Some Characteristics of the Oxidation Zone of Sulfide Ore Deposits in Lower Yangtze Area, Southeast China

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Abstract: The characteristics of supergene zoning and processes of oxidation of disulfide-rich ore deposits in Lower Yangtze area, Southeast China, are representative to the warm and humid area in medium latitude zone. The distinguishing features are (1) limonite gossans extended to a great depth due to the slow uplift of the area during the long process of oxidation; (2) the existence of a subzone of current secondary sulfide enrichment due to the rapid decomposition of Cu sulfide ore in the upper part, which makes Cu intensively migrating downward; (3) the assemblage of secondary native copper, cuprite and their further oxidized products, tenorite and malachite, is an evidence of the ever-existence of ancient secondary sulfide enrichment; (4) carbonate and silicate are the prominent oxidation products of Pb-Zn ore deposits.

The contrasts of the characteristics of sulfide ore oxidation in Lower Yangtze area to that of the arid Northwest China are also clarified in this paper.

Introduction

The Lower Yangtze area is located in warm and humid zone of medium latitude in Southeast China. The oxidation zone of sulfide ore deposits in this area is well developed. The basis that determines the characteristic features of the zone of oxidation includes the mineralogical composition, texture-structure of the ore as well as the climate and physiographic history of the region in question.

Cu ore deposits in this area (Fig. 1) consist of 1) Cu-bearing massive pyrite bed, 2) Cu-bearing skarn and magnetite type ore deposits, with replacing Cu vein type deposits near the metasomatic zone, 3) mineralized intrusive bodies, some of them are known as porphyry copper deposits such as in Chengmenshan Mine. These three types of Cu deposits may be called "Three In One (or Thrinity)" deposits, but the third one does not occur in every mine. The pyrite or Cu-bearing massive pyrite ores bedded stratigraphically can be correlated with C1 to C2 beds (Gaolishanian to Huanglungian), it comprises chiefly disulfide (pyrite, melenikovite and subordinate marcasite) with or without pyrrhotite. In those disseminated ore of Cu-bearing skarn or magnetite type, disulfides are subordinate constituents, while Pb-Zn sulfides are rare in Cu-bearing pyrite or pyrite deposits except some local small pockets. On the other hand, a fair amount of chalcopyrite and pyrite may be present in Pb-Zn (Cu) deposits. The abundance of disulfide is the essential factor that controls the development of the process of ore oxidation in the Lower Yangtze area (Li et al., 1980).

Other factors influenced the characteristics of current development of oxidation zone are: (1) annual precipitation, generally in a range 1000 to 1500 mm, evaporation is greater than the precipitation except in rainy season; temperature varies with seasonal change, the maximum is 37° to 40°C in late July to early August, and the minimum -11° to -12°C in the late January; (2) the regional topography is mountainous to hilly, the physiographical history (Barbour, 1935) reveals that this region had suffered uplift and subsidence for several times, but now it is in
slow subsidence; (3) Neotectonic movement is chiefly shown by post-ore faults which revived even after the ore exposure oxidized (Li et al., 1980).

**Zoning**

Typical profile of the oxidation zone in the discussed area consists of the following four subzones:

*Subzone of Gossan* ($Z_1$)

Gossans of the massive pyrite or cupriferous pyrite ore deposits are developed along the dipping host beds with an inclined depth down to more than 350 m below the surface. The lower limit of vertical depth from the surface varies within the range from 60 to 150 m, average of which about 80-90 m. Ore bodies of small extent are even oxidized completely into limonite. Gossans capping the ores of copper bearing skarn or magnetite are less developed and often sporadically distributed. While on the Pb-Zn deposits where pyrite occurs only as a subordinate mineral component, extensions of their gossans vary through a wide range, and their depth of oxidation zone generally lies at 20 to 30 m below surface. The locally abnormal depth of oxidation is usually related to fractural zone of post-ore deposition.

Oxides and hydroxides of iron, the chief constituents of gossans, reveal somewhat zoning effect. In the upper part of gossans there appear much more hydrogoethite, orange-yellow in color, and a little below, more turgite, cherry red in color, then it is succeeded by the grant accumulation of mixtures of goethite and hydrogoethite, chestnut brown in
color. Occasionally, an alternative and discontinuous interbedding of orange-yellow hydrogoethite and cherry red turgite occurs in the upper gossan. There is almost no exception that manganese oxides and hydroxides which form the so-called "manganese iron hat" are present in Pb-Zn ore deposits. It is hardly to find out any supergene Cu, Pb or Zn minerals derived from the chief constituents of primary ores by naked eyes in the gossan of massive pyrite or cupriferous pyrite deposits, but chemical analysis reveals that it contains a fair amount of Cu, Pb and Zn (Fig. 2). Our study proves that Cu, Pb and Zn content of gossans can be used as a criterion to justify the kind of ore if they reach to a certain limit (Ore Oxidation Research Group, 1966).

Subzone of Secondary Oxides (Z2)

Beneath the gossan there exists an irregular and localized subzone of secondary oxides derived from an ancient secondary sulfide subzone by reoxidation. Its thickness varies from 0 to 5 m. It chiefly consists of pitch-colored limonite with native copper, cuprite and their further derivation malachite, occasionally with delafossite (c.f. Pabst, 1946; Li et al., 1980). Chalcocite was found as relics locally in this subzone. Chemical analysis and mineralogical study testified that the pitch-colored limonite is a colloidal mixture of predominant goethite with subordinate tenorite.

The occurrence of this subzone reveals that the ancient secondary enriched Cu-sulfide has been subjected to destroy by reoxidation, the present localized subzone of secondary oxides
is only a remnant of the former (c.f. Anderson, 1955).

Subzone of Disintegrated Sulfides ($Z_3$)

This is the uppermost part of the primary ore subjected to strong oxidation and decomposition. Sulfides here disintegrate and become loose and sandy. It directly underlies the gossan except where the subzone of secondary oxides is present between them. The thickness varies from 0 to 10 m, occasionally exceeding 10 m. Here, the intense oxidation and leaching make the useful elements of ore going into solution, moving down to the lower part and reacting with primary sulfides to form a new subzone of secondary sulfide enrichment; therewith, a new formation of supergene minerals is going on intensively, a great number of hydrosulfates are deposited thereby, newly formed limonite settled down by hydrolysis could be observed locally. The cupriferous massive pyrite ore on the stope wall not seldomly ignited due to the strong and rapid oxidation. The principal part of this subzone lies between 35 to $-25$ m relative to the sea level in Tongkuanshan Mine, but they occur chiefly above the sea level in all other deposits. The boundary between this subzone and its underlying cementation zone is vague in most cases, because sooty chalcocite has already sparsely appeared among sandy sulfides, and hydrosulfate is also present in the underlying subzone even though in much smaller amount.

Subzone of Secondary Sulfide Enrichment ($Z_4$)

It develops in various degrees in all copper-bearing massive pyrite deposits. Obviously, its time of formation is not so long enough as to make the supergene sulfide having a greater thickness. Only by the time not very far from regional uplift in the nearest past might it begin. The sooty supergene chalcocite accumulated in pockets or lenses, distributed sporadically within the scope of this subzone. Observation of polished sections indicates that the replacement of primary sulfides by supergene chalcocite and covellite scarcely tends to have completed. Supergene enrichment increased the grade of ore from 1 weight percent to as much as 20 weight percent. The thickness varies from 0 to 5 m, locally exceeding 10 m. Typical supergene enrichment phenomena in two of cross-cuts are illustrated as in Fig. 3 (Zhou, 1965).

The deposition of supergene sulfides is related to the detention effect of ground water circulation caused by the impermeability of foot-wall beds. The sites where supergene sulfides enriched are much nearer to the foot wall bed, they occur almost parallel with the latter. The elevations they existed vary with different ore deposits, most of them occur above the 0 m level, but in Tongkuanshan Copper Mine it sets on 35 to $-25$ m levels. The interface between this subzone and its underlying primary ore is irregular, it is not uncommon that the former cuts into the latter.

As to the copper bearing skarn and magnetite type ores, the supergene enrichment is represented by the accumulation of large amount of copper carbonates at certain levels.

Due to the detention effect on groundwater circulation along the impervious foot wall beds dipping in a medium angle ($45^\circ$ nearly) in Tongkuanshan Copper Mine, the oxidation profile shows a lateral zoning character.

The most notable feature of the oxidation zone of Cu-bearing massive pyrite ore deposits in the Lower Yangtze region are that the gossans extend to a much more depth than usually expected, and the existence of a subzone of secondary oxides representing an ancient supergene sulfide enrichment. It seems to be a result of a long period of uplift of this region since post-Pliocene (Barbour, 1935). Judging from the remnant terraces of present physiography, this region had suffered fluctuation several times, but it reflected on the profile of oxidation zone only by an uplift after the formation of subzone of ancient sulfide enrichment—as indicated by the reoxidation of the ancient supergene sulfides, and by sinking down not far back from the present—as most of the gossans situated far below the present ground-water table.

Development

Characteristic features of zoning of sulfide
Oxidation of Sulfides in Lower Yangtze Area

When the pyrite-rich ore body exposed to the surface, it began to oxidize and gave rise to free sulfuric acid. As soon as it had been present, oxidation of sulfides went on with accelerated rate, the acidity of oxidizing solution increased rapidly and the concentration of Fe\(^{2+}\), Fe\(^{3+}\), Cu\(^{2+}\), SO\(_4\)\(^{2-}\), etc., raised a high peak. Data of analyses of groundwater samples at 35 m level were representatives of the character of such solution in the intense oxidation zone (corresponding to the upper part of disintegrated sulfides, Table 1, Fig. 4).

The rapidity of oxidation was also shown by the great intensity of sulfate mineral formation. A great amount of sulfate minerals of iron,
copper, aluminium, magnesium and other elements were observed in those strongly oxidized parts of ore. The ferrous sulfates (melanterite, holotrichite, siderotil) predominated over the ferric one. Part of ferric sulfates (chiefly copiapite) was derived from ferrous sulfates. The transformation of sulfate from ferrous to ferric might be observed within a few days in parts of mining stopes of good air circulation. Newly settled limonite in association with hydrosulfate was also noted in some mining pits.

Analyses of groundwater samples from 5 m level show that the Cu\(^{2+}\) ion concentration reached to a highest peak (average of 25 samples: 2482 mg/l) and it reveals that there went on a strong decomposition of copper minerals above that level; while the Fe\(^{3+}\) ion concentration had a sudden fall, that might be a result of the high concentration of Cu\(^{2+}\) ion which had promoted the hydrolysis of ferric sulfate (Fig. 4).

Because of the frequent rainfall and alternative warm and cold seasonal temperature change, ionic concentration of the solution might show a much wavy character, so the formation and precipitation of sulfate minerals therewith should be changeable from time to time. The sulfate minerals, however, existed very temporarily, they vanished soon after they had appeared in those comparatively arid part in the stope. It is impossible to form stable precipitants as in the arid regions of Northwest China (Tu et al., 1963). Just because of it, the major component elements of sulfide ore largely migrated downward, forming supergene sulfide enrichment in the lower part by reaction with primary sulfides; and due to the same reason, the sulfide ores were quickly destroyed, and instead, gossans grew up downward rapidly. However, this did not mean a through oxidation of sulfides, there remained sparsely dispersed small relic particles of sulfides in gossans as observed under microscope.

While in those ore deposits lacking in disulfide, the role of this stage was much less important.

In those ore deposits such as copper-bearing skarn and magnetite type as well as in Pb-Zn or polymetallic ore deposits of disseminated and vein type in carbonate rocks, the formation of carbonate minerals immediately succeeded the sulfate stage. While in those deposits rich in disulfides, i.e. in pyrite or Cu-bearing pyrite deposits, the formation of carbonate minerals was commonly weak or even absent due to the apparent reason that the acidity of solution did not favour to the formation and precipitation of carbonates. This is proved by the rarity of malachite and azurite in gossans of Cu-bearing massive pyrite deposits. The presence of a few amount of malachite or azurite in present gossan is nothing but an oxidation product belonged to another supergene geochemical cycle (e.g. native copper and cuprite in secondary oxides subzone transformed into malachite in the air). However, the supergene enrichment of copper in those Cu-bearing skarn or magnetite type ore took place mainly at carbonate stage.

The formation of limonite in the sulfate stage was discontinuous and sporadical in keeping with the seasonal change of ionic concentration and relative proportions among Fe\(^{2+}\), Fe\(^{3+}\), Cu\(^{2+}\), SO\(_4^{2-}\) and others. The hydrolysis of ferric sulfate in large scale was
only possible when sulfide ore body had been nearly wiped out by oxidation, no supplement of sulfuric acid was available and the solution had gradually became more dilute.

The colloidal precipitants of iron oxide and hydroxide hydrolysed from ferric sulfate would be transformed by a series of successive changes, i.e., leaching, transportation, dehydration and further oxidation, such as shown in texture-structure and mineralogical composition. The manganese, for example, which has settled in iron oxides and hydroxides as colloidal and isomorphic mixtures, was then separated from the latter in the basified medium, and formed independent minerals. We often found manganese oxides and hydroxides attached on the stalactitic limonite surface or in the latter's colloform cavities, they generally existed in the upper part or at the top of gossans. Besides, a series of transitional species from manganous to manganic with decreasing in depth from the surface had been noted. Hematite and turgite (Smirov, 1945) were probably the result of further oxidation and dehydration of goethite (Gakhale, 1961a, 1961b); they are present often in the upper part or near the surface of gossans, occasionally in the colloform cavities of goethite.

As compared with those of the arid region of Northwest China (Tu et al., 1963), hematite with turgite never formed independent accumulation, they existed only in the upper part of gossans sporadically, vast accumulations are the goethite and hydrogoethite; besides, hematite in contrast with turgite is even much less in quantity.

In the Pb-Zn ore deposits, the formation of silicate succeeding that of oxide and hydroxide is quite distinct. Hemimorphite occurs as crusted veinlets cut across the limonite and forms mamillated grains in the pore-space of colloform limonite. Monheimite altered into limonite and hemimorphite around its margin was noted at an outcrop of polymetallic ores.

Copper silicate is very rare. This may be explained by that when the oxidizing medium became basified, during which silica began to dissolve in a large quantity, there remained very few Cu\(^{2+}\) ions in solution, so that the silicic acid had hardly any chance to combine with copper to form silicate. The very few Cu\(^{2+}\) ions in solution during this period might possibly go into the crystal lattice of certain silicates as isomorphic mixtures or adsorbed by clayey minerals. Nontronite, a variety of high iron content, found as veinlets in gossans, contains copper as much as 1.1\%, while X-ray analysis and DTA failed to discover any trace of independent copper minerals.

Other silicates in gossans—the hydroaluminium silicates (hydromica, kaolinite and holoysite) and the hydromagnesium silicates (sepiolite)—are mostly weathering products in connection with gangue minerals.

Phosphorous, arsenic, molybdenum and other elements generally present in country rocks and ores might have already entered into solution in their low valence when the oxidizing media still kept for weakly acidic to acidic condition (Tu et al., 1963). They precipitated in high valence in forms of complex salt only after the media completely basified. Skorodite, beudantite, turquoise and wulfenite occurred in gossans were evidently formed after the formation of oxides and hydroxides of iron and manganese, most probably later than the formation of silicates.

As to the thin leaves of native gold in limonite cavities, the author considers that they were the final oxidation products precipitated from solution with complex salt in which gold had combined with chlorine.

The essential features of development stages in oxidation of different kinds of ore deposits are given in Table 2.

A Comparison

The development of oxidation zone of sulfide ore deposits in Lower Yangtze area may be representative to most part of Southeast China and show specific features contrast to that of Northwest China. The following discussion is chiefly on comparison of the characteristics of sulfide ore oxidation between deposits in Southeast China and those in Northwest China, the data of the latter is based on the works of Dr. Guangzhi Tu et al. (1963).

(1) Solution produced by oxidation of
Table 2 Development stages of oxidation zone of sulfide ore deposits in the Lower Yangtze area (Li et al., 1980)

<table>
<thead>
<tr>
<th></th>
<th>Cu ore deposits</th>
<th>Pb-Zn (-Cu) ore deposits</th>
<th>Pyrite deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulfate Stage</strong></td>
<td>Fe, Cu, Mg, Al hydrous sulfates developed in large amount. Formation of secondary chalcocite and covellite. Intensive oxidation with great rapidity.</td>
<td>Formation of anhydrite and angle- site.</td>
<td>Large quantity of hydrous Fe-sulfate. Intensive oxidation with great rapidity.</td>
</tr>
<tr>
<td><strong>Carbonate Stage</strong></td>
<td>Cu-carbonates mainly occurred in Cu-bearing skarn and Cu-bearing magnetite ores, but very rare or even absent in massive Cu-pyrite deposits.</td>
<td>Formation of cerussite, smithsonite and small amount of malachite. Where the wall rock is limestone, a paragenesis of cerussite and gypsum is common. An important stage in Pb-Zn ore deposits.</td>
<td>Rare occurrence of malachite and azurite, siderite present in a few deposits. In massive pyrite deposits, this stage is of no importance.</td>
</tr>
<tr>
<td><strong>Oxide-Hydroxide Stage</strong></td>
<td>Precipitation of Fe-oxides and hydroxides, SiO₂ precipitated as colloidal mixture with limonite. Mn as colloidal mixture in Fe oxide-hydroxide separated from limonite and transferred from manganous to manganic. Reformation of gossan limonite both in chemical composition and texture-structures.</td>
<td>Precipitation of Fe-Mn oxide-hydroxide, presence of supergene barite. Fe separated from monohemite to form limonite. Plattnerite appeared. Mn transferred from lower to higher valency.</td>
<td>Fe(Mn) oxide-hydroxide precipitated in great amount. Supergene barite, jasper and limonite precipitated simultaneously. Mn transferred from manganous to manganic.</td>
</tr>
<tr>
<td><strong>Silicate Stage</strong></td>
<td>Presence of Fe, Mg, Al-silicates. Very few crysollita in few Cu deposits. Microcrystallized drusy quartz in limonites.</td>
<td>SiO₂ bearing solution reacted with smithsonite, most of the latter transformed into hemimorphite. It is an important stage of oxidation process of Pb-Zn ore deposits.</td>
<td>Microcrystallized drusy quartz in limonite.</td>
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<tr>
<td><strong>Complex Salt Stage</strong></td>
<td>Hydrous Cu-phosphate (turquoise) occurred in some oxidized outcrops of Cu ore deposits. This stage is quite insignificant.</td>
<td>Wulfenite and beudantite occurred in small quantity. Insignificant in the development of oxidation processes.</td>
<td>Scorodite is the only rare complex salt developed in this stage. Precipitation of thin leaves of native Au in colloidal cavities of limonite.</td>
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</table>

sulfide ore in the arid Northwest China generally has a pH value 1–3 and higher total degree of mineralization several thousand mg/l, whereas the water analysis from the sulfide-rich ore in Lower Yangtze area, the pH value and total degree of mineralization vary greatly. Value of pH of the surface spring in the mine area is 6–7, degree of mineralization generally lower than 100 mg/l; while the mine water underground especially those from intensely oxidized part, pH value may be lower than a unit, commonly 2–4; total degree of mineralization reaches several thousand mg/l, few analyses may be as high as above 10,000 mg/l. However, with increase of depth, the pH value goes up gradually, total degree of mineralization decreases. So it is hardly to say that the solution produced by oxidation in sulfide ore
is necessary higher in pH value and lower in total degree of mineralization in view of the rich rainfall in the discussed area.

(2) The essential factor controlling the oxidation process is the abundance of disulfide both in South and Northwest China. In the Lower Yangtze area, the frequent rainfall does not impede the solution in the early stage of oxidation with growing acidity and concentration of free sulfuric acid as well as ionic content of Fe$^{2+}$, Fe$^{3+}$, Cu$^{2+}$ etc. The seasonal change of rainfall may cause a strong undulation of their concentration. The hydrosulfate stage differs from that of the arid region by its limited mineral species and their transient feature. Sulfates cannot accumulate to huge amount as those in Northwest China. However, sulfate stage in South China does exist as long as the sulfide ore exists. In the arid region of Northwest China, sulfate produced by oxidation of sulfide ore may occur up to the surface exposure, while those in South China generally occur in the lower part of the subzone $Z_3$ and the upper part of subzone $Z_4$, and never observed on the surface (c.f. Fig. 4).

(3) As to the vertical zoning in the humid and warm area, subzone of gossan is extremely developed, it reaches 100-200 m below surface. Jarosite (c.f. BROWN, 1971) is never found in it. In most of the Cu-ore deposits in Lower Yangtze area, native copper, cuprite and tenorite as well as relics of chalcocite are common, this assemblage may be correlated with the subzone of native sulfur and gypsum in the Cu deposits where secondary sulfide suffer a reoxidation due to the downward movement of water table (Tu et al., 1963). In our case, it is also true that native copper-cuprite assemblage represents the occurrence of a subzone of ancient secondary sulfide enrichment. Beneath this subzone is the disintegrated and loose sulfide, the thickness of which is much greater than that of the Cu deposits in Northwest China.

(4) Carbonate minerals are rare but occur both in the Lower Yangtze area and Northwest China. The difference is that in the former area sulfate stage directly passed into oxide-hydroxide stage due to strong acidic condition unfavorable to the formation of carbonate, while in the latter area the sulfate stage went on very slowly due to the stability of sulfate minerals on the surface. As to the process of oxidation of Pb-Zn ore deposits, carbonate and silicate stage are more important than in the Cu-bearing massive pyrite ores, smithsonite and hemimorphite which are rarely found in Northwest China (Tu, 1964) are much more common in Lower Yangtze area.

(5) K, Na, Ca, Mg in oxidized zone are largely leached out under the climate condition such as in Lower Yangtze area, except Fe$_2$O$_3$ and SiO$_2$ preserved in the gossan. Most exposures of the pyrite and Cu-bearing pyrite ore deposits in Lower Yangtze area are at the oxide-hydroxide stage, the sulfate stage can only be observed where sulfide ores are not yet demolished. Most of the exposures of oxidized Pb-Zn ore deposits are at the carbonate or silicate stage. As compared with the arid region of Northwest China, it is a problem related to the rate of oxidation. The hydrosulfate minerals as an early oxidation product are relatively stable on the exposure, so it protects the primary ore from further oxidation, the speed of development in contrast to that of the humid and warm area in South China (including Kuangdong, Guangxi and Yunnan Provinces) is rather slow. A comparison of the essential features of oxidation between the sulfide ore deposits in Lower Yangtze area and that in arid region of Northwest China is given in Table 3.

Acknowledgement: The present paper is a brief of the past collaborative work on the project of “Evaluation of gossans and oxidized outcrops in Lower Yangtze area”. Here I express my thanks to the colleagues in Nanjing Institute of Geology and Mineral Resources for their doing field work and laboratory work with me, and excuse me for not listing their names (that will be too long to this paper). Geologists of the field prospecting teams provided me with their data of gossan analyses, among them are the senior geologists: Mr. Enbang HUANG of the Prospecting Team of Northwestern Jiangxi Province and Mr. Zhihua ZHOU of the Tongling Copper Mining
Table 3  Characteristics of the oxidation zone of sulfide ore deposits in humid and warm region contrast to that of arid region.

<table>
<thead>
<tr>
<th></th>
<th>Humid and warm region (Lower Yangtze area)</th>
<th>Arid region (Northwest China) (Tu et al., 1963)</th>
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<tbody>
<tr>
<td><strong>Vertical Zoning</strong></td>
<td></td>
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<tr>
<td>Subzone of gossan (limonite)</td>
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<td>Subzone of limonite-hematite</td>
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<tr>
<td>Subzone of secondary enriched oxide (subzone of palaeo-secondary Cu-sulfide enrichment)</td>
<td>Subzone of jarosite</td>
<td></td>
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<tr>
<td>Subzone of disintegrated and loose sulfide (subzone of current intensive oxidation and leaching)</td>
<td>Subzone of gypsum-native sulfur</td>
<td></td>
</tr>
<tr>
<td>Subzone of secondary sulfide enrichment (chiefly in Cu-ore deposits)</td>
<td>Subzone of disintegrated and loose sulfide</td>
<td></td>
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<tr>
<td>Zone of primary sulfide ore</td>
<td></td>
<td>Subzone of secondary sulfide enrichment</td>
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<tr>
<td></td>
<td></td>
<td>Zone of primary sulfide ore</td>
</tr>
<tr>
<td><strong>Oxide and Hydro-oxide of iron</strong></td>
<td>Goethite and hydrogoethite overwhelmingly predominant, few amount of hematite and hydrohematite.</td>
<td>Mainly goethite, hydrogoethite, but hematite also fairly developed. Variegated in color: earthy brown, yellowish brown, reddish brown, etc.</td>
</tr>
<tr>
<td></td>
<td>Hematite much less than hydrohematite.</td>
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<td></td>
<td>Yellow (hydrogoethite) and red (hematite) in the upper part, hematite increasing in amount in the tectonically stressed area.</td>
<td></td>
</tr>
<tr>
<td><strong>Jarosite</strong></td>
<td>Rare, only found in the oxidized zone of pyrite deposits in volcanic area, they are often surrounded by quartz (they may be of thermal spring origin).</td>
<td>Well developed, generally formed separate subzone, and comprised an important part of gossan.</td>
</tr>
<tr>
<td><strong>Gypsum and native sulfur</strong></td>
<td>Absent</td>
<td>Well developed, especially in those deposits in limestone, it forms independent subzone.</td>
</tr>
<tr>
<td><strong>Sulfate minerals</strong></td>
<td>Well developed in the subzone of disintegrated and loose sulfides and also in that of secondary sulfide enrichment; they are hydro-sulfate or Fe$^{2+}$, Fe$^{3+}$, Cu$^{2+}$, Mg$^{2+}$ such as melaniterite, siderotil, holotrichite, copiapite, pickeringite, chalcanthite, epsomite, ferrohexahydrate, etc., but their occurrences are rather temporary. Ferrous sulfate changes into ferric sulfates all the times. Sulfates are always present as a transient phenomenon. Not so developed in Pb-Zn sulfide deposits.</td>
<td>Very well developed, with numerous species, in huge amount, widely distributed, occurred from lower portion of limonite-hematite subzone to that of secondary sulfide enrichment. The ratio ferric sulfate/ferrous sulfate increases with decrease of depth.</td>
</tr>
<tr>
<td><strong>Carbonate minerals</strong></td>
<td>Malachite and azurite commonly existing in hosted intermediate acidic igneous rocks and limestones. Concentrations of Cu-carbonate are found in Cu-sulfide disseminated skarn and Cu-bearing magnetite ore. Poorly developed in the Cu-bearing massive pyrite ore deposits. Pb- and Zn-carbonates are common in Pb-Zn ore deposits.</td>
<td>None to poorly developed, even in the Pb-Zn deposits in limestone host rocks. No smithsonite or cerrusite was found.</td>
</tr>
<tr>
<td><strong>Mine water</strong></td>
<td>Surface spring water: pH=6–7, mineralizing degree below 100 mg/l. Mine water from oxidizing part of sulfide ore body varies greatly: pH may be lower less than 1, generally 2–4, degree of mineralization above 1000 mg/l, may be up to 10000 mg/l. But with increase of depth, pH value increases and degree of mineralization decreases.</td>
<td>pH=1–3, high degree of mineralization, generally several hundred to several thousand milligrams per liter.</td>
</tr>
<tr>
<td><strong>Geochemistry</strong></td>
<td>Fe concentrated in oxidation zone, Ca, Mg, Na, and K leached out, a very small portion of Al preserved, Cu, Pb and Zn partly preserved in gossan.</td>
<td>Fe, S, K, Na, Mg, Al, Ca, etc., concentrated in oxidation zone.</td>
</tr>
<tr>
<td><strong>Stage of development</strong></td>
<td>Fe(Mn) oxide-hydroxide stage well developed in pyrite and Cu-pyrite ore deposits Carbonate and silicate stage well developed in Pb-Zn ore deposits.</td>
<td>Sulfate stage well developed.</td>
</tr>
</tbody>
</table>
Company, I owe a great deal to them. The author also wishes to express his sincere gratitude to Dr. Bingxi ZHANG, former Professor of the Peking Geological College and now advisor of the Ministry of Geology and Mineral Resources, and Dr. Guangzhi Tu, the Director of the Institute of Geochemistry of Chinese Academy of Science, for their critical reading of the original manuscript.

References


揚子江下流域の硫化物鉱床酸化帯の特徴

李 文 達

要旨：揚子江下流域の硫化物鉱床にみられる酸化帯と硫化物二次富化帯とは、中緯度、温暖湿潤地域における酸化・二次富化作用の代表例とみることができ、その特徴は次のようにまとめられる。

(1) 綾銅鉱や金は長時間に亘る緩慢な隆起の結果深く酸化する。

(2) 上部の鋼硫化物の急速な分解、鋼の下方移動によって、二次硫化物富化帯が限られたゾーンに発達する。

(3) 二次的な自然銅、赤銅鉱がみられ、それらが、さらに孔雀石、黒銅鉱に酸化していることは、地質時代における銅二次富化作用の存在を意味する。

(4) 鉱産鉱床の酸化帯生成物は炭酸塩、珪酸塩鉱物である。

揚子江流域と非常に乾燥している中国北西部の鉱床酸化帯の特徴の比較についても述べた。