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Characteristics of melt inclusions in skarn minerals from Fe, Cu(Au) and Au(Cu) ore deposits in the region from Daye to Jiujiang

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Abstract A vast amount of the melt inclusions and fluid-melt inclusions have been found in skarn minerals from Fe, Cu(Au) and Au(Cu) ore deposits distributed from Daye to Jiujiang along the Yangtze River besides vapor-liquid inclusions. The melt inclusions are many and varied in shape. They mainly consist of crystallized silicate phases (C_{Si}), iron phases (Fe), amorphous silicate phases (A_{Si}) and vapor (V) with different volume percentages, and some of them contain several crystallized silicate phases. These melt inclusion sizes are commonly (10—46)×(6—15) μm^2. A difference between the fluid-melt inclusions and melt inclusions is that the liquid phase appears in the former and their homogenization temperatures are lower than the latter. We measured the homogenization temperatures of the melt inclusions, fluid-melt inclusions and fluid inclusions in ten thin sections from eight ore deposits on Leitz microscope heating stage 1350 which was made in Germany. Forty-eight homogenization temperature values have been obtained. Among them, thirty-nine values are homogenization temperatures of the melt inclusions in garnet and pyroxene from skarns, two values are homogenization temperatures of fluid-melt inclusions, others belong to the fluid inclusions. Melt inclusions in garnet and pyroxene have homogenization temperatures of 890—1115℃. Fluid-melt inclusions have homogenization temperatures of 745—750℃. Homogenization temperatures of fluid inclusions are between 580℃ and 675℃. The average of thirty-nine homogenization temperatures for the melt inclusions is 1029.9℃. We think studied skarns to be magmatic genesis on the basis of available data relative to the characteristic features of phase states within the melt inclusions and the fluid melt inclusions and their homogenization temperatures.

Keywords: skarn, melt inclusion, magmatic origin.

The skarns and skarn deposits are widely distributed at home and abroad. The skarn deposits include many kinds of ores and higher ore grade. Some of them are broad in scale. Scientists of ore deposits from different countries have paid and are paying great attention to the study of skarn deposits. A traditional and single theory of metasomatic origin of the skarns has been spread far and wide among the geological circles and has been adopted since the 1940s.

There are some reports in an aspect of the study of magma-genetic skarns. Cotta, von has stated that the garnet rocks " are probably, for the most part, the results of the combination of the lime in the limestone with the silicates of the banatites, by melting under a high pressure, and subsequent cooling-off in enclosed places”[1,2]. Li Binglun et al. are the first to measure homogenization temperatures of the melt inclusions in andradite from the Meishan iron ore deposit, Jiangsu Province, but they did not propose an idea about the magma-genetic skarn due to the reason that the given iron ore deposit is not thought to be typical ore deposit of skarn type[3]. Then, Qiu Ruilong’ s investigated results of REE distribution patterns of skarns and the melt-fluid inclusions in the skarn minerals from the Tongshan Cu(Au) ore deposit, Anhui Province were reported and he considered that the skarn-forming fluids were probably further fractionated products of the residual melts, their chemical properties were situated between residual melts and hydrothermal solutions[4]. Lin Xinduo et al. have clearly presented a conception on an existence of the magma-genetic skarns in the ore-forming skarns based on the observation of the geological occurrences of skarns from the iron ore deposits within the region of Hubei Province, and indicated that the skarn-forming fluids were transition series from the magma to hydrothermal solutions[5,6]. Wu Yanchang has also indicated that such a kind of skarns is magmatic origin based on the fact that skarns from some ore deposits of the skarn type in the area of Anhui Province occur in the shape of veins within surrounding rocks[7,8]. Zhang Shuzhen et al. have provided one value of the homogenization temperature of the melt inclusion in garnet from the Dongshizishan Cu(Au) ore deposit and thought this ore deposit to be copper ore deposit of magma-genetic skarn type[9]. Some amounts of evidence from experiments, melt inclusions, oxygen isotopes, and rare earth elements for magma-genetic skarns have been provided by our research group and these data play an important role in a real establishment of the idea about magma-genetic skarns, determination of their distribution range and dimensions[10−14]. Although spectacular progresses have been made in the study of the magma-genetic skarns, there are some serious lacks. They are mainly poor in the data of preciously measured homogenization temperatures and chemical compositions of the melt inclusions, isotopes of the skarns, experiments at high temperatures and pressures, dimensions of magma-genetic skarns, and their distribution ranges, ore-forming element contents in the melt incluions and distinguished indicators between the magma-genetic skarns and metasomatic skarns. These studies are not only a contention over scientific opinions among different schools, but also concern important problems of increasing ore-forming theory level of skarn deposits, study of their ore-forming regularity and ore-search. Therefore, it is necessary to study skarns of this type. The present paper will only report preliminary research results on characteristic features of phase states in the melt inclusions and fluid-melt inclusions within skarn minerals and the measured data of their homogenization temperatures.

1 Geological setting

This region belongs to the western part of the Fe, Cu, Au ore belt and is situated in the area of southeastern Hubei Province to northwestern Jiangxi Province, extending along the southern bank of the Yangtze River with northwest striking (fig. 1). The tectonic site is located in a south-ex- tending terminal end of a backbone of Huaiyang epsilon (€) structure style and is sandwiched between the Tongbai-Dabie orogenic belt and the Jiuling-Mufu domed belt which belongs to the middle part of the Jiangnan dome. Its structure framework and strained form are controlled by the continent-continent collision of south-north on both sides[15].

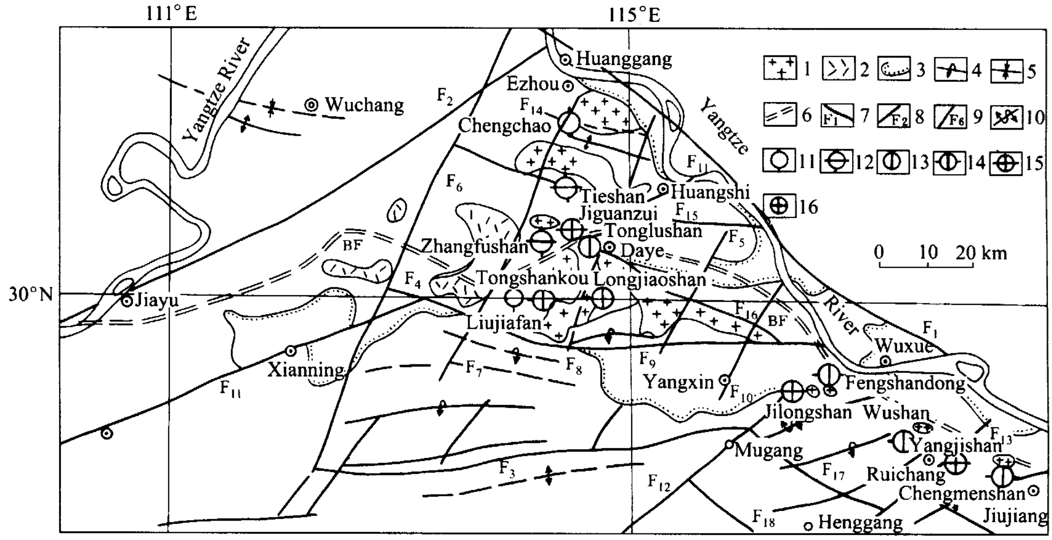


Fig. 1. Simplified geological map of the Daye-Jiujiang region and locations of ore deposits (from ref. [15] , 1997). 1, Granitoid intrusives; 2, volcanic basins; 3, sedimentary basins of Mesozoic era and Cenozoic era; 4, overturned anticlines; 5, synclines; 6, utra-crust fault (BF); 7, faults of northwest by west (N.W.b.W) and near-east-west latitudinal faults (F_1, F_3, F_4, F_5, F_{14}, F_{15}, F_{16}, F_{17}, F_{18}); 8, north-east faults (F_2, F_{11}, F_{12}, F_{13}); 9, faults of northeast by north (F_6, F_7, F_8, F_9, F_{10}); 10, convolute anticlines; 11, iron deposits of ore-magma injection; 12, iron deposits and ore magma-hydrothermal iron-copper deposits; 13, contact-metasomatic iron, copper, gold ore deposits; 14, porphyry-skarn copper-molybdenum ore deposit; 15, skarn-hydrothermal gold-copper ore deposits of the low to moderate temperatures; 16, lead-zinc (strontium) ore deposit of low to moderate temperatures. Tiezishan is in less than an kilometer from Liujiafan iron deposit and Lijiawan is about tens of meters from Fengshandong.

Basement rocks of this area consist of metamorphic rock series of Proterozoic era, the cover rocks of the basement outcrop completely except for an absence of the mid- and lower-Devonian series. The sediments from Sinian system to Quaternary system outcrop altogether and their overall thickness exceeds about 10 km. The strata of the Sinian system to the Lower Triassic series are mainly marine carbonate rocks and secondly the clastic rocks. The strata above mid-Triassic series are dominantly continental clastic rocks and locally volcanic rocks. According to geophysical data, the main shape of Moho is characterized by the uplift in the middle and a depression in the south and north of the regional range of Hubei Province and this area belongs to a region of the mantle uplift. Magmatic activities are dominated by magmatic intrusions of mid-late periods of the Yanshan movement. Rock types comprise biotite-diopside-diorite, diorite, monzodiorite, quartz monzonite, quartz diorite, granodiorite, granodiorite-porphyry, syenodiorite-porphyrite and granite. They all belong to granitoid evolutionary series of typical continental margin.

2 Study methods

Study of phase state characteristics of melt inclusions can be carried out under a common optical microscope. It is very easy to recognize crystallized phases and amorphous body with the aid of optical properties of the crystallized materials. In the light of an optical orientation, we can identify how many crystallized phases there are in the melt inclusions. Then, we can also distinguish whether the liquid and vapor phases exist in them. The inclusion shapes and relations between phases can be clearly seen under polarization microscope. They are the main basis for distinguishing inclusion types and the classifications of the melt inclusions, and are also important for the understanding of the inclusion evolutions with the decreasing temperatures and volatile pressures after they were closed. Note down the observed results and take microphotographs.

Homogenization temperature measurements of the melt inclusions and fluid inclusions have been accomplished on Leitz microscope heating stage 1350 which was made in Germany. A platinum palladium-platinum thermopile was used for temperature determinations and their values were read by a thermometer matching with it. Before the experiments the thermopile was calibrated by a UJ33a type direct current potentiometer which was made in a direct current instrument plant, China, and measured values are in a precision of 0.05%. Increasing temperatures was conducted on the principle of slow heating and the constant temperatures were controlled by the stages. Below 600℃, the increasing of temperatures was more rapid, while slower for the fluid-melt inclusions and very slow for the fluid inclusions. Above 600℃, temperatures were elevated on the basis of constant temperatures by the stages. Runs were kept for about 30 min at each temperature interval after increasing temperature was near 40℃ and the lasting time for measured temperatures of each inclusion sample was 8—10 h. The changing features of the inclusion phase states for each temperature stage were noted in the processes of whole experiments.

3 Phase state characteristics of the melt inclusions and fluid-melt inclusions in skarn minerals

Research results are shown in figs. 2 and 3.

A focus of this study is the melt inclusions, so only a few measured temperature data are listed for the fluid-melt inclusions and fluid inclusions.

3.1 Melt inclusions

According to Li Zhaolin's classification method of the melt inclusions with different phase states in zircons from the granites[16], the melt inclusions in the skarn minerals of this area can be divided into two-phase and multiphase inclusions. The inclusions in the minerals are mostly distributed in the shapes of an irregularities and isolations indicating their primary genesis.

3.1.1 The two-phase melt inclusions (A_{Si}+V, V+C_{Si} or C_{Si}+V). They are all distributed in the skarn minerals from the Daye iron ore deposit, Fenshandong Cu(Au) ore deposit, Tonglushan

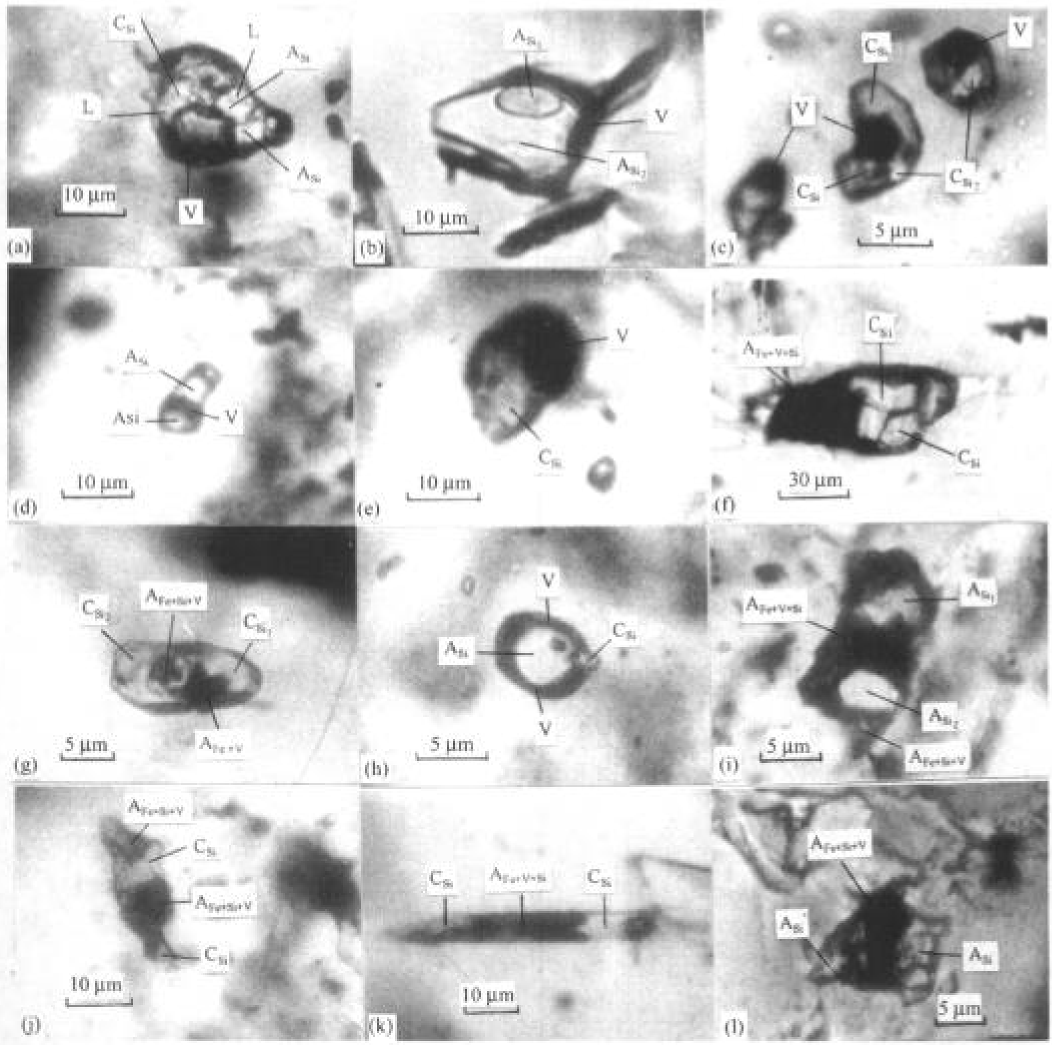


Fig. 2. Micrographs of melt inclusions and fluid-melt inclusions in garnet and pyroxene from some Fe, Cu(Au) and Au(Cu) ore deposits within the Daye-Jiujiang region. (a) Z-98-6 (Daye); (b) Z-98-21 (Jiguanzui); (c) 80-205 (Tonglushan); (d) Z-98-64 (Tongshankou); (e) Z-98-37 (Tonglushan); (f) Z-98-44 (Longjiaoshan); (g) Z-98-66 (Tiezishan); (h) Z-98-98 Fengshandong); (i) Z-98-148 (Jilongshan); (j) Z-98-157 (Wushan); (k) Z-98-174 (Chengmenshan); (l) Z-98-128 (Lijiawan). The melt inclusions are all in garnet except for the Z-98-37 melt inclusion which is in pyroxene. Fluid-melt inclusion is shown in (a), others are melt inclusions. The inclusion in (a) is fluid-melt inclusion. A, Amorphous; C, crystilline; Si, silicates; Si1, phase 1 of silicates; Si2, phase 2 of silicates; Fe, iron and iron oxide; V, vapor; L, liquid; the same below.

Cu(Au) ore deposit, Longjiaoshan Cu ore deposit and Wushan Cu-Mo(Au) ore deposit. Most of them consist of vapor+crystallized phases ($V+C_{Si}$) and amorphous phase+vapor phases ($A_{Si}+V$). The vapor phase in the two-phase melt inclusions make up about 10%—60% (see figs. 2 and 3). Among all the ore deposits mentioned above, the contents of vapor phase in the two-phase melt inclusions in the skarn minerals from the Fengshandong and Wushan ore deposits are the smallest, about ten volume percent of the inclusions, followed by that of the inclusions in the skarn minerals from the Longjiaoshan Au(Cu) ore deposit. In sample Z-98-3 from the Daye iron ore deposit, the

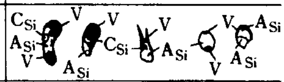
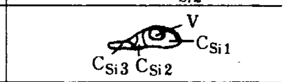
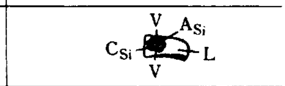
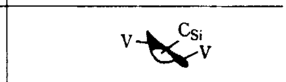
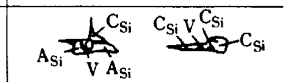
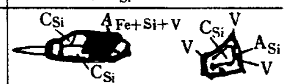
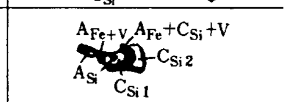
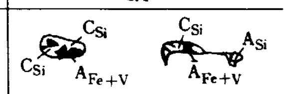
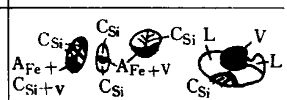
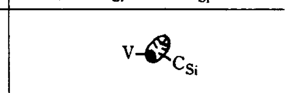
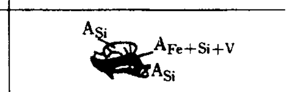
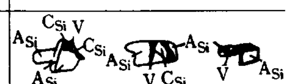
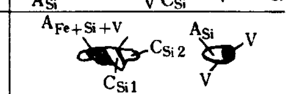
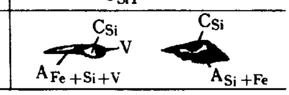
Deposit	Sample number	Rock name	Sampling location	Phase state characteristics of inclusions
Daye Fe deposit	Z-98-3	garnet-pyroxene skarn	carbonate rock of eastern part	
Jiguanzui Au(Cu) deposit	Z-98-21	pyroxene-garnet skarn	place of CM-25 on –320 m-level	
	Z-98-23		near Z-98-21	
Tonglushan Cu(Au) deposit	Z-98-34	pyroxene-bearing garnet skarn	5415 producing area of 8th ort on –245 m-level	
	Z-98-35		5414 producing area of 10th ort on –245 m-level	
Longjiaoshan Cu deposit	Z-98-42	garnet skarn	lower side of gopher drift on +230 m-level	
	Z-98-44		room of drilling hole on upper side of orebody on +230 m-level	
Tongshankou Cu(Au) deposit	Z-98-64	pyroxene garnet skarn	eastern side of southern margin of 3rd orebody on +74 m-step of opencasting area	
Tiezishan Fe deposit	Z-98-66		picked sample from spoil heap of opencasting-pit	
Fengshandong Cu(Au) deposit	Z-98-82	garnet-pyroxene skarn	core from 319.3 m to 321.0 m of ZK-3 drilling hole	
	Z-98-96	pyroxene-garnet skarn	core from 375.70 m to 378.15 m of ZK-3 drilling hole	
Lijiawan Cu(Au) deposit	Z-98-128	pyoxene-bearing-garnet skarn	on lower side of 2nd orebody near granodiorite porhyry in west of No. 0 line on –100 m-level	
Jilongshan Au(Cu) deposit	Z-98-151	pyroxene-garnet skarn	30th ort on –250 m-level near marble	
Wushan Cu-Mo (Au) deposit	Z-98-157	pyroxene-bearing garnet skarn	about 5 m from contact of western end of 2nd area in south on –110 m-level	
Chengmenshan Cu(Au) deposit	Z-98-174	marble with garnet veins	from 268.3 m core of PF-51 drilling hole	

Fig. 3. Phase state characteristic features of melt inclusions and fluid-melt inclusions in skarn minerals from some Fe, Cu(Au) and Au(Cu) ore deposits distributed in the area from Daye to Jiujiang. The host minerals are all garnet; L-bearing phase in Z-98-82 is fluid-melt inclusion, the others are melt inclusions.

vapor phases in the two phase inclusions make up also about ten volume percent, while in sample Z-98-7 from the same deposit, the vapor phase is about sixty volume percent. The vapor phase in the two-phase inclusions is about sixty volume percent in the skarns from the Tonglushan Cu(Au) deposit and Jilongshan Au(Cu) ore deposit, respectively. Most of the vapor phase is distributed in the rims of the melt inclusions, but it is also simultaneously dispersed along the rims of the melt inclusions and in the shape of individual bubbles in them (see samples Z-98-3, Z-98-23, Z-98-44 and Z-98-157). The two-phase melt inclusions are (10—32)×(6—8) μm^2 in size, the maximum is 32×8 μm^2.

3.1.2 Multiphase melt inclusions ($C_{Si}+A_{Si}+V$, $A_{Fe}+A_{Si+V}$, $A_{Fe}+C_{Si+V}$, $A_{Fe}+C_{Si}+A_{Si+V}$, $A_{Fe+Si}+C_{Si}$, $A_{Fe+Si+V}+C_{Si+V}$, $A_{Fe+Si}+C_{Si}+V$, $A_{Fe+V+Si}+A_{Si}+V$, $A_{Fe+Si+V}+A_{Si}+V$, $A_{Fe+Si+V}+C_{Si}+V$, $nC_{Si}+A_{Fe}+V$, $nC_{Si}+A_{Fe+Si+V}+V$). The multiphase melt inclusions consist of the crystalline, amorphous and vapor phases, generally three phases, and have been almost distributed in all studied skarn samples. The multiple phases are the main characteristics of phase states in the melt inclusions. In some multiphase melt inclusions vapor phase and iron phase are homogeneously distributed in the silicates, forming mixtures ($A_{Fe+Si+V}$ and A_{Fe+Si} are used in this paper so as to distinguish this from other cases) and becoming important part of the melt inclusion constituents. The vapor phases in the melt inclusions are usually well or not well distributed in the iron-bearing silicates, so its volume percent in multiphase inclusions is difficult to be estimated, but the contents of the vapor phase in the multiphase melt inclusions are smaller than those of the two-phase melt inclusions, showing that the density of the former is larger than the latter. A remarkable characteristic of the multiphase melt inclusions is the mixing between the silicates and iron phases. The inclusions of this type contain commonly the mixture of fixed amounts of vapor phases, bad-distributed brown, light brown colors emerge under the single polarizing microscope. The forms of the melt inclusions are chiefly extended, elliptical, and then subround, conical and in the shapes of the calabash and needle, etc. The inclusion sizes are (64—6)×(3—15) μm^2, but (15—46)×(7—15) μm^2 are the main. Multiphase melt inclusions in the skarn minerals from Daye, Longjiaoshan, Tonglushan and Fengshandong are distributed in the shape of large blocks or are arranged directionally along annular growth zoning of the garnet. Judging from the characteristcs of the phase states of the melt inclusions in the skarn minerals, they are similar to the melt inclusions in zircon from granites in many aspects[16].

3.2 Fluid-melt inclusions

The fluid-melt inclusions ($L+V+A_{Si}+nC_{Si}$, $L+V+A_{Si}+C_{Si}$, $L+V+C_{Si}$) in the skarn minerals from the Daye iron ore deposit, Tonglushan copper (gold) ore deposit and Fengshandong copper (gold) ore deposit have been observed. The inclusions of this type are not widely distributed and have been rarely seen before. We can see from figs. 2 and 3 that the liquid phase (L) in the liquid-melt inclusions constitute a large volume percent, the vapor phase in them is usually circular in shape. Such a characteristic is the same as found in the vapor-liquid inclusions. The contents of the crystallized and amorphous silicates in the inclusions of this type are small, constitute *n* volume percent ($n < 10$) to 40 volume percent of the total volume of the inclusions. The fluid-melt inclusions are (8—20)×(6—16) μm^2 in size.

3.3 Vapor-liquid inclusions and multiphase fluid inclusions

The vapor-liquid two-phase inclusions are rarely found in the garnets and pyroxene from the skarns but the daughter-bearing multiphase fluid inclusions are usually observed. The daughter minerals are mostly NaCl.

4 Homogenization temperatures of inclusions in skarn minerials

The changing characteristics of the melt- and fluid-melt inclusions in the heating processes and their homogenization temperatures are respectively shown in fig. 4 and listed in table 1.

From fig. 4 the following characteristics can be found. (i) In the comparison of the melt inclusions after experiments with the initial states of the melt inclusions, most of their shapes do not obviously change during the experiments. (ii) In the heating processes the vapor phases were gradually diffused or bubbles were deformed first accompanied by partial melting of the silicates till the bubbles were lost and most silicates were melted away, then the whole inclusions became dark due to vapor diffusion, and light points appeared in the inclusions with increasing temperature, those are residual crystallized material remaining after the silicates were melted. They changed smaller and smaller in size with increasing temperature and were lost finally. The inclusions have shown only their outlines, indicating that the silicates have been fully melted and reached the homogeneous states. Some melt inclusions have become dark or colorless when their homogeneous states have been attained, depending on the iron content of the inclusions. (iii) The homogenization temperatures of the melt inclusions change between 895℃ and 1115℃ in the ore-forming belt of about 100 km straight distance. The maximum difference in the homogenization temperatures of the melt inclusions is 220℃. A comparison of the average homogenization temperature of the melt inclusions in the skarn minerals from one deposit with the others from different ore deposits has shown that those of the Jilongshan are the highest (1070℃), while those of the Jiguanzui is the lowest (975℃). The difference in the average homogenization tempetatures between Longjiaoshan and Jilongshan is only 5℃, and such difference values between Daye and Wushan as well as Tonglushan and Fengshandong are respectively 2.5℃. The average homogenization temperature of the melt inclusions from Tonglushang is 4℃ lower than that of Daye. In summary, the homogenization temperatures of the melt inclusions in the garnets from most ore deposits approximate each other. The differences between the homogenization temperatures of the melt inclusions depend on the compositions of the solid phases, their contents, kinds of the volatile components and their concentrations. (iv) The observations under the microscope for the inclusions indicate that the inclusions are colorless when they reached the homogeneous states except for a few. This depends also on the contents of vapor and iron phases in the melt inclusions. (v) Some inclusions were blasted in the heating processes, the vapor phase escaped from them,

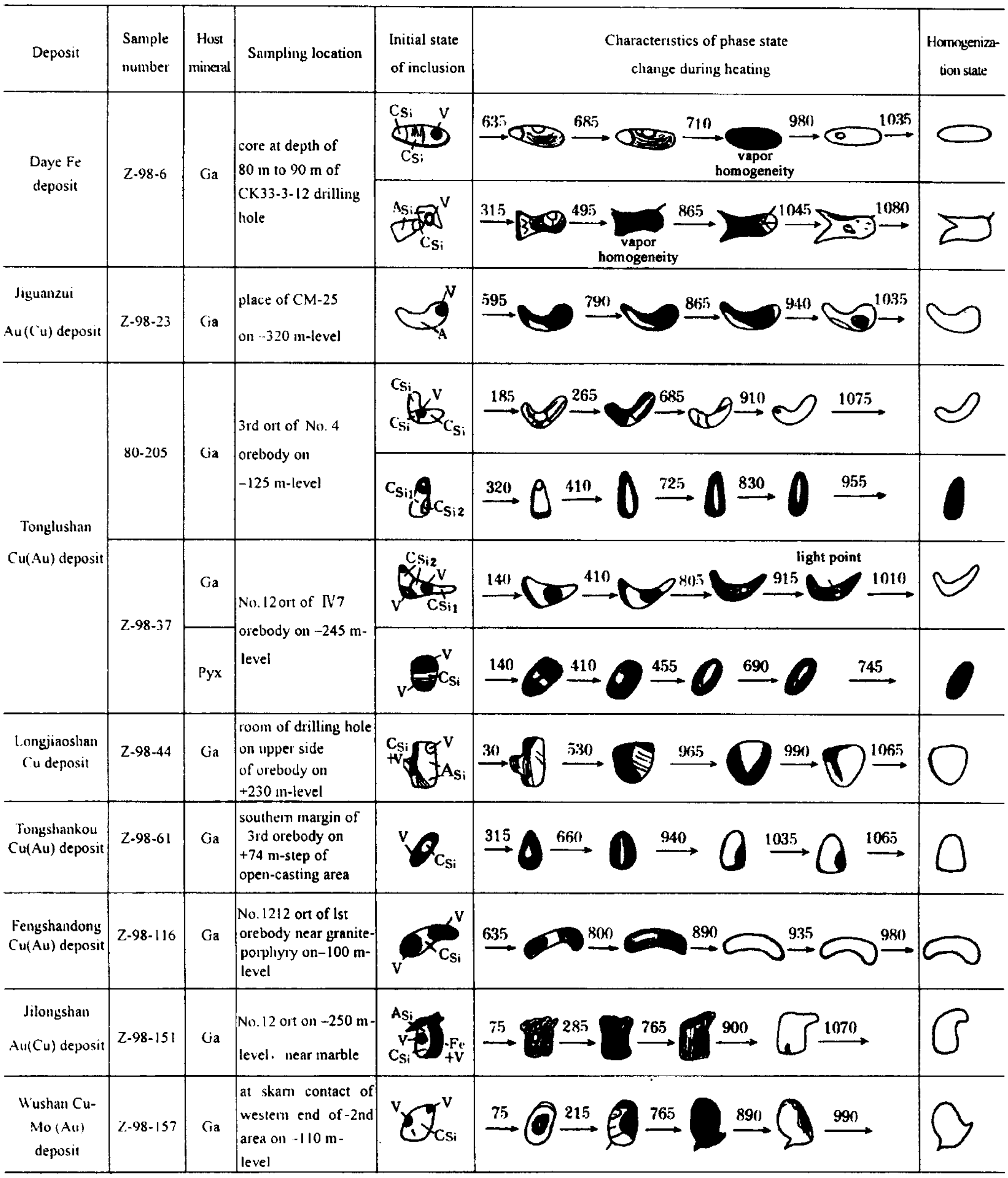


Fig. 4. Variation of phase states in melt inclusions during the heating time and their homogenization temperatures. Ga = garnet.

bringing the materials out of the melt inclusions, looked like horse's tail in shape (for example, it has been seen in the sample of Z-98-116). (**vi**) The skarn of 80 —205 specimen that was partially melted by later diorite magma is in the subround shape. We can see from a polished surface of this hand specimen that the skarn in the quartz diorite has a texture looking like a sieve. The average homogenization temperature of the melt inclusions in the garnets from this specimen is 62.25℃ more than the pyroxenes and is about 50℃ more than the garnets from the same mine. The dif-

Table 1 Measured results of homogenization temperatures of melt inclusions and fluid-melt inclusions in skarn minerals from different ore deposits and comparison of them with the data published in literature

Deposit	Sample number	Host mineral	Inclusion type	Homogenization temperature T/°C	Source of data	Remark
Meishan Fe deposit, Jiangshu Province		andradite	melt inc.	1050	[3]	quenching method
Zhangfushan Fe deposit, Hubei ProvInce		diopside		1080	[6]	no explanation
Changlongshan Fe deposit, Anhui Province		garnet	melt inc.	930		
		hedenbergite	fluid-melt inc.	730		
		calcite	fluid-melt inc.	730		
Anqing Cu(Au) deposit, Anhui Province		garnet	melt inc.	980		
		diopside	melt inc.	1020		
		quartz	fluid-melt inc.	780		
		actiolite	fluid-melt inc.	870		
Wushan Cu-Mo(Au) deposit, Jiangxi Province		garnet	fluid-melt inc.	740		
Dongshizishan Cu(Au) deposit, Anhui Province			melt inc.	920	[9]	
				1195–1290	[11]	homogenization method
Fuyoushan Cu(Au) deposit, Jiangshu Province				1080–1250		
Dongguashan Cu(Au) deposit, Anhui Province				1120–1290		
Xiaotongguanshan Cu(Au) deposit, Anhui Province				1280–1300		
Huanren Pb-Zn deposit, Liaoning Province				1300		
Daye Fe deposit, Hubei Province	Z-98-6			955	this study	
				1080		
				1010		
Jiguanzui Au(Cu) deposit, Hubei Province	Z-98-1	calcite		1035		
	Z-98-23			945		
				795		
				1035		
Tonglushan Cu(Au) deposit, Hubei Province	Z-98-37	garnet	melt inc.	1010		
				895		
				1010		
				955		
			fluid-melt inc.	750		
	80-205		melt inc.	1045		
				1115		
				1020		
				975		
				1075		
				1035		
				975		
				975		
				1020		
	Z-98-37	pyroxene	melt inc.	955		
			melt inc.	955		
			fluid inc.	580		
			melt inc.	955		
				900		
			fluid-melt inc.	745		
			melt inc.	990		

(*To be continued on the next page*)

(*Continued*)

Deposit	Sample number	Host mineral	Inclusion type	Homogenization temperature T/℃	Source of data	Remark
Longjiaoshan Cu deposit, Hubei Province	Z-98-44	garnet	melt inc.	1065	this study	homogenization method
Tongshankou Cu(Au) deposit, Hubei Province	Z-98-61	calcite		1035		
		garnet		1065		
				1035		
				1035		
Fengshandong Cu(Au) deposit, Hubei Province	Z-98-116			980		
				1070		
				1070		
			fluid inc.	605		
				595		
				630		
				675		
Jilongshan Au(Cu) deposit, Hubei Province	Z-98-151		melt inc.	1070		
				1070		
				1070		
Wushan Cu(Au) deposit, Jiangxi Province	Z-98-157			990		
				1055		
				1055		
				990		

inc = inclusion.

ference between the homogenization temperatures of the latter two is in the range of measured errors. It seems that the difference values in the homogenization temperatures of the melt inclusions in the garnet and pyroxene from Tonglushan Cu(Au) deposit are probably caused by the diversity in crystallized order of the crystals from the magma and the heterogeneity in the trapped inclusion compositions or twice intrusions of skarn magma.

5 Discussions

5.1 Valuation on the data of measured homogenization temperatures of melt inclusions in skarn minerals

The measured homogenization temperature errors of the melt inclusions after calibration are small and do not exceed 10℃. The range in a variety of the homogenization temperatures furnished in this paper for the melt inclusions and fluid-melt inclusions are close to those provided by Li Binglun and Lin Xinduo, but are smaller than those of ref. [11] (see table 1). The melt inclusion homogenization temperatures we provided before may be on the high side, they need to be examined again. Due to the small volume of furnace chamber on the heating stage and its low heat-retaining capability, temperature equilibrium between the inclusions in the minerals and the furnace chamber could be maintained for a long time, the melt inclusions that originally could be homogenized at the lower temperatures were quickly melted by the increasing temperatures for the reason of time limit of the heating stage working at high temperatures, resulting consequently in measured temperature values on the high side. In the light of the diffusion (such as the diffusion of hydrogen), the volatile components in some melt inclusions were lost, causing also the homogenization temperatures on the high side. For this reason, measured temperature values represent probably the homogenization temperatures after they were formed and preserved to the present states. They are always smaller than host mineral formation temperatures or approximate to them.

5.2 Evolution characteristics of the melt inclusions and fluid-melt inclusions in skarn minerals after they were closed and their significance

According to the measured homogenization temperature data of the melt inclusions provided by different authors in table 1, we think that a great majority of magma-genetic skarns were formed under the conditions of the slightly changed high temperatures. The melt inclusions in the skarn minerals studied in this paper, either the binary or the triple, contain silicates and iron besides the vapor phase. The values of the volume percentage for the crystalline and amorphous silicates in the melt inclusions have changed strongly in different ore deposits. The values of the volume percentage for the amorphous silicates in the melt inclusions within the skarn minerals from the Daye iron ore deposit and Jilongshan gold (copper) ore deposit are larger than those of the crystallized silicates. The melt inclusions belong to weakly evolved type among the classifications of the melt inclusions, the others are of the evolved type. The melt inclusions of the weakly evolved type imply that magmatic crystallization occurred in shallow places near the surface, host minerals were quickly cooled, the silicate melts trapped by the inclusions could be in equilibrium with the host minerals becoming glasses by the quenching. After the melt inclusions were closed, a certain amount of the crystallized daughter minerals in the melt inclusions were separated out due to a drop in temperature, and then weak evolution happened. In the melt inclusions of the evolved type the amorphous silicates are the residual melts left after daughter minerals were crystallized and separated out[17]. The melt inclusions of the evolved type suggest that host minerals underwent a slow cooling process. Under such conditions the silicate melts trapped in the inclusions could not be in equilibrium with their host minerals, leading finally to a series of evolutions taking place within the melt inclusions, and thus large amounts of crystallized silicate daughter minerals were separated out.

According to the percentage values of the vapor phase in the melt inclusions and its distribution forms, the degrees of the melt viscosity and density can be distinguished. Thus it can be known that the low values of vapor phase in the melt inclusions among the ore deposits mentioned above represent the higher viscosity and density of the magma. The percentage values of vapor in the melt inclusions from the Daye iron ore deposit change strongly, indicating the local heterogeneous distribution of the volatile components in the magma. The volume percentages of vapor in the melt inclusions from the Tonglushan copper (gold) ore deposit and Jilongshan gold (copper) ore deposit are large, indicating high contents of the volatile components of the magma and their small values in viscosity and density.

The fluid-melt inclusions in the investigated area are characterized by the fact that their vapor volume percentages are larger than those of the crystallized and amorphous silicate phases. They are different from those observed in the skarn minerals from the Tongling area at lower reaches of the Yantze River and in tungsten-molybdenum extremely large ore deposit of Shizhuyuan before. In those fluid-melt inclusions, the silicate phases, including crystallized and amorphous silicates, have higher values of volume percentage than the vapor-liquid phases. This indicates that the skarn magma from some ore deposits of this area has the evolved characteristics. As we have discussed, the temperature interval for the formation of the fluid-melt inclusions is wide. Their formation began from the time when the first portion of the volatile components escaped from the magma and was trapped by the melt inclusion, and continued up to the disappearance of the final drop of the silicate melt in the magmatic chamber all along[18]. The inclusions of such a type could probably be formed by the residual magma that was trapped by some defects of skarn minerals from middle to late stages of the magmatic crystallization. Only those fluid-melt inclusions trapped in skarn minerals at later stage of magmatic evolution are close to the nature of a transition from silicate-bearing supercritical fluids of the magma to hydrothermal solutions. Such supercritical fluids probably contain ore-forming elements in high concentrations, but this needs to be studied further.

5.3 Magma-genetic skarns and formations of melt inclusions and fluid-melt inclusions in them

The melt inclusions and fluid-melt inclusions, which were trapped by minerals either from earth or from celestial bodies in the processes of their growth, are thought to be silicate melts or magma[19−22]. Up to now, nobody has explained the formation problem of the melt inclusions in the skarn minerals, although some models on the skarn formation of the magmatic origin were presented. Formation mechanism of the melt inclusions is a key to understanding the origin of skarn. If the definition of melt inclusions in the volcanic rocks and magmatic rocks is cited to the study of the skarn genesis, then at least those skarns that contain melt inclusions from lower reaches of the Yangtze River must be of magmatic origin. The magmatic inclusions (or called melt inclusions) are natural magmatic drops entrapped by the lattice defects of the minerals in the forming processes of magmatic rocks, then they were quenched, condensed to glasses or silicate daughter minerals, metallic phase and liquid phase that were separated out during their further crystallization, with the cooling of host minerals. The melt inclusions in skarn minerals have various phases and very high homogenization temperatures, satisfying the definition of the magmatic inclusions. Therefore, using the melt inclusions as a direct piece of evidence of the magma-genetic skarns has firm basis.

Experimental data at high temperatures and pressures indicate that great amounts of K, Na and Si, minor amounts of Ca and Fe, and micro amounts of Mg and Al could be extracted from the rocks by the supercritical fluids. So whether the supercritical fluids cause the formation of the melt inclusions and fluid-melt inclusions needs to be considered. H_2O-NaCl-CO_2 system can be used as the hydrothermal fluids that derived from the magma in the crust. The solubilities of Al, Mg, Ca, Fe and Si in the supercritical fluids containing 1—4 mol/L NaCl are limited[23,24], considering the data of partitioning coefficients of the elements between the fluids and granitic silicate melts under the conditions of temperatures blow 900℃ and pressures below 200 MPa. The results of experiments carried out under the conditions of 133—170 MPa and 800℃ show that the fluids with 1—4 mol/L NaCl have contained (90—9000) μg/g K_2O, (5700—61400) μg/g SiO_2, (50—530) μg/g CaO, (60—980) μg/g Fe_2O_3, (9—32) μg/g MgO and <15 μg/g Al_2O_3. If we compare each of the highest element oxide contents of the fluids with that of the starting materials, 37% K_2O, 9.5% SiO_2, 2.2% Fe_2O_3, 1.2% CaO, 0.24% MgO and 0.091% Al_2O_3 (all of weight percent) of the starting material were extracted by NaCl fluids. It can be seen that potassium is the easiest to be brought out by the sodium chloride fluids, then silicon, but others, in particular magnesium and aluminum, are hard to be solved; therefore, the contents of the chemical components required for the formation of skarns cannot be satisfied. It can be assumed that such supercritical fluids could rise quickly along open tensional fractures and could permeate through interlayer-gliding faults or the fracture systems near contact zones under tectonism. Skarns could be formed by metasomatism between pelitic sedimentary carbonate or pure carbonate and supercritical fluids at shallow places below the surface. Owing to the slow temperature dropping, the skarn minerals formed in this way can contain high temperature and high salinity vapor-liquid inclusions; however, there are absolutely no melt inclusions and fluid-melt inclusions. This is in consistency with the fact that most fluid inclusions of skarn minerals do not contain silicate daughter minerals even if their homogenization temperatures are as high as up to 700℃[25]. Magnesian skarns formed at the magmatic stage indicated by Korzinskii were probably the results of the metasomatism between the high temperature fluids and dolomites[26]. But it is difficut to interpret the formation of Al component-bearing garnet that generated at the exocontact zone between intermediate-acid intrusive rocks and pure carbonate rocks by using supercritical fluids which have similar chemical compositions to those obtained in the experiments at high temperatures and high pressures.

Our unpublished Sm-Nd isotopic composition data show that most skarns copper (gold) ore deposits have model-neodymium age of two stages ranging from 1.1 Ga to 2.0 Ga with the exceptions of a low one (0.9 Ga) of the Chengmenshan and a high one (2.6 Ga) of the Fengshandong Cu(Au) deposits. These model-neodymium ages are in the correspondence with that of the main formation time of the Yangtze block[27]. This means that two-stage model-neodymium ages of skarns from this area reflect some significant geological events, such as the differentiation of the crust-mantle and rapid growth of the continental crust, and may represent the average age of the local continental crust. Therefore, the depleted mantle two-stage model-neodymium ages of the skarns correspond to the basement formation stage of middle-upper Proterozoic continental crust of this area. During this stage, this area underwent a strong Jinning movement accompanied by strong folding and regional metamorphism. The metamorphic basement of this area consists of a set of green schist facies predominating metamorphic rock series, which formed from the late mid-Proterozoic period to late upper Proterozoic period. Primary rocks of the low-grade metamorphic rock series are carbonate rocks, including limestone and dolomatic limestone, sandstones, calc-argillaceous flysch sediments and minor spilite-keratophyre, andensite lava and volcanic clastic rocks. The formation temperatures and pressures of the green schist facies are estimated at 300℃—500℃ and 0.3—0.8 GPa[28], much lower than the average homogenization temperature (1029.9℃) of melt inclusions of skarns, so the skarn magma could not be generated by the low-grade metamorphism.

Skarn magma could be formed by many ways. Sr-Nd isotopic study results indicate that there is no genetic connection between skarns, intermediate-acid igneous rocks and sedimentary carbonate rocks. For this reason, the opinion on the formation of the skarn magma by melting of some sedimentary carbonate rocks at shallow places below the surface due to intrusion of intermediate-acid magmas can be ruled out. Additionlly, in the e_{Sr} versus e_{Nd} diagram, the intermediate-acid rock bodies display negative correlation trend suggesting the mixing of crust-mantle two-end members, while the skarns have the positive trend with a high slope, and the data points of the sedimentary carbonate rock are plotted between the skarns and the igneous rocks and display the trend of being perpendicular to e_{Sr} axis. This means that the source materials of the skarns have nothing to do with the igneous rock bodies and the sedimentary rocks, the skarn has an independent source of skarn magma.

According to the above discussions, we propose that this independent skarn magmatic source was entirely possibly in the lower crust. The crust thickness of the Yangtze block is about 35—37 km[29]. The bottom of the metamorphic basement is close to Moho. As mentioned above, this region is located in the mantle uplifted area, the possibility that upwelling mantle materials had brought the heat to the strata of the bottom of the continental basement is great, thus the formation of the skarn magma probably relates to the existence of the great amounts of the hydroxyl-bearing minerals (such as mica group and amphibole minerals) in the lower crust and the transmission heat from the upwelling mantle materials to lower crust.

6 Conclusions

(1) The melt inclusions and fluid-melt inclusions have been found in the skarn minerals from most skarn deposits distributed in the Daye-Jiujiang area and their homogenization temperatures are very high. These indicate that the skarns studied in this paper are of magmatic genesis, rather than contact-metasomatic origin. They are large in size and are wide in spatial distribution.

(2) The fluid inclusions with high temperatures and high salinities existing in the skarn minerals could be formed by the metasomatism of the sedimentary carbonate rocks in the presence of the fluids similar to supercritical fluids obtained at the high temperature and high pressure experiments. But it is impossible to form either magma-genetic skarns in this way, or magmagenetic

skarns by the effect of supercritical fluids on the carbonate rocks.

(3) Remarkable diffierence between the high temperature melt inclusions existing in the skarn minerals and low-grade metamorphic rock series of the continental crust basement of this area suggests that the skarns of the magmatic origin could not result from the regional metamorphism.

(4) The formation mechanism of skarn magma is perhaps related to the existence of the large amounts of hydroxyl-bearing minerals in the lower crust and the effect of the heat brought by the upwelling mantle materials on the lower crust, resulting in partial melting of the lower crust, which formed the independent magmatic source.

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