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Geological characteristics and mineralization process analysis in Pa Ben gold mine, Luang Prabang Province of Laos

Pa Ben gold mine is located in the contact belt of the Gondwanaland and Laurasialand. The North West part of Laos Bau County is connected with the Sanjian fault belt in western Yunnan Province. The running of the Pa Ben gold mainly occurs in the Permian limestone, and the adjacent contact zone. By studying the fluid inclusions and deposits role geological features of Pa Ben gold mine, it indicates that the metallogenic salinity is lower than that of the basin brine salinity (greater than 20%), and the fluid temperature is between 140 and 295 DEG C, the characteristics of metallogenic depth is less than 1 km. Considering that the gold mine are subjected to the ductile-brittle shear deformation stage, the early stages of mineralization, the main mineralization stage, the late stage, and the late tectonic activity stage, which can broke into five mineralization stage in the area. It is concluded that the genesis of the ore deposit belongs to the typical magmatic hydrothermal gold ore deposit of the middle-low temperature.

Keywords: *Pa Ben gold; Deposits role Geological features; Characteristics of fluid inclusion; Mineralization stages*

1. Introduction

Pa Ben gold mine occur in the contact zone of Phongsali-Phrae (Thailand) Mesozoic depression zone (II) and Luang Prabang - Loei (Thailand) Variscan fold belt (III). It is near to the Luang Prabang fault (F2), and extremely favorable conditions for mineralization in the tectonic position [1-4]. The main area is exposed in the late Paleozoic strata lithology of the volcanic, clastic marine carbonate magmatic rocks (Fig.1).

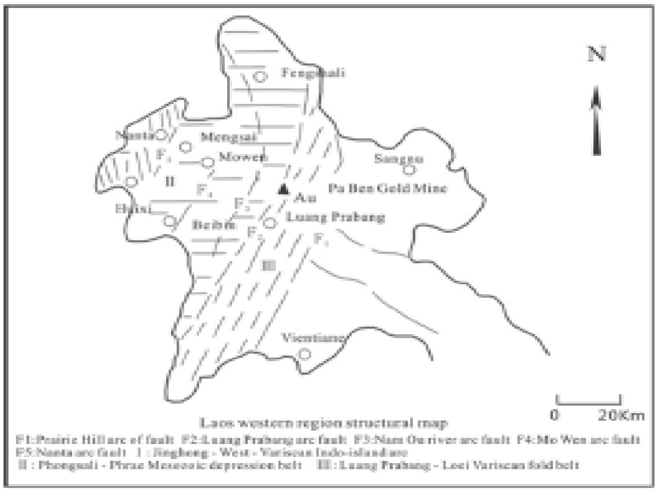

Fig.1 Regional tectonic geological sketch in northwestern Laos

Luang Prabang fault zone is trending southward extended and extended along with the Uttaradit, Thailand. It may connect China Ailaoshan band to the north, where it is the west branch of the construction zone. This area develops intensive structure activities, and it has good geological condition of mineralization. The acidic rocks, and mafic rocks are exposed. Along with the volcanic activity, the volcanic intrusive rocks are development. It is also very rich in mineral resources in the region, known as iron, tin, antimony, copper, lead, zinc, gold, silver and other minerals.

2. Mining geology

2.1 Mining formation

The late Paleozoic of Permian and Quaternary mine strata outcrops relatively completing. As the result of the special tectonic position and movement at the frequent occurrence of the region, the formation of deletions and overlap phenomenon is more common. Ore belt mainly exposed in the

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Late Paleozoic Permian strata and Quaternary systems (Fig.2):

(1) Permian (P): The lower of P_2^1(Permian) formation is located in the northwest region, and it is mainly included the gray-green dense block of basalt, dolerite, basaltic tuff (molten) rock and local folder greenstone, along with the volcanic eruption. The andesitic tuff is on the bottom. It is integrated with the upper sandstone and contacted with the relationship [5]. The upper of P_2^1 formation is distributed in the central and eastern parts of the region, as continental clastic rocks, which are mainly included red sandstone, siltstone, mudstone and shale. Central clip set conglomerate, and the upper and lower strata are angular unconformity, and the fault of local contacts. Its thickness is greater than 300m[6]. The P_2^2 (Permian) formation is located in the central area, which belongs to irregular lens-shaped marine carbonate. The lower part is dark gray limestone and black shale, the upper part is gray limestone, dolomite with marble, composed of steep ridges [7]. The main formation is host rock mining. Its thickness is about 550m. The main fossils have dragonflies, corals, and bryozoans.

(2) Quaternary (Q): It is mainly in located in the region of valleys and low-lying areas, mainly for the red clay and gravel, etc.

2.2 Mine construction

2.2.1 Mining fold

The large fold structure is more developed in the mining area. It is mostly distributed in the area of continuous folds, and relatively strong majority eroded anticline suffered late. The core part of the Devonian strata exposed at the surface, and the two wings are the Carboniferous and Permian layers.

The small mine fold structure is not obvious, and it can only see some small crumpled and folded structure in the Devonian sandstone, phyllite and other older rock. (Fig.2)

2.2.2 Mining fracture

The north east of Luang Prabang fracture is extremely development. Throughout the region, the fracture performance is in ductile-brittle shear type. The main brittle faults are north-east, north-northwest, and north-west. Among them, the north-northwest trending fault is the main ore-controlling structure [8-10].

2.3 Magmatic

The mine is located in the Luang Prabang and the zone magmatism is strong activity. Acidic and basic rocks are exposed on the earth's surface.

(1) Extrusive rocks

Fig.2 Small folds in sedimentary rock

The effusive volcanic body is andesite in western mine. The diabase, diorite and andesite are large-scale exposure. Little phenocrysts are substantially aphanitic, even weak green plate rock have alteration phenomenon.

(2) Intrusive rocks

Currently, it can only found dioritic intrusive rocks existing in the western L2-3 region. It exposes a smaller scale in the Little Rock branches form output. The rock is weathering strong, and it is observed only known phenocrysts, strong clay-based surface, and twin crystals observed phenomenon. The rock have significantly intrusive contact relationships. Determined by microscopic identification sheets for fracturing, it existes sericite, chlorite and colored diorite.

3. Geological characteristics of the deposit

3.1 Ore body characteristics

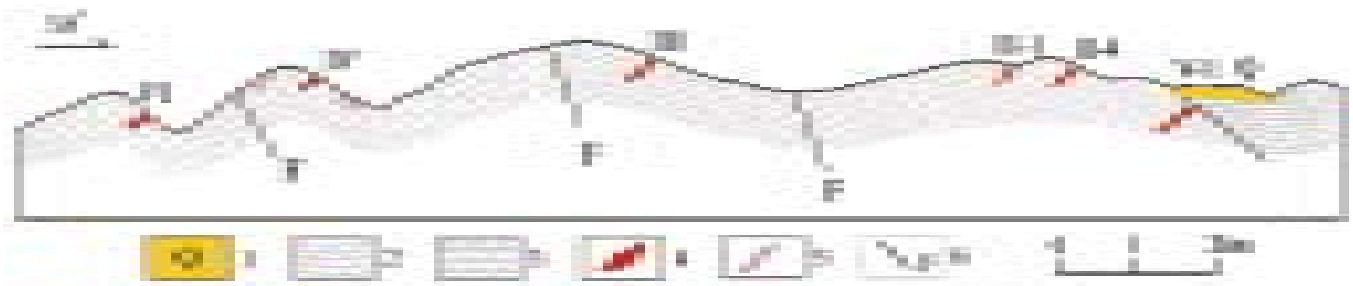
3.1.1 Ore distribution

Through field reconnaissance and prospecting, it can reveal that Pa Ben mines is found from the north east to southwest, which can divide into V, II, III, IV, VI number five ore bodies. The II ore body can separate into two parallel ore bodies of II-1 and II-4. All the ore bodies locate in the Permian limestone weathering residue. The belt is controlled by NE direction of brittle-ductile shear zones, and the ore body is controlled by NNW direction fracture. A few ore is parallel veins, the profile imbricate arranged in parallel, the overall trend NNW direction (355°), and the angle of the belt is between 35 and 40°, The ore bodies display parallel, occurring as a vein zone, equidistant spacing substantially, and the distance of space is about 300m.

The ore bodies extend toward stability and the tendency extend relatively stable (Fig.3), but there is another group of NW trending faults, resulting to make the ore produce dislocation in the southwest of the mining area.

3.1.2 Ore body morphology

Through using the ore body plane, the profile characteristics of ore body are mainly affected by the north-east and north-west ductile deformation stage. It is controlled by the ductile-brittle faults early ductile deformation zone



1-Quaternary 2-Sandstone 3-Limestone 4-Ore body 5-Mineralization 6-Fault

Fig.3 Cross-sectional schematic ore distribution

superimposed transformation. Ore body shapes are overall relatively simple explanation for the fracture fissure filling ore. Ore vein and wall rock interface are clearer, the vast majority of mutations are contact with lots of relationships, cystic ore body local swelling part. Due to hydrothermal mineralization strong, the appeared infection ore body and rock hold into a gradual contact relationship. II-1, II-4 ore body:

These two ore bodies look like the same basically, roughly parallel with the d! ore body. There also have expansion and contraction, and branching phenomenon. Observing the field of pit mining, the branches of ore are located in the ore body on the plate. The composite phenomenon is not observed, and a branch of the ore body thickness is increased. The construction is affected by the superposition of different directions. Overall mine with rock deformation is weak. The late tectonic superposition play more obvious role in the performance of broken ore.

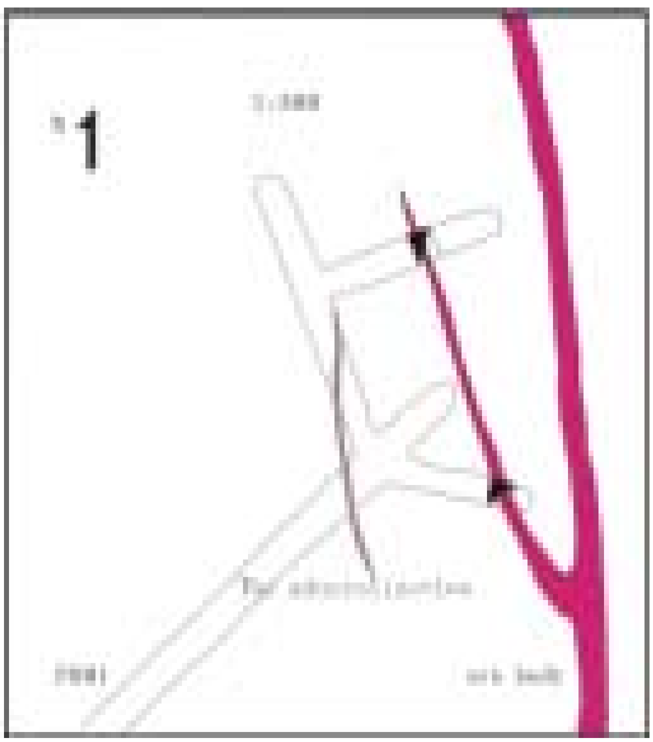


Fig.4. II-1 PDM1-1 ore body schematic form

Vein ore bodies: Paralleling tod!ore body, the main of the fault zone development in the north-west direction and inclination SW (265° ∠50°), where the development of calcite veins "red" of alteration phenomena along with the structure surface, and the structure surface is relatively stable. It constitutes the main part of the ore veins. There is more developed in the ore-controlling structure and early piece physicochemical band in the same direction (towards north-east, south east tendencies), but inclination relatively slow set of bedding with ductile-brittle fault zone. Rock crushing is strong growth, and breccia type ore is development. Intense tectonic activities can produce the pre-stress, which are more concentrated form fracture zones. The latter explanation filling cemented hydrothermal mineralization.

Ore vein branches: The fracture has controlled the mine rupture on the plate branch. The lower plate is no branch of the lower plate fracture, which the existence of branches broken needs re-evaluation of the actual engineering controls. The ore body extends generally is not long, and usually between 5 and 15m. Away from the main ore body is about 1 to 6m, and it appears pinch. Occurrence tendency is about 265° and the tilt angle is between 50 and 65° (Fig.4).

3.2 Ore characteristics

3.2.1 Ore types

The samples were light sheet by grinding and large glossy polishing, and it carried out detailed rock and mineral identification and petrographic analysis.

In the trenches, the alteration zone mineral ore is disseminated red and weak red. The course of reddening is controlled by tectonic fissures and obvious reddening consistent with mineralization, indicating that the "red" of alteration. The mineralization had very close relationship. "Reddening" substantial alteration is due to early Fe among hydrothermal ore mineralization in the latter part of the process, the formation of trivalent iron ions, disseminated carbonate wall rock colored red.

3.2.2 Ore mineralogy

By using light thin section and electron microprobe analysis, it can determine the mineral composition of the ore deposits in relatively simple, metal minerals are native gold, limonite, siderite, goethite, metal sulfides. Non-metallic minerals are calcite, dolomite, quartz, apatite, arsenopyrite, realgar, and orpiment.

3.2.3 Structure of the ore, construction

Ore structure is mainly euhedral, subhedral granular structure, granular shaped structure following. There is some ore mortar texture. Ore structure composed mainly disseminate structure, thin veins or band structure and break brecciated structure [11-14].

4. Characteristics of fluid inclusion

4.1 Microscopic characteristics of inclusions

Deposit of fluid inclusions in calcite is liquid gas (L-V) two-phase inclusions, which is generally is round, oval, bars, kidney, eye, triangular and irregular shape, Particle size is between (2-10) μm and (2-6) μm. It is in groups or in bulk distribution. It is given priority to with liquid phase composition, and the liquid phase composed mainly gas-liquid volume fraction of the majority of 5% to 15%, part of them between 20% and 30%.

According to the analysis the composition of fluid inclusion body fluidÿit can be seen that: (1) The liquid phase is composed of Na^+, K^+, Ca^{2+}, Mg^{2+}, and there are $Na^+>K^+>Ca^{2+}>Mg^{2+}$ cation concentration sequence. The characteristic is $Cl^->HCO_3^->F^-$. In general, the ore-forming fluid is in the Na-K-Cl type brine. (2) Concentrations of each component are significantly lower than the typical basin brine, reflects the ore-forming fluids are low salinity (low maturity) of the hot brine. (3) The samples of the X_{Na}/X_K are greater than 2, the average is 6.12 (the X represents the amount of substance concentration); (4) The inclusion of water pH value between 7.28 and 8.56. Belonging to the near weak alkaline environment, it may not represent the metallogenic period of fluid pH, but the late inclusion of internal water rock reaction results. From the inclusion composition, the ore-forming fluid in the gas phase is mainly composed of CO_2, followed by a small amount of CH_4, and N_2, C_2H_6 and CO were not detected, which accounted for more than 97.5% of the total gas CO_2. It shows that the ore-forming fluid is a fluid rich in CO_2.

Salinity test results show that (Table 1), the higher temperature of deposits phase salinity range from 1.22% to 2.55%, which the average value is 1.77%, and the lower temperature phase salinity range from 4.17% to16.7%, which the average value is 7.64%. It shows metallogenic salinity is not high, significantly lower than the thermal basin brine salinity (>20%). The salinity of the ore-forming fluid is to determine fluid source of an important symbol.

The salinity fluid inclusions of Pa Ben deposit are low, indicating that the ore-forming hydrothermal fluids may be either magmatic hydrothermal, metamorphism air or water hydrothermal . Basic geological conditions show that the ore-

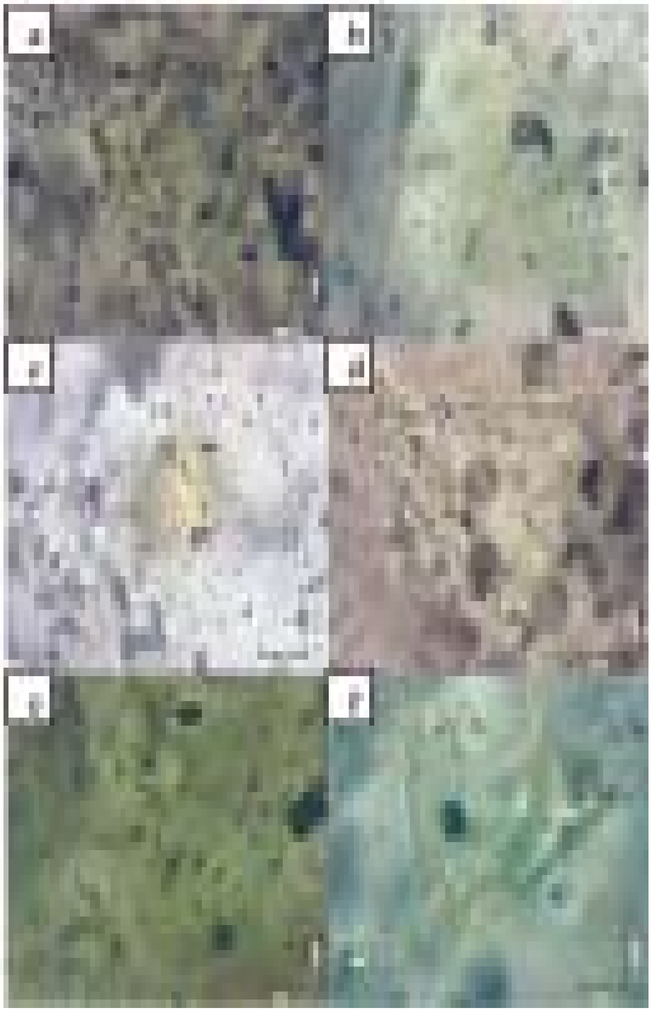


Fig.5 Microscopic characteristics of inclusions

forming fluids deposits does not exist metamorphic hydrothermal origin. In addition, the mining area northwest of 4km at the L2-3 and L5 region exist diorite. And in mining area north east direction 8km at L8 boreholes and tunnels exist anchorite. In the mining area of about 20 km exposure the Late Permian - Early Triassic granite flash rock.

The fold belt are developed in the Late Paleozoic - Early Mesozoic orogenic stage and pre orogenic continental margin of the granite magma intrusion are activity in the area, extensive development phase of the basic, neutral, acidic volcanic eruption and overflow. Especially in the Permian and Jurassic, the granite intrusive rocks mainly developed the gold mineralization. There have been found more than 30 gold points in Thailand [15-17].

At the running of the region and Pa Ben gold, it has been found numerous mineralization points, gold dispersed flow, and heavy sand anomalies. Preliminary thought it should be directly with the late Paleozoic - early Triassic magmatic intrusion. Volcanic activity has a direct relationship including the rush area of gold metallogenic epoch and the south of nonferrous metal metallogenic.

Namely, the age of magmatic fluid provides the ore-forming materials, and the ore deposits in the shallow brittle faults. It is supposed that the post magmatic hydrothermal fluid, accompanied by the presence of atmospheric water hydrothermal and hybrid origin [18-19].

4.2 Inclusion thermometry

According to the fluid inclusions microthermometry (Fig.5), sample of 354 gas-liquid two-phase inclusions temperature statistics, it shows that homogeneous temperature 107-332ºC (Table 1) in the 10 samples. And according to the mineralization stage corresponding fluid inclusions specimens, each made metallogenic stages corresponding to a uniform temperature histogram (Fig.6).

Studying the homogenization temperature chartÿit can be seen that the frequency of uniform temperature is mainly concentrated in three intervals: 120-230ºC, 230-310ºC, 310-340ºC, of which up to 120-230ºC segment, reached 153 individual, which is about accounting for 43% of the total.

Phase I of the homogenization temperature is mainly range 310 to 340ºC, phase II homogenization temperature is mainly 230 - 310ºC, stage III homogenization temperature is mainly 120 - 230ºC, homogenization temperature is decreased. But in II and III mineralization stages, the homogenization temperature is mainly 160 to 240ºC.

Failed to be completely separate in the two phases, indicating that fluid may be the continuous fluid, which can be as the main ore-forming fluid phase fluid temperature, the bottom may also be associated with fluid inclusions represent, in order to determine the fluid and mineralization related activities can be divided into two phases.

The high temperature of the first period can reach more than 300ºC, may be associated with the post magmatic hydrothermal evolution, with hydrothermal, later gradually sedimentary water or adding meteoric water.

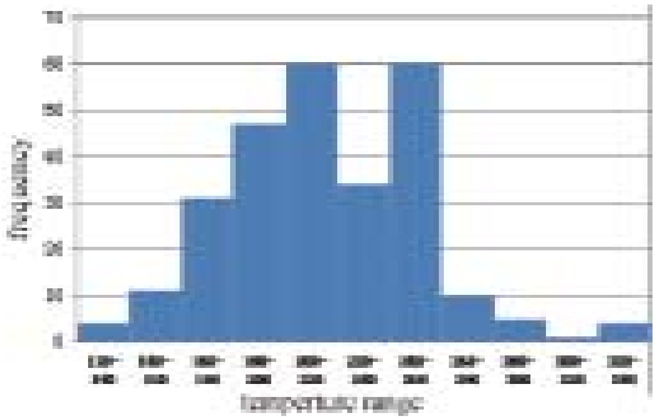


Fig.6 Histograms for homogenization temperature of fluid inclusions

Hydrothermal activity has a period of time. According to the ore mineral metasomatic and surrounding rock incident, it can judged that the early hydrothermal fluid is a weak acid, and it is conducive to the activation and migration of gold, when after entering the occurrence of hydrothermal ore space conducive to carbonatitic rocks, which are altered account of late due to the dissolution of carbonate minerals, when the hydrothermal evolved into a weakly basic, and more conducive to the enrichment of gold again.

4.3 The pressure of inclusions and metallogenic depth

The area measured inclusions freezing temperature are change from –10.7 to –0.5ºC, it can in line with low salinity NaCl-H_2O system , and there is no obvious boiling inclusions evidence. According to ore-forming pressures and depth of experience formula , it can be calculate that mineralization pressure P1 is obout (9.34 - 21.37)×10^5Pa, with an average of 16.3×10^5Pa, and calculated mineralization H_1 should be 0.48 - 0.960km. It can determine the Pa Ben gold deposit belongs to epithermal deposits (Fig.6).

Regional geochemical results show realgar, orpiment, arsenopyrite, and cinnabar. A series of typical sericite epithermal mineral assemblages appear on the abnormal,

Table 1. Analysis results of homogenization method temperature measure for the fluid inclusion in calcite

No.	Sample Number	Mineral	Inclusion characteristics			Freezing point(–ºC)	Salinity (wt.%NaCl)	Homogenization temperature (ºC)	Average temperature ºC)	Test number
			Type	Size (μm)	Comparison (%)					
1	PB005-1	Silica	V-L	2-8×1-4	10-25	0.5-5.2	3.23-15.8	121-202	153	42
2	PB005-2	Silica	V-L	2-10×1-5	10-20	0.8-6.5	2.57-16.7	107-195	148	35
3	PB005-3	Silica	V-L	2-15×1-10	10-40	3.3-6.5	2.64-12.54	126-232	162	40
4	B255-5	calcite	V-L	4-33×1-8	10-40	0.7-4.8	1.22-7.15	182-285	193	29
5	B261-3	calcite	V-L	4-12×2-10	10-20	1.6-4.1	2.89-6.72	140-238	186	45
6	B256-4	calcite	V-L	3-12×1-7	5-25	10.7-2.3	1.22-4.17	121-252	187	24
7	B276-33	calcite	V-L	3-6×2-5	15-30	3.2-4.4	5.25-7.01	214-332	252	29
8	B012-1	calcite	V-L	3-12×2-6	5-60	1.0-4.3	1.73-6.87	156-235	165	23
9	PB009-2	calcite	V-L	3-10×2-4	10-30	3.4-4.2	5.55-6.87	167-286	209	43
10	B270-4	calcite	V-L	3-5×2-4	15-20	2.4-4.5	4.01-7.44	144-266	211	44

mineral assemblages As, Hg, Sb, Ti and other trace elements in combination, which can indicate that the hydrothermal temperature are lower. It also can see a small amount of sphalerite, galena, chalcopyrite, pyrite, etc., It can determine the mineralization is hydrothermal-magmatic low temperature fluid, which is also consistent with the inclusion temperature measurement results (140-295ºC).

5. Mineralization process analysis

According to a comprehensive study of the regional geology and mining background in the study area, the geological characteristics indicate that gold mineralization Pa Ben process can be divided into the following stages:

(1) Ductile-brittle shear deformation stage

Indo-Yanshan early forms the basic structural pattern of north-east and north-west fracture squeeze tensional faults, which provides the necessary conditions for mineralization. After the pattern formation, although affected by the post-tectonic activity, but the basic pattern does not much change for the multi-stage mineralization consecutive and provide a stable geological condition.

(2) The early stages of mineralization

In the late magmatic activity, volatile-rich hydrothermal fluids pooled to form the high-pressure soda hydrothermal activation in the formation of magmatic evolution. Extracting of Au, As, Sb and other elements go into the fluid. The forming hydrothermal fluids along through the deep and deep fault shear zone shallow rapid rise in migration. And enter the tensional faults and fractures and rock metasomatism occurred. Then, precipitated silica, pyrite and other sulfide take shape. The gold complexes destroyed, and released to crack gold. The gold inclusions present in the quartz, pyrite, siderite, and pyrite inclusions as well as the presence of high-grade gold ore sulphide content that is a lot of evidence that the procedure. Meanwhile, the acidic magma itself has a high fO_2, and gold - sulfur complexes with carbonate minerals action surrounding rock will produce O_2, part of the iron will combine with oxygen to form limonite, disseminated surrounding rock formation early "red" of alteration, mineralization is a direct sign. This phase is mainly formed of disseminated ore bodies. Early construction of the interchange and the fracture surface fracture zones account for fracture zone breccia, and metasomatic mineral formation breccia cemented breccia type ore, ore veins form of cystic. To contact metasomatic mineralization based.

(3) The main mineralization stage

At this stage, the occurrences of physical and chemical properties of the ore-forming fluids have a big change relatively. Due to the increasing number of dissolution of carbonate minerals, the HCO_3^- ion concentration is also increasing. Ore-forming fluids show weakly alkaline. Under the action of this fluid, the original silicified carbonate and

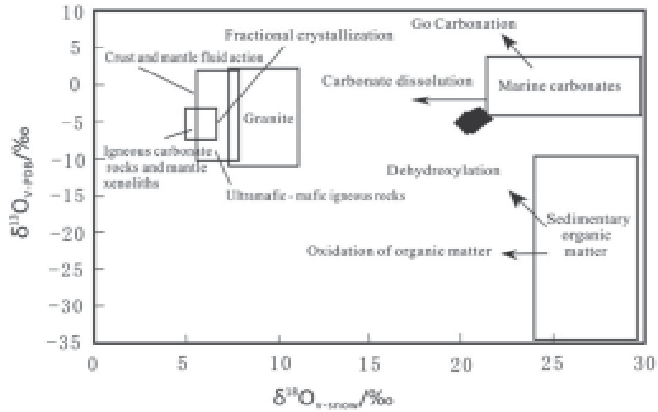


Fig.7 Mineralization pattern schematic

minerals quartz minerals are reactions by the metasomatism.

At the same time, the release of gold occurs in carbonate minerals. In the meantime, part of the sulfate minerals continues to be oxidized, especially pyrite. The sulfur is released. The iron is oxidized further to form a "red" of siderite alteration or alteration, and unoxidized pyrite remains observed inclusions gold.

Similarly calcite ore and oxygen isotope analysis also showed that the occurrence of gold calcite mineral products for fluid and Permian marine carbonate rock interaction. 13CV-PDB (‰) values distributed between –4.5 and –5.2, ^{18}OV-SMOW (‰) values distributed range 20.0 to 20.8 (cited in Pa Ben Gold calcite C, O isotopic composition tables). The mining isotopic compositions of the relative concentration of the sample can indicate its causes single. Causes of CO isotopes in carbonate diagram, isotopic composition of marine carbonate projection are landed near the area, and showed again precipitated that the crystalline carbonate dissolution causes evolutionary trend (Fig.7).

Description gold-rich calcite veins surrounding rock and post-carbonate ore fluids, dissolution and re-precipitated crystals form. The results of analysis and mineralization processes are consistent, and it consistent with the geological facts.

This stage is the stage of enrichment gold again, it is essential for the formation of ore bodies. First of all, a lot of gold is to be released, re-distribution, re-enrichment, easy to high-grade ore. Furthermore, due to calcite crystallization speed, a lot of fine gold late into the crystal interior. A large number of fine gold particles together to form a large bright gold distributed among the calcite crystals fracture. The calcite is highly soluble in groundwater action will release the gold, resulting in the formation of bright gold, which improved the quality of the ore greatly.

This stage mineralization mainly accountable and filling the main role of ore-bearing hydrothermal fluids, in addition to continue to account for ore bodies surrounding rock formation. It is worth noting at this stage accompanied by

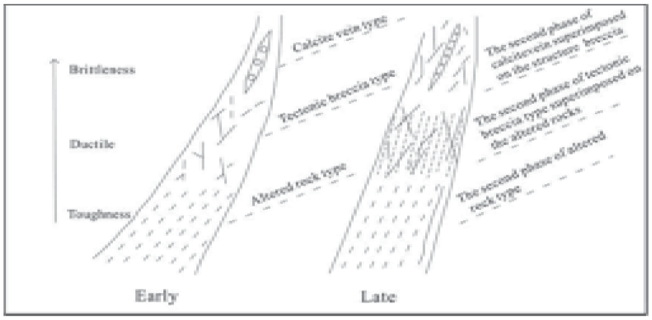


Fig.8 Sketch of metallogenic model of Pa Ben gold mine

tectonic activity. Through the study of the relationship between structure and mineralization and alteration and ore structure, there are some structural breccia breccia ore early alteration minerals. The cement and breccia have high The gold grade, and pure limestone breccia confessed grade would be much lower. Explain the cause of the high-grade ore is mineralized rock in the early formation of tectonic activity after broken, and then cemented by late hydrothermal mineralization. That can prove that the existence of tectonic activity during the two hydrothermal. This also shows that mineralization shear events simultaneously, or mineralization is cut before the end of the late activity (Fig.8).

Regional geological evolution in Laos, in the Early Triassic to Middle Triassic, due to oceanic crust subducted from NE to SW, led basin closure, rock fold uplift. Then the northeastern Laos and long folds formed hill zone (shear zone), accompanied by large-scale acidic magmatism, which is consistent with the region of magmatic age (255 ± 10Ma) basically. It can judge that the mineralization may the late indosinian shear activity or slightly early Yanshan. It is the same with other magmatic hydrothermal deposits in the region basically. It also can indicate that the Pa Ben gold mineralization fluid is inextricably linked with magmatic activity within the region.

(4) Late phase

This stage occurs in hydrothermal late. When the fluid temperature is lower, the ability of alteration and mineralization explain weak. Only can take shape form some weak mineralization filling. Filling calcite are mainly coarse crystalline particles.

(5) Late stage tectonic activity breaks mine

It mainly affected by NE-SW compressional tectonic activity in Yanshan primarily. The event forms a series of north-west to the pressure-shear fault. Through field research field observations, the series is not the size of the fault, but in the southwestern mining ore produces so obvious dislocation and displacement.

6. Conclusions

The salinity test results shows that the higher temperature of deposits phase salinity range from 1.22% to 2.55%, which the average value is 1.77%, and the lower temperature phase salinity range from 4.17% to 16.7%, which the average value is 7.64%. It shows that metallogenic salinity is not high, significantly lower than the thermal basin brine salinity (> 20%). The salinity of the ore-forming fluid is to determine fluid source of an important symbol.

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Through systematic analysis of the regional geological background of Pa Ben's gold deposits research, characteristics of ore bearing strata, geological feature of ore deposit, pressure of inclusion and the mineralization depth, it is concluded that the genesis of the ore deposit belongs to the typical magmatic hydrothermal gold ore deposit of the middle-low temperature.

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