Emanation-Sedimentary Metallogenic Series and Models of the Proterozoic Rift in the Kangdian Axis

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Abstract The Kangdian axis basement can be divided into two tectonic layers. The lower tectonic layer is the crystalline basement which is made up of the Archaean Dibadu Formation and early Proterozoic Dahongshan Group. The former is a kata-metamorphic basic volcano-sedimentary formation of the old geosyncline (old continental nucleus), and the latter is a medium-grade metamorphosed alkali-rich basic volcanic (emanation)-sedimentary formation of the Yuanjiang-Dahongshan marginal rift. They are in disconformable contact. The upper tectonic layer is the folded basement, and made up of the middle-late Proterozoic Kunyang Group. It is the result of Dongchuan-Yuanjiang intercontinental rifting with discordant contract with the underlying and overlying strata. Along with the evolution of Proterozoic from early to late, four types of emanation-sedimentary deposits in the Kangdian axis rift were formed in turn: ① emanation-sedimentary iron-copper-gold deposits related to basic volcanic rocks in the Yuanmou-Dahongshan marginal rift; ② emanation-sedimentary iron-copper deposits related to intermediate-basic volcanic rocks in the early stage of the Dongnchuan-Yuanjiang intercontinental rift; ③ emanation-sedimentary copper deposits related to sedimentary rocks in the middle stage; ④ copper deposits related to the late tectonic reworking. From early to late Proterozoic, with the evolution of the Kangdian axis rift and lowering volcanic basicity, the ore-forming elements also evolved from Fe, Cu and (Au) through Cu and Fe to Cu.

Key words: metallogenic series and model, rift evolution, emanated hot water, Kangdian axis

1 Metallogenic Geology Setting

The crust of the Kangdian axis can be divided into three tectonic layers (Li Chunyu, 1963; Hua, 1959; Yuan, 1989). The lower layer includes the Dahongshan Group and the underlying Dibadu Formation. As shown by the deep drill hole in the Dahongshan region, the Dibadu Formation is made up of migmatite, katametamorphism and amphibolite-granulite facies, and its primary rocks is basic volcano-sedimentary rocks. It is disconformable with the Dahongshan Group and obvious different from the latter in many aspects such as lithological association, texture and structure, metamorphic grade, etc. It can be compared to the upper Wudukeng Formation of the Ailaoshan Group, Pudeng Formation of Zulin Group in Yuanmou, and Kangding complex in the west of Sichuan Province. (Table 1).

As a medium-grade metamorphosed (epidote-amphibolite facies) volcano-sedimentary formation, the Dahongshan Group is composed of schist, siliceous rocks, marble and granulite, with alkali-rich basic volcanic (spilite) formation well developed, and the main rocks of crypto-volcano-intrusion facies are sodic diabase and albitophyre. It is the product of the Proterozoic Yuanmou-Dahongshan marginal rifting and the Dahongshan-type iron-copper deposit is also produced in rift. In stratigraphy it can be compared to the Alayi Formation of the Zulin Group in Yuanmou and the Hekou Formation in the west of Sichuan Province. The Dahongshan Group can be divided into the Laochanghe Formation, the Manganghe Formation and the Feiweihe Formation from bottom to top and every Formation can also be further divided into the upper, middle and lower members. Although some geologists created the "Hongshan Group" between the Manganghe Group and the Feiweihe Group, through the research of the stratigraphic occurrence, contact relationship, inner texture and regional stratigraphy, the so-called "Hongshan Group" is only a composite volcanic body instead of a stratigraphic unit. The Dahongshan Group, the Zulin Group and the Hekou

Table 1 Synthetic stratigraphy, sedimentary formation, rift evolution and metallogenic series in the Kangdian axis area

Erathem, System and Series	Formation	Thickness (m)	Sedimentary formation	Evolution of rift series			Metallogenic series		Samples of deposit
Middle and Upper Subgroup of Upper Proterozoic Kunyang Group		>8000	(Jinning movement 900 Ma) Marine clastic formation and carbonatite formation			Closing			
	Lüzhijiang Formation	840–1771	Marine carbonate formation					The deposits related to late tectonic reworking (Fensha-type)	Yimen Fenshan, Luoci Dameichang, Yuanjiang Jiguanshan
	Etouchang Formation	888–1015	Marine clastic formation, with silicious formation at bottom		Dongchuan-Yuanjiang intercontinental rift	Opening			
Lower Subgroup of Middle Proterozoic Kunyang Group	Luoxue Formation	137-205	Marine clastic formation with silicious formation	Proterozoic rift series in Kangdian axis			Marine emanation-mineralization series	Emanation-sedimentary Cu deposits related to sedimentary rock (Dongchuan-type)	Tangdan, Yinming, Luoxue in Dongchuan, Shishan, Tongchang Shizishan in Yimen, Honglongchang, Bailongchang in Yuanjiang
	Yinming Formation	551-806	Littoral turbidity flow flysch formation and sea-floor trench intermediate-basic volcanic eruption formation			Rifting		Emanation-sedimentary Cu deposits related to basic-intermediate volcano (Xikuangshan-type)	Dongchuan Xikuangshan, Etouchang and Yinanchang in Wuding, Yuanjiang Ganzhuang
	Feiweihe Formation	520	(Dongchuan Movement 2000 Ma) Shallow marine carbonate formation			Closing			
Lower Proterozoic Dahongshan Group (Zulin Group)	Manganghe Formation	559	Alkali-rich basic volcanic sedimentary formation		Yuanmou-Dahongshan marginal rift	Opening		Emanation-sedimentary Fe-Cu(Au) deposits related to basic volcano (Dahongshan-type)	Xinping Dahongshan in Yunnan Province, Huili Lalachang in Sichuan Province
	Laochanghe Formation	417	Clastic formation and debris flow flysch formation			Rifting			
Archaean Ailaoshan Group	Dibadu Formation	684	(Lüliang Movement 2500 Ma) Volcanic sedimentary formation	Protogeosyncline					

Group are distant to each other in space, but their fold and schistosity were all oriented in an E-W direction. This shows that there exits an old E-W structure and the lower Proterozoic volcano-sedimentary was controlled by an old E-W-trending rift. This rift at the edge of the old continental nuclear maybe was the western part of the old Yangtze geosyncline.

The middle tectonic layer is composed of the Kunyang Group which can be divided into 11 formations from bottom to top: Yinmin Formation, Luoxue Formation, Etouchang Formation, Lüzhijiang Formation, Dayingpan Formation, Heishantou Formation, Dalongkou Formation, Meidang Formation, Liubatang Formation and Huajianqing Formation. The first four formations make up the lower Kunyang subgroup, the last two formations constitute the upper Kunyang subgroup and the rest five formations belong to the middle Kunyang subgroup. The Kunyang Group is dominated by debris flow flysch formation, intermediate-basic volcanic formation and carbonatite formation. They are the products of the middle-late Proterozoic-Yuanjiang intercontinental rifting and belong to the folded basement, unconformable to the superposed strata and the underlying crystalline basement. The lower, middle and upper Kunyang subgroup can be approximately compared to the Changcheng System, Jixian System and Qinbaikou System in North China. The Yinmin Formation and Luoxue Formation of the lower Kunyang subgroup are the main ore-bearing strata. The Yingmin Formation is made up of debris rock, intermediate-basic volcanic rocks, silicious rocks and carbonite with the Xikuangshan-type copper deposit while the Luoxue Formation is mainly dolomite and striped silicious rocks with the Dongchuan-type copper deposit. In the Yimen-Yuanjiang region, some geologists divided the Luzhijiang Formation into the Shishan Member and Fengshan Member, and the Shishan Member was further divided into a purple layer, complex layer and black layer from bottom to top. According to the contact relationship, lithocomplex, ore-bearing feature and geochemistry, the authors think that the three layers can be separately compared to the Yingmin Formation, the Luoxue Formation and the Etouchang Formation. So the two most important types of bedded iron-copper deposits of the lower Kunyang subgroup in the Kangdian axis region were produced in two stratigraphic units: the Yingmin Formation with the Xikuangshan-type iron-copper deposit and the Luoxue Formation with the Dongchuan-type copper deposit. In fact, the Shishan copper deposit in Yimen area and the Jiguanshan copper deposit in Yuanjiang area, which have been regarded to be produced in the Lüzhijiang Formation, are the Dongchuan-type copper deposits in the Luoxue Formation (Ren and Li, 1984; He, 1965).

The N-S-trending Luzhijiang lithosphere fault is the most important fault. The stratigraphy, lithofacies, magmatic activity and metallogenesis action are obviously different from its two sides. The Mesozoic Dianzhong (central Yunnan) continental faulted basin occured on the west side of the fault and the Dahongshan Group is exposed in the form of “upward windows” along the east edge of the Luzhijiang fault. According to the geophysical data, the basement of the basin is the Dahongshan Group. Along the fault belt there are also ultrabasic-basic-acidic intrusive rocks. From the fault eastwards to the S-N-trending Xichang-Yimen fault, the Kunyang Group is distributed in a narrow and long SN-NE-trending region. According to the geophysics data, the Yuanmou-Shuangbai structure belt is a mantle rise and its two sides are mantle sinking belts. The Yuanmou-Luzhijiang fault developed longitudinally along the mantle rise. It is an ultracrust synfault and also a main channel of ore-bearing magmas and hydrothermal solutions.

2 Metallogenic Series and Models

The Kangdian axis is the main area of iron and copper deposits in Yunnan province and their reserves are about 70% of the whole province. They are primarily Proterozoic emanation sedimentary deposits. According to the evolution of the rift and the metallogenic process, they can be divided into four types (Shi, 1984; Qin and Ma, 1994; Zhuang et al., 1996) (Table 1).

2.1 Emanation sedimentary iron-copper-gold deposits related to basic volcanic rocks

The most typical deposit of this type is the Dahongshan deposit in Xingping, called the “Dahongshan-type” deposit. The deposit was produced in the upper

Manganghe Group and lower Feiweihe Group, which is the transition between volcanic rocks and marble, and was formed at the late stage of emanation sedimentation in the late volcanic evolution. The main ore-bearing rocks are emanation sedimentary rocks, such as amphibole biolite schist, albite leptite, silicious rock and chelrusfordite marble, etc. The volcanic rock is spilite which is rich in Fe, Na, Ti and Al and poor in K, Ca and Mg, compared with spilite in other places of the world. In the graphs of Al-Ti and Al-Na+K, the projective points of silicious rock are in the zone of hot brine origin. The ore bodies are bedded, bedded-like and lenticular, conformable to the country rocks, and are folded together with country rocks contemporaneously. The ore bodies are concentrated around the volcanic apparatus, and while the volcanic and emanation rocks become thinner from centre to outside, crypto-volcanic action and alteration become weaker, and the thickness of ferrous-copper ore body also become thinner and even pinched. The metal minerals are mainly magnetite, chalcopyrite and minor pyrite, bornite and siderite, while the nonmetallic minerals albite, quartz, hornblende, apatite, tourmaline and dolomite. The metalliferous ores are always distributed as fine grains along stratification with albite and quartz, which form a laminated stripe structure. The granularity of tourmaline is smaller than 0.01 m, and it is Fe-Mg transitional tourmaline. The ore-forming elements are Cu, Fe (Co) and Au (Ag).

The value of $\delta^{34}S$ is −2.99‰–+11.11‰ and the average is 6.75‰. Sulphur came from volcanos and ocean water. Lead isotopes are normal in a single stage evolution. Its projective points fall on the line of island arc, suggesting that its source is the crust and mantle. The ore lead isotope is consistent with the stratigraphic (volcanic rock) lead isotope, suggesting that the source is consistent with the evolution. The mineral inclusions include fluid, gas inclusions and molten inclusions. The temperature is 207–314°C and the salinity is 12%–39%. The value of Co/Ni of sulphides is 1.76. It is the middle hot brine mineralization.

2.2 Emanation sedimentary iron-copper deposits related to intermediate-basic volcanic rocks

The typical deposits called "Xikuangshan-type" deposits are the Xikuangshan deposit in Dongchuan and Etouchang deposit in Wuding, Yunnan province (Li Xiji et al., 1953; Li Hongmo and Wang, 1941; Chien and Wu, 1959). The ore-bearing strata are the Yingming Formation. Its lower part is purple debris flow clastic rock, the middle is spilite-beratophyre and rhyolite with a bimodal volcanic composition and the upper is mainly volcanic emanation sedimentary rocks such as biotite-chlorite, tourmaline sodaclasic rock and ferrous silicious rock. The ore bodies concentrate around the volcanic belt and centre. For example, the Xikuangshan deposit occurs in the volcanic sedimentary seg between the north and south volcanic lava domes. The main ore body is about 1 km long while its extension longer than its dip and the thickness is about 10 m with layered and lenticular forms. The main ore body is conformable to its wall rocks. The main ores are massive-oolitic Cu-bearing magnetite and hemitite, and brecciated hemitite, Cu-bearing albitite, Cu-bearing spilitic tuff and Cu-bearing albite silicous rock. Magnetite has fine-micro granular and oolitic textures and massive, banded brecciated structures. Copper minerals are mainly chalcopyrite and bornite occurring as laminae and fine networks.

The $\delta^{34}S$ value changes from −10.92‰ to +5.3‰, suggesting that its source is a mixture of ocean water and volcanoes. The lead isotopes show multistage evolution with the age of 1544–1603 Ma. The lead isotope projective points concentrate around the line of orogenetic zone in the tectonic environment graph, suggesting that its source is crust and mantle. Hydrogen-oxygen isotopes have values falling in the atmosphere water zone and the left magmatic water zone, suggesting that its source is mixture of magmatic water and atmosphere water. The metallogenic fluid is acidic-weakacidic, weak reductive middle-lower hot brine.

2.3 Emanation sedimentary copper deposits related to sedimentary rocks

This is called the "Dongchuang-type" produced mainly in the Luoxue Formation. The lower Luoxue Formation is thin- and the medium-bedded argillaceous and sabulous dolomite and partly callcareous silicious slate with wave mark, mud mod and wavy and prismatic stromatolith; the middle and the upper parts of the Laoxue Formation are thick-bedded dolomite, banded silicious dolomite and dolomatic silicious rock. The silicious rock which is composed of fine-micro grained quartz always forms lamellar and nodular structure with albite and sulphides. The ore body is obviously controlled by the strata, showing bedded and stratoid and is conformable to the country rock, both show progressive transition. The ore body is also curved with the folded strata. Metal minerals are mainly chalcopyrite and pyrite while the nonmetallic minerals dolomite and minor albite and quartz. The ores have banded, cydothem, nodular, horsetail structures and typical syngenetic sedimentary features.

The values of $\delta^{34}S$ of 44 sulphide samples in the Dongchuan copper deposit change from −1.68‰ to +15.2‰, with 41 of 44 samples having positive values and the modal value of +7‰, while those of 41 samples in the Yimen copper deposit from −6.0‰ to +20‰ with the modal value of +6‰. The sulpher isotopic compositions are consistent in the two places, suggesting that the ore sources and metallogenic environments are consistent. The sulpher mainly comes from enclosed retention ocean water and partly from the mixture of volcanoes and biological sources. Most of the 22 lead isotope values in Dongchuan are projected around the mantle lead line and upper crust lead line while they mostly obey the normal lead evolution line, suggesting that the lead sources are the mixture of crust and mantle. Most of the 14 lead isotope values in Yimen are projected around and in the island arc lead line and upper crust lead line as well as their upper right side, suggesting that the lead is mainly from the crust and partly from the mantle. The Pb-Pb isochronism age of lead isotopes in Dongchuan and Yimen is 1785–1893 Ma, approximately the same as the stratigraphic age. The 7 hydrogen-oxygen isotope values are projected on the left edge of the magma water and metamorphic water and in the scope of ocean water, suggesting that the water medium is the mixture of magma-water and ocean water. The temperature of ore-forming inclusion is 105–209°C and the salinity is 16.7%–20.5wt%NaCl indicating low-temperature brine.

2.4 Deposits related to tectonic reworking

The large Fengshan copper deposit in Yimen is an typical example of this kind of deposits, called the "Fengshan-type" deposit. It is related to diapirism, that is to say, underlying strata of the Yimin Formation and Luoxue Formation and ore bodies migrated upwards in the form of plastic flows and penetrated superposed strata. The Fengshan deposit occurs in the form a diapiric structure in dolomite of the Lüzhijiang Formation with ore bodies appearing as penetrating bed irregular prisms, veins, and chambers. The deposit features obvious branch compound and complex inner structure, composed mainly of fragments whose primary rock was the underlying ore-bearing formations and ore bodies of the Yimin and Luoxue Formations which underwent tectonic compression and physical transport. Fine copper networks and large copper veins formed by hydrothermal filling are frequently seen. Compared with the Dongchuan deposit, the Fengshan deposit is rich in bornite and dolomite, and has obvious silicification and carbonatization. Some minerals are coarse in grain and brecciated, cataclastic, vein-like and molten structures well developed. The ore has a high grade.

The $\delta^{34}S$ value of the Fengshan deposit is similar to that of the Shishan deposit, changing from −4.37‰ to +19.99‰ with a modal value of +4‰. The lead isotopic values of the two deposits are projected around the same straight line, which is abnormal lead of two stages resulting from normal lead polluted by radiation, suggesting that the lead and sulphur have the same source. Rare-earth elements in the two deposits are similar, all of which are of the light rare-earth type with Eu and Ce deficient. The homogeneous temperature of the Fengshan deposit is 146–360°C with a modal value of 240°C, a little higher than that of the Shishan deposit; while the salinity is 4–18 wt% NaCl with a modal value of 10 wt% NaCl, a little lower than that of the Shishan deposit.

3 Metallogenic Models

The Lüliang movement in the Kangdian axis made the primary geosyncline closed and the Ailaoshan Group was folded and uplifted to form an old continental nuclear. At the beginning of the early Proterozoic, under the N-S-trending tensile stress, the E-W-trending rift began to form on the margin of the old continental nuclear in the west of Luzhijiang fault. Rise of the mantle, lateral extension of the crust and gravity sliding resulted a clastic formation and turbidity flow flysch formation of the Laochanghe Formation. The breaking caused by sinking of the Manganghe Stage led to large scale volcanic eruption and resulted in a basic volcanic formation. At the end of the volcanic eruption, subvolcanic action was strong, the ore-bearing gas and liquid rose and acted with the ocean water, then emanated rocks and emanation sedimentary bedded iron-copper deposits were formed. The metallogenic medium is medium-temperature brine, and the depth of the ocean water is 100–750 m. At the Feiweihe Stage, the emanation came to the end, the basin closed, and the carbonite rock was formed.

Under the N-S-trending compressive stress, the Dongchuan movement at the end of late Proterozoic formed the E-W-trending structural belt, and E-W-trending tensile stress resulted in the formation of the N-S-trending Dongchuan-Yuanjiang long and narrow intecontinental rift in the east of the Lüzhijiang fault belt. At the beginning of the rifting, because the mantle rose, crust became thinner and viscosity lower, and also because stress was given off and gravity slided, the purple turbidity flow formation was accumulated in the lower Yinmin Formation with many dynamic sedimentary structures such as ripple marks, scouring pits, ooides and slump. At the sinking stage of the rift, because the rift sank deeply and cut the lithosphere to cause volcanic eruption and form intermediate-basic volcanic formations and emanation sedimentary formations of the middle and upper Yinmin Formation, and also form the Xikuangshan-type volcanic emanation sedimentary iron-copper deposit. The metallogenic medium is mainly magmatic water and partly ocean water. The metallogeny is related to acidic-weakacidic, weak reductive and medium- to low-temperature brine.

After the volcanic eruption of the Yinmin Stage took place long-period and extensive emanation until the early Etouchang Stage. Convection and circulation are the main ore-forming processes for the Luoxue Stage, that is, ocean water was permeated down along faults, heated in depths and flowed up through the underlying ore-bearing formations where metal and sulpher were leached and extracted, then erupted up into the ocean as hydrothermal fluids, as a result hydrothermal sedimentary deposits were formed. This is metallogeny related to low-temperature brine.

The Jinning movement at the end of the Proterozoic is the most important folding movement, which ended the evolution of the Dongchuan-Yuanjiang rift. Owing to the strong E-W-trending compressive stress, the N-S-trending fold and overthrust fault were formed. Tectonic force and buoyancy made the underlying ore-bearing formations and ore bodies of the Luoxue Formation migrate upwards in the form of plastic flows and insert into the dolomite of the Lüzhijiang Formation to form a diapiric structure and the Fengshan-type deposit. The ore-forming source is the underlying ore-bearing formations and deposits. The mineralization is related to medium- to low-temperature brine.

The mantle in the Kangdian axis area is rich in iron and copper. The Proterozoic two cycles rifting brought about a plenty of ore-forming materials, and at the same time provided good metallogenic environments and places. This is the basic reason of the concentration of iron-copper deposits in Kangdian axis. From the early to the late Proterozoic, with the evolution of the rift, the crust was gradually differentiated and thickened and marine volcanic action became weak, so the association of ore-forming elements has an evolution sequence of Fe-Cu-(Au)→Cu-Fe→Cu.

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