Research Article

Fluid Inclusions and C-H-O-S-Pb Isotope Systematics of the Changfagou Deposit, Jilin Province, Northeast China

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The Changfagou Cu deposit in Jilin province, China, is located in the eastern segment of the northern margin of the North China Craton and lies at the southern end of the Lesser Xing'an Mountains-Zhangguangcailing Mountains. According to the mineral paragenetic association and its various relationships, the hydrothermal mineralization can be divided into 4 metallogenic stages from early to late: stage I is K-feldspar-quartz-magnetite, stage II is quartz-molybdenite, stage III is quartz-chalcopyrite (polymetallic sulfide), and stage IV is carbonate. Stages II and III are the main metallogenic stages. Overall, the metallogenic fluid associated with the Changfagou deposit is characterized as a F-rich CO₂-H₂O-NaCl hydrothermal system. The hydrogen and oxygen isotopic characteristics suggest the initial ore-forming fluids of the Changfagou deposit evolved from a primitive magmatic fluid and mixed with meteoric water. The sulfur and lead isotopic characteristics show that the metallogenic material was derived from partial melting of the lower crust. Phase separation or immiscibility is the important mechanism in the precipitation of molybdenum, whereas a decrease in temperature is the important mechanism in the precipitation of copper polymetallic sulfides. The above characteristics are similar to those of the porphyry deposits related to continental environments. Compared with the deposits in the Xilamulun metallogenic belt, both have similar metallogenic ages and tectonic positions. In conclusion, the Changfagou deposit formed in an intracontinental extensional environment due to lithospheric thinning. The mineralization was related to magmatism associated with partial melting of the lower crust. The intersection of the Dunhua-Mishan fracture and Kangbao-Chifeng fracture along the northern margin of the North China Craton is a promising location for porphyry ore deposits related to a continental tectonic setting.

1. Introduction

The Xilamulun fault belt, located in the middle segment of the northern margin of the North China Craton (NCC), features a series of porphyry Cu and Mo deposits related to Mesozoic intermediate-acidic magmatism, including the Chehugou and Kulitu porphyry Cu-Mo deposits [1, 2], the Jiguanshan and Xiaodonggou porphyry Mo deposits [3], and the Haolibao and Aolunhua porphyry Mo-Cu deposits. Together, these deposits constitute a nearly NNE-trending Cu-Mo metallogenic belt (Figure 1, [4]). The nearly N-S-trending calc-alkaline to high-K calc-alkaline granite belt

in the Lesser Xing'an Mountains, Zhangguangcailing Mountains, and mid-eastern Jilin province in northeast China features large-scale porphyry-skarn Mo polymetallic mineralization (Figure 1, [5]), forming the Luming, Daheishan [6, 7], Huojihe [8], Gaogangshan [9], Fu'anpu [10, 11], and Jidetun [12] porphyry Mo deposits. The deposits in the two metallogenic belts are obviously different in metallogenic background, characteristics, and evolution of the ore-forming fluids ([6, 13]; Ma et al., 2009; [1-4, 7, 14]).

The Changfagou Cu deposit is the typical porphyry Cu deposit to be newly identified in Jilin province, northeast China. However, to date, it has been little studied, and an

FIGURE 1: Simplified geological map showing the distribution of porphyry deposit in northeast China (modified from [15]). (1) Huojihe; (2) Cuiling; (3) Luming; (4) Yezhugou; (5) Kanyuangou; (6) Fu'anpu; (7) Jidetun; (8) Dashihe; (9) Daheishan; (10) Aolunhua; (11) Haolibao; (12) Banlashan; (13) Hutulu; (14) Xiaodonggou; (15) Kulitu; (16) Jiguanshan; (17) Nianzigou; (18) Mengguyingzi; (19) Chehugou; (20) Sadaigoumen; (21) Dacaping; (22) Lanjiagou; (23) Xintaimen; (24) Dayangshugou; (25) Hekanzi; (26) Xiaosigou.

integrated study of this deposit has not yet been reported. Its metallogenic background remains unclear, and it may be linked either to the nearly NNE-trending metallogenic belt along the northern margin of the NCC or to the nearly N-S-trending Lesser Xing'an Mountains-Zhanggangcailing Mountains metallogenic belt. This uncertainty restricts generalizing the regional metallogenic regularity and ore-forming potential evaluation. Therefore, this paper summarizes the geology of the deposit, analyzes fluid inclusions (FIs), and studies C-H-O-S stable isotopes and Pb radiogenic isotopes to reveal the characteristics and evolution of the ore-forming fluids. Finally, the metallogenic mechanism and geodynamic setting of the deposit are discussed.

2. Regional Geology

The Changfagou Cu deposit is located in the eastern segment of the NCC and lies to the south of the Xilamulun fault belt at the southern end of the Lesser Xing'an Mountains-Zhanggangcailing Mountains. It lies to the southeast of the crustal-scale Dunhua-Mishan fault, and the Kangbao-Chifeng fault, which runs along the northern margin of

the NCC, crosses the northern portion of the mining area (Figure 1). The area experienced superposition and conversion between Paleo-Asian and the Circum-Pacific tectonic domains [17, 18].

The exposed strata in the regional area mainly belong to the Archean Anshan Group. The main rock types are biotite-bearing plagioclase gneiss, plagioclase hornblende gneiss, amphibolite, and biotite-bearing plagioclase leptynite. The structures in the regional area are complex and are mainly affected by the northern margin fault of the NCC (Kangbao-Chifeng fault) and the large-scale sinistral strike-slip motion of the Dunhua-Mishan fault. The latter has created a relatively large-scale drag structure and secondary fractures, forming N-S-, E-W-, and NE-trending structures that intersect and overlap, which is advantageous for mineralization. The magmatic rocks are well developed and include Archean basic-ultrabasic rocks and granitoids, Proterozoic moyite, and Yanshanian quartz porphyry. The Yanshanian intermediate-acid intrusive rocks are closely associated with the mineralization, in which a large number of copper-molybdenum deposits had been produced (i.e., Changfagou, Tianhexing, and Ermi).

FIGURE 2: Geological map of the Changfagou deposit.

3. Ore Deposit Geology

The exposed strata in the Changfagou ore district are mainly lower members of the Archean Yangjiadian Group (Figure 2), which is an association of biotite-bearing plagioclase gneiss, amphibolite gneiss, leptynite, and amphibolite. The strata also include the upper members of the Archean Sidaolazi Group, an association of biotite-bearing amphibole plagiogneiss, amphibolite, chlorite-schist, and biotite plagioclase gneiss. The geological structure of the Changfagou ore district is complicated and is characterized by fractures. The faults can be divided into a premetallogenic period, a metallogenic period, and a postmetallogenic period. The faults associated with the premetallogenic period are N-S compressional faults and E-W tensional faults. The faults associated with the metallogenic period exhibit NNW extensional shear properties, obviously controlling the orebodies and quartz porphyry. The faults associated with the postmetallogenic period destroyed the orebodies and porphyry to some extent and are NE compressive shear faults and NW, NNW extensional shear faults. The exposed area of magmatic intrusions in this deposit is large, and the intrusions include Archean granite, Yanshanian quartz porphyry, and dike rocks, for example, diorite-porphyrity, rhyolite porphyry, and sillite (Figure 2).

Yanshanian intrusion is a composite body composed of less-phenocryst quartz porphyry and quartz porphyry. The less-phenocryst quartz porphyry is distributed on both sides of the composite body. The quartz porphyry intruded into the less-phenocryst quartz porphyry and the Archean granite, exposed area 0.18 km². Moreover, according to the characteristics of rock breccia and nonbreccia, it is divided into porphyry and breccias facies, distributed on the edge and front of the corresponding quartz porphyry.

Most of the ore bodies are hosted within the quartz porphyry body, which is divided into three sections that include a total of 14 copper bodies, 4 zinc orebodies, and 3 molybdenum bodies. But most ore bodies are insidious and controlled by drill holes; therefore it cannot be visible in surface. The zinc orebodies are distributed in the upper portion, and the molybdenum orebodies are located beneath the copper orebodies. Each orebody has a similar occurrence, and the strike is nearly E-W, with a dip angle of nearly 0° (Figure 3). Ore sections I and II dip to the north, and ore section III dips to the south.

The metal mineral assemblage of the ore is mainly made up of chalcopyrite (Figures 4(a) and 4(b)), pyrite (Figure 4(a)), molybdenite (Figure 4(c)), secondly sphalerite, and galena (Figures 4(d) and 4(e)). The gangue minerals are

FIGURE 3: Cross section along exploration line 3 in Changfagou area.

mainly quartz, plagioclase, minor hornblende, and biotite. The ore texture includes euhedral granular, subhedral-anhedral granular (Figure 4(b)), solid solution separated (Figure 4(e)), metasomatic erosion, and cataclastic textures (Figures 4(d) and 4(e)). The ore structures include disseminated, vein (Figures 4(g) and 4(h)), secondly massive, and conglomeration structures (Figures 4(f) and 4(i)). According to the mineral paragenetic association and its various relationships, two mineralization periods are identified: a hydrothermal period and a supergenic period. The hydrothermal mineralization is the main metallogenic period and is divided into 4 metallogenic stages from early to late: stage I is K-feldspar-quartz-magnetite (a mineral association of K-feldspar, quartz, magnetite, pyrrhotine, and pyrite),

stage II is quartz-molybdenite (a mineral association of quartz, K-feldspar, molybdenite, chalcopyrite, and pyrite), stage III is quartz-chalcopyrite (polymetallic sulfide) (a mineral association of quartz, sericite, chalcopyrite, pyrite, galena, and sphalerite), and stage IV is carbonate (a mineral association of carbonate, fluorite, chlorite, epidote, pyrite, galena, and sphalerite).

Wall rock alteration is developed and characterized by surface zoning (Figure 5). From inside out, this zoning includes a potassic alteration zone, a quartz-sericitization zone, a kaolinization zone, and a porphyritic zone (chloritization, epidotization, and carbonate alteration assemblages). Potash feldspathization is widely developed in the quartz porphyry and its wall rock. The mineral association is

FIGURE 4: Microphotographs showing intergrowth of minerals (a–e), photographs of rock cores (f–i); (a) subhedral-anhedral pyrite and chalcopyrite; (b) subhedral-anhedral galena and sphalerite; (c) quartz coexisting with molybdenite; (d) metasomatic magnetite by pyrrhotite and chalcopyrite; (e) solid solution separated sphalerite and chalcopyrite; (f) mass chalcopyrite in quartz porphyry; (g) vein quartz coexisting with chalcopyrite; (h) vein molybdenite in quartz porphyry; (i) conglomeration molybdenite in quartz porphyry (Py: pyrite; Ccp: chalcopyrite; Gn: galena; Mag: magnetite; Mlb: molybdenite; Po: pyrrhotite; Sp: sphalerite; Qtz: quartz).

quartz + potash feldspar. Silicification is also widespread and is frequently superposed with other styles of alteration. Silicification closely related to mineralization is developed in the quartz porphyry and superposed with sericitization. The metasomatic rock is formed in silicified veinlets or net-like veins of quartz. The sericitization is mainly developed in the quartz porphyry and metallogenic structural fissures. The kaolinization is developed in the top of the quartz porphyry and external contact zone. The chloritization and epidotization are both in the quartz porphyry and external contact zone, frequently superposed with carbonization.

The structure of the ores has a certain spatial regularity. From the center to the exterior, the type of mineralization transitions from disseminated to veinlet-disseminated to vein structures. The mineralization zoning, from the center to outside, is as follows: molybdenite, chalcopyrite → pyrite and

chalcopyrite → sphalerite and pyrite → galena and pyrite, which is consistent with alteration zoning. The molybdenite and chalcopyrite are related to potassic alteration and silicification. The pyrite is related to sericitization, the sphalerite is related to kaolinization and sericitization, and the galena is related to chloritization and epidotization (Figure 5).

4. Sampling and Analytical Methods

The samples in this study were collected from different depths of the drill holes (ZK803, ZK801, ZK313, ZK1303, and ZK901). The quartz and calcite samples formed in different hydrothermal stages were used for microthermometric and laser Raman analyses of fluid inclusions. Six quartz samples from quartz-molybdenite and quartz-chalcopyrite veins were

FIGURE 6: Photomicrographs of representative fluid inclusions from the Chafagou deposit. (a) V-type fluid inclusions; (b) W-type fluid inclusions; (c) C-type fluid inclusions; (d) S-type fluid inclusions. V_{H_2O} , vapor phase H_2O ; L_{H_2O} , liquid phase H_2O ; V_{CO_2} , vapor phase carbon dioxide; L_{CO_2} , liquid phase carbon dioxide.

spectrometer, and the measurement accuracy was better than 0.005% for $1 \mu\text{g}$ of $^{208}\text{Pb}/^{206}\text{Pb}$.

5. Results

5.1. Fluid Inclusion Study

5.1.1. Fluid Inclusion Petrography. Four types of FIs were identified under the microscope through the research on different mineralization phases and compositional components. These types of FIs are described below:

(1) Liquid-rich aqueous two-phase FIs (W-type): they are composed of liquid water and water vapor; $2\text{--}12 \mu\text{m}$ in size; oval, semi-round, and polygonal and contain bubbles that usually account for 10–30% of the volume (Figure 6(a)). These FIs can be homogenized into the liquid phase when heated. FIs of this type are randomly distributed throughout different stages of the quartz sulfide veins in groups or isolated clusters.

(2) Gas-rich aqueous FIs (V-type): they are composed of liquid and gas phases; $3\text{--}12 \mu\text{m}$ in size; oval and semi-round and contain bubbles that usually account for 40–80% (most in the range of 60–80%) of the volume. The phase boundary line and bubble colors are rather dark (Figure 6(b)). Most of these FIs can be homogenized into the gas phase and a minority in the liquid phase when heated.

(3) CO_2 -bearing multiphase FIs (C-type): most of these FIs can be found in early-stage quartz veins. These FIs are oval, semi-round, or trapeziform in shape, with sizes of $3\text{--}12 \mu\text{m}$. These FIs, from the center to the exterior, feature

gas phase CO_2 (V_{CO_2}), liquid CO_2 (L_{CO_2}), and liquid water (L_{H_2O} , Figure 6(c)). Most of CO_2 -bearing bubbles are in the three-phase inclusions at room temperature. In addition, the CO_2 -bearing bubbles in the two-phase inclusions at room temperature turn into three-phase inclusions when cooled. Both types of FIs can be homogenized in the liquid CO_2 liquid.

(4) Daughter mineral-bearing multiphase FIs (S-type): they are composed of a gas phase, liquid phase, and transparent daughter minerals; polygonal, oval, and semi-round in shape; $3\text{--}10 \mu\text{m}$ in size and contain daughter minerals, that is, white or colorless sodium chloride crystals, which are cubic in structure. The FIs of this type are randomly distributed throughout the different stages of the quartz sulfide veins as groups or isolated clusters (Figure 6(d)).

5.1.2. Microthermometric Data. The microthermometric data, summarized in Table 1, were obtained from different types of FIs of different hydrothermal stages.

Quartz crystals from the early hydrothermal stage (I) contain W-type, V-type, C-type, and S-type FIs. The ice melting temperatures of the W-type FIs range from -16.41 to -4.8°C , and their salinities range from 7.58 to 19.95 wt.% NaCl eq. These FIs homogenized into the gas phase at temperatures of $250.8\text{--}436.2^\circ\text{C}$ (Figures 7(a) and 7(b)). The calculated densities range from 0.64 to $0.91 \text{ g}\cdot\text{cm}^{-3}$. The V-type FIs yield final ice melting temperatures (T_i) of -17 to -7.7°C and salinities of 11.36 to 20.43% NaCl eq. These FIs are homogenized into the liquid phase at temperatures between

TABLE 1: Microthermometry and relative parameters of FIs in the Changfagou deposit.

Mineralization stage	Type	Number	Size (μm)	V	W-, V-type FIs		S-type FIs		Tm-co ₂ (°C)	C-Type FIs	Th (°C)	Salinity (wt% NaCl eq.)	Density (g/cm ³)
K-feldspar-quartz-magnetite	W	46	2-12	10%-25%	Tm-ice (°C)	Th (°C)	Td-bud (°C)	Td-dm (°C)	-56.8 to -59.2	3.3-6.7	22.8-27	398.2-449.9	0.64-0.91
	V	25	3-12	40%-80%	-16.4 to -4.8	250.8-436.8							
	C	18	3-12		-17 to -7.7	272.4-413.6							
	S	13	2-8	10%-20%			219.3-317.6	293.8-427.5					0.78-0.92
Quartz-molybdenite	W	49	3-12	10%-30%	-12.8 to -4.7	256.2-390.8							0.73-0.89
	V	18	4-12	40%-70%	-10.4 to -7.9	312.4-390.3							0.73-0.82
	S	14	3-12	10%-25%			132.7-310	177.3-424.2				30.80-50.17	1.10-1.11
Quartz-chalcopyrite (polymetallic sulfide)	W	49	2-12	10%-30%	-11.4 to -2.9	161.3-335.7							0.83-0.99
Carbonate	S	15	3-10	15%-25%			165.3-267.9	215.3-315.4					1.10-1.11
	W	22	2-8	15%-30%	-8.7 to -1.3	123.1-261.9						2.23-12.54	0.82-0.99

Note: Tm-co₂: melting temperature of solid CO₂; Tm-cla: temperature of CO₂-clathrate dissociation; Th-co₂: homogenization of CO₂; Tm-ice: final melting temperature of ice; Th: total homogenization temperature; Td-bud: bubble disappear temperature; Td-dm: daughter mineral disappear temperature; V: percentage of bubble volume.

FIGURE 7: Continued.

FIGURE 7: Histograms of salinities and homogenization temperatures of FIs in the Changfagou deposit.

272.4 and 413.6°C (Figures 7(a) and 7(b)). The calculated densities are 0.78–0.92 g·cm⁻³. The bubbles of the S-type FIs disappear first and then daughter minerals dissolve, and all FIs homogenized into the liquid phase when the S-type FIs are heated. The melting temperatures of the daughter minerals are 293.8–427.5°C, and the calculated salinities and densities are 37.69–50.55% NaCl eq. and 1.08–1.11 g·cm⁻³, respectively (Figures 7(a) and 7(b)). The initial CO₂ melting temperature of the C-type FIs is –59.2 to –56.8°C, which is lower than the triple point, suggesting the presence of other gases. The clathrate melting temperature is 3.3–6.7°C, and the salinities range from 2.96 to 8.82 wt.% NaCl eq. The partial homogenization temperatures are 22.8–27°C, the total homogenization temperatures are 398.2–449.9°C, and the calculated fluid densities are 0.77–0.85 g·cm⁻³ (Figures 7(a) and 7(b)).

The W-type, V-type, and S-type FIs are present in the quartz-molybdenite stage (II). The W-type FIs final ice melting temperatures range from –12.8 to –4.7°C, and their calculated salinities range from 7.44 to 15.75% NaCl eq. These FIs homogenized into the liquid phase at temperatures of 256.2 to 390.8°C (Figures 7(c) and 7(d)), and their calculated densities are 0.73–0.89 g·cm⁻³. The V-type FIs final ice melting temperatures range from –10.4 to –7.9°C, and their calculated salinities are 11.11–14.42 wt.% NaCl eq. These FIs homogenized into the liquid phase at temperatures of 312.4–390.3°C. When heated (Figures 7(c) and 7(d)), the bubbles of the S-type FIs disappear first, and then the daughter minerals dissolve, with all the FIs homogenizing into the liquid phase. The homogenization temperatures range from 254.9 to 325.3°C, and the melting temperatures of the daughter minerals range from 254.9 to 325.3°C. The calculated salinities and densities are 30.80–50.17% NaCl eq. and 1.10–1.11 g·cm⁻³, respectively (Figures 7(c) and 7(d)).

The FIs of the quartz-chalcopyrite (polymetallic sulfide) stage (III) are primarily W- and S-type FIs. The W-type FIs

final ice melting temperatures range from –11.4 to –2.9°C, and their calculated salinities range from 5.25 to 15.45% NaCl eq. These FIs homogenized into the liquid phase at temperatures of 161.3–335.7°C (Figures 7(e) and 7(f)), and their calculated densities are 0.82–0.91 g·cm⁻³. The bubbles of the S-type FIs disappear first, and then the daughter minerals dissolve, with all of the FIs homogenizing into the liquid phase when heated. The homogenization temperatures range from 145.3 to 281.2°C, and the melting temperatures of the daughter minerals range from 145.3 to 281.2°C. The calculated salinities and densities are 32.67–39.3% NaCl eq. and 1.10–1.11 g·cm⁻³, respectively (Figures 7(e) and 7(f)).

Only W-type FIs are observed in the carbonate stage (IV). The W-type FIs final ice temperatures range from –8.7 to –1.3°C, and their calculated salinities are 2.23–12.54% NaCl eq. All the FIs homogenized into the liquid phase at temperatures of 123.1–261.9°C (Figures 7(g) and 7(h)).

5.1.3. Laser Raman Analysis. Laser Raman spectra analysis is an effective method to confirm the gas compositions of individual fluid inclusions. We analyzed representative FIs of different mineralization stages, and the test results show that the gas compositions of the FIs are dominated by H₂O and CO₂. This is consistent with the microphysiography and phase transition characteristics observed during microthermometry.

The gas phase in stage I FIs is primarily composed of CO₂ (1283.3 cm⁻¹, 1386.7 cm⁻¹), with minor N₂ (2328.9 cm⁻¹, Figure 8(a)), although the gas phase of some FIs is only CO₂ (Figure 8(b)). The gas phase in stage II FIs is primarily composed of H₂O (3488.7 cm⁻¹) and CO₂ (1283.3 cm⁻¹, 1385.5 cm⁻¹, Figure 8(c)), with minor N₂ (2328.9 cm⁻¹). The gas phase in the stage III FIs also contains H₂O (3439.4 cm⁻¹) and CO₂ (1283.3 cm⁻¹, 1385.5 cm⁻¹), with minor N₂ (2328.9 cm⁻¹, Figure 8(d)). The gas phase in the stage IV FIs contains only H₂O. The microthermometry and laser Raman spectra

FIGURE 8: Laser Raman spectra of the Chafagou deposit.

analyses show that the ore-forming fluid belongs to the H_2O - NaCl - $\text{CO}_2 \pm \text{N}_2$ system.

5.2. Hydrogen-Oxygen Isotopes. It is difficult to accurately calculate the $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ value of the fluid, as the homogenization temperatures acquired from the FIs in quartz vary widely. Therefore, we used the mean of the homogenization temperatures as the lowest capture temperature. The oxygen isotopic value of the water trapped in quartz was calculated from the oxygen isotope value of the analyzed quartz using the fractionation equation $1000 \ln \alpha_{\text{quartz} - \text{water}} = 3.38 \times 10^6 T^{-2} - 3.40$. The δD values were obtained from FIs data from quartz, and the results are shown in Table 2. The homogenization temperatures of the quartz-molybdenite stage from quartz samples range from 300°C to 360°C , with a mean of 330°C . The calculated $\delta^{18}\text{O}$ values of the fluid range from 0.6 to 2.3‰, and the δD values range from -100‰ to -112.8‰ ; the homogenization temperatures of the quartz-chalcopyrite (polymetallic sulfide) stage from quartz samples range from 180°C to 300°C , with a mean of 256°C , and δD values range from -110.9‰ to -89.2‰ .

5.3. Carbon-Oxygen Isotopes. Calcite samples from the late ore-forming stage were analyzed to determine their oxygen and carbon isotope compositions, and the results are shown in Table 3. The $^{13}\text{C}_{(\text{PDB})}$ values range from -1.6‰ to 0.4‰ , and the $\delta^{18}\text{O}$ values range from 6.8‰ to 8.3‰.

5.4. Sulfur Isotopes. The sulfur isotopic compositions of fourteen metallic sulfide samples from the Changfagou deposit are shown in Table 4. All the metallic sulfide samples from different stages range from -1.3‰ to 4.7‰ , with a mean of 2.5‰. The $\delta^{34}\text{S}$ values of two pyrrhotite samples are between 3.9‰ and 4.6‰, with a mean of 4.3‰; the $\delta^{34}\text{S}$ values of three molybdenite samples are between 2.7‰ and 4.7‰, with a mean of 3.8‰; the $\delta^{34}\text{S}$ values of three chalcopyrite samples are between 2.0‰ and 4.4‰, with a mean of 2.9‰; the $\delta^{34}\text{S}$ values of five pyrite samples are between -1.3‰ and 2.9‰, with a mean of 1.88‰; and the $\delta^{34}\text{S}$ values of one sphalerite sample is 1.3‰.

5.5. Lead Isotopes. The pyrite samples from the main metallogenic stage were analyzed to determine their Pb isotopic

TABLE 2: Hydrogen and oxygen isotope compositions of the Changfagou deposit.

Number	Sample number	Mineralization stage	Mineral	Th (°C)	$\delta D_{\text{VSMOW}}/\text{‰}$	$\delta^{18}O_{\text{SMOW}}/\text{‰}$	$\delta^{18}O_{\text{H}_2\text{O}}/\text{‰}$
1	I5CFG-1	Quartz-molybdenite	Quartz		-110.2	9.7	3.81
2	I5CFG-2	Quartz-molybdenite	Quartz	330	-112.8	10.2	4.31
3	I5CFG-3	Quartz-molybdenite	Quartz		-100	7.8	1.91
4	CFG-1	Quartz-chalcopyrite (polymetallic sulfide)	Quartz		-89.2	9	0.30
5	CFG-2	Quartz-chalcopyrite (polymetallic sulfide)	Quartz	256	-106.8	9.1	0.43
6	CFG-3	Quartz-chalcopyrite (polymetallic sulfide)	Quartz		-110.9	7.4	-1.27

TABLE 3: Carbon and oxygen isotope compositions of the Changfagou deposit.

Number	Sample number	Mineral	$^{13}\text{C}_{(\text{PDB})}$	$^{18}\text{O}_{(\text{SMOW})}$
1	CFG-Zk1402-B88	Calcite	0.4	8.3
2	CFG-Zk1402-B96	Calcite	-1.5	6.8
3	CFG-Zk801-B20	Calcite	-1.6	7.4

TABLE 4: Sulphur isotopic composition of the Changfagou deposit.

Number	Sample number	Mineralization stage	Mineral	$^{34}\text{S}_{\text{V-CDT}} (\text{‰})$
1	CFG-ZK1601-S	K-feldspar-quartz-magnetite	Pyrrhotite	3.9
2	CFG-ZK1402-B80	K-feldspar-quartz-magnetite	Pyrrhotite	4.6
3	15CFG-1	Quartz-molybdenite	Molybdenite	4.7
4	15CFG-2	Quartz-molybdenite	Molybdenite	2.7
5	15CFG-3	Quartz-molybdenite	Molybdenite	4.1
6	CFG-ZK1401-BS2	Quartz-chalcopyrite (polymetallic sulfide)	Sphalerite	1.3
7	CFG-ZK204-B83	Quartz-chalcopyrite (polymetallic sulfide)	Pyrite	-1.3
8	CFG-ZK1401-BS1	Quartz-chalcopyrite (polymetallic sulfide)	Pyrite	2.9
9	CFG-ZK1401-BS2	Quartz-chalcopyrite (polymetallic sulfide)	Pyrite	2.0
10	CFG-ZK1401-BS3	Quartz-chalcopyrite (polymetallic sulfide)	Pyrite	2.9
11	CFG-ZK1401-BS4	Quartz-chalcopyrite (polymetallic sulfide)	Pyrite	2.9
12	CFG-ZK802-B35	Quartz-chalcopyrite (polymetallic sulfide)	Chalcopyrite	2.0
13	CFG-ZK204-B83	Quartz-chalcopyrite (polymetallic sulfide)	Chalcopyrite	2.3
14	CFG-ZK204-B79	Quartz-chalcopyrite (polymetallic sulfide)	Chalcopyrite	4.4

TABLE 5: Lead composition of the Changfagou deposit.

Number	Sample number	Mineral	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	t (Ma)	μ	$\Delta\alpha$	$\Delta\beta$	$\Delta\gamma$
1	CFG-Zk802-B9	Pyrite	16.82	15.48	37.75	1152.8	9.48	62.76	17.34	59.62
2	CFG-Zk1003-B22	Pyrite	16.89	15.48	37.69	1109.0	9.47	62.81	17.04	55.83
3	CFG-Zk802-B2	Pyrite	16.69	15.46	37.79	1230.3	9.49	61.93	17.35	64.72

compositions, and the results are shown in Table 5. The $^{206}\text{Pb}/^{204}\text{Pb}$ ratios range from 16.82 to 16.69, with a mean of 16.80 and a range of 0.2. The $^{207}\text{Pb}/^{204}\text{Pb}$ ratios range from 15.46 to 15.48, with a mean of 15.47 and a range of 0.02. The $^{208}\text{Pb}/^{204}\text{Pb}$ ratios range from 38.69 to 38.79, with a mean of 37.74 and a range of 0.1. The modeled ages are 1109–1230 Ma, and the μ values range from 9.47 to 9.49, with a mean of 9.48.

6. Discussion

6.1. Source of the Ore-Forming Fluids and Materials. Many hydrogen and oxygen isotopic studies have shown that the ore fluids associated with porphyry copper-molybdenum deposits are mainly from magmatic water or the mixing of magma and meteoric water to varying degrees and that in the late-mineralization stage, meteoric water may seep extensively into the hydrothermal system [27–29]. The δD and $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ values from quartz in the Changfagou deposit are lower than those of magmatic water (-50‰ to -85‰ and 5.5‰ to 9.0‰ , resp.; [30]). However, in a δD - $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ diagram (Figure 9), all the data points plot near the magmatic water field, suggesting that the ore-forming fluids involved

lower δD and $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ fluids. Therefore, the initial ore-forming fluids of the Changfagou deposit were mainly of magmatic origin but mixed with meteoric water. We plotted the $\delta^{18}\text{O}$ and δD values in Figure 10, and all the points are located in the granite field, slightly off the mantle values. Therefore, the hydrogen and oxygen isotopic compositions show that the ore-forming fluids were derived from an acidic magma, with a minor contribution from a mantle-derived basic magma.

Generally, there are three accepted carbon sources in a hydrothermal ore-forming solution: (1) marine carbonate, with $\delta^{13}\text{C}$ values near zero and ranging from -4‰ to 4‰ ; (2) magma or mantle emanations, with $\delta^{13}\text{C}$ values of -5‰ to -2‰ and -9‰ to -3‰ , respectively [31]; and (3) organic carbon from different rocks, with low $\delta^{13}\text{C}$ values (organic carbon is rich in ^{12}C) ranging from -30‰ to -15‰ , with a mean of -22‰ [32]. However, as the observed values vary from -1.6 to 0.4 within a small range, organic carbon is excluded as a potential source. Additionally, all of the samples plot in the granite and ultrabasic-basic rock fields in the $\delta^{18}\text{O}$ versus $\delta^{13}\text{C}$ diagram (Figure 11), indicating that the carbon was mainly sourced from acidic magma and mantle-derived basic magma in the late-metallogenic stage.

FIGURE 9: δD versus $\delta^{18}O$ diagram of the Chafagou deposit (after [19]).

The $\delta^{34}S$ values of fourteen metallic sulfide samples are between -1.3‰ and 4.7‰ , with an average of 2.5‰ , suggesting that the sulfur source was consistent among the different stages. These values vary slightly more than that of meteorite sulfur (0‰ – 1‰). Two potential reasons can explain this positive deviation: (1) contamination by seawater or marine sulfate sediments or (2) increasingly acidic rock produces larger absolute $\delta^{34}S$ values. Because the area was being uplifted, no marine facies sediments had been deposited since the formation of the Archean basement, and the wall rock is composed of Archean granites with a small amount of supracrustal rocks. Therefore, marine sulfate sediment can be excluded, implying a deep acidic magmatic source of sulfur. On the other hand, the $\delta^{34}S$ values of pyrrhotite (mean of 4.3‰), molybdenite (mean of 3.8‰), chalcopyrite (mean of 2.9‰), and sphalerite (1.33‰) decrease gradually from early to late ore-forming stages, eventually reaching the values of meteorite sulfur (Figure 12). Therefore, the acidity of the ore fluid decreased during the evolution of the mineralization, probably due to the escape of a considerable quantity of volatiles (i.e., CO_2 and CH_4) from the magma.

Lead isotope compositions cannot change significantly under various physicochemical conditions except by radioactive decay and mixing effects. Additionally, sulfide minerals usually contain very low concentrations of U and Th and insignificant concentrations of radiogenic Pb isotopes [33]. Therefore, the Pb isotope compositions of sulfides from ore deposits are commonly used to constrain the source of sulfides [34, 35], in lead growth curve (Figure 13). The samples all plot the field of lower crust. Most scholars considered μ value of >9.58 to be consistent with high quantities of radiogenic crust-derived lead and representative of the mean of the lower crust. In contrast, μ values of <9.58 are consistent with low quantities of radiogenic lead, and the mean isotopic composition of mantle-derived lead is 8–9 [36]. Therefore, the observed lead isotopic values (mean of 9.48) are lower than

those of the upper crust but higher than those of the mantle, indicating that the Pb was derived from the lower crust.

6.2. Nature of the Ore-Forming Fluids. The quartz veins of stage I contain W-, V-, C-, and S-type FIs. These FIs are located in high-temperature (peak homogenization between 400°C and 460°C) and moderate- to high-temperature intervals (peak homogenization between 280°C and 400°C). The high-temperature FIs are characterized by low salinities (6–12% NaCl eq.), and the moderate- to high-temperature FIs are characterized by large variations in salinity (12–52% NaCl eq.). The presence of magnetite in the mineral assemblage during the early stage indicates that the ore-forming fluid had a high oxygen fugacity. The petrographic studies reveal the presence of CO_2 -bearing FIs, and the laser Raman spectroscopy indicates that CO_2 is predominant, with minor N_2 , in both V- and W-FIs. Thus, the ore-forming fluid was characterized by a high oxygen fugacity and belongs to a H_2O -NaCl- $CO_2 \pm N_2$ system.

The stage II quartz veins primarily contain W-, V-, and S-type FIs, and their ore-forming fluids are characterized by moderate to high temperatures and large variations in salinity. The peak homogenization temperature interval of these FIs ranges from 300°C to 360°C , and the salinity ranges from 8% NaCl eq. to 52% NaCl eq. Although the petrographic studies did not reveal the presence of CO_2 -bearing FIs, the laser Raman spectroscopy indicated the presence of H_2O , CO_2 , and minor N_2 in W-type FIs. Therefore, these FIs belong to an H_2O -NaCl- $CO_2 \pm N_2$ system.

The stage III quartz veins primarily contain W- and S-type FIs, and their ore-forming fluids are characterized by moderate temperatures and large variations in salinity. The peak homogenization temperature interval of these FIs ranges from 180°C to 300°C , and the salinity ranges from 6% NaCl eq. to 40% NaCl eq. The laser Raman spectroscopy also indicated the presence of H_2O , CO_2 , and minor N_2 in the FIs. Therefore, these FIs belong to an H_2O -NaCl- $CO_2 \pm N_2$ system.

The stage IV calcite veins contain only W-type FIs. The presence of a few fluorite crystals in the mineral assemblage indicates that the ore-forming fluid was enriched F^- . The laser Raman spectroscopy identified only H_2O , indicating that the fluids were characterized by low to moderate temperatures (peak homogenization of 160 – 240°C) and low salinities (peak salinity of 4–12% NaCl eq.) and belong to a H_2O - H_2O -NaCl system.

In summary, the ore-forming fluids of the Changfagou deposit belonged to an F-rich H_2O -NaCl- CO_2 system, characterized by the evolution of high temperatures and high salinities to low temperature and salinities.

6.3. Metallogenic Mechanism. Previous studies have shown three potential fluid formation mechanisms: (1) formation at magmatic temperatures, in which intermediate-felsic magma in a chamber becomes saturated to oversaturated in terms of volatile content through crystallization and separation to a certain extent, forming high- and low-salinity fluids [37, 38]; (2) formation from hydrothermal fluids with low to moderate salinities through liquid immiscibility or decompression

FIGURE 10: Contrast of H-O isotope composition and natural H-O isotope in Chafagou deposit (base map from [20]).

FIGURE 11: $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ diagram of the Chafagou deposit.

FIGURE 12: Sulfur isotope histogram of the Chafagou deposit.

boiling resulting from the fracturing of caprocks; or (3) volatile exsolution from late residual magma associated with crystallization during hypabyssal magmatic emplacement [39].

The coexistence of liquid-rich high-density FIs and daughter mineral-bearing, high-salinity FIs at similar temperatures yields contrasting salinities at different stages [40], which is a typical characteristic of phase separation or immiscibility processes. Thus, the Changfagou ore-forming fluid cannot have formed from direct exsolution from a magma. On the other hand, the ore-forming fluid in stage I belongs to the $\text{H}_2\text{O}-\text{NaCl}-\text{CO}_2 \pm \text{N}_2$ system, whereas the petrographic studies did not reveal the presence of the CO_2 -bearing FIs in stage II. This implies that the values of $\text{CO}_2/\text{H}_2\text{O}$ decreased. As the system transitioned into

stage III, the ore-forming stage changed to a $\text{H}_2\text{O}-\text{NaCl}$ system, indicating that it experienced phase separation or immiscibility of the volatiles (i.e., CO_2 and CH_4). The S isotope characteristics also indicate that the acidity decreased during the evolution of the mineralization, implying the large escape of volatile (i.e., CO_2 , CH_4) from magma. Although the H and O isotope characteristics exhibit a component of meteoric water, the mixing ratio is insufficient to cause large-scale fluid boiling. The hydrothermal breccia facies at the top of the quartz porphyry is main ore-bearing lithofacies and is direct evidence of an explosive hypogene environment. Thus,

FIGURE 13: Diagram of lead isotopic compositions of the Chafagou deposit (base map from [21]).

we conclude that the ore-forming fluids experienced multiple stages of phase separation or immiscibility, causing the escape of CO_2 and CH_4 . As the temperature of the fluid decreased and the pH value increased, chalcopryrite and other metal sulfides precipitated, which may be critical to the formation of the Changfagou deposit.

Experimental studies have shown that the solubility of copper and other metal sulfides increases with increasing temperature and decreases with decreasing temperature. Thus, a reduction in temperature can induce large-scale precipitation of ore-forming metals. The study of the FI microthermometric data shows that no obvious variations in the copper polymetallic sulfide stage are present in terms of salinity, CO_2 content, and mixing ratio of meteoric water compared with molybdenum mineralization. However, the temperature was significantly lower, according to the fluid inclusion petrography, and stages II and III contain the coexistence of liquid-rich high-density FIs and daughter mineral-bearing, high-salinity FIs at similar temperatures, indicating phase separation or immiscibility processes occurred at both stages. However, the precipitation of molybdenum mainly occurred at stage II, suggesting phase separation or immiscibility is not the main copper precipitation mechanism but is the main molybdenum precipitation mechanism, further indicating that large-scale precipitation of copper polymetallic sulfide may be correlated to decreases in temperature.

The above characteristics show that boiling and cooling are the main factors responsible for the abundant precipitation of metal-bearing material in hydrothermal systems. Although the Cu and Mo were introduced into hydrothermal system by the same processes, the metallogenic mechanisms differ. The precipitation of molybdenum was related to phase separation or immiscibility, whereas the precipitation of

FIGURE 14: P-T-W diagram of the Changfagou deposit (modified after [22]). Color: blue, C-type FIs, red, V-type FIs, black W-type FIs, and gray, S-type FIs.

copper polymetallic sulfide is mainly related to decreases in temperature.

6.4. Trapping Pressure of FIs and Metallogenic Depth. The study of the ore-forming fluid revealed the presence of multiple stages of phase separation or immiscibility during the ore-forming process. Thus, if the fluid pressure is equivalent to the external pressure, the homogenization temperatures of the inclusions at that moment represent the formation temperature of the fluids and do not require a pressure correction [41]. The four stages of quartz and calcite veins correspond to peak homogenization temperature intervals of 300–440°C, 300–360°C, 180–300°C, and 160–240°C, respectively.

Using the $\text{NaCl-H}_2\text{O}$ system phase diagram (Figure 14) according to the method of Urusova [42], Haas [43], and Bodnar et al. [44], we find that the metallogenic pressures of stages I, II, III, and IV are 9–39 MPa, 9–20 MPa, 6–9 MPa, and 3–6 MPa, respectively, corresponding to estimated metallogenic depths of 0.9–1.47 km, 0.75–0.9 km, 0.34–0.6 km, and 0.23–0.3 km, respectively, based on an ancient ground pressure gradient of $0.0265 \text{ GPa}\cdot\text{km}^{-1}$.

6.5. Evolution of Ore-Forming Fluids and Metallogenic Processes. The S and C-O isotopic characteristics show that the metallogenic material was mainly from acidic magma, and the hydrogen and oxygen isotopes show that the ore-forming fluids originated from magmatic water and then mixed with abundant meteoric water. Therefore, we conclude that the initial fluid formed via exsolution from a magma. Recent studies have shown that fluids from deep magma chamber exsolution are usually supercritical, with salinities of $\pm 10\%$ [45–48]. As fluid ascended to the top levels of the porphyry fractures, with the concomitant transition from lithostatic to hydrostatic pressures, the primitive unsaturated magmatic fluid evolved into liquid-rich high-density fluids

and gas-rich high-salinity fluids at temperatures of 300°C to 450°C and pressures of 9 to 39 Ma. Because the exsolution pressure of Cl^- from magma is lower than that of CO_2 and H_2O , the CO_2 -bearing magma produced CO_2 -rich low-salinity fluid in deeper areas and liquid-rich high-salinity fluids in shallower regions during the evolution of the system. The high salinity increased the solubility of Cu and Mo in the fluid; thus, the high-salinity and high-temperature fluid can carry large amounts of ore-forming elements. The first minerals to crystallize were K-feldspar, magnetite, and pyrite.

The fluid ascended to 0.9 km and was at pressures of 9 to 20 MPa and temperatures of 300°C to 360°C. Intensive phase separation or immiscibility of the fluid may have resulted in HF and CO_2 escaping from the fluid system, resulting in rapid precipitation of molybdenite at high temperatures. This ascending ore-forming fluid mixed with meteoric water and caused the porphyry and wall rocks to become strongly potassic.

As the fluid ascended to 0.6 km, the pressure ranged between 6 and 9 MPa, and the temperatures ranged between 180°C and 300°C. The decrease in the temperature and the increase in the pH resulted in rapid precipitation of abundant sulfides, forming chalcopyrite, galena, and sphalerite. This ascending ore-forming fluid mixed with abundant meteoric water and caused the porphyry and wall rocks to become strongly sericitic and silicification. Because of the hypergene emplacement of Changfagou porphyry, the solubility of H_2O and other volatiles decreased in the magma, and boiling of the magma resulted in the formation of an independent fluid phase.

As the fluid rose to 0.3 km, the pressure ranged from 3 to 6 MPa, and the temperature ranged from 180°C to 270°C. The temperature and salinity of the ore-forming fluid decreased further, suggesting an open late ore-forming fluid system. The hypothermal magmatic water mixed with abundant meteoric water and finally formed large area of propylitization. However, the ore-forming fluid had already unloaded most of the polymetallic sulfide, and this period is not the main metallogenic stage.

6.6. Metallogenic Background. The NNE-trending copper-molybdenum metallogenic belt along the Xilamulun fault belt on the northern margin of the NCC, which includes the Chehugou and Kulitu porphyry Cu-Mo deposits (Zhu et al., 2010), the Jiguangshan porphyry Mo deposits [3], and the Aolunhua porphyry Cu deposit, has similar ore-forming fluid characteristics (Table 6), including two-phase gas-liquid FIs that are CO_2 -rich and contain daughter minerals. The initial ore-forming fluids belong to a high-temperature, high-salinity, CO_2 -rich H_2O - CO_2 -NaCl system, which is similar to that of the Changfagou deposit located on the northern margin of the NCC, indicating a similar origin of the fluids. However, the N-S-trending porphyry Mo metallogenic belt, which includes the Daheishan [14], Luming [23], and Fu'anpu [11] porphyry Mo deposits, features ore-forming fluids that belong to a medium-high-temperature, medium-high-salinity, CO_2 -poor NaCl- H_2O system, containing only gas-liquid FIs and daughter mineral-bearing FIs (Table 6), which are different from those of the Xilamulun metallogenic

belt. The above differences may be closely related to different tectonic settings, the nature of the initial fluids, and its evolution process.

Recent studies have shown that the NNE-trending porphyry Cu-Mo metallogenic belt along the northern margin of the NCC is related to postcollisional extensional, tectonic stress transformation, or an intracontinental extensional environment associated with lithospheric thinning [4]. The N-S-trending porphyry Mo metallogenic belt of the Lesser Xing'an Mountains-Zhanggangcailing Mountains is related to an active continental margin or island arc environment in the paleo-Pacific plate subduction system. Recently, many scholars have found differences between the porphyry deposits associated with continental and magmatic arc environments, and further study of the metallogenic fluid characteristics and magmatic sources of continental porphyry deposits is needed. Most scholars suggest that porphyry deposits in continental environments mainly originate from partial melting of the continental crust [49–55] because continental crust is poor in H_2O , Na, and Cl and rich in K and F. Thus, the fluid formed by magmatic differentiation of partial melting of the crust is enriched in CO_2 and F. In contrast, the magma formed in active continental margin and island arc environments is related to subduction between oceanic and continental plates and is derived from the upper mantle or the crust-mantle boundary. Thus, the fluid derived from this magmatic differentiation belongs to the CO_2 -poor NaCl- H_2O system.

The metallogenic fluids of the Changfagou deposit were highly saline and belonged to the F-rich CO_2 - H_2O -NaCl hydrothermal system, similar to intrusion-related hydrothermal deposits [56, 57]. The Pb isotopic analysis shows that the metallogenic material was derived from the lower crust. These features demonstrate that this deposit is obviously different from porphyry deposits that formed in a magmatic arc environment but is similar to ones that formed in a continental environment. Thus, this deposit formed in a tectonic setting related to a continental environment based on the metallogenic fluid characteristics. This deposit formed during the Early Cretaceous (114 Ma, [58]), coinciding with the peak of large-scale lithospheric thinning in eastern China [59–61] and with a period of strong mineralization in the Xilamulun metallogenic belt [4]. The deposits that formed at this time are located mainly at the intersection of the Xilamulun fracture and the Da Xing'an Mountains major ridge fracture. The Changfagou deposit is located to the south of the Xilamulun fault belt and the intersection of the Dunhua-Mishan fracture and the Kangbao-Chifeng fracture at the northern margin of the NCC. Based on the metallogenic timing and tectonic location, this deposit is comparable to contemporaneous deposits in the Xilamulun metallogenic belt. In conclusion, the Changfagou deposit formed in an intracontinental extensional environment due to lithospheric thinning, and the mineralization is related to magmatism associated with partial melting of the lower crust. The intersection of the Dunhua-Mishan fracture and Kangbao-Chifeng fracture on the northern margin of the NCC may be a promising location for porphyry ore deposits related to a continental tectonic setting.

TABLE 6: Ore-forming fluids characteristics of typical deposits.

Deposit	Fluid inclusion type	Homogenization temperature	Salinity	Initial ore-forming fluids	Metallogenic epoch	Analytical methods	Geodynamic setting	Reference
Chehugou	CO ₂ -bearing multiphase daughter mineral-bearing multiphase	Early: 400–270°C	Early: 58.41–1.06% Nacl _{eqv}	High temperature, high salinity, CO ₂ -bearing, CO ₂ -NaCl-H ₂ O system	250.2 ± 7.2 Ma	Molybdenite Re-Os dating	Postcollision local extension	[1, 2]
	liquid-rich two-phase gas-rich two-phase	Middle: 370–160°C	Middle: 48.21–0.88% Nacl _{eqv}					
	pure gas phase	Late: 230–120°C	Late: 8.41–0.71% Nacl _{eqv}					
Jiguanshan	CO ₂ -bearing multiphase daughter mineral-bearing multiphase	Early: >480°C	Early: >66.75% Nacl _{eqv}	High temperature, high salinity, CO ₂ -bearing, high oxygen fugacity, magmatic hydrothermal	151.1 ± 1.3 Ma	Molybdenite Re-Os dating	Tectonic regime transformation	[3, 4]
	liquid-rich two-phase gas-rich two-phase	Middle: 480–320°C	Middle: 56.76–4.65% Nacl _{eqv}					
	pure CO ₂ -bearing pure liquid phase	Late: 320–180°C	Late: <10.86% Nacl _{eqv}					
Aolunhua	CO ₂ -bearing multiphase daughter mineral-bearing multiphase	Early: 430–330°C	Early: 58.41–1.06% Nacl _{eqv}	High temperature, high salinity, CO ₂ -bearing, high oxygen fugacity, CO ₂ -NaCl-H ₂ O system	129.4 ± 3.4 Ma	Molybdenite Re-Os dating	Continental extension related to lithosphere thinning	[13], Ma et al., 2009
	liquid-rich two-phase gas-rich two-phase	Middle: 350–250°C	Middle: 48.21–0.88% Nacl _{eqv}					
	pure gas phase	Late: <270°C	Late: 8.41–0.71% Nacl _{eqv}					
Daheishan	CO ₂ -bearing multiphase daughter mineral-bearing multiphase	Early: 391–286°C	Early: 44–3% Nacl _{eqv}	Medium-high temperature, high salinity, NaCl-H ₂ O system	168.2 ± 3.2 Ma	Molybdenite Re-Os dating	Active continental margin or island arc	[6, 7, 14]
	gas-liquid two-phase	Late: 379–232°C	Late: 9–1% Nacl _{eqv}					
	Daughter mineral-bearing multiphase							
Luming	liquid-rich two-phase gas-rich two-phase CH ₄ -bearing	449–133°C	53.1–1.2% Nacl _{eqv}	High temperature, medium salinity NaCl-H ₂ O±CH ₄ system	176.7 ± 4.4 Ma	Molybdenite Re-Os dating	Plate subduction	[23]
Fu'anpu	Gas-liquid two-phase	257.8–123.8°C	17.47–1.39% Nacl _{eqv}	Medium-low temperature, medium salinity NaCl-H ₂ O ± CH ₄ system	168.22 ± 0.87 Ma	Molybdenite Re-Os dating	Plate subduction	[11]

7. Conclusions

(1) The initial ore-forming fluids of the Changfagou deposit belonged to a high-temperature, high-salinity, CO₂-rich, high oxygen fugacity CO₂-NaCl-H₂O system.

(2) The precipitation of molybdenum was related to phase separation or immiscibility, whereas the precipitation of copper polymetallic sulfide is mainly related to decreases in temperature.

(3) The S and Pb isotopic characteristics indicate that the metallogenetic materials were mainly derived from deep acidic magma, perhaps from the lower crust.

(4) Based on the metallogenic fluid characteristics and regional tectonic study, the Changfagou deposit may form in an intracontinental extensional environment due to lithospheric thinning.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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