-grained quartz sandstone, containing uncommon fusinid fossils. This unit is approximately 188-m-thick. The middle-upper part of the unit is dominantly composed of a thin layer of grayish pebbly siltstone, a thin layer of argillaceous quartz siltstone, quartz siltstone, fine-grained quartz sandstone, quartz sandstone, silty mudstone, and small amounts of thickly bedded gray conglomerate, pebbled silty mudstone, and carbonaceous mud, which are ~950-m-thick in total.

The Tejinaiqikedaban Fm. is distributed in a NW-trending band. The bottom of this formation is not seen below and it is unconformably overlain by the Upper Permian Daliyueer Fm. The main lithotypes include a gray−black carbonaceous mudstone, thick calcareous siltstone, thin (silty) micrite, and gray, moderately thin, fine-grained quartz sandstone, with a small amount of silty mudstone and fine-grained limestone and a total thickness of approximately 2273 m. At the bottom of Daliyueer Fm., it is conglomeratic. The main lithology includes a purple mudstone, thickly bedded, purple, fine-grained feldspar−quartz sandstone, thinly bedded, purple fine-grained lithic arkose, and a thick layer of gray to green fine-grained quartz sandstone, as well as a small amount of quartz sandstone and argillaceous siltstone with Ca-rich powder, silty mudstone, and dark purple Fe-rich silty micrite. The total thickness is ~1233. Lastly, the main lithology of the Kesimake Gr. Includes a thickly bedded, gray micritic bioclastic limestone, a thick, gray film of bioclastic micrite, and a thick, gray sparry bioclastic calcarenite, with a small amount of fine-grained limestone, sparry aggregated bioclastic limestone and calcareous mudstone, and very small amounts of feldspathic sandstones and siltstones, with a total thickness of ~456 m (Fig. 4).

3.3.3. Sedimentary evolution and mineralization of the basin

During the Carboniferous, a set of deep-water clastic sediments were deposited to form the Talong Gr. (Table 1). The Kuerliang Gr. was deposited in a deep-sea−shallow shelfal environment and part of it records turbidity currents. The strata of the Tejinaiqikedaban Fm. are mainly moderately thinly bedded, with fine grain sizes and more limestone, including fossils, such as *Fusulina* and corals. They formed on a shallow marine shelf, indicating that the sedimentary environment of the basin had shallowed. The absence of Middle Permian sediments in the basin and the retention of red clastic rocks in the Late Permian suggest that the basin had also been transformed into an uplifting environment. Small outcrops of the Kesimake Fm. represent the deposition of the residual basin. Late Carboniferous folding and Permian granite intrusion suggest the existence of a compressive tectonic transition during the deposition of the basin (Table 1). During the evolution of the basin, the Talong Gr. was deposited in a typical deep-water clastic environment. The ore-bearing rocks of the Zhuwuluke Mn ore are black argillaceous shales with Fe−Mn micrite; these are defined as sedimentary Mn deposits (Mao, 2019; Li et al., 2019).

3.4. Deep-water basin of the Kuerliang intracontinental rift

3.4.1. Basin distribution

The Kuerliang Basin lies in a long and narrow belt that extends nearly E−W in the Akazi−Kuerliang−Tuoman area, and is bounded by the Harasitan River fault to the north and the Kuerliang−Tuoman fault to the south (Cui et al., 2013). The exposed geological units include the Carboniferous Talong Gr., Kuerliang Gr., and Yishake Gr. volcanic rocks, Early Paleozoic intrusions in the form of structural windows or flying peaks, and fragments of the Jixian System. The folds are mainly isopachous and were formed by primary stratification, and the cleavage of the axial plane of the folds is not well-developed, which reflects the deformation characteristics of middle structural strata. Because most of the faults were traced and modified by later faults, they were mainly brittle and tended to have steep southward inclinations. At present, they are mainly thrust and strike−slip faults. In the western Xihexiu area, the volcanic rocks of the Yishake Gr. form a synclinal fold.

3.4.2. Lithostratigraphic characteristics

The Talong Gr. is distributed in an E−W-trending belt and is controlled by faults on both sides. It is in contact with the faults of the overlying Kurliang Gr. and a set of fine-grained marine clastic rocks unconformably contact the underlying Qizilafu Fm. and contain a small amount of carbonate, coarse clastic, and pyroclastic rocks. The lithology ranges from a limestone to a black carbonaceous−argillaceous siltstone, quartz sandstone, marble intercalation, crystalline lithic tuffs, and partially intercalated sericulus chloride-quartzose schists. In profile, the rocks are dark in color, and the lower part is mainly composed of fine-grained clastic rocks with a small amount of carbonates in the upper part, which is generally reflective of marine sediments. Only microscopic body fossils (sporopollens) were found in these strata. Laterally, the lithology of the main body has not changed much, and a small number of volcanic rocks (dacites) are locally exposed. Horizontal bedding and grain sequence bedding are developed and reflect the depth of the seawater. The coral, snail, foraminifera, and crinoid stems all reflect shallow sea water. The sedimentary environment of the Talong Gr. Ranges from shallow to deep sea facies according to these lithological and fossil characteristics.

The Yishake Gr. is defined as a set of lava and pyroclastic lithic formations that protrude from the western part of the basin. It is divided into two sections according to their lithologic characteristics. Section A is composed of massive andesite, lens-shaped stomatal andesite, and andesitic conglomerate. According to the petrogeochemical characteristics and tectonic environment, it has been concluded that it formed in an island-arc environment. Section B is a pyroclastic bed, the lower part of which is composed of gray–green and purplish red andesitic conglomerate, tuffaceous sandstone, and fine-grained sandstone. The upper part is an interbedded gray–green sandy tuff and light gray–green tuffaceous siltstone, which is locally siliceous, representing products of a deep-water environment. Radiolarian fossils were used to determine an Early Carboniferous age. Based on these results, the Yishake Gr. was characterized by an island-arc environment in the early stages of deposition; during later stages, it was transformed into a back-arc basin, and the basin deepened in the late stages.

The Kuerliang Gr. is intermittently distributed in the E–W-trending belt due to the destruction of faults and intrusions. The north side is in contact with the Talong Gr., while the south side is in contact with different strata. It is mainly composed of a set of clastic rocks with intermediate and basic volcanic rocks and a small amount of carbonate rocks, and the underlying Talong Gr. is the fault contact. The lower part is composed of normal clastic rocks, while the middle is composed of gray and gray–black metamorphosed sandstones, clastic limestone, carbonaceous siltstone, and quartz schist. The upper part is composed of mixed color clastic and volcanic rocks, belonging to neritic and littoral facies. The depositional age is Late Carboniferous. In profile, a lower formation is mainly composed of a set of conglomerates, sandstones, siltstones, and shales, with a small amount of altered andesite and limestone. The main lithology includes a thickly bedded, gray, coarse-grained feldspathic quartz sandy conglomerate, coarse-grained gravely feldspathic quartz sandstone, gray, fine–coarse-grained feldspathic quartz sandstone, and coarse-grained lithic quartz sandstone, seriate conglomeratic feldspar–lithic quartz sandstone, thinly bedded, gray feldspathic quartz sandstone, quartz sandstone, and argillaceous siltstone containing carbon. The Bouma sequence in the formation is clear, and it is generally a set of deep-water turbidites interbedded with basic volcanic rocks. The lithology and lithofacies vary greatly laterally. From west to east, the clastic rocks decrease gradually, while the volcanic rocks (dacites) similarly increase. According to its petrogeochemical characteristics, the Kurliang Gr. formed in an intraplate rift basin (Fig. 4).

3.4.3. Basin evolution and mineralization

The base of the basin is the West Kunlun Block, and the Devonian tectonic pattern was transformed because of the subduction of the Paleotethys oceanic crust, resulting in the formation of back-arc extension. In the Late Devonian, the Qizilafu Fm., composed of molasse, was deposited. The intensification of Carboniferous extension resulted in the formation of volcanic and pyroclastic rocks in the Yishake Gr., as well as the clastic rocks in the Talong and Kurliang groups, with volcanic rocks in some places. In the Late Carboniferous, West Kunlun pyrolysis was further intensified, and the basic rocks in the Kurliang–Arqiang rift basin and the Arqiang volcanic rocks in the Early Permian were formed. At the beginning of the Middle Permian, the transition of the basin via compression resulted in folding and invasion by late Hercynian granitic porphyry ($P_2\gamma\pi$), suggesting the beginning of rift closure and the absence of Late Permian deposition (Table 1). According to this theory, the Kurliang Basin is a back-arc rift zone, which began to open in the Early Carboniferous, continuing through the Late Carboniferous, and finally closed in the Late Permian.

Based on an analysis of the formations in the Yishake Gr., the possible metallogenic types mainly include both volcanic and tectonic hydrothermal deposits. In the former, only Cu and Pb geochemical anomalies coincided with outlying volcanic areas, while no ore deposits have been found. The latter has been found to have tectonically altered Cu mineralization (Ji et al., 2013). The Talong Gr. is composed of a set of clastic rocks with a small number of carbonates and pyroclastic rocks that were deposited in neritic and abyssal environments, in which carbonaceous carbonate rocks are rich in Mn and which may serve as ore-bearing rocks. The Kurliang Gr. is a type of flysch constructed in basic volcanic rocks during magmatism and exhibiting syntectonic characteristics. Magmatic hydrothermal mineralization is represented by the Abaleke and Xiahebasikang Cu deposits (Qi et al., 2005; Hou et al., 2007). In addition, Cu mineralization has also been found in the contact zone of the monzonite granite porphyry in southern Xiahebasikang (Ji et al., 2013).

4. Back-arc basins in distant continental environments

4.1. Tamu–Kalangu intracontinental basin

4.1.1. Basin distribution

The Tamu–Kalangu Basin is mainly distributed in the Keziletao–Kusilafu–Qipan area, which is elongated in a nearly N–SE direction. It is bounded by the Kusilafu fault, which is connected to the Tiekelike fault belt in the southwest and to the Kaokuya fault to the northeast; the overthrust overlying the Neogene strata of the Tarim Basin (Lu et al., 2013). Sedimentation in the basin began in the Middle Devonian and ended in the Late Permian, and the underlying basement is composed of Permian metamorphic, Upper Paleozoic and Triassic, and Upper Jurassic continental sedimentary strata (Table 1, Fig. 2).

4.1.2. Lithostratigraphic characteristics

(1) Middle Devonian–Lower Carboniferous: The outcropping strata include the Middle Devonian Akebaximazhaer and Keziletao formations and the Upper Devonian Qizilafu and Upper Devonian–Lower Carboniferous Kelitake formations (Fig. 4). The Akebaximazhaer Fm. is a set of clastic rocks containing palynological fossils with a thickness of >1736 m. The Keziletao Fm. consists of a set of clastic rocks intercalated with limestone, with a total thickness of ~1622 m (Li et al., 2006). The Kelitake Fm. is mainly composed of a set of mixed clastic and carbonate rocks, with a thickness of ~725.25 m (Zhu et al., 2002).

In the Kushanhe area, the lithology of the Kushanhe Fm. is similar to that of the Kelitake Fm., which is approximately 1709-m-thick. In the central part of the Kezileta Fm., volcanic and sedimentary rocks are integrated, and the facies is a basic lava of a spillover facies that is approximately 692-m-thick. The rock types mainly include basalts with a few porphyritic basalts. Basalts are gray−green and have intergranular and flakey structures. The porphyritic basalts are also gray−green but exhibit porphyritic and stromal intergranular structures. Petrochemical analyses have revealed that these rocks are supersaturated in SiO_2, and that they are an aluminized of tholeiite series that formed in on a continental plate. Therefore, they are assumed to be related to the rifting events that occurred in the Middle Devonian.

(2) Carboniferous−Lower Permian: The strata in the Tarim Basin are mainly composed of the Lower Carboniferous Huoshilafu Fm., Upper Carboniferous Kalawuyi and Azigan formations, and the Upper Carboniferous−Lower Permian Tahaqi Fm. The Huoshilafu Fm. is mainly composed of a set of mixed clastic−carbonate rocks, with the lower lithology composed of clastics and the upper being composed of carbonates interbedded with clastic rocks. It is rich in marine animal fossils and has a total thickness of approximately 732 m (Chen et al., 2008). The Karaouyi Fm. is mainly composed of clastic and carbonate rocks, contains abundant marine animal fossils, and has a total thickness of approximately 326 m. The Azigan Fm. is mainly composed of mixed clastic and carbonate rocks, which contain abundant fusinids, a few brachiopods, and gastropods, and is ~337-m-thick. The Tahaqi Fm. mainly comprises a set of carbonate rocks, consisting of gray megalospheric fine-grained dolomite, micrite, thin, gray bioclastic rocks, and a small number of fine-grained limestones that are rich in marine animal fossils. This unit is approximately 281-m-thick.

In the Early Permian, there was a magmatic eruption and volcanic rocks were distributed throughout the Kutaiyimaike area, ultimately overlying the Upper Carboniferous limestone. The lithology was a basalt−basaltic andesite−dacite assemblage dominated by basaltic andesite. The volcanic rock layer changed from the bottom to the top from neutral to basic, with the magma composition at the bottom being more felsic. It is composed of quartz andesite and tuffaceous andesite. The middle part consists of basaltic andesite, while the upper part is composed of basalt. Petrochemical analyses have revealed that these rocks are supersaturated in SiO_2 and represent an aluminized subalkaline (tholeiitic) series. They are believed to have formed on a continental marginal under the siliceous and aluminous basement (Lu et al., 2013).

(3) Permian: In the Tarim Basin, Permian strata were reported during a recent geological survey (Lu et al., 2013). The exposed strata in the Tarim Basin include the Lower Permian Keziliqiman Fm., Middle Permian Qipan Fm., and Upper Permian Daliyueer Fm. The Keziliqiman Fm. is mainly composed of a set of carbonate rocks and is ~190-m-thick. The Qipan Fm. is composed of clastic rocks in the lower part and carbonate rocks in the upper part, and is interbedded with clastic rocks and limestone of unequal thicknesses; the total thickness of the unit is approximately 231 m. The Daliyueer Fm. is mainly composed of red clastic rocks and micritic limestones, with a thickness of ~694 m. Volcanic rocks were integrated into the marine sediments of the Qipan Fm. to rocks form a set of basic rock assemblages, which mainly include the lavas of spillover facies, which are filled with pyroxenes. Rock types include lens-shaped basalt and diabase. The chemical compositions of these rocks are generally close to those of continental alkaline basalts, and the tectonic environment identified based on these traits is equivalent to that in which intraplate basalts form (Liu et al., 2003).

4.1.3. Basin evolution and mineralization

From the Middle Devonian to the Late Permian, the sedimentary environment of the Tamu−Kalangu Basin generally underwent a transformation from shallow to deep and then shallowed again (Table 1). However, some fluctuations also occurred in these sedimentary changes during deposition (Table 1, Fig. 4). The sedimentary assemblages of the Middle−Late Devonian include estuarine, beach, offshore, and tidal flat to deltaic facies. In the early Middle Devonian, the water body was generally shallower. In the late Middle Devonian, with continuous transgression, 470 m of pebbled clastic rocks and conglomerates first formed in the Qimugan area, and 550 m of basalt and 150 m of andesitic tuff were deposited due to crustal tension, followed by the rapid deposition of clastic and carbonate rocks with a thickness of up to 6000 m.

In the early stage of the Late Devonian, the area regressed and red clastic rocks formed in a tidal flat as the main body. The dominant sedimentary assemblages of the Carboniferous experienced changes during deposition on an open platform, platform margin, epicontinental shelf, and open platform once again (Zhu et al., 2002). On the basis of the Devonian oceanic basin, a stable intracontinental sedimentary basin was formed in the Early Carboniferous and a continental shelf with calcified clastic rocks was developed. During the Late Carboniferous, this region was an open carbonate platform, which persisted until the end of the Late Carboniferous−Early Permian.

The main sedimentary assemblages of the Permian underwent changes to the open platform, shoal, littoral, and fluvial sediments. The Early Permian inherited the Late Carboniferous sedimentary basin and was still a carbonate platform. However, by the middle Permian, clastic and carbonate rocks were interacting and being deposited in an open intraplate (i.e., epicontinental) environment. Due to local extension, basaltic−andesitic lava formed. Finally, in the Late Permian, large-scale regression occurred, which initially formed a fluvial sedimentary environment and then a residual oceanic basin later (Liu et al., 2003).

The four ore-bearing rocks developed during the sedimentation of the basin are shown in Fig. 5. From bottom to top, they are: (1) sandstone with argillaceous limestone in the middle of the Keziletao Fm., which contains the Tiekelieke sandy shell-bearing Cu–Pb deposit. (2) Thin limestone with sandy shale, which is the first member of the Kalabaxitage Fm., produced a clastic–carbonate Cu–Pb (Co) deposit (i.e., the Tamu Zn–Pb deposit). (3) Thick brecciated dolomite, which is the second member of the Kalabaxitage Fm., produced a carbonate rock-controlled Pb–Zn deposit (i.e., the Kalangu Pb–Zn deposit). (4) The central bioclastic limestone layer of Huoshilafu Fm. produced a structurally hosted Pb–Zn deposit (i.e., the Kalayasikake Pb–Cu deposit). These host rocks share the common characteristics of having a very thick clastic rock beneath them and an overlying carbonate rock with clastic rocks above them, which is characterized by an anoxic layer containing brecciated limestone and a combination of bioclastic limestones and carbonaceous rocks.

4.2. Duwa Basin

4.2.1. Basin distribution characteristics

The main distribution of the Duwa Basin spans the Sangzhu Township/Duwa Town area and is nearly oblong, with near E–W spreading. The south side of the basin is connected to the Tiekelike fault belt and the east side overlies the Cenozoic strata of the Tarim Basin (Cui et al., 2013). Sedimentation in the basin began during the Late Devonian and ended in the Middle Permian; it is underlain by a basement of Precambrian metamorphic strata and overlies Cretaceous limestones and sandstones, as well as and Lower Tertiary calcareous sandstones, marls, and clastic rocks (Table 1, Fig. 2).

4.2.2. Rock stratigraphic characteristics

(1) Upper Devonian: The main rock assemblages of the Qizilafu Fm. are medium-grained quartz sandstone, fine-grained calcareous quartz sandstone, fine-grained arkosic quartz sandstone, and a few thinly bedded siltstones, argillaceous siltstones, and mudstones. The upper fine-grained quartz sandstone is interbedded with thin, gray siltstone, and the bottom and middle quartz sandstones are interbedded with thickly bedded gravel.
(2) Upper Carboniferous–Lower Permian: The lower part of the Tahaqi Fm. is a gray–white arenaceous bioclastic limestone that contains a large number of biofossils. In the middle, the lithology is a moderately thick, gray–yellow and grayish fine-grained pebbly calcareous sandstone. The composition of the gravel is mainly quartz and the sand are mainly composed of quartz and feldspar; most cements are calcitic. The upper rocks are limestone–micritic limestone and microcrystalline limestone, with a small amount of argillaceous and terrigenous clasts.
(3) Middle Permian: The lower part of the Duwa Fm. is mainly composed of thickly bedded purple and gray conglomerate, sandy conglomerate with medium-grained gravely lithic quartz sandstone, and lithic feldspar sandstone. The conglomerate has a thick to massive structure and the sandstone mostly exhibits lenticular bedding. The upper part is mainly composed of thickly bedded, grayish green conglomerate, medium-grained pebbled arkose, and quartz sandstone, in which oblique bedding and grain sequence bedding are developed.

4.2.3. Basin evolution and mineralization

The Qizilafu Fm. experienced tidal, littoral, and neritic sedimentation and produced sandy gravel Cu deposits (e.g., in Mangsha, Pishan County) in the central glutenite. The Tahaqi Fm. was deposited in a neritic carbonate platform facies, in which sedimentary Mn deposits were formed in the middle bioclastic calcarenite (Li, 2018). The Duwa Fm. formed via the deposition of detrital fluvial and lacustrine sediments, resulting in the development of sandstone-like Cu deposits in the lower purple glutenite (Cui et al., 2013).

5. Typical ore deposits

5.1. Sedimentary rock-hosted stratiform Cu–Pb (Co) ore deposit

The sandstone layer of the Upper Keziletao Fm. in the Tamu–Kalangu basin contains the Tiekelieke Cu–Pb deposit (Zhang et al., 2014). The red sandstone layer of the uppermost formation of the Kushanhe Gr. in the Kushanhe Basin contains the Tugenmansu sandstone Cu deposit (Zhao et al., 2002; Wang and Zhao, 2009). The purplish red sandstone of the Duwa Fm. in the Duwa Basin contains the Buqiongnan Cu deposit (Cui et al., 2013).

5.1.1. Tiekelieke Pb–Cu (Co) deposit

The Tiekelieke Pb–Cu (Co) mining area is located in the Keziletao Township in Akto County, China (Fig. 1b, Table 2), and the outcropping strata are mainly the Kiziletao Fm, and the Lower Jurassic Salitash Fm. The lower of the Keziletao Fm. is mainly composed of a set of grayish white–light grayish brown pebbly sandstone and quartz sandstone interbedded with conglomerate (Member a). The upper of the Keziletao Fm. (Member b) can be further divided into four lithologic sections (Fig. 6). The overall monoclinal formation is oriented NNW and the F1 fault spans from the NW–N, with a northward ~40° inclination that is contemporaneous with the fault characteristics. The F2 fault spans from NE–S, and its ~40–50° inclination can be matched with the F1 reverse fault. The tectonic characteristics of the F3 fault nappe may record the tectono-sedimentary movement formed after diagenesis. In addition, there are some secondary faults, which strike nearly N–S or N–W, and are mainly compression–torsion thrust faults. Rock alteration can be divided into two stages: (1) regional dynamic metamorphism, which manifests as foliated zones and a large number of micaceous minerals in the Devonian strata and (2) hydrothermal alteration related to mineralization, such as silicification, sericitization, and limonitization.

The ore body was produced in the first lithological member of the upper subformation of the Keziletao Fm. The bottom layer is a set of grayish brown and gray Cu-bearing sandstones containing gravel. The rocks are mainly silicified and weakly limonitized, and peacock ore (i.e., bornite) is commonly seen. The middle layer is a gray−light gray, coarse-grained quartz sandstone containing galena. Most rocks are heavily silicified and galena is commonly observed. The thickness of this unit is ~50−100 m. The upper layer is mainly composed of a set of brown quartz sandstone and siltstone that are slightly metamorphosed, with weak sericitization, strong limonitization, and silicification, and alteration halos characteristic of hydrothermal mineralization. The ore body is lamellar or lenticular and is distributed in two parallel layers, of which the lower Cu body is 120-m-long at the surface, 17.45 m in horizontal thickness, and has a Cu grade of 0.47%, accompanied by an economically useable cobalt element. The top Pb ore body grew up to 1400 m; the average thickness is 15.80 m, the average Pb grade is 5.02%, the main metallic minerals present include galena, pyrite, malachite, and limonite.

The main metallic minerals in the Cu body are chalcopyrite and pyrite, while the secondary minerals are malachite, limonite, and covellite Lead mainly occurs in galena (1.15−7.67%), while the amounts are lower in secondary minerals, such as lead vanadium (0.42−0.55%), white lead ore (0.95−2.47%), and Pb chloride vanadium (0.08−0.14%). Gangue minerals are mainly quartz and calcite. The ore structure is dominantly cemented and include self-shaped crystalline, metasomatism, inclusion, crumpling, and brecciated structures. The breccia are syngenetic and epigenetic, of which the syngenetic ones contain oval quartz with a diameter of 0.3−0.8 cm. Posterior breccia is present.

5.1.2. Tugenmansu Cu deposit

The Tugenmansu Cu deposit is located in the upper reaches of the Tugenmansu River in Akto County, Xinjiang (Fig. 1b, Table 2). The outlying strata are mainly red clastic rocks of the Kushanhe Gr., followed by Cretaceous and Tertiary red clastic rocks. The former is in faulted contact with the latter. In the periphery of the mining area, there are intermediate−felsic intrusive rocks from the late Hercynian orogeny, as well as basic−intermediate−felsic volcanic rocks. According to the initial definition in the mining exploration report, there are clastic rocks at the bottom of the lower formation in the Kushanhe Gr. and carbonate rocks predominate. The lower part of the upper formation is a red clastic rock, dominated by gray−purple arkosic quartz sandstone and containing purplish red sandy mudstones, gray−white malachite-bearing quartz sandstone (Cu-bearing layer), and gray−black fine-grained sandstone and calcareous sandstone. The upper contains gray slate, sandstone conglomerate, and limestone.

The latest data have modified the Kushanhe Gr. in the mining area into the Keziletao Fm. (Lu et al., 2013). According to the characteristics of the sedimentary assemblage, the upper Kushanhe Gr. is equivalent to the upper part of the Keziletao Fm. (Table 1). The first member is mainly a quartz sandstone or quartzite with thinly bedded conglomerate. The second member is a purplish red sandstone and quartz sandstone. The third member is mainly composed of quartz sandstone, quartzite, and black, fine-grained sandstone. The fourth member is a purplish red sandstone containing fossiliferous sandstone. Finally, the fifth member is composed of black shale, slate, and phyllite.

The zone of Tugenmansu Cu mineralization is ~10-km-long, trends NW, and gradually changes to a nearly EW direction in the northwest, which is roughly consistent with the stratigraphic occurrence data. The outlying width exceeds 10−200 m. The mineralization zone may be subdivided into three ore-bearing layers: the upper ore-bearing layer mainly occurs in Member 4, which is 60−200-m-long and 20−30-m-thick. The central ore-bearing layer mainly occurs in Member 3, with a length of ~1800 m and a thickness that ranges from ~8 to 200 m. The bottom ore-bearing layer mainly occurs in Member 1 and consists of two sandstone layers containing malachite, pyrocopite, and other mineralized layers. Copper mineralization mainly occurs in Member 3, with a Cu grade W (Cu) of ~0.4−3.72%, and ranging up to 11.90%. The orebody is generally stratified and lensed, and its occurrence is consistent with that of the rock layer. Four ore bodies are ringed out of the upper layer, 100-m-long and 6.8−16.19-m-thick, while three veins and six ore bodies are ringed out of the middle-mineralized layer (100−1300-m-long and ~4.05−16.53-m-thick, with a depth of more than 300 m). Two ore bodies are ringed out of the lower mineralized layer, which is 60-80-m-long and 4.58−6.25-m-thick.

The main metallic minerals in the ore are sulfides, especially chalcopyrite, followed by chalcocite, and tetrahedrite, as well as trace amounts of galena, sphalerite, pyrite, and magnetite. Copper-containing oxides include malachite and covellite, and gangue minerals, including quartz, calcite, and a small amount of barite. Most of the metallic minerals in the ore are euhedral and semi-euhedral granules, and interstitial cements are often found in the oxidized malachite (common in the Cu-bearing silver conglomerate). The ore structures include vein-like and disseminated. The ore body is in conformity with the wall rock, and the top and bottom are dense and hard quartz sandstone, quartzite, white lime quartz sandstones, and interbedded purple red quartz sandstone. The near-surface rocks are mostly loose and fragmentary due to strong weathering. Copper mineralization occurred in the coastal, shallow marine clastic rocks of the basin and belong to a syngenetic sedimentary rock-hosted stratiform Cu deposit, which is partially superimposed with slight hydrothermal alteration and enrichment. In addition, Cu and Ag mineralization were found in red clastic rocks in the tertiary.

5.2. Carbonate rock-controlled Pb−Zn deposit

5.2.1. Tamu Pb−Zn deposit

(1) Mining area geology: The mining area is located in Tamu Village, Kizile Township, Aktao County (Fig. 1b, Table 2).

The exposed strata are the upper subformation of the Kezileta Fm., the Qizilafu Fm., a Carboniferous System, the Lower Jurassic Kangsu Fm., and a Quaternary System (Fig. 7). The Middle Devonian Kezileta Fm. is subdivided into three members; the first is a dark gray brecciated limestone, the second is a thickly bedded, dark gray, sandy limestone, and crystalline limestone, and the third is a thickly bedded gray dolomitic limestone. The Upper Devonian Qizilafuu Fm. is subdivided into two members; the first is mainly composed of maroon quartzose siltstone, green and purple medium-grained quartz sandstone interbedded with green and purple fine-grained quartz glutenite, and the second is mainly composed of thinly bedded, light gray−green siltstone interbedded with sandstone.

The Carboniferous Kalabaxitege Fm. is subdivided into three members (Fig. 7), the first of which is mainly a thinly bedded limestone and silty shale, as well as calcareous sandstone, sandy limestone, and bioclastic limestone. These include a further four lithologic layers, the first being an thin layer of ashen, light gray, argillaceous limestone, along with a thin layer of clayey sandstone and thin, limey dolomitic breccia. The second lithologic bed is a dark gray bioclastic limestone, while the third is a thinly bedded grayish yellow to gray limestone interbedded with siltstone. The fourth lithologic layer is a dark gray silty shale. The second member of the Lower Carboniferous Kalabaxitege Fm. is mainly composed of interbedded dolomitic limestone and brecciated dolomitic limestone, which can be subdivided into six lithologic layers. The third and final member of the Kalabaxitege Fm. is mainly composed of thickly bedded, gray−black limestone.

The main lithology of the Lower Jurassic Kangsu Fm. includes arkose−quartz sandstone, siltstone mixed with Fe-rich argillaceous siltstone, and coal seams. The Quaternary System is mainly composed of sand, gravel, pebble, and loess. The main fold structure in the mining area is formed by the Tamu syncline and the Kalayasikake anticline; the mineralization zone is in the western limb of the Tamu syncline. The fold axis of this syncline is consistent with the regional structural line in the NW direction, and the western wing of the syncline overturns out of the orebody. The fault structure mainly consists of two groups that strike NNW and NW and are thrust or normal faults that have had destructive impacts on the ore body. The strata on both sides of the fault have been subjected to strong foliation and mylonitization. Two diabase dikes are distributed sporadically in the fault zone, and a reaction ring and baking can be seen at stratigraphic contacts. The alteration of the surrounding rock in the mineralization zone mainly includes dolomitization, the precipitation of barite, calcite, and sericite, pyritization, uncommon silicification, and more common ferritization.

(2) Deposit features: Ore bodies occur in thick layers of dolomite and dolomitic limestone in the first lithologic section of Kalabaxitage Fm. and in the dark gray dolomite and dolomitic limestone in the second lithologic section (Fig. 7b). The mineralization zone is distributed within the brecciation zone and is consistent with the overall formation trend (Fig. 7c). The ore body grows at 750 m, with an average thickness of 19.24 m. The average grade of the surface ore body was 0.69% Pb and 5.08% Zn. In a later stage of mineralization, the superposition of remineralization was obvious and local sections filled the fine galena and sphalerite veins along the fractures and intersected the bedding planes. The orebody was stratified, with obvious branching that compounded existing trends, and great variation in occurrence.

The main ore minerals are sphalerite, galena, and pyrite, and the secondary minerals are cerusite, anglesite, and ferrimanganic oxide. Sphalerite mineralized in multiple stages and was divided according to its color, from dark to light. There are at least four kinds of sphalerite, ranging from black to light yellow, generally indicating the evolution of the system. The gangue minerals are dolomite, calcite, quartz, and muscovite. Overall, there were two stages of mineralization. The first stage involved the formation of a dense ore, mainly composed of Zn. The second stage included the formation of ore veins, mainly with thick Pb and closely syngenetic Pb−Zn. Ore structures with spherical, strawberry-shaped, solid solution separation, residual, banded, brecciated, and vein structures of pyrite formed in the early stages of mineralization.

Spherical, strawberry-shaped structures are distributed in the fractures of carbonatites, while part of the fine-grained euhedral pyrite is scattered therein. Lead-zinc sulfides veins filled a dolomitized limestone fracture zone, along with breccia, brecciated dolomitized limestone, and dolomite, which bound to the Pb−Zn sulfide. Alteration of wall rock can be divided into dolomization, calcitization and silicification. The dolomitization and calcitization mainly occur in veins, which are reticular and granular in surrounding rocks. Next to calcite veins, sphalerite, galena, and pyrite occur successively. Silicification is generally distributed along the fault structure, veins, and dolomitization zone.

5.2.2. Kalangu Pb−Zn deposit

(1) Mining geology: The Kalangu Pb−Zn mining area is located in Kalangu, Kusilafu Township, Aktao County (Fig. 1b, Table 2). The Upper Devonian Qizilafu Fm. and Lower Carboniferous Kalabaxitake Fm. are mostly observed in this area. The former can be divided into four lithologic members: (1) a sage green siliceous siltstone, (2) folded siliceous clayey sandstone, (3) quartz sandstone, and (4) celadon quartz sandstone interbedded with shale, purple sandstone with celadon, quartz sandstone, gray quartz sandstone, glutenite, and purple sandstone with green and purple sandstone. The latter is divided into three lithologic segments, the first of which is limestone interbedded with sandstone and shale; the second is composed of limestone, carbonaceous shale, and pebbled limestone. Limestone, sandstone, and carbonaceous shales occur in

the third lithologic member. The second member is the main ore-bearing rock series, which is divided into six lithologic layers from top to bottom (Fig. 2). These include the following: Gray pebbled limestone with calcareous conglomerate; Thickly bedded gray limestone; Thinly bedded, grayish black limestone intercalated with carbonaceous shale; Gray pebbly limestone intercalated with conglomerate; Thickly bedded gray limestone; Thinly bedded grayish black limestone intercalated with carbonaceous shale.

The ore-bearing rocks are composed of a set of clastic rocks containing carbonates, in which there are two layers of thick gray limestone as the ore-controlling beds, and the local facies changes to that of carbonaceous or dolomitic limestone. The structure is dominated by plastic deformation, forming folds, traction folds, and creases, and a breccia belt formed between strata is the main ore-bearing space. The Qizilafu anticline is a main fold structure superimposed with secondary folds (Kalangu syncline) on the eastern wing of the fold. The two wings of the syncline are distributed with ore bodies along the bedding planes. Faults within the mining area can be divided into syngenetic faults and late faults, the former agreement is strange since the Qizilafu anticline axis, and a fault slip breccia belt serve as the main ore body. The ore-controlling faults suggest that there is a secondary basinal sedimentary rock — a thickly bedded gray limestone with angled conglomeratic−dolomitic limestone. The late fault exhibits nappe compression, cross-cutting the strata and the earlier fault. In the tectonic metamorphic zone, the rocks on both sides of large regional faults are heavily foliated.

(2) Deposit characteristics: The ore body is irregular in shape but it is generally distributed along the bedding planes and has some stratified characteristics. The ore-rich body mainly occurs in the middle of the breccia belt, which is lenticular and gradually thins on both sides. The ore changes from blocky and brecciated to disseminated or veined. The Pb ore bodies mainly occur in the fragmentary dolomite in the second lithologic member, and the occurrence of ore bodies is consistent with the stratigraphic successions (Zhang et al., 2014). The footwall rock of the ore body is a moderately thin layer of carbon-bearing dolomitic limestone, while the top plate is a quartzose gravely carbonatite or gray−white calcium quartzose glutenite. The main mineralization zones are the northern and southern ore zones, in which the former has two ore-bearing beds in thickly bedded limestone or breccia. The lower ore zone is 750-m-long and 10−30-m-thick, with an average grade of 3.19% Pb and extremely low zinc contents. The associated elements are Cu, Co, Ag, and Ga. The upper layer is 400-m-long and 10−50-m-thick, with an average grade of 4.13% Pb. The southern ore zone is 200 m in length, with an average thickness of 7.74 m and an average Pb grade of 4.77%. The ore minerals are mainly granular galena, followed by chalcopyrite, pyrite, sphalerite, and trace As−Ni ores. The secondary minerals are malachite, covellite, chalcocite, cerusite, and ferrimanganic oxide. The gangue minerals are mainly dolomite and calcite. The ore structures are granular, coarse-grained, skeletal crystalline, metasomatic, disseminated, and vein structures. The main alteration of the surrounding rock occurred via dolomitization and silicification.

5.3. Sedimentary Mn deposit

The Mn ore belt in the Oytag Basin is ~100-km-long and 200−2000-m-wide from E−W, and Mn ore layers are found in the western part of the ore belt within ~60 km from Kalaate River to Orto Karnash. One large deposit has been discovered in Orto Karnash and two medium-sized deposits have been reported from Muhu and Malkansu (Zhang et al., 2018). The central strata of the Talong Gr. in the Qiaer-long Basin include the Zhuwuluke Mn deposit (Mao, 2019). The Tahaqi Fm. in the Duwa Basin contains the Duwa Mn deposit (Cui et al., 2013; Li, 2018).

Orto Karnash Mn deposit: The mine is located in the Muji Township, Aktao County (Fig. 1b, Table 2) and the tectonic background has been identified as a back-arc basin related to the northward subduction of Paleotethys Ocean (Gao et al., 2013). The outlying strata of the mine include the Middle Devonian Keziletao Fm., the Lower Carboniferous Wuluate Fm., and the Upper Carboniferous Kalaatehe Fm., as well as the undivided Lower Permian volcano-clastic sedimentary formations (Fig. 8). The sedimentary assemblage, which includes the Mn rock series (Kalaatehe Gr.) along the Late Paleozoic Malkansu rift basin, contains bioclastic to sandy limestone, argillaceous limestone, and carbonaceous−argillaceous limestone, from bottom to top, and can be divided into three lithologic members. The first member is a bioclastic limestone mainly composed of small calcite grains and bioclasts. The second member is a sandy limestone that is dominantly composed of fine limestone debris, fine sand, quartz grains and aggregates, and a small amount of clay minerals. It is light yellow−green, with a fine-grained sandstone and massive structure. The third member is an argillaceous limestone, with some argillaceous limestone that is intercalated with argillaceous rocks and tuffs, and can be further subdivided into three lithologic layers. The first lithologic layer is an argillaceous limestone intercalated with argillaceous rocks; the second is an Mn ore body, which is grayish black and has a muddy to microcrystalline structure or blocky structure; the third is a thin layer of carbonaceous−argillaceous limestone sandwiched with tuff (abundant strawberry pyrite). The nucleus of the Malcansu-complex anticline is a Permian stratum symmetrically distributed over two wings. The Kalaat River fault is developed to the north of the anticlinal axis, which corresponds to the boundary between the Lower Permian altered andesite and the third member of the Upper Carboniferous Kalaatehe Fm.

The mineralization belt is distributed along the Upper Carboniferous Kalaatehe Fm., which contains Mn in a narrow and long belt that is approximately 5-km-long and 1-km-wide.

Manganese ore occurs in the third member of the Upper Carboniferous Kalaatehe Fm., which contains carbonaceous–argillaceous limestone sandwiched with strips of fine-grained micrite. The stratified Mn carbonate ore body is strictly controlled by the strata of the Mn-bearing rocks, and its occurrence is basically consistent with that of the surrounding rocks. The spacing between the two main orebodies is ~20–40 m, and the thickness of the orebody varies greatly.

The true thickness of the singly controlled ore body is between 0.36 and 22.32 m, with an average thickness of 4.14 m and an average grade of 37.8% Mn. The main types of Mn ore are siderite, with occasional quartz–siderite, calcite–siderite, permanganite–siderite, and other ore types in local areas. Manganese carbonate ore has a dense massive structure with fine crystals and a uniform distribution. Part of the ore body can be seen in the original bedding or laminae. The ore minerals are mainly composed of Mn carbonate (siderite) and contain small amounts of Mn, siderite. Gangue minerals are mostly clays.

The surrounding rocks of the host ore are all carbonaceous–argillaceous limestone and the closer to the ore body, the higher the carbon content becomes, indicating that there is a close relationship between the sedimentary environment of the carbonaceous limestone and the formation of the Mn carbonate ore body. The mineralization stage can be roughly divided into the sedimentary–diagenetic, hydrothermal, and supergenic oxidation stages. A calcite–rhodonite vein developed in the contact position between the ore body and surrounding rock due to interlayer slippage, which suggests that the ore body was affected by hydrothermal activity. Supergenic oxidation is only manifested in a small amount of pyrolusite and hydromanganese in the fracture development of Mn carbonate minerals, and the state of primary depositional diagenesis and mineralization is still largely preserved. Metallogenesis was determined to occur in a marine volcanic hydrothermal Mn carbonate deposit (Zhang et al., 2018; Xu et al., 2018).

5.4. VMS deposits

5.4.1. Saluoyi Cu VMS deposit

The mining area is located in Bositantielieke Township, Wuqia County (Fig. 1b, Table 2). The outcropping layer is mainly the Lower Carboniferous Wuluate Gr. The lower strata are dominated by basic volcanic rocks, mainly pillows, blocks, and lens-shaped quartz tholeiites, and there is a small amount of basic volcanic breccia in the lower strata. The middle stratigraphic unit is mainly composed of pyroclastic, hydrothermal sedimentary, and a small amount of normally deposited carbonate rocks. The upper stratigraphic unit is mainly composed of pillow basalt, massive quartz tholeiite and neutral volcanic rocks (Jia et al., 1999). The hydrothermal sedimentary rocks primarily include flints, banded siliceous rocks, jasper, and tuffaceous brecciated carbonates (Sun et al., 2003). The ore-bearing volcanic rocks are petite porphyritic sedimentary rocks with hydrothermal sedimentary rocks. The rock are mainly basalt, basaltic andesite, andesite, and a small amount of felsic and carbonate rocks. The ore bodies occur in the monoclinal strata on the northern wing of the regional anticline, and some small extensional faults cross-cut the strata and ore bodies. In the northern periphery of the mine area are granite and quartz porphyries, which are coarse pyroclastic rocks that intrude into the top of the Wuluate Fm. in the form of walls or dikes.

The mineralization belt extends irregularly NW and its distribution is basically consistent with the stratigraphic strike, with a length of >1000 m and a width of 50–150 m. Copper mineralization is obvious in some parts of the belt and chalcopyrite, malachite, and azurite can be seen on the surface. The Xinjiang Geology and Mineral Bureau surveyed three ore bodies and five limonite bodies in the western ore section and one ore body and two limonite bodies in the eastern ore section. The ore body was produced near the contact between the lower and middle stratal units. This occurrence is consistent with the stratigraphic sequence. The ore body is inclined to the northwest by 50–75°. The largest single ore body is 220-m-long and 25-m-thick. The ore type is mainly a primary sulfide ore with a small number of oxidized orse. There are three main types of primary sulfide ore combinations—pyrite, pyrite–chalcopyrite, and pyrite–chalcopyrite–sphalerite ores. According to the ore structures, they can also be divided into three morphotypes: lumpy, banded, and veined. The content of the sulfide in ores ranges from 60 to 85%, mainly including pyrite, small amounts of chalcopyrite, sphalerite, and magnetite, and the gangue minerals are mainly quartz, chlorite, and a small amount of calcite, epidotes, and muscovite.

The main metallic minerals in the ores are pyrite, chalcopyrite, a small amount of sphalerite, porphyry, magnetite, and vitrinite. Secondary minerals are limonite, azurite, malachite, covellite, jarosite, and natural sulfur deposits. The gangue minerals are quartz, plagioclase, calcite, chlorite, and epidote. The ore structure mainly consists of allochthonous granular, subhedral granular, filling metasomatic granular, syngenetic, solid solution separation, residual, and cataclastic textures.

The ore structure is mainly sparsely disseminated, with dense disseminated, veined, and massive structures also observed, and a vein-like structure can be seen locally. The sparse disseminated structure is distributed on the bottom and top of each ore body and consists of disseminated pyrite. The dense disseminated structure is distributed in the middle and upper parts of the ore body or in the microfractures. The alteration of surrounding rocks mainly includes chloritization, pyritization, silicification, and carbonatization. There is obvious alteration in the surrounding rock, spilite and basic tuff. From the ore body to the surrounding rock, the sequence was: strong pyritization → silicification → carbonatization → chloritization → chloritization–pyritization.

5.4.2. Aktash Cu VMS deposit

The Aktash Cu VMS mining area is located in Oytag Township, Akto County (Fig. 1b, Table 2). The Carboniferous System above the outcrop is dominant, followed by the Jixian System in the Mesoproterozoic and Quaternary System (Fig. 9). The Jixian System is an extrinsic nappe of the basin that thrusts against the Upper Carboniferous strata, lithologically consisting of grayish white to white massive marble interbedded with greenish chlorite schist, with a thickness >240 m. The Upper Carboniferous Tahaqi Fm. is a set of marine sedimentary facies, including crystalline limestone and micrite, with marine fossils, that overlies the stratigraphic contact with the Keziliqiman Fm. The latter are widely exposed in mining areas as a set of marine volcanic sedimentary rock series, whose lithology mainly consists of basalt, rhyolite, rhyolitic tuff, laminated limestone, marl, and sandstone, the thickness of which exceeds 400 m. The formation is further divided into four lithologic sections: (1) metamorphosed sandstone, crystalline limestone, and marl; (2) medium basic tuff and keratophyres interspersed with fine jasper, with thin layers of crystalline limestone and strong pyritization and silicification in the upper part; (3) quartz keratophyre and quartz keratophyre tuffs, most of which have been metamorphosed into sericite and sericulite schist, and the pyrite content gradually increases from the bottom to the top. Massive sulfide ore bodies occur at the top of the quartz keratophyre tuff layer, and local ore bodies are covered by siliceous rocks. (4) Keratophyres and medium basic tuffs interspersed with fine blue rocks and a thin layer of crystalline limestone, wherein the tuff has metamorphosed into a greenschist. The Jixian System outcrops as a nappe, thrusting over the Upper Carboniferous, strengthening is stratification, and forming some compression—torsion and normal faults.

The ore bodies are layered or tabular in quartz keratophyric tuffs or quartz keratophyres at the top of the third member of the Keziliqiman Fm. Oxidation zones are composed of jarosite and limonite on the surface, and local areas are produced in the form of an iron cap. The ore layer is in a gradual transition with the floor rock and abrupt contact with the roof. This occurrence is consistent with the surrounding rock. The ore body has an obvious double-layer structure, the upper part is a massive sulfide layer and the lower part is a strip-disseminated sulfide layer. The ore consists of a lower disseminated strip ore and an upper massive or dense disseminated ore. Six ore bodies were found with a Cu grade of 0.63—4.87% and sulfur grade of ~8.49—48.00%.

The maximum length of a single ore body is 1600 m and they are approximately 8-m-thick. The ore type is mainly a primary sulfide ore with a small amount of oxide ore. The primary sulfide ore can be further divided into massive and veined sulfide ores. The former has a massive and dense structure, and the metallic minerals mainly include pyrite, a small amount of chalcopyrite, trace sphalerite and tetrahedrite, while the gangue minerals are mainly quartz and a small amount of sericite, muscovite, and calcite. The latter has a disseminated structure and the metallic minerals are mainly composed of pyrite, a small amount of chalcopyrite, and trace sphalerite. Gangue minerals mainly include quartz, sericite, plagioclase, and a small amount of chlorite, tetrahedrite, epidote, and calcite, and occasionally gypsum.

The ore minerals are mainly pyrite and chalcopyrite, a small amount of sphalerite, Zn-bearing tetrahedrite, Cu-porphyry, and occasionally galena and arsenopyrite. Gangue minerals are quartz, sericite, calcite, chlorite, and plagioclase. Secondary minerals are malachite, covellite, limonite, natural sulfur, and jarosite. The ore structure is mainly blocky, strip-like, disseminated, veined, and brecciated and includes allochthonous granular, semi-autochthonous granular, interstitial, conjunction edge, sieve, inclusion, and directional crushing structures. The surrounding rocks are mainly altered acidic tuffs and quartz keratophyric tuffs, and the alteration types are silicification, sericitization, chloritization, and carbonatization. The Aktash deposit type is similar to the VMS of the back-arc hydrothermal system (Zhang et al., 2020).

5.5. Magmatic hydrothermal deposit

The Abalieke Cu—Ni sulfide deposit is located in Sangzhu Township, Pishan County (Fig. 1b, Table 2). The outcropping layer of the mining area is the Carboniferous Kurliang Gr. and the upper formation is mainly composed of medium—thickly bedded, medium-grained, gray arkose—quartz sandstone, quartz siltstone interspersed with arkosic and lithic quartz sandstone, and chloride feldspathic basalt. The lithology of the lower formation is a gray—green conglomerate, glutenite, carbonaceous arkose—quartz sandstone, siltstone, and bioclastic siltstone. Among them, gabbro and diabase dikes are developed in the upper strata of the Kuerliang Gr. and most of the rocks are hypabyssal, and the distribution of basic dikes is mostly controlled by the structure. In the periphery of the mining area, Permian biotite—monzonitic granite intruded into the Kuerliang Gr. and basal, ultrabasic rocks with tectonic lenses were developed intermittently along the Kuerliang—Tuoman fault (Fig. 10).

Based on the available data (Qi et al., 2005; Hou et al., 2007) three Cu-bearing gabbro veins (Nos. 5, 6, and 7) have been found. Copper mineralization is mainly concentrated in the footwall of the intrusion and rocks have been strongly broken and altered. The basal dikes are veined and convex in shape, which are distinct from the surrounding rock boundaries. The surrounding rock is a quartz siltstone with feldspar—lithic quartz sandstone/graywacke, and basalt. The No. 5 ore body is ~20 m in length, 1 m in width, and 4 m in band alternation. It slopes steeply to the southeast by 120°. The No. 6 ore body is ~200-m-long and 10-m-wide, and slopes steeply to the southeast by 135°. The No. 7 ore body is approximately 1200-m-long and 27-m-wide, with a slope of 100°. The ore minerals are mainly chalcopyrite, porphyry, and pyrite, and chalcopyrite has been converted into malachite and azurite by secondary diagenesis. Ores form other granular, intrusive, and blocky structures. The alteration types are mainly silicification and limonitization, associated with gold, silver, chromium, nickel, platinum, and palladium mineralization (Cu grade: No. 5 = 0.28%; No. 6 = 0.45%; No. 7 = 0.41%; Ni: 427—940 ppm, with an average of 565 ppm) (Qi et al., 2005; Hou et al., 2007).

Genetic analysis: The mineralized Cu ore bodies occur directly in the gabbroic dike, indicating that the metallogenic materials originated from deep magmatic hydrothermal fluids. The intrusion of the gabbro dikes into the Upper Kurliang Gr.

suggests that it formed later than the Late Carboniferous and represents the product of the tectonic rifting in the basin. However, the Late Permian Heiyun monzogranite intruded during the tectonic transition period of the Kurliang Gr. It is concluded that the metallogenic epoch of the Abalek Cu deposit may have been the Early Permian and the genesis was magmatic fusion.

5.6. Tectonic hydrothermal (orogenic) deposits

5.6.1. Kalayasikake Pb−Cu deposit

The Kalayasikake Pb−Cu mining area is located in Tamu Village, Keziletao Township, Aktao County (Fig. 1b, Table 2). The ore body occurs at the fault contact between the Upper Devonian Qizilafu Fm. and the Lower Carboniferous Kelitake Fm., with some structural breccia and foliated limestone (Fig. 11a). The footwall of the fault is composed of a purplish red sandstone and there is a thin layer of pebbled calcareous quartz sandstone on the side of the main fault that is approximately 20-cm-thick. Near the ore body is a light gray, medium-grained calcareous quartz sandstone that is approximately 2-m-thick. The proximal section of the upper wall of the fault is a dark gray dolomitic limestone and the distal section is a cataclastic dolomitic limestone (Fig. 11b). Mineralization is mainly concentrated in the dark gray dolomitic limestone and partly in the calcareous quartz sandstone. Mineralization is zoned, with Pb being concentrated in carbonate rocks on the upper plate of the fault (Fig. 11c), Zn in the dolomitic limestone further up, and Cu in the calcareous quartz sandstone. The ore-bearing belt is ~4000-m-long and 40−100-m -ide, with two Pb ore bodies and two Cu bodies scattered intermittently.

The Pb ore body is produced in the gray dolomite of the second member of the Kalabaxitage Fm. and extends up to 50 m. The ore body is 9.37-m-thick, with an average grade of 3.03% Pb and 0.35% Zn. Due to the superimposed late-stage mineralization, the local section has been enriched and fills the galena and sphalerite fine vein along the fissure and intersects the bedding. The main metallic minerals are galena, followed by chalcopyrite and sphalerite. Brecciated, porphyritic, veined, and disseminated Pb−Zn ore were the most common. The main ore type is an impregnated Pb ore. A small amount of galena occurs in the form of fine, dense lumps. Some galena occurs in calcareous quartz sandstone and is cemented by quartz. Sphalerite with biological residues or colloidal ring structures are found in fine, dense bulk ore. The Cu ore body is produced from calabash dolomite with thin silty shale in the first member of the Kalabaxitage Fm. It extends over 80 m, with a horizontal thickness of 3.63 m and an average grade of 0.55% Cu. The main metallic minerals are galena, sphalerite, pyrite, and chalcopyrite, and the secondary minerals are malachite, covellite, cyanite, cobaltite, and Fe−Mn oxides (Fig. 8i, j).

5.6.2. South Akazi tectonically altered Cu deposit

The South Akazi Cu mining area is located in Xihexiu Township, Yecheng County (Fig. 1b, Table 2). The outcropping strata include the Middle Proterozoic Kulangnagu Gr. and the Yishake Gr. The former assemblage includes biotite−quartz schist, anorthosite−quartz schist, anorthosite−amphibolite schist, anorthosite−quartz schist with tremolite feldspar, and minimal marble. The latter includes blocky basalt, lens-shaped basalt, and pillow basalts (Fig. 10). The mineralization zone is located in feldspars and the fault contact between them and extends NW in space. The length is > 300 m, the width of the exposure is 24−30 m, and the angle of occurrence is 220° ∠ 55°.

The mineralization zone is filled with altered granulite and strongly deformed anorthosite−black cloudy quartz schist. The shape and occurrence of the ore body are subject to the mineralization zone and generally manifested as lenticular, unequally sized, structurally broken, and altered blocks. The ore is fine-grained and impregnated, containing >0.2% Cu and associated Pb. The ore minerals are mainly chalcopyrite, pyrite (limonite), and gangue minerals include sericite, potassium feldspar, plagioclase, and quartz. The ore has fine disseminated and massive structures. The alteration of surrounding rock is mainly silicification, potassium feldspathization, natrification, pyritization, and sericitization, and the oxidized minerals are mainly fine disseminated limonites. Mineralization occurred in tectonically broken altered rocks and the mineralization age is presumed to coincide with the tectonic transition period (Middle Permian) of the basin.

6. Discussion

6.1. Relationship between back-arc extensional basins and Paleo-Tethys convergence

According to studies on the regional geological structures (Li et al., 1996; Xiao et al., 2005), the jumbled tectonic zone along the Kangxiwa−Mazha−Waqia line represents a Paleotethyan suture zone (Fig. 12). The Paleotethyan convergence between the Tianshuihai Block and the West Kunlun Block probably began in the Middle Devonian (Cheng and Zhang, 2000), corresponding to granites produced by the marginal arc environment on both sides of the Kangxiwa suture zone (388−324 Ma, Li et al., 2006; Kang et al., 2015) as well as the sedimentary response of the foreland basin in the Early and Middle Devonian (Chen et al., 2008). The main developmental stage of arc magmatism occurred during the Carboniferous−Early Permian. The mountains in the Andalitake and Agazi areas developed antero-type granites and quartz−mica diorite as well as related sedimentary rocks under a continental arc environment (Henan Institute of the Geological Survey, 2006; Kang et al., 2015). The acidic intrusive bodies of the Middle Permian are decomposed into banded ones, suggesting that the extensional structure begins to turn, due to the complex depositional volcanic system during the Carboniferous and Permian. The geological events associated with the closure of the Paleotethys Ocean include a large amount of exposed Indochinese S-type granite (258−241 Ma, Gao et al., 2013; Kang et al., 2015), along with the overall uplift of the West Kunlun Block resulting from the compressed tectonic environment. This is evident in the fact that the Triassic Sailiyadaban Fm. overlying the tectonic melangite belt belongs to an intermountain molar-rock formation (Chen et al., 2010). Therefore, it can be inferred that the subduction of Kangxiwa oceanic crust was initiated in the Middle Devonian and the development period occurred in the Early Carboniferous−Early Permian, while the formation of the tectonic belt occurred in the Late Permian−Early Triassic.

In the extensional environment of the back-arc basin, the base exhibited a relatively stable intracontinental environment at the end of the Early Paleozoic (Chen et al., 2010), and only began to develop a set of transgressive sequences in the Middle Devonian, including the Middle−Late Devonian Akebaximazhaer and Keziletao formations and clastic and carbonate rocks from the Qizilafu Fm. that are interbedded with basalts and pyroclastic rocks; its characteristics, and sedimentary rock chemical combination consistently show a tensional environment (Table 1). During the Late Devonian, the sedimentary basin was separated into two parts by the action of the Tiekelike fault (also called the Yetimusu fault in the western section). The southern parts of the uplift belt consist of a series of back-arc basins, mainly including the Oytag, Kushanhe, Qiaer-long, and Kurliang basins (Fig. 1). The igneous activity related to these sedimentary basins differs over with time and space; large-scale activity on the western side occurred in the Early Carboniferous and includes basic−acidic volcanic and intrusive rocks, and local ultrabasic rocks (Oytag Basin). To the east, there are small-scale Late Carboniferous−Early Permian volcanic rocks and intrusive rocks (Kurliang Basin). On the northern side of the fault uplift, the Tamu−Kalangu and Duwa basins were formed and Carboniferous−Permian sedimentary strata overlay the Middle−Late Devonian (Fig. 4).

During the Permian−Early Triassic, the extensional structure began to twist and entered the transformation stage. The main evidence of this activity includes the lack of a Permian series in back-arc deposits as well as the fact that few residues exist in the Qiaer-long Basin's Permian series, in the Daliyueer and Kesimake formations, which unconformably overlap the Tajinaiqikedaban Fm. This indicates the complete shutdown of the back-arc basin by the Late Permian. In the Tamu−Kalangu Basin, the basic rocks of the Middle Permian Qipan Fm. belong to continental alkaline basalts (Liu et al., 2003), while the red sandstone of the Upper Permian Daliyueer Fm. represents a continental deposit. The main identifying marks of the regional tectonic transition during the Triassic include the absence of Triassic deposits across a large area, the exposure of marine−continental coal-bearing clastic rocks in the Late Triassic Huoerxa Fm. over a very small range, and the development of K-rich volcanic rocks in continental fault basins.

From the comparison, the arc magmatism and tectonic evolution of the Kangxiwa−Mazha−Waqia fault were determined to correspond to the evolution of the back-arc extensional tectonic environment of the basin (Fig. 12). The subduction of the West Kunlun Block under the southern margin of the Tarim massif has been continuing since the Middle Devonian in the Kangxiwa subduction zone (Fig. 3a). In the resulting Kangxiwa−Mazha tectonic mélange belt and the back-arc basin within the Oytag−Kurliang Basin (Yang, 1994), the former developed an epicontinental arc environment with a tonalite−trondhjemite−granodiorite (TTG) rock series, characteristic of plagioclase granite and tonalite (Li et al., 2006; Kang et al., 2015), while the latter developed with trondhjemite and tonalite, characteristic of back-arc basins (Ji et al., 2018).

The geological events associated with the closure of the Paleotethys Ocean include a large number of exposed Indosinian S-type granites (Gao et al., 2013; Kang et al., 2015), and the back-arc basin corresponds to closed magmatic activities (Wang et al., 2013; Lu et al., 2013; Ji et al., 2013; Hou et al., 2007). The overall uplift of the western Kunlun region was caused by compression. In addition, there were three stages of tholeiite activity during the sediment deposition in the Tamu−Kalangu Basin, suggesting that they were caused by the upwelling of the asthenosphere resulting from subduction. There are multiple regular occurrences of sedimentary processes in the basin's sequence structure, namely, the presence of huge, thick clastic rock, wherein the upper section consists of clastic rocks, carbonate rocks, and brecciated limestone interbedded with bioclastic limestone and carbonaceous shale. This sequence structure is similar to those found in Australia's northeastern Mt. Isa Basin (far-field continental back-arc basin, Betts et al., 2003). Therefore, it can be speculated that the remote effect of the Kangxiwa (Paleotethyan) subduction zone, manifested as the upwelling of the asthenosphere, led to the stretching and thinning of the crust, and hence the formation of the Oytag−Kurliang back-arc and the Tamu−Kalangu far-field continental back-arc basins, respectively. Their structural patterns show the entire sag superimposed with local rifting early in the Hercynian orogeny, and they were transformed into fold belts via basin−mountain transformation later during this orogenic period.

6.2. Distribution of metallogenic types and environments

Although the Oytag−Kurliang back-arc basin and the Tamu−Kalangu back-arc continental basin both formed in a back-arc extensional tectonic environment. The corresponding metallogenic types differ due to the differences in the sedimentary and tectonic characteristics of these basins. In the Oytag Basin, the Early Carboniferous basic volcanic rocks erupted to form the VMS Cu deposit (Saluoyi), the Late Carboniferous intermediate acidic volcanic rocks erupted to form another VMS Cu deposit (Aktash), which is related to hydrothermal deposition and the Orto Karnash sedimentary Mn deposit in the Carboniferous marl limestone of the Kalaatehe Fm. at the end of the Late Carboniferous.

In the Kushanhe Basin, the Tugenmansu sedimentary rock-hosted stratiform Cu deposit is formed in the red sandstone in the upper part of the Middle Devonian Keziletao Fm. In the Qiaer-long Basin, the main Uruk sedimentary Mn deposit is formed in the black argillaceous shale with Fe−Mn micrite. In the Kurliang Basin, the magmatic hydrothermal Abalek Cu deposit occurs in the basic dike intruding into the Kurliang Gr (Qi et al., 2005; Hou et al., 2007). In the Tamu−Kalangu basin, the Fe-rich sedimentary rock-hosted stratiform Cu deposit formed in the red sandstone intercalated limestone layer in the upper part of the Middle Devonian Keziletao Fm., and the carboniferous brecciated dolomitic rock in the Lower Carboniferous Kalabaxitage Fm. forms the carbonate rock-controlled Pb−Zn deposit (Tamu and Kalangu).

In the Duwa Basin (Cui et al., 2013), sandy gravel Cu deposits (Mangsha, Pishan County) are produced in the sandstone (Qizilafu Fm.). The bioclastic calcarenite of the Upper Carboniferous Tahaqi Fm. formed the sedimentary Mn deposits (South Duwa) and a sandstone Cu deposit (South Buqong) was formed in the purplish red glutenite of the Middle Permian Duwa Fm. The genetic types of the deposits in the back-arc extensional tectonic environment can be divided into sedimentary and magmatic hydrothermal types. In addition, during the tectonic transition of the basin during the Middle Permian−Early Triassic, folding and faulting induced hydrothermal activity to form tectonic hydrothermal deposits. For example, the Kalayasikake Zn−Pb deposit occurs in purplish red clastic rocks and in the lower rocks of the Upper Devonian Qizilafu Fm. Additionally, the Kalayasikake Zn−Pb deposit occurs in the interlayer fault zone, where the purple clastic rocks of the Qizaraf Fm. meet the limestone of the Kelitake Fm.; its mineralization type is identified as a tectonic hydrothermal deposit. The South Akazi Cu deposit occurs in the tectonically altered rocks of the fault contact zone between the Kulangnagu Gr. and the Ishake Gr. The mineralization type is recognized as tectonic hydrothermal and the mineralization era is presumed to be the same as the basin tectonic transition period in the Middle Permian.

In the study area, sedimentary-type ore deposits can be subdivided into sedimentary rock-hosted stratiform Cu deposits, carbonate Pb−Zn deposits, and sedimentary Mn deposits. Even though these deposits formed in different sedimentary environments, it is believed that they indicate an oxidizing environment, which created a reducing depositional, for the following reasons: (1) the sedimentary rock-hosted stratiform Cu deposits of the underlying sediments, the large amount of oxidized purple sandstone just near the posterior of the ore-bearing bed, which changed into a gray sandy shale and carbonaceous limestone; (2) the ore-bearing layer of the carbonate strata-controlled Pb−Zn deposit is located at the stratigraphic interface of rapidly changing clastic to carbonate rocks, and the upper rock assemblage is mostly massive dolomite and carbonaceous dolomite; (3) the clastic and carbonate rocks in the ore-bearing beds of the Mn deposit are interbedded with carbonaceous shale and bioclastic limestone. Among them, local zones with huge sedimentary thicknesses suggest that they are in secondary depression or restricted basins, and carbonaceous mudstones or carbonaceous limestones in ore-bearing sediments and overlying strata indicate a reductive depositional environment (Feng et al., 2009; Zhang et al., 2013). Therefore, these ore-bearing sediments have the sedimentary characteristics of anoxic sedimentary basins.

Magmatic hydrothermal deposits are mainly distributed in the Oytag−Kurliang back-arc basin and, according to the metallogenic tectonic environment, can be subdivided into rift basin and closed-basin magmatic hydrothermal deposits. The former mainly includes the Saluoyi Cu deposit within the Early Carboniferous basic volcanic rocks, the Aktash Cu deposit within Late Carboniferous moderately acidic volcanic rocks, and the Abalieke Cu and Ni-sulfide deposits within the Late Carboniferous to Early Permian basic dike. The latter mainly includes granite and granite porphyry that intruded into basinal strata in the Late Hercynian period, indicating the tectonic environment of the closed period of the basin. Magmatic hydrothermal Cu deposits related to the monzogranite porphyry have been found in the Xiahebasikang area of the Kurliang Basin.

Structurally controlled hydrothermal deposits generally refer to deposits associated with tectonic activity. In a narrow sense, this study is limited to a hydrothermal deposit formed during the sedimentary construction of a basin during a late stage of folding and faulting, and can signify the tectonic environment in the basin−mountain transformation process. In the study area, there are mainly Kalaysikake Pb−Cu deposits in the Tamu−Kalangu basin and South Akazi Cu deposit in the Kurliang Basin. The mineralization range of the former is limited to the ore-bearing layer and the ore body occurs in veins or cysts in the fault zone that crosscuts local strata, indicating that the mineralization is not only restricted by the tectonic activity, but also closely related to the ore-bearing strata in the basin. A possible explanation for this is that tectonic movement caused the hydrothermal fluid of metallogenic elements in the strata to migrate and mineralize along fractures (Yang, 2009), and its mineralization is similar to that of orogenic Pb−Zn deposits (e.g., Chen et al., 2000). The latter group is located in accordance with the fault contact between the Yishake Gr. basalt and Kulangnagu Gr. metamorphic rock; the mineralization of Cu occurs at the side of the basalt. Fine-grained disseminated chalcopyrite, pyrite, and galena fill in the structure of the metamorphic rock cranny. This indicates that the migration of hydrothermal fluid occurred along the fractures and metamorphic basalts (Yang, 2009). Its mineralization was therefore controlled by the fault resulting from the basin-to-mountain tectonic transition.

6.3. Model of regional tectonic mineralization

Most mineralization in the study area can be divided into the Hercynian and Indosinian orogenic periods through a detailed study of the characteristics of the deposits. Hercynian-aged syngenetic sedimentary and magmatic hydrothermal deposits occur in rifts basins; the metallogenic age range is 337−333 Ma (Zhang et al., 2014, 2018, 2020). Indosinian mineralization mainly includes magmatic hydrothermal and tectonic hydrothermal deposits that formed in a closed basin, for which the mineralization age range is 245−206 Ma (Zhang et al., 2014).

The results of the study on the source of metallogenic materials of the deposits indicate that the ore-forming fluids of the Pb−Zn deposit in the Tamu−Kalangu Basin had multiple sources (Wang et al., 2001; Kuang et al., 2002), which may reflect the multi-stage mineralization process (Feng et al., 2009). Sulfur isotopic records also indicate that there may have been two types of ore-bearing hydrothermal fluids that had different properties during mineralization (You et al., 2011). The Pb isotopic composition reflects that the ore-forming materials originated from the basement of ore-bearing rocks (Kuang et al., 2002; Shen et al., 2012). Based on these findings, the following regional tectonic metallogenic model is proposed (Fig. 12). First, during the Devonian to Early Permian, a back-arc extension environment developed because the Paleotethys oceanic plate was subducted, causing asthenospheric upwelling and thinning of the crust to form an extensional back-arc basin and mainland far-field back-arc basin environments. During deposition, hydrothermal sedimentary and sandy shale deposits were formed due to the superposition of a local sag (secondary basin) and anoxic environment caused by syngenetic faults. Volcanogenic massive sulfide and magmatic hydrothermal deposits were formed during the rifting period of the basin (Fig. 12a).

The Middle Permian−Early Triassic was the transition period of back arc extensional environment and basin tectonic transformation. Due to the complete closure of the Paleotethyan suture zone, the region was transformed into a compressional environment, which resulted in a decrease in mantle heat flow and asthenospheric subsidence, and the thickening and uplift of the crust. At this time, the basin structure was transformed into fold belts, forming tectonic hydrothermal deposits and magmatic hydrothermal deposits in the closed phase of the basin under the action of folding and faulting (Fig. 12b). During the Triassic regional orogenic stage, the intermontane basin was formed by the transverse tensile of orogenic belt, and the longitudinal compaction formed fold structures. This changed the original spatial distribution of the ore-bearing layer, making the ore body in the fold collapse and the extrusions change their forms. Therefore, veined ore bodies formed by late hydrothermal activities were superimposed on the layered ore bodies.

7. Conclusions

Subduction and closure of the Paleotethys Ocean dominated the tectonic evolution of the West Kunlun Mountains, forming the Kangxiwa−Mazha−Waqia arc magmatic belt, and resulting in formation of the basin belt under the extensional setting in northern West Kunlun Mountains, including the Oytag−Kurliang back-arc basin and the Tamu−Kalangu far-field continental back-arc basin.

The evolution of the basins began in the Middle Devonian and ended in the Late Permian, during which the Middle Devonian−Early Permian marked the period of extension. Hydrothermal sedimentary deposits and sedimentary rock-hosted deposits were formed in the hypoxic environment of the local secondary basin, and VMS and magmatic hydrothermal deposits were formed via the magmatic hydrothermal activity of basinal rifting. Subsequently, in the Middle Permian−Early Triassic, tectonic hydrothermal and magmatic hydrothermal deposits formed, and were transformed by regional uplift or orogenesis in the Triassic. Therefore, the evolution of the extensional tectonic basin in the Late Paleozoic corresponds to the subduction−collision of the Kangxiwa tectonic belt. During the extension and closure process, mineralization related to primary deposition could be divided into sedimentary, magmatic hydrothermal and tectonic-hydrothermal deposits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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