The Pre-Sinian Basement and Mineralization on the Western Margin of the Yangtze Paraplatform

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Abstract

The pre-Sinian basement on the southwestern margin of the Yangtze paraplatform consists of three metamorphic rock series of different ages. Being products of different tectonic events and environments, they differ markedly in original rock sequences, metamorphism, tectonic style and characteristics of granitoids and mineral deposits. The Late Archean Kangdian craton mainly comprises the Kangding and Julin Groups with a metamorphic age of nearly 2500 Ma. They are supracrustal rocks dominated by mafic volcanics enclosed in trondhjemitic rocks. The craton is believed to represent a granite-greenstone terrane of Late Archaean age. There occur mineral deposits such as graphite and kyanite deposits of metamorphic origin, muscovite deposits in pegmatites and gold quartz veins in gneissic granites, banded hornblende-magnetite mineralization and copper and zinc mineralizations related to felsic volcanics. Large V-Ti-bearing magnetite deposits were also formed in the mafic-ultramafic stratiform intrusions emplaced on the margins of the craton during the Middle Proterozoic. Copper and nickel deposits are found in several ultramafic intrusions. Extending in a north-south direction, the Proterozoic mobile belt consists mainly of the Early Proterozoic Hekou Group and Middle Proterozoic Huili and Kunyang Groups, and they are thought to be accumulations in a Proterozoic rift trough or aulacogen. During the Early Proterozoic, the rift trough was characterized by intense volcanism and presence of iron ore deposits of volcano-magmatic type, iron-copper deposits of exhalative-sedimentary type. The Mid-Late Proterozoic of the rift trough mainly witnessed the formation of sedimentary stratiform copper deposits and submarine sedimentary iron deposits. In the wake of the emplacement of the Jinningian and Chengjiangian granites in the Late Proterozoic, skarn-type tin and tin-iron ore deposits were formed.

In western Sichuan and eastern Yunnan on the southwestern margin of the Yangtze paraplatform (Ren Jishun et al., 1980), the pre-Sinian old basement is exposed, which comprises such metamorphic rock series as the Kangding, Hekou, Huili, Yanbian, Julin, Kunyang and Dahongshan Groups that jointly make up the main part of the "Kangdian axis" named by Professor Huang Jiqing (1953). Recent investigation indicates that the pre-Sinian rocks in the "Kangdian axis" can be divided into three metamorphic rock series of different ages which differ markedly in types and characteristics of metamorphism, original rock sequences, tectonic pattern and tectonic directions, types of granitic rocks and mineral deposits and isotopic ages. They are products of different tectonic environments and tectonic epochs, but constitute in combination a pre-Sinian old land. It is therefore considered that the "Kangdian axis" is actually a superpositional geological-tectonic unit which has experienced polytectonism, repeated magmatism and multiple metamorphism and may be divided into two important parts as described below.

I. Late Archean Kangdian Craton

This craton exists in a region including Kangding, Luding, Xichang and Dukou of Sichuan Province and extends southward into Yuanmou, Ailao Mountains and some other places of Yunnan Province. It consists mainly of the Kangding Group (Feng Benzhi et al., 1985) and Julin Group, the tectonic trend of which is basically east-west. The common metamorphic rocks in each group include amphibolite, gneiss, marble, quartzite, metagabbro, etc. The metamorphism it experienced is of regional dynamic heat flow type, mostly characterized by the extensively-distributed amphibolite facies, chiefly of the low-pressure and locally of moderate-pressure series (Lu Minjie, 1986), and possibly by granulite facies at depth. Due to the effect of heat flow, the metamorphosed rocks were partly remelted in situ or at depth, resulting in the formation of anatectic magma; later, as a result of recrystallization accompanied by metasomatism, large quantities of gneissic tonalite, trondhjemite, granodiorite and quartz-monzonite were formed in this region, belonging mainly to the trondhjemite series.

The lower part of the original rocks of the metamorphic rock series was a thick sequence of submarine basic volcanic rocks (over 5000 m thick), dominated by tholeiitic types near the bottom and by calc-alkaline ones upward. Such a basic volcanic formation was widespread and quite persistent in this region, thus serving as a marker horizon and indicating the existence of extensive and intense (mainly basic) volcanic eruption at the early stage of the Late Archean. The protoliths of the middle part more than 2000 m thick were largely intermediate-acid volcanic rocks and tuff of calc-alkaline series intercalated with basic volcanic rocks, volcanic graywacke as well as siltstone and claystone, with more fine clastic rocks rich in aluminous and carbonaceous materials in its upper portion, giving rise to sillimanite-schist, kyanite-schist, and graphite-schist after metamorphism. The original rocks of the upper part were primarily arenaceous, silty and clay rocks intercalated with quite a few beds of volcanic graywacke and thick-layered siliceous dolomite, belonging to a flyschoid formation more than 1000 m thick. In short, towards the end of the Late Archean, sedimentation played a leading role in this region, and only in local areas there remained some moderate volcanic activities. It can thus be seen that the original rocks in the Late Archean as a whole made up a rather complete gigantic volcanic-sedimentary cycle characteristic of transformation from a simatic environment to a sialic one and indicating the evolutionary features of the early continental crust. In addition, these supracrustal rocks dominated by mafic volcanic rocks are enclosed in rocks of trondhjemite series, and this is quite similar to the granite-greenstone association of K. C. Condie (1981). This craton is hence considered to be the middle and uppers parts of a Late Archean granite-greenstone terrane.

The Late Archean metamorphic rock series is of great thickness, and the volcanic rocks make a considerable proportion, suggesting that volcanic activities were very strong and lasted for quite a long time during its formation. It is of irregular distribution and fails to show obvious lineament. These characteristics, together with its age, have led the author to infer that the original tectonic environment during its formation might have been an embryonic geosyncline of open sea type or a huge palaeovolcanic-sedimentary basin (Condie, 1981).

The Kangding Group in the region and the Julin Group in Yuanmou have U-Pb concordant ages of 2451 Ma (Qin Jiaming, 1986) and 2478 Ma (Wu Maode, 1985) respectively, which indicate that an important metamorphic event might have taken place in this craton at the end of the Late Archean around 25000 Ma, which was also the age of cratonization. The age of the protolithic formations was probably Late Archaean (Ma Xingyuan et al., 1985; Cheng Yuqi et al., 1985).

Prior to the Jinning Stage, this region was probably connected from western Sichuan eastward with the Central Sichuan block (Xie Qi and Zhang Zhongmin, 1982) under the cover (eastward, it reached the Huangling block), constituting an approximately NE-trending craton. During the Proterozoic, the craton was rifted and cut by the Kunming-Huili geosyncline.

Ⅱ. Proterozoic Kunming-Huili Geosynclinal Mobile Belt

The above-mentioned old basement was then disintegrated in the Proterozoic, resulting in a new geosynclinal system. On the western margin of the craton, the rifting led to the formation of the Kunming-Huili geosynclinal mobile belt, which extends in a north-south direction and is bordered on both sides by deep fractures. To the north of the Mianning, Ganluo region, it cuts the craton and is connected with the Longmenshan-Micangshan geosyncline, forming somewhat a trifurcate structure with one of the limbs not so developed. This mobile belt represents a palaeorift trough formed in the Proterozoic, with the Hubei-Guizhou-Hunan open sea trough type on its eastern side and the small-sized Proterozoic Yanbian aulacogen and the Dahongshan aulacogen on the western side (Fig. 1).

The Kunming-Huili geosynclinal mobile belt comprises the Early Proterozoic Hekou Group① and the Mid-Late Proterozoic Huili Group, Kunyang Group, Dengxiangying Group and Ebian Group. Proterozoic metamorphic rock series in the Longmenshan-Micangshan deep sea trough are Huangshuihe Group, Baishuihe Group, Tongmuliang Group, and Huodiya Group②. In the Dahongshan aulacogen there occurs the Early Proterozoic Dahongshan Group, whereas Yanbian Group in the Yanbian aulacogen might be of Middle Proterozoic age. The fold axes of the Proterozoic formations mostly trend north-south; in a few areas, however, the rocks strike east-west as influenced by the configuration of the original sedimentary basin or the later structural transformation. The metamorphism that the Hekou and Dahongshan Groups experienced belongs to the regional dynamic heat flow type, mostly under greenschist facies conditions; whereas that of the Huili and Kunyang Groups was characterized mainly by deformation with only insignificant influence of heat flow, belonging to the low-temperature regional dynamic type, giving rise mainly to such rock types as extensively-distributed slate, phyllite, schistose or phyllitic volcanic rocks, metamorphosed sandstone and crystalline limestone.

① Zhang Honggang, Li Chengyan, Presinian in Sichuan.

② Institute of Geology and Mineral Resources, Sichuan Bureau of Geology, 1981. Explanatory Notes for the 1:1000000 Geological Map of Sichuan Province.

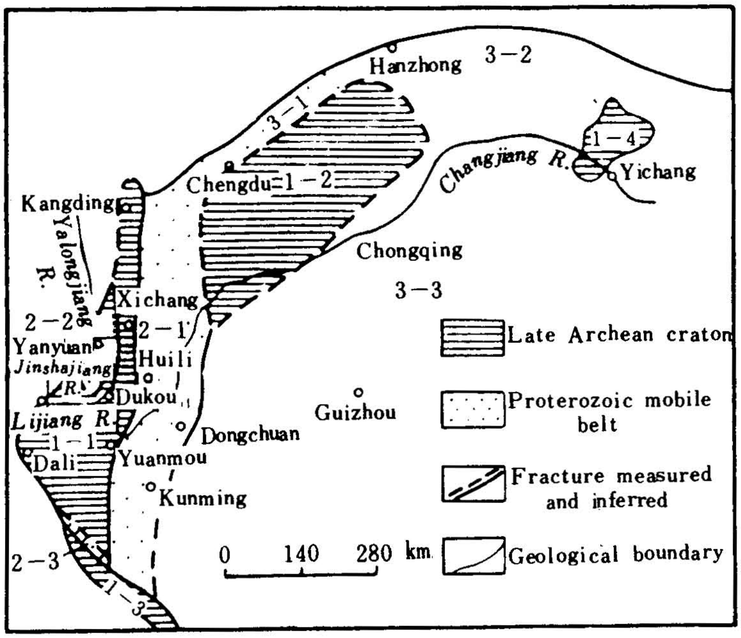

Fig. 1. Sketch map of Proterozoic tectonic units in southwestern China.
(Compiled from 1: 4000000 Geological Map of China)
1. Late Archean craton 2. Proterozoic mobile belt 3. Measured and inferred fractures 4. Geological boundary.
1−1. Kangdian block; 1−2. Central Sichuan block; 1−3. Ailaoshan block; 1−4. Huangling block; 2−1. Kunming- Huili geosyncline; 2−2. Yanbian aulacogen; 2−3. Dahongshan aulacogen; 3−1. Longmenshan-Micangshan deep sea trough; 3−2. Northern Yangtze Margin deep sea trough; 3−3. Hubei-Guizhou-Hunan open sea trough.

The original rocks of the Helou Group were dark fine clastic rocks-siliceous claystones and spilito-keratophyre, whose formation might be attributed to the following process: during the initial stage of the geosyncline, a deep water basin was formed, and as the water body was not in free circulation, the rate of sedimentation was lower than that of subsidence, which led to the deposition of a set of uncompensated black fine clastic rock-siliceous claystone formations[1]; in the meantime, fissures appeared in the basin due to the effect of stretching, and this led to the repeated eruption of pulsating sodic magma, forming a spilito-keratophyre formation. During the Middle Proterozoic, with the further development of the geosyncline, a set of marine sedimentary rock series of great thickness were formed in the deep water environment. At the early stage, there were ferruginous volcanic rocks and complex terrigenous clastic-carbonate formation; during the middle stage, comparatively thick terrigenous clastic flysch formation and carbonate flysch-wideflysch formation were developed. With the frequent extensional fracturing, there occurred multiple gravity flow deposition in the basin; in consequence, the basin was filled continuously,

1 Wen Qiongying, 1985. The original rocks and the formation environment of the metamorphosed sedimentary rocks of the Huili Group, Yearbook of Scientific Research Reports, Changchun College of Geology.

and the depth of the water body was reduced to a certain extent. At this moment, the rate of deposition became higher than that of the subsidence of the basin, and the deposition was turned into compensation type in the basin; the last stage was dominated by the variegated complex terrigenous clastic-volcanic flysch formation and the rhyolite-dacite formation, suggesting that the water body in the basin got shallower and the geosyncline gradually became contracted and closed. In brief, the characteristics of sedimentary formation and sedimentary environment demonstrate that the Proterozoic Kunming-Huili trough was characterized by the activities of a rift trough.

The granitic activities were quite strong in the belt and, as a result, a series of intrusive bodies of different sizes were formed from south to north. The main intrusions are the Eshan Granite in Yunnan and those occurring in western Sichuan, including Mosuoying and Changtang in Huili, Lugu in Mianning and Huangcaoshan in Hanyuan. The intrusive bodies, in the forms of stock to batholith, are mostly distributed along the anticlinal axis of the Middle-Upper Proterozoic formation. Skarn-type mineral deposits may be formed in some of the contact zones of the granites. These intrusive bodies are mostly 650–850Ma① in age, and thus should belong to the Jinning-Chengjiang Stage.

In addition, the data from regional geological survey in Yunnan province indicate that there exist several "skylights" of the Julin Group west of Dukou and Yuanmou in the Yanyuan-Lijiang platformal fold belt. This, together with the deep geophysical data, indicates that the basement of the fold belt comprises mainly Kangding Group or Julin Group, and it is inferred that the basement should belong to the Kangdian craton. Nevertheless, there exist locally on the basement Proterozoic metamorphic zones consisting of Yanbian Group and Dahongshan Group, which might be products in the small-sized aulacogen that appeared in some places in company with the disintegration of the basement during the Proterozoic. The aulacogen also shows characters of a mobile belt.

It is generally recognized that the Hekou Group in western Sichuan can be correlated with the Dahongshan Group in southeastern Yunnan. The metamorphic rocks at the bottom of the Dahongshan Group has ages of 1700 Ma (whole rock Rb-Sr age) –1900 Ma (zircon U-Pb age)②, which indicates that a metamorphic event happened in the aulacogen at that time. Rb-Sr ages of 900–1000 Ma③④ have been obtained for the rocks at the top of the Huili Group and Kunyang Group, which were intruded by the granites dated 850 Ma. These intrusions, in turn, were overlain unconformably by the Lower Sinian. This indicates that the Mid-Late Proterozoic geosynclinal sequence was folded during the Jinning movement, hence suffered low-temperature regional dynamic metamorphism under strong stresses. During or following the metamorphism, there were extensive intrusions of acid magma. It was also during this movement that the Kangding Group and Julin Group might

① Institute of Geology and Mineral Resources, Sichuan Bureau of Geology, 1981. Explanatory Notes for the 1:1000000 Geological Map of Sichuan Province.

② No.1 Geological Party, Bureau of Geology and Mineral Resources of Yunnan Province, 1983. Geological Research Report of ZK1312, Dahongshan, Yunnan Province.

③ Regional Geological Surveying Party, Bureau of Geology and Mineral Resources of Yunnan Province, 1986. Explanatory Notes for the Metamorphic Map of Yunnan Province.

④ Regional Geological Surveying Party, Panxi Geological Party and East Sichuan Geological Party of the Bureau of Geology and Mineral Resources of Sichuan Province, 1987. Explanatory Notes for the Metamorphic Map of Sichuan Province.

have been affected by a stage of superposed metamorphism of retrogressive nature, as evidenced by the occurrence of secondary schistosity and mylonization in the metamorphic rocks of the Kangding Group on both sides of the Anning River. In addition, the main E-W-folds in the graphite-schist of the Lengzhuqing Formation of the Kangding Group in the Dukou area are superposed by later N-S-trending folds probably of Jinningian age.

It can be concluded from what has been mentioned above that on the Late Archean craton, the Proterozoic mobile belt which had been developed through rifting gradually became stable and, when the Jinning tectonic cycle came to an end in this region, the development of the Yangtze Paraplatform having a double-layer tectonic basement began. The data recently obtained from deep geophysical prospecting in the western Panzhihua area also demonstrate that, under the Sinian-Paleozoic-Meso-Cenozoic cover, the basement has a double-layer structure. In short, during the evolution of the pre-Sinian metamorphic basement which had experienced repeated tectonic disturbances, the effect of heat flow turned from strong to weak; therefore, the early stage metamorphism was of regional dynamic heat flow type, whereas the late stage was the type of regional low- temperature dynamic metamorphism, suggesting that the metamorphism in this region constituted a complete cycle.

Ⅲ. The Kangdian Movement

As mentioned above, there exist remarkable differences between the Kangding Group and the Huili Group or Kunyang Group. They are not products of the same evolutionary stage of the crust, but represent those of two rather significant tectonic cycles. From the ages of the Kangding Group or its corresponding metamorphic rocks (2451 Ma–2478 Ma) determined in recent years, it can be inferred that an important tectonic movement took place in the Yangtze region around 2500 Ma, which brought about regional folding, metamorphism and uplifting of the Kangding Group, Julin Group, Ailaoshan Group[1] and other relevant groups, forming the early crust in the Yangtze paraplatform. This movement might have occurred between the Late Archean and the Early Proterozoic. In the Yuanmou-Xichang area, the tectonic line of the Archean and that of the Proterozoic obviously intersect each other (Feng Benzhi et al., 1985), and this may serve as important field evidence. It was generally considered that the basement of the Yangtze paraplatform was composed of the Middle-Late Proterozoic Huili Group, Kunyang Group and Banxi Group; nevertheless, recently more data have demonstrated that beneath these formations there exist older rocks related to the Kangdian tectonic cycle. The relevant tectonic movement has proved to be of great significance in the early pre-Sinian crustal evolution in southwestern China. In the wake of this movement, the crust entered a new development stage, i.e., the Late Archean old land began to come into existence; later, it gradually disintegrated and splitted, leading to the formation of obliquely- cutting geosynclines. Therefore, the coexistence of Proterozoic platforms and geosynclines made up the geotectonic framework at that time. As the products of this movement are quite distinguishable in the Kangdian

1 According to He Farong, the An Pei gneiss of north Vietnam, which is the south extension of Ailaoshan Group, has a K-Ar age of 2300 Ma. The author holds that such ages are generally somewhat younger than the true ages. Besides, Ailaoshan Group is more similar to Kangding Group in characters.

region, we suggest that this movement be named Kangdian movement①. Since then, the region was affected repeatedly by tectonism and, hence, no direct contact between the Archean and Proterozoic metamorphic series have been found.

On the basis of the above discussion, the Archean and Proterozoic and important relevant tectonic movements of the western margin of the Yangtze paraplatform are summarized in Table 1.

Table 1

Eon	Era	Typical strata		Tectonic movement	Time (Ma B.P.)
Phanerozoic	Palaeozoic	Cambrian (Є)			
					570
Proterozoic	Late Proterozoic	Sinian (Z)	Z_2		
			Z_1	Chengjiang movement	700
	Late and Middle Proterozoic	Huili Group, Kunyang Group (Pt_{2-3})		Jinning movement	900–850
				?	1900
	Early Proterozoic	Hekou Group, Dahongshan Group (Pt_1)			
				Kangdian movement (?)	2500–2400
Archean	Late Archean	Kangding Group, Julin Group (Ar_2)			

Ⅳ. Pre-Sinian Mineralization

The western margin of the Yangtze paraplatform is one of the important metallogenic regions in China, and ferrous metal and nonferrous ore deposits are exceedingly abundant in pre-Sinian metamorphic rock series within the basement.

A. Mineralization in the Late Archean Kangdian Craton

So far as the present knowledge goes, the mineral deposits formed during the Kangdian movement in the craton was dominated by metamorphic types. The most important ones are graphite and kyanite deposits in the upper succession of the greenstone belt.

Graphite deposits are formed in the Dukou and Ailao Mountains regions, in the Lengshuiqing Formation of the Kangding Group and Along Formation of the Ailaoshan Group. They are layered or lenticular in form, with graphite either sparsely or densely disseminated in different types of medium to coarse lepidoblastic graphite-schists and also in graphite-plagioclase gneiss. Where the graphite-bearing rocks were affected by granitic activities, the graphite scales grew in size as a result of recrystallization, and the grade of the

① The author previously named it "Chuandian movement" (1983); for reason of avoiding repetition, now he changes the name into "Kangdian movement".

deposits was further raised, as is represented by the Pingba deposit in Dukou.

Kyanite deposits[1] occur in the Pudeng Formation of the Julin Group, with the Reshuitang deposit in Yuanmou as a typical example. Kyanite appears as platy porphyroblasts and its nodular aggregates in mica-schist and kyanite-quartz-schist, formed under amphibolite facies conditions of the medium-pressure type from the original aluminium-rich pelitic or semi-pelitic rocks.

Besides, banded amphibole-magnetite ore occurrences[2] similar to the Anshan-type iron deposits are seen in the greenstone of Miyi, western Sichuan; copper-zine ore occurrences are found in the metamorphosed acid volcanic rock series of the Julin Group in Yuanmou and Muding of eastern Yunnan; and muscovite and rare metal mineralizations are noticed in the Late Archean gneissic granite. And gold-bearing quartz veins are found in the fractured zone of the Kangding gneissic granite. These are only preliminary investigations. From now on, attention should also be paid to the prospecting for gold deposits and base metal massive sulfide deposits related to the greenstone belt.

B. Mineralization in the Marginal Belt of the Kangdian Craton

There was only minor magmatic vanadiferous titanomagnetite mineralization related to small basic-ultrabasic intrusions emplaced in the Kangdian movement, such as the Yangxiu ore deposit in Mianning. After the cratonization of this area, the appearance of the deep (or great) fractures on the side of the Proterozoic rift along the margin of the craton led to the repeated activities of basic-ultrabasic magma during the period of 1500–1100 Ma B.P., which intruded into the consolidated craton on the outer flank of the fracture, forming basic-ultrabasic dyke (body) groups. Some intrusive bodies were accompanied by obvious magmatic differentiation and mineralization and, as a result, important vanadiferous titanomagnetite deposits and copper-nickel sulfide deposits were formed; some ore deposits of platinum group elements might also have something to do with basic magmatic activities of this period. Therefore, the basic-ultrabasic event which happened at the late stage of the Middle Proterozoic had great significance in mineralization.

1. Fe-, V- and Ti-bearing stratiform intrusions

According to the degree of differentiation, the intrusions might be classified into two types: gabbro type and gabbro-pyroxenolite-augite peridotite type. They are distributed in the craton area on the side of the margin of the mobile belt, assuming stratiform, basin-like or veinlike form and appearing in groups along certain tectonic belts, such as the basic-ultrabasic intrusive groups in western Panzhihua. Their chemical composition, in which $M'/F' < 2$ (between 0.2–1.65)[3], indicates that they belong to Fe-rich ultrabasic rocks and ferriferous basic rocks with the latter characterized by the existence of rich titanaugite. As the intrusions were extensively subjected to regional dynamic metamorphism, gneissic structure is well developed. Because of comparatively perfect differentiation, the ore-bearing intrusive bodies have formed obvious igneous "rhythmic"

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① Yunnan Regional Survey Party, 1985. Metamorphic complexes in Yunnan, Explanatory Notes for the 1:1000000 Metamorphic Geological Map of Yunnan Province.

② Zeng Xingeng, 1981. Plate tectonics and distribution of ore deposits in the western Panzhihua area.

③ Institute of Geology and Mineral Resources of Sichuan Bureau of Geology, 1981. Explanatory Notes for the 1:1000000 Geological Map of Sichuan Province.

structure whose general pattern is in downward succession of leucogabbro→melanogabbro →olivine gabbro→ore-bearing gabbro, with orebodies frequently located at the bottom of the rhythm. Besides iron, vanadium and titanium, the useful elements in the ore include cobalt, nickel, copper, chromium, selenium, tellurium, scandium, etc., which can be used comprehensively. The orebodies are great in size, and the ores are of good quality, so that the deposit is of extremely great economic significance. The average $^{40}Ar/^{39}Ar$ age of titanaugite from the ore-bearing intrusion is 1508.8 ± 5.17 Ma (Feng Benzhi et al. 1985), suggesting that the Panxi ore-bearing basic rock group intruded into the Kangdian craton during the Middle Proterozoic.

2. Intrusions containing copper-nickel sulfide deposits

They occur at the contact between the Late Archean and the Proterozoic metamorphic rock series or in the Proterozoic. The intrusive bodies are stock-like or lopolithic and comprise mainly ferruginous ultrabasic rocks, some of them display obvious differentiation. From the margin to the center of the intrusion, diorite→gabbro→peridotite zones can be recognized, showing mainly gradual relations. The copper-nickel mineralizations are concentrated on the margin or at the bottom of the intrusive body, and the ore deposits may be of medium size. The Gaojiacun ore-bearing intrusive body at Yanbian, whose whole rock K-Ar age is 1112–1252 Ma, might serve as a typical example.

In addition, in the Julin Group in Yuanmou, eastern Yunnan there exists a basic-ultrabasic belt consisting of tens of intrusive bodies. In those of gabbro-pyroxenolite-peridotite type, platinum, palladium, copper and nickel mineralizations can be found, and in some others, platinum group elements can make up economic orebodies①. It is worth further investigating whether these intrusive bodies are of pre-Sinian age.

C. Mineralization in the Proterozoic Geosynclinal Mobile Belt

During the formation of the protolithic Hekou and Dalongshan Groups in the Early Proterozoic, relatively large-scale submarine sodic magmatic activities prevailed in the relevant mobile belts, which brought there abundant ore substances and therefore played an important role in the volcano- magmatic iron mineralization or volcanic exhalative-sedimentary iron-copper mineralization. During the Middle-Late Proterozoic (formation of the Huili or Kunyang Group), the related mobile belt was dominated by sedimentation with occasional submarine volcanism. From various sources (including the weathering of the craton), the sea water brought in ore substances, and the iron mineralization proceeded was however rather insignificant. During the Middle Proterozoic, shallow-water environment appeared locally, and algal reefs were developed in the sea basin, which were favourable for the final enrichment of copper in the sediments, giving rise to the formation of gigantic sedimentary copper deposits. Towards the end of the Proterozoic, following the inversion of the geosynclinal mobile belt, intrusion of voluminous granitic magma took place, associated with skarn-hydrothermal mineralization. In short, the Proterozoic seems to have been an important period for the formation of metallic ore deposits in this belt, and this must have had much to do with the tectonic environment at that time.

1. Volcanic mineralization

①Shi Qingqin, 1981. The control of the basic-ultrabasic intrusions and their related ore resources by the tectonic system of Yunnan Province. Papers presented at the Annual Meeting of the Geological Society of Yunnan Province, 1981.

Related to such mineralization are volcano-magmatic type iron ore deposits and volcanic exhalative-sedimentary type iron-copper or copper ore deposits. The ore deposits occur in the Early Proterozoic Dahongshan Group or Hekou Group and are controlled by certain volcanic mechanism. Besides, they have intimate connection with the specific facies in the spilito- keratophyre formation or occupy a certain position in the volcanic exhalative-sedimentary cycle.

The ore-bearing rock series is a metamorphosed marine volcanic-sedimentary series in great thickness, which was formed in the deep-water rift trough or aulacogen. The rock series comprises quite a few volcanic exhalative-sedimentary cycles: in the lower part of each cycle is a spilito-keratophyre formation, with tuffaceous breccia and tuff at its bottom; upward there is basic and intermediate volcanic lava which is noted for abundant sodium (Na_2O = 4–10%, $K_2O < 0.5\%$) and rich in iron, copper, vanadium, phosphorus, etc. The upper part of each cycle is a tuff-magnesian carbonate formation which contains several intercalations of siliceous and carbonaceous rocks and in which tuffaceous rocks gradually decrease whereas carbonate rocks increase in upward succession. The iron ore deposits are mainly distributed in the keratophyric volcanic lava in the lower part of the cycle. The orebodies are stratified, stratoid or lenticular in form, and have no distinct boundaries with the wall rocks but only transitional relationship. Appearing in groups, they make up a large-size ore belt. The ores exhibit characters of lava, and it is thus inferred that the iron ore deposits are syngenetic with the wall rocks and should belong to the volcano-magmatic type.

The iron-copper ore deposits occur mainly in the upper part of each cycle which include metamorphosed tuff, carbonaceous slate and dolomite-marble. Orebodies also assume stratoid and lenticular forms and constitute two iron-copper ore belts within two volcanic exhalative- sedimentary cycles. The ores have disseminated, spotted, banded to laminated and brecciated structures, and some of them show rhythmic and clastic structure which indicate their volcanic eruption-sedimentary origin. The iron-copper deposits are hence considered to be formed as a result of deposition of mineralizing substances brought by volcanic exhalation or hydrothermal fluids during the intermissions of volcanic activities. Later, the ore substances were further migrated because of diagenesis and metamorphism, and this accounts for some epigenetic characters in the ore deposits.

These iron ore or iron-copper deposits are generally of medium-large size, represented by the Dahongshan deposit in Yunnan.

In addition, the Lalachang copper deposit of Huili in the Hekou Group occurs in metamorphosed keratophyre, tuff and subvolcanic-albite porphyry. Orebodies are stratoid and lenticular in form and accompanied by hydrothermal alterations such as fluoritization and albitization. The ores show characteristics of both hydrothermal and sedimentary nature, implying that this deposit might also be of volcanic exhalation-sedimentation type.

2. Sedimentary mineralization

Mineral deposits of this category are stratiform copper and iron ones.

Of the copper ores, the Dongchuan copper deposit in Yunnan is the most famous. It is the product of the middle stage of the development of the Kunming-Huili rift trough and represents an important sedimentary ore-forming process of base metals in the Middle Proterozoic mobile belt.

The deposit occurs at the bottom of the Yinmin Formation and also in the Luoxue Formation (both in the upper part of the Kunyang Group). The rocks of these two formations make up the Proterozoic copper-bearing formation whose lower part is composed of volcanic clastic rocks and intermediate-basic volcanic rocks whereas whose upper part is made up of banded to laminated ferruginous slate, tuffaceous slate, siltstone as well as dolomite and stromatolithic algal dolomite. From such a rock association, it is quite evident that this formation was formed through a continuous process of volcanism→deep-water turbidite sedimentation→neritic platform sedimentation, and that the ore deposits with marked economic significance are related to stromatolithic algal reef dolomite of platform sedimentation. This indicates that the sedimentary mineralization took place during the relatively stable period of the rift trough.

Due to the diversity of mineralization, there exist varied types of ore deposits in the Dongchuan orefield. Of them, the stratiform copper deposits in the argillaceous-arenaceous dolomite and also in the stromatolithic dolomite are the most important. The stratiform and lenticular orebodies occur in certain rather persistent horizons. The ores consist mainly of bornite, chalcocite and chalcopyrite, and the gangues have the same minerals as the wall rocks. The structures that indicate the genesis of the ores commonly include disseminated, spotted, laminated, horsetail-shaped algal and oolitic ones. The ore deposits are of medium-large size.

An integrated study demonstrates that the volcanic activities in the rift trough brought large quantities of ore substances into a second-order sedimentary basin and, in a favorable paleogeographic environment, such substances precipitated together with carbonate and argillaceous as well as tuffaceous materials. In the successive stage of diagenesis, the rich algae contained in the sediments went rotten and hence produced abundant hydrogen sulfide which provided a reduction environment where the copper substances were gradually transformed into sulfides and then concentrated to form ore deposits. When regional metamorphism took place these ore deposits experienced various degrees of transformation. It can thus be seen that the copper deposits are the products of comprehensive volcanic activity and chemical and biogenic processes and belong basically to sedimentary deposits confined to certain horizons.

In addition, marine sedimentary iron ore deposits are widely distributed in the Kunyang Group and Huili Group and confined at least to six horizons①. They include hematite deposits in phyllite, ferruginous meta-sandstone and sandy conglomerate, hematite (magnetite) deposits in ferruginous tuff and tuffaceous breccia, siderite deposits in limestone and dolomite, magnetite-siderite deposits in marble, cupriferous hematite (magnetite) deposits in tuff, etc. The ore deposits were all formed in the Middle Proterozoic and generally subjected to regional metamorphism. They are mostly of medium-small size, occasionally of large size.

3. Skarn-hydrothermal mineralization related to granitic intrusion

The skarn mineralization was mainly related to the granite of the Late Proterozoic Jinning Stage, and a few deposits were probably associated with the granite of the Chengjiang Stage.

Skarn type or pyrometasomatic cassiterite-sulfide deposits have been formed near the contact zone between the Jinningian granites and the carbonate rocks or calcareous basic volcanic rocks of the Huili Group. Deposits of this type are the oldest cassiterite deposits in

① Xue Bugao, 1979-1981. Types, metallogenic regularity and prospects of iron ore deposits along the Kangdian axis (research report).

China, generally medium or small in size. The biotite-granite of the representative Chahe deposit in Huili is of the Al-oversaturated calc-alkaline type with Na_2O+K_2O content nearly 8% and the initial $^{87}Sr/^{86}Sr$ value of 0.714, suggesting the character of crustal source (Peng Qiming, 1986). it is obviously enriched in tin, boron and fluorine and altered by potash feldspathization, albitization, greisenization, tourmalinization and fluoritization. Where the impure striped Al-, Si-rich marble appears near the contact zone, there occurs a composite skarn zone divisible from the contact zone outwards into successive zones of vesuvianite-garnet, wollastonite-sahlite and cassiterite-magnetite-actinolite. The stratiform or stratoid cassiterite-sulfide orebodies appear in the actinolite zone or at the contact between the actinolite zone and the hornfels and are obviously controlled by fissures. The ores are mainly characterized by a cassiterite-pyrite-arsenopyrite association. And they show laminated, disseminated and massive structures. According to thermometric data, the formation temperatures of the cassiterite are within the range of 450–350℃, and the fluid inclusions in the cassiterite have $\delta D = -70‰$ (Peng Qiming, 1987), suggesting an intimate relationship between the formation of the ore deposits and hydrothermal fluids related to the granites.

In this area, granitic magma remained active in the Early Sinian. The age of the relevant granite body is 650–700 Ma. Magnesian skarn-hypothermal magnetite deposits might be found at the contact zone between the granite intrusion and the magnesian carbonate rocks of the Proterozoic Dengxiangying Group. These deposits, though generally small in size, are often of very high grade. Some orebodies are also rich in cassiterite and hence constitute cassiterite-iron ore deposits.

The ore deposits of different ages in different tectonic units of the basement and their genetic types are shown in Fig. 2.

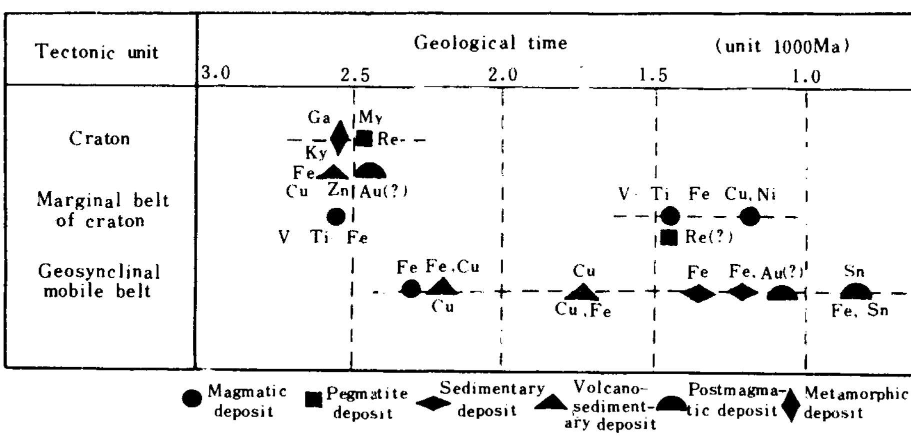

Fig. 2. Ore deposits in different tectonic units and their genetic types.

Re-rare element; Ga-graphite; Ky-kyanite; My-muscovite.

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