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Massive Sulphide Deposits Related to the Volcano-Passive Continental Margin in the Altay Region

WANG Jingbin, DENG Jiniu, ZHANG Jinhong and QIN Kezhang

Beijing Institute of Geology for Mineral Resources, State Bureau of Nonferrous Metal Industry, Andingmenwai, Beijing 100012

Abstract The Devonian volcano-passive continental margin in southern Altay is a significant volcanogenic massive sulphide metallogenic belt. Acidic volcanism has been dominant on the inner side of the volcano-passive continental margin, i.e., near the old land, resulting in a Pb-Zn metallogenic sub-belt, in which the ore deposits are hosted by sedimentary rocks in volcanic series, as represented by the large Koktal Pb-Zn deposits. In the central part of the margin far away from the old land, bimodal volcanic formations are well developed, forming volcanics-hosted Cu-Zn metallogenic sub-belts, e.g., the large-scale Ashele Cu-Zn deposit. The Qiaoxiahala sub-belt on the outer side of the margin near the ocean ridge is located at the spreading central trough, where ophiolite suites are developed. This type of deposits is rich in gold and copper, similar to the Cyprus-type Fe-Cu-Au metallogenic sub-belt in metallogenic environment (represented by the Qiaoxiahala medium-scale Fe-Cu-Au deposit). From the old land to the ocean, the mineralizing age becomes younger, i.e., from Early Devonian→Early and Middle Devonian→Middle Devonian, forming a complete metallogenic zoning series on the volcano-passive continental margin. Comparative studies show that the massive sulphide deposits distributed on the volcano-passive continental margin are different from those formed under a plate subduction regime and oceanic ridge environment; the former have their unique features and wide distributions, representing a new type of volcanogenic massive sulphide deposits—the Altay type.

Key words: volcano-passive continental margin, massive sulphide deposit, Altay type, Xinjiang

He Guoqi et al. (1994), in their studies of the Palaeozoic orogens of Central Asia, especially northern China including Xinjiang, have confirmed the existence of an independent structural element—the volcanics-type (magmatic type) passive continental margin, which is a product of the extensional transitional crust stage during the development of the Palaeozoic crust. And they further suggested a 5-stage crustal evolution model of the Palaeozoic interconti-nental orogenic belt, i.e. basement continental crust→ extensional transitional crust→ oceanic crust→ compressive transitional crust→ new continental crust. Taking the Devonian volcanic rock belt in the southern Altay Mountains as an example, the authors aim to explain that the volcano-passive continental margin is an important environment for the occurrence of volcanogenic massive sulphide deposits with unique metallogenic features of their own.

1 Basic Features of the Altay Volcano-Passive Continental Margin

The Devonian volcanic rock belt in the southern Altay Mountains lies at the southern margin of the Siberian plate, starting from the Bazhai fault in the north and ending at the Ertix fault in the south. It is over 360 km in length and 30–70 km in width, trending northwest in general. It is an important metallogenic belt for massive sulphide deposits in Xinjiang, in which there are a number of large-scale mineral deposits such as the Ashele Cu-Zn deposit and Koktal Pb-Zn deposit (Fig. 1)

1.1 Basement rocks of the volcanic sedimentary basin

The basement of the volcanic-sedimentary basin in the area is formed of two metamorphic rock series. One is the Meso-Neoproterozoic crystalline basement, consisting of high-grade metamorphic rocks such as gneiss, granulite and migmatite, mainly distributed NW of Wuqiagou (Fuyun County) and Qongkur township, and scattered in the Ertix compressional belt. The other is the folded basement formed in the Caledonian, consisting of a greenschist-facies metamorphic series dominated by Palaeozoic Cambro-Silurian schist and metasiltstone, mainly distributed in the Caledonian

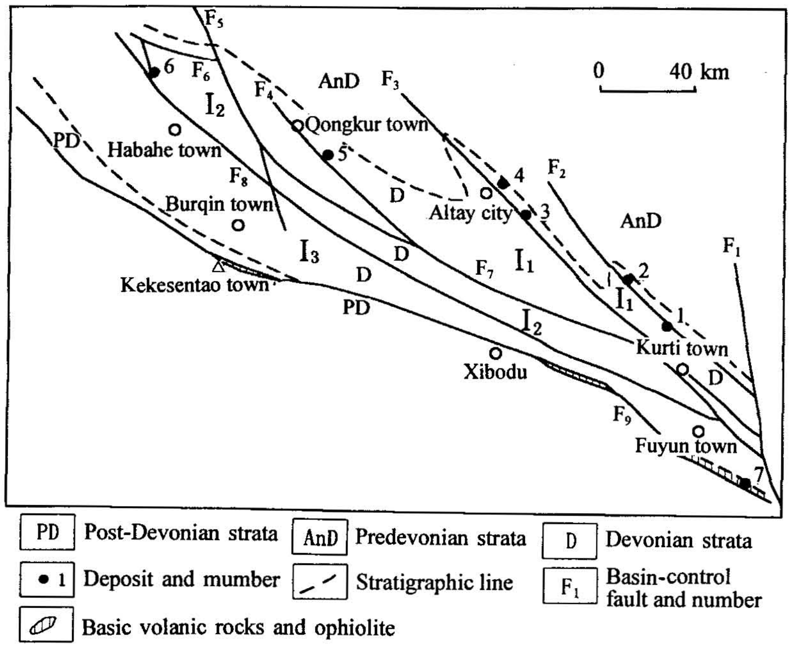

Fig. 1. Devonian metallogenic belt in southern Altay.

1. Koktal Pb-Zn deposit; 2. Mengku Fe deposit; 3. Abagong Pb-Zn-Fe deposit; 4. Tiemurte Cu-Pb-Zn deposit; 5. Keyinbulak Zn-Cu deposit; 6 Ashele Cu-Zn deposit; 7. Qiaoxiahala Cu-Au-Fe deposit; I_1—Koktal Pb-Zn sub-belt; I_2—Ashele Cu-Zn sub-belt; I_3—Cu-Au-Fe sub-belt; F_1—Kalaxian'ger fault; F_2—Bazhai fault; F_3—Abagong fault; F_4—Qongkur fault; F_5—Habahe fault; F_6—Bielietike fault; F_7—Kezijiaer fault; F_8—Markakuli-Kuertix fault; F_9—Ertix fault.

uplifted area to the north of the volcanic-sedimentary basin.

The Devonian System in this area overlies the Silurian System ($S_{2\text{-}3}k$) in faulted contact, and all the sedimentary sequences in the whole basin are marine deposits lacking in continental mollasic formations. This indicates that it was not formed in the interior of the continent but in a faulted continental margin environment.

1.2 Basic features of the volcanic rock belt

The volcanic rock belt in southern Altay consists of constrained volcanic sedimentary basins such as Maizi, Kelang, Qongkur and Ashele, which turned into synclinal (synclinorium) structures in the late-stage folding orogeny. The volcanic rocks in the belt have the following features. (1) Bimodal or para-bimodal type volcanic rocks are well developed. In the Ashele area, the ore-bearing Mid-Lower Devonian Ashele Formation is dominated by Na-rich dacitic volcanic rocks in the early stage and spilite in the late stage, resulting in typical bimodal volcanic formations; in the Kuerti area, there occur inter-bedded volcanic rocks formed from alternated eruptions of acid and basic rocks. Acid volcanic rocks predominate in the Maizi-Chonghuer area, with the basic: intermediate: acid ratio about 10:3:40, showing a parabimodal distribution. In short, andesite occurring in large amount under an island-arc or compressive transitional crust environment is not well developed in this area, and only occurs in lenticular interbeds. (2) The volcanic rocks are characterized by a rich alkali content; alkaline basalts and high-K tholeiites are well developed in the belt, obviously differing from the Andean continental-margin volcanic arc and the island-arc volcanic rocks of Japan (Han et al., 1991). (3) The REE distribution patterns are all of the LREE-enriched type. Obvious negative Eu anomalies are found in the acid volcanic rocks; and various projection diagrams of petrochemistry and trace elements all indicate a continental-margin environment (Wang et al., 1998).

1.3 Ophiolitic mélange belt in the neighbouring areas

In the 150 km-wide zone from southern Altay to northern Junggar there are three ophiolite belts: the Ertix, Aermantai (-Honggulelleng) and Kelamaili belts. The Ertix belt goes along the Ertix large fault, formed of serpentinized peridotite, gabbro, pillow basalt, radiolarian silicalite and trondhjemite around the Laoshankou-Qiaoxiahala-Kekesentao area. The radiolaria is dated as the Early Devonian, the trondhjemite is aged 390 Ma with the K-Ar dating (Chen et al., 1995), and the pillow basalt occurs in the middle and lower parts of the Mid-Devonian Beitashan Formation. therefore this ophiolite belt should have been formed in the Early-Middle Devonian. The Aermantai belt consists of several tens of ultrabasic rock bodies containing podiform chromite, intercalated with minor basic volcanic rocks and radiolarian silicalite as well as Early-Devonian olistostrome rocks (He et al., 1990). The Kelamaili belt is overlain unconformably by the Lower Carboniferous Nanmingshui Formation. The whole rock K-Ar ages of the gabbroic cumulate are

388–392 Ma.

It can thus be seen that as viewed from the regional tectonic setting the Early-Middle Devonian was the hemera of the ocean basin extension, prior to a subduction-compression regime. Besides, pillow basalts are found in the Mid-Devonian Altayzhen Formation in Luotuofeng, Altay City; the Dakalasu gabbro dated 397 Ma by the Sm-Nd method, all of which are evidence for the extensional regime this area was subjected to at that time. In other words, the volcanic rock belt of southern Altay was formed in the extension-transitional crust stage. During the extensional period, the continental margins were transformed by the tectonomagmatic action and the crust was broken and thinned, resulting in increasing permeability and decreasing maturity. Therefore it was a volcano-passive continental margin unrelated to subduction. After the Middle Devonian, this area gradually turned into a compressional regime, but sedimentary strata after the Middle Devonian are absent in the Maizi-Chonghuer area.

2 Massive Sulphide Deposits Related to the Volcano-Passive Continental Margin Environment

2.1 Division of metallogenic sub-belts

The southern Altay volcanic rock belt can be divided into three sub-belts according to the volcanic formation and metallogenic features. The northeast side consists of three constrained volcano-sedimentary basins, Maizi, Kelang and Chonghuer, forming the Maizi-Chonghuer structure-formation belt. The exposed strata are the Lower Devonian Kangbutiebao Formation (D_1k) and Mid-Devonian Altayzhen Formation (D_2a) and the former can be subdivided into the upper and lower subformations. In the Maizi basin, the lower subformation, which consists of a suite of spilite –quartz keratophyre and other Na-rich pyroclastic rocks, lava–meta-arenaceous-metapelitic rocks–carbonate rocks formation, about 3000 m thick, is the ore-bearing horizon of Fe, in which there occurs the large-scale Mengku volcanic rock-type Fe deposit; the upper subformation, consisting of a suite of metamorphic calc-alkaline dacitic and rhyolitic volcanic rocks–arenaceous and pelitic rocks–carbonate rocks formation, c. 4600 m in thickness, is the ore-bearing horizon for polymetals Pb, Zn etc. The lithologic and metallogenic features of the Kang-butiebao Formation are basically identical in the Kelang and Chonghuer basins, only the lower subformation is poorly developed, and iron mineralization is not well developed. The Altayzhen Formation, consisting mainly of meta-arenaceous-metapelitic rocks–carbonate rocks, intercalated with minor volcanic rocks, is not well related with metallogeny. In general, the volcanic activities in this belt are mostly of an acidic nature, characterized by Pb and Zn polymetallic mineralizations, which may be represented by the Koktal large-scale Pb-Zn deposit, and thus named the Koktal Pb-Zn metallogenic sub-belt. The orogenic plutonic rocks associated in the belt are dominated by S-type granites and there occur the Dakalasu and Xiaokalasu Be, Nb and Ta deposits. The above features indicate that there may be a fragmented old continental basement in the belt.

South of the Koktal Pb-Zn metallogenic sub-belt lies the Ashele Cu-Zn metallogenic sub-belt, which is formed of the Ashele volcanic basin and its eastward extension. The exposed strata in the basin are the Mid-Lower Devonian Ashele Formation ($D_{1-2}a$) and the Mid-Upper Devonian Qiye Formation ($D_{2-3}q$), unconformably contacting each other. The Ashele Formation is a Na-rich bimodal volcanic formation, c. 2000 m thick, with the basic volcanic rock comprising 36.4% of the total, in which there occurs the large-scale Ashele Cu-Zn deposit; the Qiye Formation consists of a suite of parabimodal volcanic rocks intercalated with terrigenous clastic rocks, c. 1800 m thick, with no massive sulphide mineralization found up to the present. It is inferred on the basis of geophysical data (Zheng, 1997) that the basin goes through the Habahe fault and extends eastward to the Xibodu area. It can also be inferred based on the ground surveys that the Ashele structure-formation extends eastward to the Supute area. The plutonic rocks in the belt are dominated by I-type granodiorites and plagiogranites, which are related to gold mineralization. It is suggested that the crust of this belt has been subjected to intensive extension and thinning and strong transformation of basic volcanic-plutonic activities, and turned into an extension-transitional crust (in a narrow sense).

To the south of the Ashele metallogenic sub-belt is the Ertix belt, which lies at the junction of two large structural elements, Altay and Junggar, and thus has the structure-formation features of the two. It is formed mainly of Precambrian fragments and the Mid-Upper Devonian strata. Among them the Fuyun-Qiao-

Table 1 Geological features of major Pb-Zn (polymetallic) deposits in the Koktal sub-belt

Name of basin	Maizi			Kelang		Qongkur
Deposit	Koktal	Akeharen	Daqiao	Tiemurte	Abagong	Keyinbulak
Size Grade (%)	Large Cu 0.08, Pb 1.51, Zn 3.16	Medium-small Pb 2.89, Zn 0.13	Medium Pb 0.29, Zn 1.44[1]	Large-medium Cu 0.50, Pb 1.39, Zn 3.18	Medium Cu 0.09, Pb 1.91, Zn 3.49	Medium-small Cu 0.12-1.27, Pb 0.04-0.26, Zn 1.52-9.20
Tectonic location and hosting horizon	North limb of reversed Maizi synclinorium; middle part of $D_1k_2^2$	South limb of Maizi synclinorium; upper part of $D_1k_2^3$	South limb of Maizi synclino-rium; lower part of $D_1k_2^2$	North limb of Kelang synclinorium; middle part of $D_1k_2^2$	North limb of Kelang synclino-rium; middle part of $D_1k_2^2$	Qongkur synclinorium, middle part of $D_1k_2^2$
Host rock	Metatuffaceous siltstone, schist, impure marble	Meta-acid lava, schist, marble	Impure marble, schist, tuff	Schist, metasiltstone, marble, with minor tuff	Schist, metasiltstone, with tuffite	Schist and metatuffaceous siltstone interbedded
Ore mineral	Galena, sphalerite, pyrite, pyrrhotite, chalcopyrite	Galena, fluorite, barite, sphalerite	Magnetite, sphale-rite, galena, chal-copyrite, barite, pyrite	Galena, sphalerite, chalcopyrite, pyrite, pyrrhotite	Galena, sphale-rite, chalcopy-rite, pyrrhotite	Chalcopyrite, sphalerite, pyrite, galena,
Feature of minerali-zation	Minor disseminated veinlet mineralization in the lower altered pipe; ferrosiliceous exhalite at the bottom of the upper stratiform mineralization; banded, massive and disseminated sulphide layers in the upper part	Intersected veinlet disse-minated mineralization in lower metalava; laminar-disseminated mineralization in upper part	Sulphide lenses in impure marble and metatuffite	Dominated by stratiform mineralization, intersected mineralization undeveloped; massive-densely disseminated ores formed in central part of the depression, gradually turning into banded and disseminated mineralization on both sides	Minor dissemi-nated minerali-zation in lower volcanics, banded sulphide lenses in upper part	Thin-layered and banded mineralization, with minor massive-densely disseminated ores
Wall-rock alteration	Stratabound K-feldspathized (lower) and chloritized (upper) zones and altered pipes developed in the foot wall; weak epidotization seen in the hanging wall	Pipe-like and fissured silicified and fluoritized zone developed in foot wall	Stratiform K-altered zone and veinlet epidotization developed in foot wall	Stratiform K-altered chloritized zone and altered pipe developed in the foot wall	Stratiform silici-fied and K-altered zone developed in foot wall	Alteration not obvious

Note: 1. Average grade calculated from surface workings

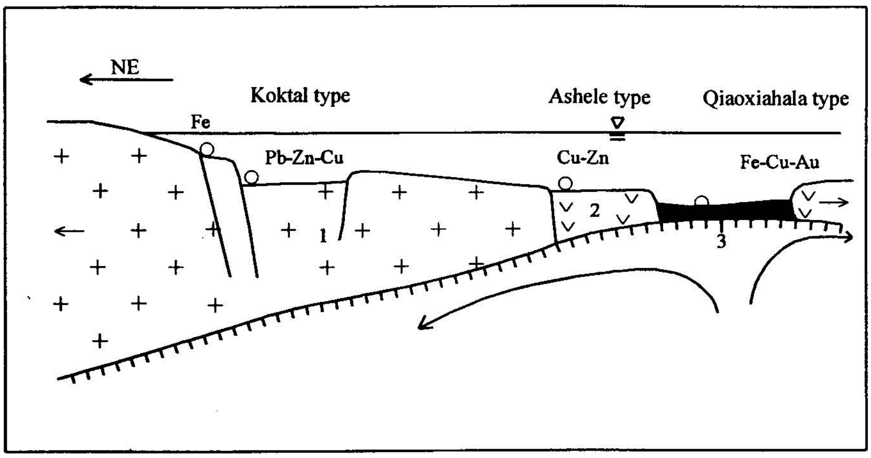

Fig. 2. Sketch showing metallogenic zoning of the Altay volcano-passive continental margin in the Devonian.
1. Broken continental crust; 2. extensional transitional crust; 3. oceanic crust.

xiahala segment is a most typical one, in which the Mid-Devonian Beitashan Formation (D_2b) basic volcanic rocks are distributed in a NW-trending belt along the Ertix fault (south side), with a length over 150 km and widths only 2 to 5 km. There occur ophiolite suites of metaperidotites, pillow basalts, radiolarian silicalite etc. The basalts belong to the tholeiitic series, which fall into the oceanic tholeiite and oceanic ridge area in most of the diagrams, and their REE patterns are also close to those of modern oceanic ridges (Chen et al., 1995). This shows that an oceanic crust has been formed because of strong extension, the deposits associated with which are the Cu-Au magnetite deposits related to basalt-basaltic andesite. These deposits are represented by the Qiaoxiahala deposit, hence the name "Qiaoxiahala Fe-Cu-Au metallogenic sub-belt".

2.2 Representative deposits

(1) Koktal and related polymetallic deposits

The Koktal deposit, which is located at the southeastern turn of the northeast limb of the Maizi syncline, was discovered in 1986 during the exami-nation of chemical anomalies (B-10, 11 anomalies) and assessment of the gossan. About 3 million tons of Pb+Zn reserves have been controlled, and more than 10 orebodies delineated. The largest one is the No. 11 orebody, which is 1350 m in length, 9.46 m in thickness and 690 m in extending depth. The ore-bearing Kangbutiebao upper subformation (D_1k_2) can be divided into three members, which, in descending order, are as follows:

$D_1k_2^3$: rhyolitic-dacitic brecciated crystal tuff, schist, marble

d: Fe-Mn marble intercalated with schist;

c: acid brecciated and crystal tuff;

$D_1k_2^2$: b: ore-bearing horizon: schist, metasilt-sone with tuff, marble, hydrothermal sedimentary rock– sulphide lenses;

a: acid lava, crystal tuff, with local agglomerate;

$D_1k_2^2$: acid lava, crystal tuff and schist.

The orebodies occur concordant with the strata in stratified or bedded form, generally in single layers, locally (exploration lines 0–15) 2 to 3 layers, in which there develop massive, banded and disseminated structures. At the lower and pinching-out parts of the orebodies, there often occur metamorphic hydrothermal sedimentary rocks such as banded microlitic quartz schist and laminar magneto-quartzite. In the foot wall of the ore bed are recongnized a large-scale stratiform sericitized zone and a chloritized-epidotized pipe, but veinlet mineralization is not well devloped in the pipe. In a word, the Koktal deposit was formed through exhalative deposition in the local sedimentary depression nearby the centre of the volcanic eruption.

Some other important deposits have also been found in the Koktal metallogenic belt (Table 1). They have the common feature that all of them were formed during the intermittent periods of volcanism. The direct wall rocks are dominated by metasedimentary rocks such as metasiltstone, schist and marble, and in the volcanic rocks underlying the orebodies there often occur agglomerate, breccia, cryptovolcanic rocks and dikes, reflecting the existence of volcanic apparatuses. The authors (1998) called these sedimentary

Table 2 Comparison of three metallogenic sub-belts in southern Altay

Name of Metallogenic sub-belt	Koktal	Ashele	Qiaoxiahala
Tectonic location	Fault-depression zone	Extensional transitional zone	Paraoceanic crust close to Spreading axis
Volcanic rock formation	Rhyolite-dacite-(basalt)	Basalt-dacite	Pillow basalt-basaltic andesite-radiolarian silicalite
Host rock	Tuffaceous fine clastic rock-marble bed in intermittent periods of volcanic eruptions	Dacitic tuff bed at transitional part from dacite to basalt	Fine clastic rock-marble (hang-ing wall) and basaltic andesite (foot wall)
Major metallic mineral	Galena, sphalerite, pyrite, Chalcopyrite	Chalcopyrite, sphalerite, pyrite, galena	Magnetite, pyrite, chalcopyrite
Ore-forming element	Pb-Zn-(Cu)	Cu-Zn	Fe-Cu-Au
Type of deposit	Sedimentary rock-hosted ma-ssive-disseminated sulphide in volcanic rock series	Volcano-hosted massive sul-phide	Volcanics-hosted Cu-Au-Magnetite
Metallogenic epoch	D_1k (Kangbutiebao stage)	$D_{1-2}a$ (Ashele stage)	D_2b (Beitashan stage)
Case of deposit	Large Pb-Zn deposit in Koktal, large-medium Pb-Zn-Cu depo-sits in Tiemurte	Large Cu-Zn deposit and occu-rrences in Ashele	Cu-Au-Fe deposits in Qiaoxiahala
Type of granite	S-type	I-type or I-S transitional type	I-type
Crustal type of basin basemnt	Continental crust, with obvious features of block faulting	Extensional transitional crust	Oceanic crust

Table 3 Comparison of contents of ore-forming elements in the Kuroko-type and the Altay-type deposits

Type of deposit	Occurrence	No. of deposit	Cu (%)	Zn (%)	Pb (%)	Ag (g/t)
Kuroko[1]	Australia	10	1.0	11.8	4.7	117
	Canada (Pz)	20	0.6	5.5	2.2	62
	Japan (R)	11	1.7	4.7	1.1	97
Altay[2]	Koktal		0.08	3.16	1.51	17.4
	Tiemurte		0.50	3.18	1.39	11.0
	Abagong (A4)		0.09	3.49	1.91	49.7
	Akeharen		trace	0.13	2.89	11.8

Notes: 1. Based on data from Large, 1992; 2. calculated on the level of control by the present workings (equivalent to the E+D category).

rock-hosted Pb-Zn-dominant poly-metallic deposits in the volcanic rock series the Koktal-type deposits, which reflect certain transitional features between the volcanic rock-hosted and sedi-mentary rock-hosted massive sulphide deposits.

(2) Ashele Cu-Zn deposit

It is the only large-scale deposit in the Ashele sub-belt, with some copper occurrences and small deposits in the surroundings. The deposit is controlled by the strata and synclinal structures. Altogether 4 orebodies have been delineated, which are in concordant contact and as synchronous fold with the strata in a lenticular form. The largest No. 1 orebody has a controlled length of 843 m along the strike, 1250 m along the dipping, and a thickness from 5 to 120 m. Its copper reserves comprise 98% of the total, and most of them are of high grade (Chen Yuchuan et al., 1996). The ore-forming elements are dominated by Cu, secondly Zn, with certain amounts of Pb, Ag and Au. The ore-bearing Ashele Formation can be divided into three lithologic members, which are (in descending order):

$D_{1-2}a^3$: thick-bedded spilite with minor keratophyre;

$D_{1-2}a^2$: intermediate-acid pyroclastic rocks, lava with spilite beds; with silicalite rocks, limestone and baritic rock lenses and massive sulphide orebodies in the top layer;

$D_{1-2}a^1$: stratiform intermediate-acid pyroclastic rocks-tuffaceous siltstone and crystalline limestone.

The mineralization was controlled by the centre of volcanic eruption, having double-layer mineralized strucutres: the upper part consists of stratiform sulphide orebodies, dominated by fine-grained massive, banded and laminar ores; while in the pyrite-phyllic altered pipes in the lower part there occurs cross-cut veinlet-disseminated mineralization. Upward and outward from the lower cross-veined zone there shows a zonation of pyrite ores→ Cu-bearing pyrite ores→ Cu-Zn pyrite ores→ polymetallic ores→ poly-metallic barite ores. To sum up, the Ashele deposit has the typical features of volcanogenic massive sulphide deposits.

(3) Qiaoxiahala Cu-Au-magnetite deposit

Although this deposit is not a typical massive sulphide deposit, it has a close relationship to the latter. The Qiaoxiahala metallogenic sub-belt shows a discontinuous NW-trending distribution with a length of c. 13 km, and can be divided into three ore blocks, the west, the central and the east. The ores are dominated by the Cu-Au magnetite (hematite) type, followed by individual Cu and Au orebodies. The iron deposits are small ones while the Au and Cu deposits are of medium scales.

The exposed strata are mainly the Mid-Devonian Beitashan Formation and Yundukala Formation; the former one is the ore-bearing horizon, which consists of three members:

D_2b^3: intermediate-basic pyroclastic rocks;

D_2b^2: the upper part: tuff with thin-bedded limestone, ferruginous silicalite and Cu-Au magnetite lenses; the lower part: olivine basalt, pillow basalt and basaltic andesite;

D_2b^1: basalt, basaltic andesite and relevant pyroclastic rocks.

The iron beds occur concordantly with the strata. Generally 2–3 beds can be seen, dominated by massive and banded ores and associated with hydrothermal ferruginous silicalite, indicating their formation from exhalative deposition in a submarine volcanic environment. The copper minearlization occurred in two stages. The first stage was the same with that of iron mineralization, in which it was enclaved in magnetite in a scattered form, or relatively enriched in the lower and pinching-out parts of iron beds. In the second stage, it cut the iron ores in irregular vein-like forms, but was still confined within the iron beds. It was closely related with crypto-volcanic intrusions and associated with strata-bound skarnization. Gold and copper show a positive corre-lation. Chalcopyrite has an average gold content of 230×10^{-6}, while bornite 395×10^{-6}. Relatively rich Cu-Au orebodies often occur at the superimposed part of the two stages of mineralization. This deposit is gene-tically similar to the Cyprus-type deposits, and can be compared with the hydrothermal deposits in the deep of the Red Sea, where abundant magnetite and hema-tite are deposited with high copper and gold contents.

There are similar mineralizations along the southeastward extension of this deposit to Laoshankou, most of which are mined by local people. Along the NW extension there are also occurrences of Cu-bearing magnetite-hematite, but of no commercial values. Such mineralizations are rather common in the Qiaoxiahala slit-like spreading trough.

2.3 Metallogenic zonation related to volcano-passive continental margin

As illustrated above, the volcano-sedimentary basins in the area were formed on the background of continental margin extension. The extension caused thinning of the crust. The revived activity of basement faults, formation of contemporaneous faults and the associated volcanic and hydrothermal processes formed an environment favourable for mineralization. Because of the different features of the basins' basement and the volcanism-sedimentation at different extension structural locations, the tectono-magmatic-hydrothermal systems also had different characteristics, which resulted in the various metallogenic sub-belts (Table 2, Fig. 2).

On the inner side (the old land side) of the volcano-passive continental margin, the Koktal Pb-Zn metallogenic sub-belt is an extensional broken continental crust zone. The basement of the volcanic basins was an old continental crust with block-faulting features. The volcanism is mainly acidic, with plentiful supply of terrigenous fragments, thus forming the Kokal-type Pb-Zn-rich polymetallic deposits hosted by sedimentary rocks in the volcanic rock series. In the Ashele sub-belt far away from the old land, the maturity of the crust is remarkably reduced by extension and thinning of the crust as well as the strong tectono-magmatic reformation, which turned the crust into an extension-transitional one (in the narrow sense), re-

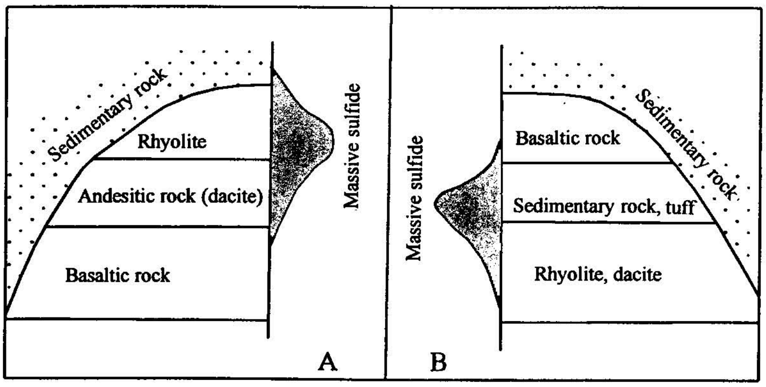

Fig. 3. Two types of ore-bearing volcanic-sedimentary columns

A—Kuroko type (after Sangster, 1985); B—Altay type.

sulting in bimodal volcanic formations and the Ashele-type Cu-rich massive sulphide deposits. The southernmost Qiaoxiahala sub-belt was then at the position of the spreading central trench, in which there developed ophiolite suite of an oceanic nature, which resulted in the Qiaoxiahala-type Fe-Cu-Au deposit similar to the Cyprus-type in meta-llogenic environment.

From the Koktal sub-belt near the old land in the north→the Ashele sub-belt in the central part→ the Qiaoxiahala sub-belt in the south, the volcanism related with mineralization became younger in age, that is, from $D_1k \rightarrow D_{1\text{-}2}a \rightarrow D_2b$, and tended to be more intensified in strength, with a drastic increase of basic volcanics. The assemblages of ore-forming elements changed from PbZn→CuZn→FeCuAu. The spreading centre gradually migrated southward (seaward), resulting in three organically interrelated meta-llogenic sub-belts in the volcano-passive continental margin.

3 Discussion

3.1 Features of massive sulphide deposits related to the volcano-passive continental margin

Hutchinson (1980) grouped the volcanogenic massive sulphide depo-sits into 4 types: the Cyprus type (Cu-Au), the “primary type” (Cu-Zn), the Kuroko type (polymetallic) and the Besshi type (Cu-Zn-Au). They form a set of deposit series closely related to the plate subduction regime, characte-rized by a trend of getting younger in metallogenic age from the sea trench to the land, and a distribution of ore-forming elements with increases in Pb and Ag contents and reductions in Cu and Au contents.

Compared with the deposits related to the plate subduction regime, the southern Altay metallogenic belt shows some similarities and at the same time obvious differences; it has its won metallogenic features, which may be summed up as follows:

(1) **Tectonic setting** Unlike the massive sulphide deposits occurring in the trench-arc-basin system represented by the Kuroko-type, the southern Altay-type massive sulphide deposits were formed on a volcano-passive continental margin, unrelated to subduction, but related to crustal extension and thinning. One of the important features is that old continental fragments of different scales are often found in the volcano-metallogenic belt related to such environment.

(2) **Time-space evolution of mineralization** Contrary to the trend of the metallogenic ages being younger from the trench to the continent under the plate subduction regime, the metallogenic ages of the deposits related to volcano-passive continental margin become younger towards the oceanic basin. But the two have similar distributions of ore-forming elements, with Pb and Ag increased while Cu and Au decreased towards the land.

(3) **Ore-bearing volcanic rock series** The Kuroko-type deposits related to subduction in Japan, Canada and Australia are associated with calc-alkaline volcanic rocks with continuous basic→ intermediate→ acid differentiation. There occurs more andesite in the section, e.g., in the Kuroko area of Japan, the marine volcanic rocks have a basic: intermediate: acid ratio of 13:33:54. This area, however, is dominated by alkali-rich bimodal volcanic rocks, with andesite poorly developed. Generally, the acid rocks were earlier than the basic rocks in eruption sequence. The deposits were formed on the acid pyroclastics side of the transition part from acid to basic rocks, or in the interbeds of sedimentary rocks in the acid volcanic rock series (Fig. 3).

(4) **Composition of ores and type of associated deposits** Compared with the Kuroko-type depostis which are also polymetallic, deposits of this area are characterized by enriched Pb, depleted Cu and low Ag (Table 3), and plenty of associated elements such as Ba, As, Bi, Se, Te, Mo, Sn, Ag, Au, Cd and In; the Kuroko type deposits have much less asso-

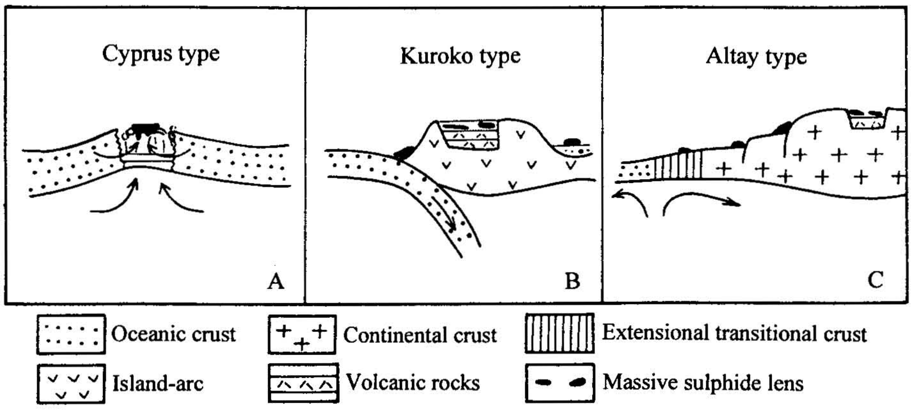

Fig. 4 Tectonic settings for three types of volcanogenic massive sulphide deposits
A—Cyprus type; B—Kuroko type; C—Altay type.

ciated elements (Ba, Ag, Bi, Au, Co, Ni etc.). Besides, there occur individual Pb deposits (e.g. the Akeharen deposit) which are not seen in the Kuroko-type deposits. The main types associated with the polymetallic deposits in this area include the phosphorus- and REE-rich volcanics type (Kiruna-type) iron deposits such as Abagong, Mengku and the Nb-Ta-Be deposits related to the granite-pegmatite in the orogenic period. Neither of the two types has ever been found in a typical Kuroko-type ore belt. The Ashele-type Cu-Zn deposit shows little difference in ore composition as compared with the primary-type deposits, which reflects a certain trend of assimilation in the assemblages of ore-forming elements between the extension-transitional crust and the compression-transitional crust.

3.2 Wide distribution of massive sulphide deposits related to volcano-passive continental margin

The five-stage model of crustal opening and closing is a common law in Palaeozoic intercontinental orogenic belts (He et al., 1994), therefore the distribution of massive sulphide deposits related to volcano-passive continental margin during the extensional-transitional crust period is also common.

(1) **The Altay ore belt of Khazakstan** The Altay of Khazakstan, which is connected with the Altay Mountains in China, is an important base for polymetallic deposits in former USSR. In the "Ore-bearing Altay" (Rudny Altay), 90% of the massive sulphide polymetallic deposits occur in Devonian volcano-sedimentary beds, which are closely related to basalt-rhyolite formations with the acid: intermediate: basic ratio of 11.5:1:2. They have a similar regional metallogenic zonation with the southern Altay of China: the Pb and Zn polymetallic deposits mostly occur in the north belt near the old land (the Leninogorsk-Zeryanov and Kholzun-Sarymktin subbelts), consisting mainly of acid volcanics; the Cu-rich deposits are distributed in the southwest belt, with more basic volcanics.

(2) **The pyrite (Cu polymetallic) ore belt of Spain-Portugal** This belt, which is 230 km long with an average width of 35 km, distributed in a nearly E-W strike, is a well-known Hercynian metallogenic belt in Europe. Late Precambrian metamorphic massifs are found in the Beja-Aracena geoanticline north of the belt, and metamorphic basement is also seen in the volcanic rock belt, which implies that it may be a rift zone on the margin of the Iberian massif, i.e., a volcano-passive continental margin. The ore-bearing Carboniferous sequence in the area is as follows (Song, 1982):

④ slate and greywacke
③ marine acid volcanic rock, agglomerate and tuff
② c: spilite and diabase sills
  b: tuff/carbonaceous slate-ore-bearing bed
  a: marine acid volcanic rock and tuff
① mudstone, silicalite and tuffaceous slate

The mineralization is related to bimodal volcanic formations. Massive polymetallic deposits and pyrite deposits occur in sedimentary interbeds of transition from Na-rich acid volcanics to spilite, also belonging to the sedimentary rock-hosted massive sulphide deposits in volcanic rock series.

(3) **The Qilian Mountains volcanic rock belt** This belt is developed on the southern margin of the

Sino-Korean massif which was already solidified in the Palaeoproterozoic, which has an evolution sequence as follows: crustal extension and rifting in the Meso-Neoproterozoic→ formation of oceanic basins in the Terminal Cambrian-Early Ordovician→ convergence and subduction in the Mid-Late Ordovician→ closing and orogeny in the Late Ordovician-Early and Middle Silurian, during which the volcanic activity weakened until ceased. The famous Baiyinchang deposit lies to the north of this belt, the ore-bearing volcanic rocks of which are Neoproterozoic in age as shown by latest data, i.e., they were formed in the extensional transitional crust stage. The mineralization is related to Na-rich bimodal volcanic formations; the deposits occur in the lower acid (quartz keratophyre) beds, controlled by the NNW-trending main fault. The intersected part of this main fault with the NE-trending basement concealed fault is most favourable for the emplacement of deposits. This also indicates that the metallogenic volcanic basin has a block-faulted basement.

(4) **The Red Sea area** This area is a volcano-passive continental margin which is still active at present. Volcanic activities occur mainly on the margin of the Proterozoic old massif northeast of the area. It was destroyed by extension and transformed by deep magmas since the Tertiary and became an extensional transitional crust (He et al., 1994). The Red Sea spreading centre is one of the typical areas of present-day sea-floor hydrothermal activity. The A-II Deep is 14 km long and 6 km wide, with metallic sediments over 20 m thick at the bottom of the brine pool. Sediments in the upper 10 m contain 1.06 Mt of Cu (grade 1.3%), 2.90 Mt of Zn (grade 3.4%), 80 kt of Pb (grade 0.1%), 4500 t of Ag (54 g/t), 45 t of Au (0.5 g/t) and 900 Mt of iron ore (silt) (grade 29%), showing typical mineralization in an environment related to modern volcano-passive continental margin.

3.3 Significance of massive sulphide deposits related to volcano-passive continental margin

(1) **Classification of volcanogenic massive sulphide deposits** Based on the tectonic setting and ore-bearing volcanic formation as well as the metallogenic features of the deposits, volcanogenic massive-sulphide deposits are grouped into three major types (Wang et al., 1996): a) deposits of the Cyprus type related to ophiolite suite or tholeiite, which occur in an oceanic ridge environment; b) those of the Kuroko type related to calc-alkaline volcanic rock series (characterized by large amount of andesite), occurring on convergence margins of plates; and c) those related to volcanic formation dominated by bimodal or acid volcanic rocks, occurring in a crustal extension environment. The latter are called the Altay-type ones because they are represented by the Altay polymetallic belts in China and Khazakstan (Fig. 4).

(2) **Deposits (belts) in pairs and prediction of deposits** Song Shuhe (1993) put forward the concept of "paired deposits" as he found in his study of marine volcano mineralization that massive sulphide deposits in volcanic rocks often occur in pairs with those in sedimentary rocks. The authors consider that volcano-passive continental margins are favou-rable environments for occurrence of metallic deposits in pairs. For example, the Early Carboniferous Aljustrel deposit occurring in volcanic rocks in pair with the Neves-Corvo deposit occurring in tuffaceous sedimentary rocks in the Iberian pyrite belt, the Mesoproterozoic Boin Sum volcanic-type Cu polymetallic deposit with the Dongshengmiao polymetallic deposit in tuffaceous sedimentary rocks in Inner Mongolia (Song, 1993), and the Ashele deposit with the Koktal volcano-sedimentary rock-hosted polymetallic deposit in southern Altay are all good cases for such deposits. Generally speaking, volcanics-hosted deposits are rich in Cu, lying near the ancient ocean; whereas the sedimentary rock-hosted or volcano-sedimentary rock-hosted ones containing rich Pb are located near the old land. This distribution feature of the paired deposits can be used for their prediction. On the other hand, although there are a number of volcano-sedimentary cycles in the sedimentary columns of volcanic basins in the intercontinental orogen, important deposits are usually found in only one or two of the cycles. Besides, the metallogenic cycles are generally located in the lower part of the volcano-sedimentary columns, i.e., they were formed in the extensional stage, especially the transitional part from acid to basic volcanics; some were also formed in the oceanic crust stage. When deposits had been formed in the extensional stage, very little mineralization occurred in the volcano-sedimentary cycle at the convergence stage. This is also a feature to be noted.

(3) **Indicative significance to tectonics** Massive sulphide deposits, no matter they are related to the convergence regime or to the extensional regime, have a similar distribution pattern of ore-forming ele-

ments, i.e. from the oceanic crust→transitional crust→continental crust, the contents of Pb and Ag are increasing and those of Cu and Au are decreasing, analogous to the distribution of the K content in volcanic rocks. This feature can be used to define the relative positions of the continental and oceanic crusts, but to determine whether it is the extensional or the compressive regime, additional indicators are required, e.g., time-space variations of the metallogenic ages. If the age becomes younger towards the continent, it may be under a compressive regime; if it is in the opposite case, it would be under an extensional regime. In the 5-stage evolution of the intercontinental orogenic belt, the extension-transitional stage may be indicated by the age of the volcano-sedimentary cycles of the metallic deposits.

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About the first author

Wang Jingbin Born in 1961; graduated in 1989 from the Department of Geology, Central-South University of Technology with a doctor's degree; left the post-doctoral centre of the Institute of Geochemistry, CAS in 1991, mainly engaged in researches on metallic deposits; now a senior geologist with the Beijing Institute of Geology for Mineral Resources.