Crust-Mantle Structures and Gold Enrichment Mechanism of Mantle Fluid System *

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Abstract: Gold enrichment mechanism of ore-forming fluid is the essence of gold metallization. This paper summarizes the distinguishing symbols of mantle fluid and effect of crust-mantle structure on fluid movement. Fluid moving processes include osmosis, surge, gas-liquid alternation and mutation of fluid speed. During fluid movement, gold will be enriched gradually. Finally, a layered circulatory system is illustrated in this paper.

Key words: crust-mantle interaction; gold-bearing fluid movement; gold enrichment mechanism

1 Introduction

Gold enrichment mechanism of ore-forming fluid is the essence of gold metallization since it determines the formation and distribution of gold deposits. Crust-mantle interaction activates ore-forming fluid and affects its layered circulatory system. Much work has been focused on the fluid origin and reactions among magma, water and rocks (Sun Fengyue et al., 1995; Deng Jun et al., 1996, 1998; Zhai Yusheng et al., 1999). Taking the Jiaodong area of Shandong Province for example, this paper presents a preliminary analysis of the mechanism of gold enrichment in ore-forming fluid, i. e., gold enrichment in the moving process of ore-forming fluid.

2 Crust-mantle interaction and deep-seated structure

In the Jiaodong and Jinan areas, the formation and distribution of ore deposits are controlled by crust-mantle interactions and activities of deep-seated fluids. The North China and East Shandong plates collided during the T-J_1 period, forming the Huifahe-Tailu fault. In the Middle to Late Indosinian, the fault incised the upper mantle, leading to a conversion of mantle weak zone into arboreous network. Therefore it not only provided channel ways for mantle fluids in the crust, but also broke the former balance, resulting in the distinct imbalance between stress and energy. Then, with fluid ascending on a large scale, metallogenic elements were enriched and finally deposited as ores in the dilated locations. The shearing-induced anatexis of the Huifahe-Tailu fault is the major driving force for the movement of fluids, which constrain the formation and distribution of ore deposits directly.

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3 The distinguishing symbols of mantle fluids

Recent research shows there exist mantle fluids in addition to magmatic fluid and metamorphic fluid involved in ore deposition. There have been found five distinguishing symbols. (1) Deep fault: the Zhouping fault zone controls the formation of major ore deposits in the Jiaodong area, such as the Xiadian and Dayin' gezhuang ore deposits. (2) Gold veins are associated with basic and ultrabasic rocks, usually surrounding diabase and lamprophyre dykes. Their approximate ages indicated that the gold veins were formed during the Yanshanian period. (3) Stable isotope: $\delta^{34}S$ values are mostly within the range of 0‰ – 3.45‰ (Table 1) and $\delta^{13}C$ values, –4.6‰ – –4.8‰ (Table 2). The $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios are 17.121 – 17.247 and 15.432 – 15.508, respectively. (4) The communicating symbols of multi-layer fluid system. (5) Quartz inclusions (Table 3): the gaseous components of inclusions are mainly CO_2 and H_2O in addition to N_2, CO, H_2 and CH_4. The main cations and anion are Na^+, Ca^{2+}, K^+ and Cl^-, showing the ore-forming fluids are of the CO_2-NaCl-H_2O type (The components of inclusions are manly CO_2, NaCl and H_2O, of which CO_2 accounts for more than 40% of the total) and NaCl-H_2O type (The components of inclusions are manly NaCl and H_2O, with the ratio of gas to liquid being 10% – 30%). These characteristics reflect that the ore-forming fluids partly come from the mantle.

Table 1. Sulfur isotopic composition of the Xiadian-Xiazhuang ore deposits

Sample No.	Mineral	$\delta^{34}S$ (‰)	Sample No.	Mineral	$\delta^{34}S$ (‰)
A21-1	FeS_2	-0.23	A21-5	FeS_2	3.45
A21-2	FeS_2	-0.17	A21-6	FeS_2	3.34
A18	FeS_2	0.14	A20	FeS_2	4.57
A21-3	PbS	0.89	A21-5	PbS	3.68
A21-4	PbS	1.56	A21-6	PbS	5.2
A19	PbS	2.47	A20	PbS	4.47

Measured at the Test and Analysis Center of Jilin University.

Table 2. C and O isotopic composition of the Xiadian-Xiazhuang ore deposits

Sequence No.	Sample No.	Mineral	$\delta^{18}O$‰ (PDB)	$\delta^{18}O$‰ (SMOW)	$\delta^{13}C$ (PDB)
1	A20	Calcite	-23.8	6.7	-4.8
2	A21	Calcite	-21.0	9.0	-4.6
Average			-21.86	8.16	-4.7

Measured at the Test and Analysis Center of Jilin University.

Table 3. Composition of gas-liquid phases in quartz inclusions from the Xiadian gold deposit

Component	Positive ion group (μg/L)				Negative ion group (μg/L)				Gas group (μg/L)						
Sample No.	K^+	Na^+	Ca^{2+}	Mg^{2+}	F^-	Cl^-	NO^{-3}	SO_4^{2-}	H_2	N_2	CH_4	C_2H_6	CO	CO_2	H_2O
1	1.35	1.32	0.84	0.26	0.25	0.24	0.08	3.14	1.02	58.4	1.05	〈0.05	2.84	32.72	326.4
2	3.41	1.50	19.1	20.9	0.29	0.34	0.07	44.2	4.25	31.8	2.20	〈0.05	1.99	2173.5	342.95
3	0.21	0.15	0.08	0.06	0.10	0.10	0.13	0.09	0.53	20.4	1.80	〈0.05	0.82	85.63	198.6
4	4.32	3.35	0.21	0.29	1.98	2.19	0.07	4.01	1.57	0.23	4.16	〈0.05	0.84	10.34	356.77
5	0.62	0.62	1.18	0.56	0.11	0.18	0.03	2.70	0.84	2.46	0.98	〈0.05	0.89	410.06	1491.06

Sample No.	Na^+/K^+	Cl^-/F^-	CO_2/H_2O	$CO_2/CO+CH_4+H_2$
1	0.97	0.96	0.10	6.664
2	0.44	1.172	6.33	257.52
3	0.71	1.00	0.43	27.18
4	0.78	1.106	0.02	1.57
5	1.00	1.636	0.275	180.64

Measured at the Test and Analysis Center of Jilin University.

The salts enhanced the dissolution of gold. The partition coefficients between sulfides and silicates are within the range of $10^3 - 10^5$ (Barnes, 1993; Bemen, 1994). So it is considered that mantle fluids are more capable of enriching gold.

4 Mantle-rooted metallogenetic elements

The Earth is a continually evolutionary planet in the solar system. Under the action of Earth's synthetic stress field, the elements making up the Earth segregate in different ways. The trend as a whole is that the elements low in specific gravity move up to the crust, while those of high specific gravity move down to the core (Table 4). For example, at the initial stage, Au, as a siderophile element, moved down to the core together with Fe, Ni and so on. In different spheres of the Earth, the contents of Au are not the same, i. e. , 0.003×10^{-6}, 0.001×10^{-6}, 0.900×10^{-6} in the crust, mantle and core, respectively. It is obvious that the segregation of the Earth makes Au enrich in the core. So, the core is a huge reservoir of Au (Niu Shuyin et al. , 2001). Meanwhile, Au can be brought up to the crust by mantle plume.

5 Moving gold-bearing fluid system

5.1 Osmosis of fluid

Fault clay is thought to be waterproof, but in some cases it can contain gold-bearing fluid, which is an important contributor to metallization. The discovery of ore deposits on both sides of the Zhaoyuan-Pingdu fault provides direct evidence for the above point of view.

Osmosis is the main mechanism of fluid flow through fault clay. Assuming that fluid moves from the bottom (A point) to the top (B point), the penetrating quantity V in one unit square is defined as:

$$V = K[(H_1 - H_2)/L - I_0]$$

(L is the thickness of fault clay, H_1 and H_2 are water height at points A and B, K is the osmosis coefficient in the direction vertical to the stratum, and I_0 is the initial waterpower grade.)

When there is little difference between the two ends, that is, $I < I_0, V < 0$, no osmosis will happen, and if the difference is significant, i. e. , $I > I_0$, $V > 0$, fluids will start to penetrate downwards. Osmosis in the fault clay is also referred to as leakage. Fluids in the leakage do not obey Newton's internal friction law, requiring an outside force to overcome the resistance to shearing. The situation is different from the ideal fluids. Depending on the alternation of gaps of various sizes, the fluids move in the style of sheet flow (Liu Yutian et al. , 1992), making smaller-grained metals and nonmetals concentrated in gaps complying with their sizes separately.

Ore-forming fluids find their way into faults after penetrating fault gouges, which makes fluid permeability rise sharply. For example, in the minerogenetic process, the permeability of fluids in faults developed in different strata is modeled (Fig. 1). With time passing by, the permeability tends to decrease obviously in the Lengjiaxi Group and the upper and lower members of the Madiyi Formation of the Banxi Group. In the transitional member of the Madiyi Formation, it rises gradually first, and then goes down after 20 Ma. In the Wuqianxi Group it rises gradually. Considering the fault permeability varies with depth (Fig. 2), it is thought that the fault permeability is highest in the transitional member of the Madiyi Group and Wuqianxi Group, and its action lasts much longer. So the faults in the two strata are most beneficial for fluids to flow and be involved in mineralization. Two-dimension modeling of evolution of fluid flow field in fault (Fig. 3) shows that the development of faults is beneficial to the increase of porosity and permeability of rocks and provide channel ways for fluids.

Table 4. The distribution of some elements in different layers of the Earth

Element classified	Element	$\omega_B/10^{-6}$				
		Crust	Upper mantle	Below mantle	Core	Earth
Rare-alkali element	Li	21	4.1	0.5	-	1.4
	Rb	78	2.6	2.0	-	1.8
	Cs	1.4	0.3	0.1	-	0.09
Rare-earth metal	Sr	480	120	10	-	40
	Ba	390	76	1	-	23
Rare-earth element	Y	24	5.0	0.5	-	1.7
	La	39	0.7	0.4	-	0.5
	Ce	43	1.1	0.7	-	0.8
	Pr	5.7	1.0	0.1	-	0.3
	Nd	26	5.0	0.8	-	1.7
Rare element	Nb	19	6.0	1.0	0.1	2.1
	Ta	1.6	0.1	0.01	0.006	0.06
Halogengroup element	F	450	170	100		90
	Cl	280	50	50		-
	Br	4.4	1.1	0.5		0.6
	I	0.6	0.1	0.01		0.04
Radioactive element	U	4	1.0	0.014	0.003	-
	Th	13.5	4.0	0.056	0.013	-
Iron-group element						
	Cr	110	1600	2000	660	1500
	Mn	1300	1600	1500	360	1200
	Fe	58000	95000	98000	82000	32000
	Co	25	160	200	420	260
	Ni	89	1500	2000	48000	16000
Platinum group element	Ru	0.001	0.1	0.10	16	5
	Rh	0.001	0.02	0.02	3	1
	Pd	0.01	0.09	0.12	5.5	1.8
	Os	0.001	0.05	0.05	8	2.6
	Ir	0.001	0.05	0.05	2.6	0.8
	Pt	0.05	0.20	0.20	13	4.2
Non-ferrous metal						
	Cu	55	40			140
	Pb	12	2.1			13
	Zn	94	60			180
Precious metal	Au	0.003	0.001	0.001	0.9	-
	Ag	0.08	0.06	0.005	10	3.2

Note: ' - ' stands for zero of the element's mass content (after Liu Yingjun et al., 1987).

5.2 Gas-liquid alternation

When preliminary mantle fluid, a supercritical, highly dense, highly compressed fluid, flows upwards to a certain level, gas and liquid are separated and gas continuously ascends. As the temperature and pressure decline in a limited range, the gas state can be maintained for a long time. Ultradeep drilling in Silijan (Russia) and Oberpfalz (Western Germany) shows the existence of H_2, CH_4 and N_2 at depth (Philippe, 1990), indicating the gas state of the ore-forming fluid can be maintained until the depth reaches 10 km. Two pieces of evidence can be provided for gold-bearing fluid moving in gaseous form. First, it facilitates the transport of minute gold grains. Second, there are many gaseous inclusions, mostly composed of CO_2 (about 90%) and N_2 (Petrovskaya, 1971), in natural gold and it can be figured

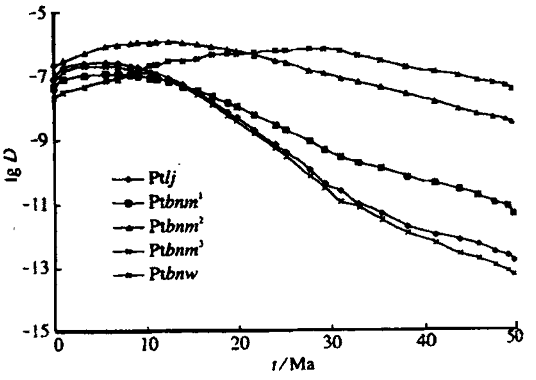


Fig. 1. The evolution fo fracture permeability in different strata during ore deposition in westerm Hunan gold deposits (after Tan Kaixuan et al. , 2001).

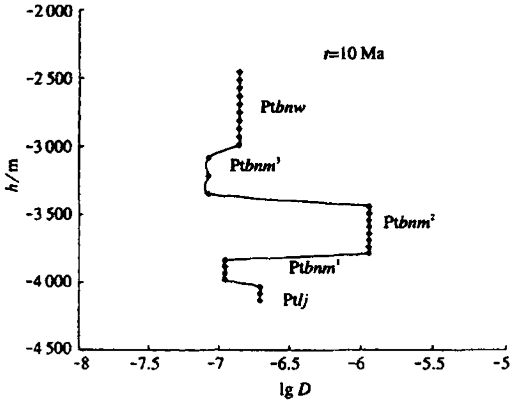


Fig. 2. The distribution of fracture permeability in different strata during ore deposition in western Hunan gold deposits (after Tan Kaixuan et al. , 2001).

out that it is in the growing stage of gold grains with bubbles attached to their surface. The most outstanding character of gas-carrying gold is that the gold can be dispersed uniformly, as may be observed in the superlarge gold deposits in the Dayin′gezhuang, Sanshandao-Cangshang and Jiaojia-Xincheng areas, Shandong Province.

5.3 Fluid surge

Fluid surge can make heavier substances congregate at the bottom and lighter ones float upwards, so that early quartz veins are low in density and late veins contain multi-metallic sulphides that are higher in mass.

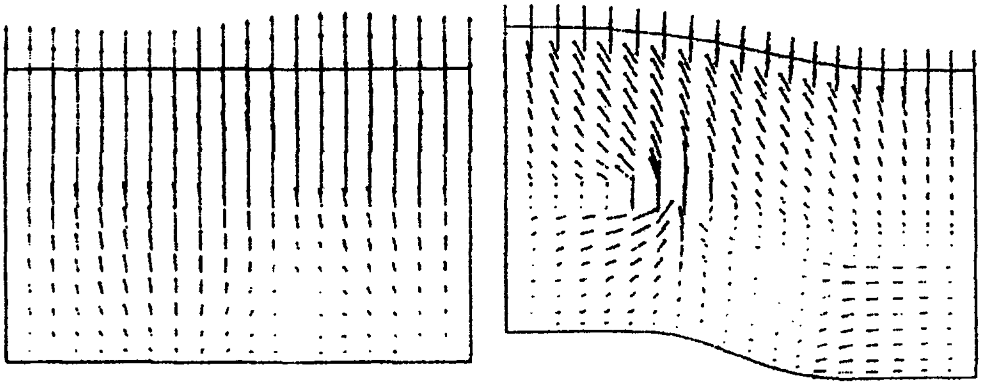
The alternation of external and internal force can also cause fluid surge except earthquake. The external force, i. e. , regional stress, drives fluids to flow toward the places where pressure is extremely low, usually moving fast along rifts from deep to surface, spreading into the fractures of wall rocks, or arriving at the surface with volcanic eruptions. Moreover, the bulk variation can cause fluid surge. The internal force is additional press of fluid surface. If fluid inserts at one end of a closed rift, siphoning function will drive the fluid to flow into the rift. The function is presented below:

$$Pa = a\ (1/\ R_1 + 1/\ R_2)$$

where a is the surface tension coefficient, and R_1 and R_2 are two major curvature radii. It is shown that the additional press of fluid surface Pa has an inverse ratio to R. It means the change of rift curvature radius can control the intensity of siphoning function, consequently causing fluid surge. When outside stress is strong enough to run through the closed fracture (Shao Shicai et al. , 1994), next fluid surge in the closed rift will be stimulated. Due to multi-stage surging during the ascending process of fluids, gold will be concentrated incessantly.

5.4 Mutation of fluid moving speed

Mutation of fluid moving speed plays a major role in ore deposition. The laws of fluid dynamics make it clear that the moving speed of fluid rises in the shallow levels and vice verse. Experiment with CaF_2 at the constant temperature shows that the increase of fluid speed will reduce the density of output fluid, (Zhang Ronghua et al. , 1992), indicating much CaF_2 has been precipitated. Although the CaF_2 solution



a: t=0 Ma

b: t=20 Ma

Fig. 3. The evolution of fluid flow field affected by fracturing in western Hunan gold deposits (after Tan Kaixuan et al., 2001).

and gold-bearing SiO_2 fluid are different in properties, they share similar relationships between fluid speed and solubility, which can be qualified by the following maths expression:

$$(z\infty)_{open} - (z\infty)_{close} = [f(1-a)/k]/[(f/k)+1]$$

where Z is gold solubility, f / k is fluid speed, and a is the thickness of input fluid.

The gold solubility in a circulating system is determined by fluid speed and initial thickness, especially when a < 1, its solubility will decline. The initial thickness of most natural solutions is close to zero, so their solubility will drop in the circulating system.

At the turning position from gentle to steep in a ore-controlling fault, rich ore bodies are facilitated to be formed. For example, in the narrow portion of the Jiapigou faulted zone, Jilin Province, and in the subduction zone at the depth of the Rongcheng – Wuliang structural zone's bottleneck in Shandong Province, due to the rise of fluid speed, the gold solubility decreased and more gold was precipitated.

6 Layered circulatory system of fluids

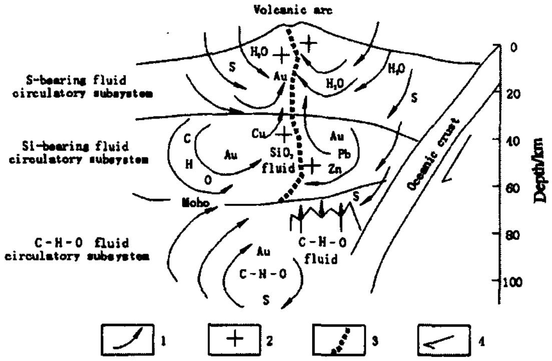


Fig. 4. Layered circulatory system of Au-bearing fluids. 1. Circulatory fluid; 2. granite; 3. deep fault; 4. subduction direction.

Based on different settings and various combinations, from the mantle to the Earth's surface, three layers of circulatory subsystem can be distinguished: the mantle C-H-O circulatory subsystem, the S-bearing circulatory subsystem located at the shallow-surface and the Si-bearing circulatory subsystem in the middle-lower crust. The significant enrichment of gold mostly occurs in subsystems bound up with tectonic surroundings. In local volcanic structures or small extensional or compressional environments, there is no adequate time for each subsystem to absorb abundant ore-forming elements. On the contrary, the fluid subsystem is enriched in much more ore-forming elements in the large-scale tectonic environment to form large or superlarge ore deposits. For instance, the Pacific plate intensely collided with the Eurasian plate during Mesozoic time, resulting in the formation of the large-sized Jiapigou and Haigou gold deposits. The Jiaodongnan-Sudongbei-Huanghai terrain underthrusted toward the Jiaobei terrain, bringing sea water or surface water into the middle subsystem and also making mantle fluids flow upwards to the middle subsystem due to deep subduction(more than 95 km). Accordingly, enormous ore-forming elements were accumulated and the Laizhou-Zhaoyuan ore-concentrated area was formed.

6.1 Permeation cycle of shallow-seated fluids

For gold deposits, shallow-seated fluids mainly include H_2O, and its density varies regularly with depth, that is, at the surface, its density is highest and decreases obviously with depth, but below 15 km, it almost maintains constant. So the difference in density is one of the driving forces for fluids to permeate downwards. But for gas-bearing (CO_2, etc.) fluids, the highest density is not at the surface, but 5 - 10 km underground. So, on the profile we can see regular variations in density, that is, changing from low to high and then from high to low. In the case of fault existence, fluids permeate downwards to form convection currents, especially in the case of the existence of deep faults, two kinds of ore-forming fluids can permeate ten to several tens of kilometers underground, forming H_2O-rich thermal solutions finally. At the depth range, it is called "fluid reservoir", and in recent years, geophysics study has shown that "fluid reservoir" is a "low-velocity zone" (Table 5).

Table 5. The distribution depth and physics parameters of low-velocity zone in the crust of East China (after Hu Wenxuan et al., 2001)

Region		Distribution depth h/km	Thickness of low-velocity zone h/km	Velocity of seismic wave Vp($km \cdot s^{-1}$)	Data source
South China	Coast of South-East China	10 - 20	3 - 8	5.13 - 6.03	Pei Rongfu et al., 1999; Ma Kaiyi et al., 1999
	Yangtze plate	15 - 25	1 - 7	5.9 - 6.3	
	Cathysian plate	10 - 20	3 - 10	6.1 - 6.6	
North China		10 - 30	3 - 10	6.1 - 6.6	Peng Cong, 1999

6.2 Interaction between deep- and shallow-seated fluids and Au-bearing ore-forming fluids

With the permeation of H_2O-rich shallow fluids, gas-rich deep-seated fluids flow upwards, and they meet with each other about ten to several tens of kilometers underground, so energy replacement, material blending and a series of chemical reactions will take place. As a result, the H, O isotopes of fluids have the double features of deep-seated and shallow subsurface waters (Hu Wensuan et al., 2001).

7 Conclusions

In the study of fluid movement, not only the starting point (rock-magma-fluid reactions) and terminal (fluid localization), but also the moving process, involving osmosis, surge, gas-liquid alternation, mutation of fluid speed and inner elements transfer within the layered circulatory system of fluid should be taken into consideration. Research on fluid moving process can help establish more effective prospecting approaches, offer further clues to fluid origin, and ameliorate the genetic classification of gold ore deposits.

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