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二长石地质温度计在估算乌拉山金矿碱性长石形成温度中的应用

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摘 要: 内蒙古乌拉山金矿田内主要出露晚太古代乌拉山群区域变质岩和规模不一的花岗岩体以及不同时代、不同种类的脉状地质体。含金矿脉中主要矿物共生组合为碱性长石、石英、斜长石、碳酸盐矿物(方解石、白云石)和少量金属硫化物。矿床的显著特征为碱性长石交代作用强烈, 碱性长石也广泛产于该地区其他各种类型的岩石中。本文采用电子显微探针分析了共生碱性长石和斜长石的化学成分, 并采用三元二长石温度模型估计了碱性长石的平衡温度。结果表明, 第一成矿阶段的碱性长石-石英含金矿脉中碱性长石的形成温度为 353 ℃, 第二成矿阶段石英含金矿脉中碱性长石的形成温度为 281 ℃, 矿脉碱性长石形成压力约为 5 kbar。这些结果与同类矿石中平衡共生的碳酸盐矿物和云母类矿物的地质温度计估计的形成温度以及共生石英中流体包裹体的均一温度非常一致。因此, 乌拉山金矿床形成和富集的温度可估测为 260~ 380 ℃, 压力约为 5 kbar。此外, 应用二长石温度计计算了本地区区域变质片麻岩和花岗岩中碱性长石的平衡温度, 所得温度比采用共生铁铝榴石和黑云母温度计估计的温度要低约 250 ℃。这表明共生的铁铝榴石和黑云母的平衡温度可能代表其寄主变质岩变质期温度及寄主花岗岩原生温度, 而区域变质岩和花岗岩中的碱性长石在经历了随后多次热液作用后, 可能重新平衡再生, 这也与前人对乌拉山金矿的矿床地质和同位素研究的结果一致。

关键词: 碱性长石; 形成温度; 二长石温度计; 乌拉山金矿床; 内蒙古
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Formation temperatures of alkali feldspars from the Wulashan gold deposit: an estimate by two_feldspar thermometry

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Abstract: The Wulashan gold deposit, Inner Mongolia, China, which is characterized by intensive alkali feldspar metasomatism, is hosted by the late Archean gneiss, amphibolite, migmatite, and marble of the Wulashan Group and surrounded by several intrusions. The general mineral assemblage of mineralized lodes is alkali feldspar + quartz + plagioclase + carbonate (calcite and Fe_dolomite *etc*). Alkali feldspar is also present as a major component within country rocks. On the basis of the microprobe analyses for coexisting alkali feldspar and plagioclase, the equilibrium temperatures of the alkali feldspars are calculated using several ternary two_feldspar geothermometers. The obtained temperatures at 5 kbar are 353 ℃ for alkali feldspars from gold_bearing veins I (K_feldspar_quartz veins), and 281 ℃ for alkali feldspars from gold_bearing veins Ⅱ (quartz veins), in good agreement with the estimated temperatures for coexisting carbonates, mica minerals and gold, and with the homogeneous temperatures of fluid inclusions in quartz and alkali feldspars. Therefore, the gold mineralization in

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the Wulashan gold deposit formed at the temperatures ranging from 280~ 360 ℃ and the pressure of 5 kbar. On the other hand, the temperatures of alkali feldspars from regional metamorphic gneiss and granite are lower than the equilibration temperatures of coexisting almandine and biotite, indicating that the temperatures of almandine and biotite may represent the peak temperature of metamorphism and alkali feldspars in metamorphic rocks and granite may re_equilibrate after experiencing numerous overprinting thermal / magmatic events.

Key words: alkali feldspar; formation temperature; two_feldspar thermometer; the Wulashan gold deposit; Inner Mongolia

1 Introduction

The chemical compositions of alkali feldspar are dependent on temperature, pressure, oxygen fugacity, fluid compositions, coexisting mineral associations, and bulk_rock composition. Therefore, some features of alkali feldspars could be useful indicators of the physicochemical environment in which it grew. Barth (1951) presented an empirical two_feldspar thermometer using measurements of the distribution of $NaAlSi_3O_8$ (Ab) between naturally occurring plagioclases and alkali feldspars. Several other two_feldspar thermometers have been calibrated considering the effect of pressure (Stormer, 1975; Powell & Powell, 1977; Whitney & Stormer, 1977; Heselton *et al.*, 1983). However, these models do not include the conditions for equilibrium provided by $KAlSi_3O_8$ (Or) and $CaAl_2Si_2O_8$ (An), and do not consider Al_Si ordering. The equilibrium of all three components in coexisting feldspars, as well as Al_Si ordering, should be taken into account in thermodynamic models of feldspar equilibrium (Parsons & Brown, 1983). Thus, more recently, the thermodynamic formulations of feldspar activity_composition relations include constraints from equilibrium among the Ab, Or and An components in coexisting alkali feldspars and plagioclases (Ghiorso, 1984; Green & Udansky, 1986; Fuhrman & Lindsley, 1988; Lindsley & Nekvasil, 1989; Elkins & Grove, 1990; Kroll *et al.*, 1993).

One unique feature of the Wulashan gold deposit is the intensive alkali feldspar metasomatism. This "potassic wash" is associated with silicification that locally extends for several meters into the host rocks (Hart *et al.*, 2002). Field studies showed that alkali feldspar metasomatism is closely associated with the evolution of gold mineralization in both space and time. Fluid inclusion and stable isotope studies of gold_bearing quartz veins have been carried out and several competing ore genesis models were therefore proposed (Hart *et al.*, 2002). Alkali feldspars widely exist in all varieties of rock types in this area, but the mineralogy of alkali feldspars in this area has not been studied in details so far. In this paper, the chemical compositions of coexisting alkali feldspars and plagioclases from the Wulashan gold deposit are analyzed using electron microprobe. The formation temperatures of alkali feldspars are estimated and compared using several ternary two_feldspar thermometers. The formation temperatures and pressure of alkali feldspars are further applied to reveal the characterization of the Wulashan gold deposit, and to provide constraints on the conditions of gold mineralization in the Wulashan gold deposit.

2 Geological setting

The Wulashan gold deposit is situated along the northwestern margin of the North China craton, and on the northern side of the Daqingshan_Wulashan fault belt (Zhang *et al.*, 1999). The major host rocks are the Archean high_grade metamorphic volcano_sedimentary rocks of the Wulashan Group, *e.g.*, banded amphibolite, garnet_biotite_plagioclase gneiss, hornblende_plagioclase gneiss, sillimanite_biotite gneiss, and magnetite_plagioclase_hypersthene_pyroxene granulite (Gan *et al.*, 1994). The Late Paleozoic Dahuabei granitoid batholite is the major intrusion in this area, which intruded the Archean Wulashan Group and is about 4 kilometers west to the Wulashan gold deposit (Nie & Bjørlykke, 1994). In addition, there are also a number of granitoid stocks, pegmatite dikes, migmatite veins, K_feldspar alteration and magmatic hydrothermal veins in this area (Nie *et al.*, 2002). The gold mineralization occurs in quartz_K feldspar veins (gold_bearing veins Ⅰ) and quartz veins (gold_bearing veins Ⅱ) with small amount of base metal sulfides, *e. g.*, pyrite, chalcopyrite and galena. Alteration throughout the mineralized region is dominated by extensive alkali feldspar flooding adjacent to veins, dikes, faults, and breccias. The mineralization veins are 200－500 m (up to 1 000 m) long along E_W or close to E_W, 1－3 m (up to 10 m) wide, and 250－400 m deep, and are spatially associated with the intrusive stocks, dikes and veins (Hart *et al.*, 2002).

3　Samples and analytical methods

Coexisting alkali feldspar (AF) and plagioclase feldspar (PF) samples were collected from all rock types exposed in the Wulashan gold deposit: (1) gneisses (*e. g.*, biotite_plagioclase gneiss, biotite_muscovite_plagioclase gneiss, mucscovite_plagioclase gneiss and feldspar_quartz gneiss), (2) migmatite, (3) granite, (4) altered granite, (5) pegmatite, (6) magmatic hydrothermal veins, (7) gold_bearing K feldspar_quartz veins, and (8) gold_bearing quartz veins.

The chemical compositions of AF and PF were analyzed using JEOL model 733 electron microprobe operating at 15 kV and 10 nA. On_line data reduction and the matrix correction procedure of Bence and Albee (1968) were employed. An alkali feldspar sample of known compositions was employed for standardization. Counting times were optimized to provide the lowest possible counting_statistical errors, while minimizing electron beam damage to the samples. For example, the counting time of 20 seconds for Na as the first element in each analysis was used to produce acceptable counting_statistic errors and to result in no measurable loss in Na X_ray intensity during analysis. The analytical uncertainties based on counting statistics are estimated on the level of ~ 2% of the amount present for major elements.

3.1　Ternary two_feldspar thermometer

At equilibrium the chemical potentials of Ab, Or and An in coexisting AF and PF are equal.

$$\mu_{Ab}^{PF} = \mu_{Ab}^{AF} \quad (1)$$

$$\mu_{An}^{PF} = \mu_{An}^{AF} \quad (2)$$

$$\mu_{Or}^{PF} = \mu_{Or}^{AF} \quad (3)$$

For each phase the equilibrium conditions may be expressed in terms of a standard state free energy term for each component and a free energy of mixing.

$$\mu_{Ab}^{PF} = \mu_{Ab}^{0PF} + RT\ln a_{Ab}^{PF} \quad (4)$$

$$\mu_{Ab}^{AF} = \mu_{Ab}^{0PF} + RT\ln a_{Ab}^{AF} \quad (5)$$

Coexisting AF and PF are assumed to be part of a continuous solution, with the same standard state free energies for each component. Therefore, the activities of Ab, Or and An in coexisting AF and PF are equal.

$$a_{Ab}^{PF} = a_{Ab}^{AF} \quad (6)$$

$$a_{An}^{PF} = a_{An}^{AF} \quad (7)$$

$$a_{Or}^{PF} = a_{Or}^{AF} \quad (8)$$

The excess free energy of mixing for ternary feldspar is expressed using a ternary Margules parameter that includes asymmetric terms for each binary and ternary interaction term. The algebra formulations for the activities of Ab, Or and An in coexisting AF and PF are developed using the excess free energy of mixing and the mole fraction of Ab, Or and An. The excess terms for ternary feldspar are defined based on the fitting to experimental data (Seck, 1971; Johannes, 1979) and given by Ghiorso (1984), Green & Udansky (1986), Fuhrman & Lindsley (1988), Lindsley & Nekvasil (1989) and Elkins & Grove (1990). Thus, three temperatures (T_{Ab}, T_{Or} and T_{An}) can be calculated at a given pressure, each one expressing the equilibrium temperature based on the activity of that component. Ideally, for two feldspars at equilibrium, these temperatures should all be the same; in reality they rarely are, because of (1) analytical uncertainty in determining exact feldspar compositions, (2) difficulties in estimating amount of exsolution and re_equilibrium that occurred after crystallization of each feldspar, (3) uncertainties in the estimation of pressure, and (4) errors associated with the model.

A SOLVCALC program package was developed for calculating the ternary feldspar solvus and for ternary two_feldspar thermometer (Wen & Nekvasil, 1994), in which the popular models of Ghiorso (1984), Green & Udansky (1986), Nekvasil & Burnham (1987), Fuhrman & Lindsley (1988), Lindsley & Nekvasil (1989) and Elkins & Grove (1990) are included. At a given pressure and a two_feldspar compositional pair, the program searches for the closest matching tie_line and calculates the equilibrium temperature by adjusting the compositions within an uncertainty as defined. The program was designed to calculate the temperature from 400℃ to 1 300℃ at the pressure range of 1 bar to 15.0 kbar. However, it has been used to calculate and give reasonable temperature data down to 300℃ (Jenkin *et al*., 2001).

The SOLVCALC program was applied in this work to estimate the equilibrium temperature of coexisting AF and PF within an uncertainty of 2% adjusted for each component in each phase. In order to test the effectiveness of this program, the end_member compositions of several coexisting AF and PF from metamorphic and volcanic rocks (Elkins & Grove, 1990) were cited to calculate the equilibrium temperatures using Fuhrman & Lindsley (1988) (F&L) and Elkins & Grove (1990) (E&G) models. The results are summarized in Table 1, in which the temperatures calculated by Fuhrman & Lindsley (1988) and Elkins & Grove (1990) are also given for comparison. Three estimated temperatures (T_{Ab}, T_{Or} and T_{An}) using the SOLVCALC program are reasonably close within ~50℃ for each coexisting AF and PF pair, and are in good agreement with the data reported by Fuhrman & Lindsley (1988) and Elkins & Grove (1990).

Table 1 Comparison of temperature calculated using different two_feldspar models

		Metamorphic rocks				Volcanic rocks			
		BM_15	IN_11	MM_2	SR_31	1	2	3	4
End_member compositions									
AF	Or	0.751	0.639	0.700	0.638	0.603	0.653	0.630	0.650
	Ab	0.235	0.348	0.256	0.314	0.379	0.319	0.362	0.337
	An	0.014	0.006	0.036	0.031	0.018	0.028	0.008	0.013
PF	Or	0.014	0.017	0.030	0.010	0.073	0.041	0.061	0.076
	Ab	0.743	0.785	0.762	0.713	0.654	0.632	0.798	0.702
	An	0.242	0.193	0.205	0.273	0.273	0.326	0.141	0.222
Fuhrman & Lindsley (1988) and Elkins & Grove (1990)									
Pressure (kbar)		8	8	8	8	1	1	1	1
F&L	T_{Ab}/℃	707	764	723	763	849	807	676	770
	T_{Or}/℃	612	604	665	598	821	756	676	772
	T_{An}/℃	708	750	725	766	832	776	671	779
E&G	T_{Ab}/℃	698	763	728	786	868	813	687	769
	T_{Or}/℃	618	615	680	616	863	782	679	770
	T_{An}/℃	685	746	807	720	862	796	680	770
This study									
Pressure (kbar)		8	8	8	8	1	1	1	1
F&L model	T_{Ab}/℃	708	769	733	801	849	808	676	789
	T_{Or}/℃	618	632	678	624	821	761	676	797
	T_{An}/℃	707	744	748	798	832	774	671	790
E&G model	T_{Ab}/℃	702	758	734	796	866	812	680	767
	T_{Or}/℃	605	618	672	621	860	785	674	767
	T_{An}/℃	676	752	816	757	861	793	677	769

3.2 The end_member compositions of alkali feldspar

The chemical formulae of AF and PF are calculated based on the electron microprobe data and 8 oxygen atoms per molecule. The normalized end_member compositions of representative coexisting AF and PF from the Wulashan gold deposit are given in Table 2, and projected in the ternary triangle diagram of feldspar (Fig. 1), where the dash lines connected some coexisting AF and PF pairs. It can be seen that the contents of Or in PF and of An in AF are very low. The PFs are albite and oligoclase. The contents of Or in most alkali feldspars are in the range of 88–99%, with the exception of one sample from migmatites (Or= 62%).

Table 2 The end_member composition of representative co_existing alkali feldspars and plagioclases from the Wulashan gold deposit

Sample #		Alkali feldspar (mol%)			Plagioclase feldspar (mol%)		
		Or	Ab	An	Or	Ab	An
Regional metamorphic gneisses	309	0.887	0.102	0.011	0.013	0.713	0.278
	312	0.915	0.075	0.010	0.017	0.689	0.294
Migmatite	901_3	0.621	0.377	0.002	0.011	0.692	0.297
	919_3	0.955	0.045	0.001	0.003	0.985	0.012
	917_2	0.895	0.097	0.008	0.001	0.998	0.001
Granite	9A_1	0.693	0.305	0.002	0.007	0.987	0.006
	306	0.876	0.117	0.007	0.038	0.826	0.136
	338	0.886	0.107	0.007	0.001	0.998	0.001
Altered granite	3111_2	0.896	0.102	0.002	0.005	0.938	0.057
	326	0.953	0.041	0.006	0.021	0.969	0.010
	342	0.924	0.076	0.001	0.010	0.875	0.115
Pegmatite	366	0.936	0.064	0.001	0.006	0.983	0.011
	382	0.958	0.042	0.001	0.016	0.977	0.007
MHV	4151_3	0.947	0.053	0.001	0.002	0.982	0.016
Gold_bearing vein Ⅰ	354_1	0.924	0.071	0.005	0.005	0.896	0.099
	317	0.950	0.041	0.009	0.005	0.829	0.166
	CM139	0.967	0.033	0.001	0.005	0.896	0.099
	337	0.963	0.037	0.001	0.005	0.809	0.186
	331	0.953	0.047	0.001	0.005	0.891	0.105
	4153	0.950	0.050	0.001	0.005	0.906	0.089
Gold_bearing vein Ⅱ	CM181	0.991	0.007	0.002	0.005	0.840	0.155
	334	0.972	0.027	0.001	0.005	0.894	0.102
	336	0.963	0.025	0.012	0.005	0.892	0.103
	367	0.970	0.024	0.006	0.005	0.916	0.079

MHV —Magmatic hydrothermal veins.

3.3 Temperatures from different models

The normalized end_member compositions are input into the SOLVCALC program and adjusted within a defined uncertainty of 2 mol%. The three temperatures (T_{Ab}, T_{Or} and T_{An}) of coexisting AF and PF from the Wulashan gold deposit are estimated at the pressure of 1, 5, and 8 kbar using four ternary two_feldspar thermometer models (Green & Udansky, 1986; Fuhrman & Lindsley, 1988; Lindsley & Nekvasil, 1989; Elkins & Grove, 1990). T_{Or} and T_{An} are generally variable in a greater range, even for the same thermometer model, indicating that T_{Or} and T_{An} may be not reliable, probably due to the low contents of Or in PF and of An in AF. The T_{Ab} data of representative alkali feldspars are given in Table 3. The T_{Ab} of alkali feldspars estimated at 8 kbar are shown in Fig. 2. The T_{Ab} of alkali feldspars estimated using Fuhrman & Lindsley (1988), Lindsley & Nekvasil (1989) and Elkins & Grove (1990) models are quite consistent and are well within ±50 ℃. The error of ±50 ℃ is an acceptable error for any meaningful two_feldspar thermometer, considering the analytical

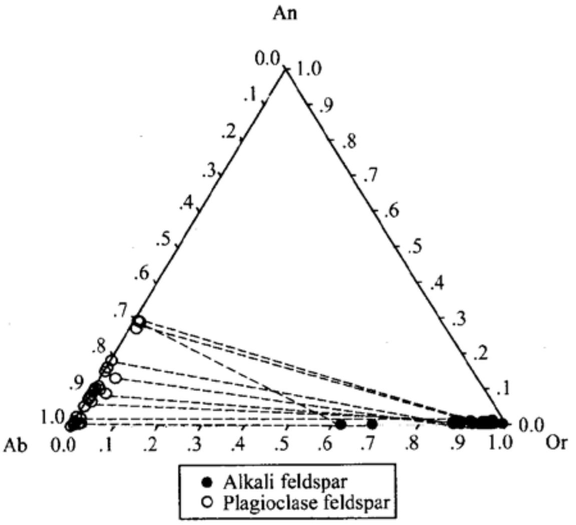

Fig. 1 Compositions of coexisting alkali feldspars (AF) and plagioclase feldspars (PF) in the ternary triangle diagram

uncertainty of exact compositions, uncertainty of estimated pressure, the possible exsolution or re_equilibrium after the crystallization of feldspars, and the possible errors of the model itself. Compared with the T_{Ab} from the other models, the T_{Ab} of alkali feldspars estimated from Green & Udansky (1986) appears too high at higher temperatures, but too low at lower temperatures, and changed within the range of ±150 ℃. Although none is taken as a prior, Fuhrman & Lindsley (1988), Lindsley & Nekvasil (1989) and Elkins & Grove (1990) models appeared to give more consistent and reasonable temperature estimates for alkali feldspars from the Wulashan gold deposit. The T_{Ab} data of alkali feldspars from Elkins & Grove (1990) model will be further discussed.

Table 3 Formation temperature (T_{Ab}/ ℃) of alkali feldspar estimated using different two_feldspar geothermometer models

Sample #		E&G model				L&N model	F&L model	G&U model	Barte(1961)
Pressure (kbar)		1	5	8	10	8	8	8	
Regional metamorphic rocks	309	434	479	**549**	555	507	527	538	510
	312	405	461	**503**	524	471	492	458	464
Migmatite	901_3	781	815	**846**	904	854	912	978	995
	919_3	292	341	**378**	403	378	368	248	360
	917_2	310	357	**393**	416	407	387	413	447
Granite	9A_1	477	524	**563**	577	567	516	600	709
	306	429	487	**525**	549	499	514	498	508
	338	324	372	**408**	432	417	403	397	462
Altered granite	3111_2	391	443	**483**	509	482	476	401	464
	326	254	301	**337**	360	336	325	311	353
	342	372	475	**465**	491	451	457	396	432
Pegmatite	366	326	377	**415**	440	353	405	329	396
	382	288	337	**373**	398	373	363	304	355
MHV	4151_3	308	**357**	395	420	330	385	362	376
Gold_bearing vein Ⅰ	354_1	325	**376**	414	439	411	406	403	420
	317	287	**336**	373	398	365	365	340	372
	CM139	284	**333**	370	394	367	360	293	345
	337	313	**365**	401	426	389	392	323	365
	331	316	**366**	404	429	400	395	337	379
	4153	318	**368**	406	431	404	397	299	383
Gold_bearing vein Ⅱ	CM181	219	**264**	298	320	290	289	174	253
	334	270	**318**	354	378	351	345	274	329
	336	237	**283**	317	340	314	308	331	323
	367	215	**260**	293	315	290	283	264	319

MHV —Magmatic hydrothermal veins; E&G —Elkins & Grove (1990); L&N —Lindsley & Nekvasil (1989); F&L —Fuhrman & Lindsley (1988); G&U —Green & Udansky (1986).

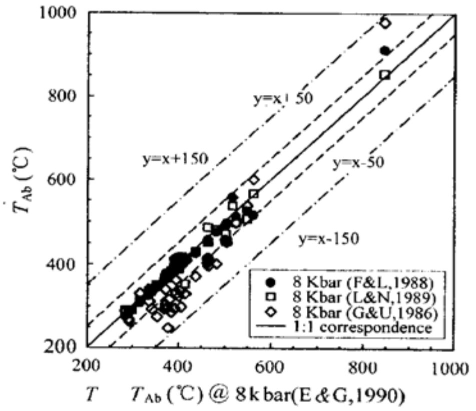

Fig. 2　Comparison of T_{Ab} of alkali feldspar from the Wulashan gold deposit estimated using different thermometer models

3.4　T_{Ab} versus pressure

The T_{Ab} of alkali feldspar from the Wulashan gold deposit were estimated at the pressure of 1, 5, 8 and 10 kbar using Elkins & Grove (1990) model. The results were also given in Table 3, and plotted in Fig. 3. It can be seen that the temperature is linearly correlated with pressure, and the estimated temperature using the two_feldspar thermometer increased ~ 10℃ with an increase in the pressure of 1 kbar. Because in the ternary two_feldspar thermometers, the three temperatures (T_{Ab}, T_{Or} and T_{An}) are all linearly correlated with pressure, at the true equilibrium and other ideal situations, the P_T equilibrium curves defined by the three ternary activity_composition expression should intersect at a unique temperature and pressure (Green & Udansky, 1986). In reality, the P_T equilibrium curves may intersect to form a triangle whose centroid defined the temperature and pressure of the AF_PF pair. However, Fuhrman & Lindsley (1988) and Elkins & Grove (1990) suggested that the pressure used in the two_feldspar thermometer be defined from other independent sources. Alkali feldspar, almandine and biotite from gneiss, granite, magmatite and pegmetite were observed to be associated in the thin sections under microscopy. Estimated equilibrium pressures of almandine and biotite are from 7.2 to 9.0 kbar (Xue *et al.*, 2000). On the other hand, alkali feldspar, calcite and mica minerals in magmatic hydrothermal veins and mineralized lodes are observed to be associated under microscope. The formation of mica is considered to be associated with hydrothermal alteration and gold mineralization. Calcite geobarometer yields a pressure of ~ 7.2 kbar, somewhat higher than the micas pressure of 3.6 kbar (Xue *et al.*, 2000). Thus, the pressure of 8 kbar was used to estimate the formation temperatures of alkali feldspars from gneiss, granite, magmatite and pegmatite, and the pressure of 5 kbar to estimate the formation temperatures of magmatic hydrothermal veins and gold_bearing veins in the Wulashan gold deposit. These pressure estimates seem to display the closest internal agreement for each feldspar geothermometer, and the closest agreement with other mineral geothermometers.

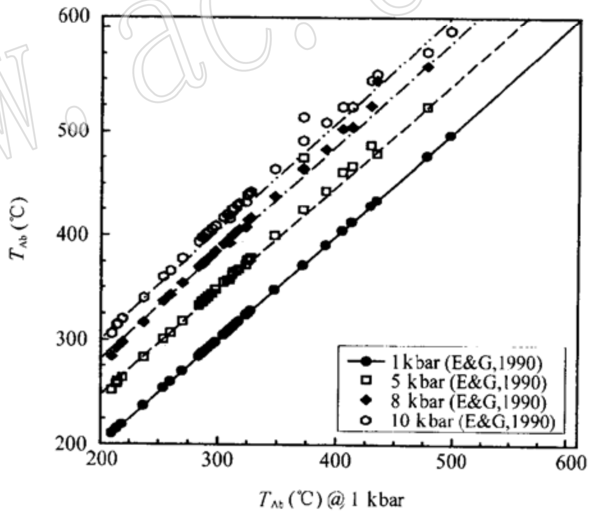

Fig. 3　Variations of T_{Ab} of alkali feldspars estimated using Elkins & Grove (1990) model with pressures

3.5　T_{Ab} of alkali feldspars versus temperatures from other sources

Garnet_biotite geothermobarometer was applied to compute the equilibrium temperature of the mineral pairs in metamorphic gneisses and granites (Xue *et al.*, 2000). The equilibrium temperatures of calcite and dolomite from gold_bearing veins Ⅰ were also estimated using carbonate thermometers. It is also known that natural gold is actually regarded as a mineral of Au_Ag_Cu solid solution, and the ratio of the elements Au, Ag and Cu depends on the equilibrium temperatures. The chemical compositions of native gold from gold_bearing veins Ⅰ and Ⅱ were analyzed using electron microprobe, and the equilibrium temperatures of gold were determined (Xue *et al.*, 2000). In addition, the homogeneous temperatures of fluid inclusions in quartz and alkali feldspars from gold_bearing veins Ⅰ and Ⅱ are measured (Wu *et al.*, 1995; Gan *et al.*, 1994; Hart *et al.*, 2002). In Table 4, the temperatures, T_{Ab}, of alkali feldspars from gold_bearing veins at 5 kbar and from other rock types at 8 kabr are compared with the temperatures obtained from other thermometers or inclusion measurements. It can be seen that the equilibrium temperatures of alkali feldspar are lower by ~ 250 ℃ than the temperatures of almandine garnet and biotite from metamorphic gneiss and granite. The temperatures of almandine and biotite may represent the peak temperature of the regional metamorphism, in agreement with the temperatures estimated for other metamorphic rocks (*e. g.*, see Table 1). In fact, one alkali feldspar sample in which the content of Or is as low as 62 mol% (Fig. 1) was collected from migmatites, and the equilibrium temperature is 846 ℃ at the pressure of 8 kbar. However, most alkali feldspars collected from metamorphic gneisses, migmatites and granites may be re_equilibrated after experiencing the numerous overprinting thermal / magmatic events, which resulted in the variation of chemical compositions and thus the lower temperature as estimated by the two_feldspar thermometer. The isotope studies in this area also proved this explanation (Hart *et al.*, 2002). On the other hand, the T_{Ab} of alkali feldspar from gold_bearing veins at 5 kbar are in agreement with the temperatures estimated by carbonate, mica minerals and gold thermometers, and with the homogeneous temperature of fluid inclusions in quartz and alkali feldspars. These results indicated that the estimated temperatures of alkali feldspars using the ternary two_feldspar thermometer are reasonable even down as low as 300 ℃ (Jenkin *et al.*, 2001). Second, the formation of gold mineralization at the Wulashan gold deposit occurred at the temperature range of 280– 360 ℃ and the pressure of ~ 5 kbar. In fact, the alkali feldspars from gold_bearing veins are intermediate to maximum microcline. The literature suggested that the formation temperatures of intermediate to maximum microcline are less than 450 ℃ (Ribbe, 1983). The temperature of alkali feldspar from magmatic hydrothermal veins is 357 ℃ at the pressure of 5 kbar, in good agreement with the formation temperature of gold_bearing veins.

3.6 Formation temperature and gold mineralization

The temperatures, T_{Ab}, of alkali feldspars from gold_bearing veins at the pressure of 5 kbar are plotted

Table 4 Formation temperature (℃) estimated using thermometers and obtained by inclusion measurements

Minerals	Regional metamorphic rocks		Granite		Gold_bearing vein Ⅰ		Gold_bearing vein Ⅱ	
	Average	Range	Average	Range	Average	Range	Average	Range
	8 kbar				5 kbar			
Thermometers								
Two_feldspar (T_{Ab})[1]	526	503~ 549	497	408~ 563	353	307~ 379	281	260~ 318
Almandine[2]	794							
Biotite[2]	794		721					
Calcite[2]					353	269~ 420		
Dolomite[2]					349	337~ 370		
Gold[2]					358	343~ 381	300	289~ 311
Homogeneous temperatures of fluid inclusions								
Quartz[3]					346	318~ 374	325	291~ 359
Quartz[4]				241~ 477		260~ 340		
Alkali feldspars[4]						300~ 345		

1—This work; 2—Xue *et al.* (2000); 3—Wu *et al.* (1995); 4—Gan *et al.* (1994) and Hart *et al.* (2002).

against the contents of Au in the same sample (Fig. 4). The formation temperatures of gold_bearing veins Ⅰ (quartz_K feldspar veins) range from 307 to 379 ℃, and those of gold_bearing vein Ⅱ (quartz veins) from 260 to 318 ℃. The gold is more enriched in the mineralization paragenesis of quartz_K feldspar veins than that of quartz veins, indicating that the higher content of K_2O in the fluids would favor the gold mineralization. On the other hand, it appears that the temperature of 320– 360 ℃ is favorable condition for gold mineralization in the Wulashan gold deposit and the contents of Au in the mineral ores that formed at the temperature of > 380 ℃ are generally lower.

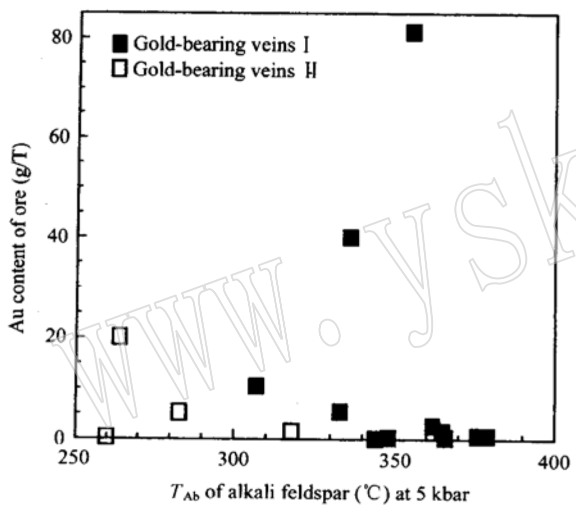

Fig. 4　The contents of Au in quartz_K_feldspar veins Ⅰ and quartz veins Ⅱ ores versus the formation temperature of alkali feldspar estimated by two_feldspar thermometer

4　Conclusions

The gold mineralization of the Wulashan gold deposit is divided into two mineralization parageneses: the gold_bearing veins Ⅰ is characterized by quartz_K_feldspar veins with a small amount of metal sulfides, and the gold_bearing veins Ⅱ by quartz veins with a smaller amount of sulfides. The formation temperature of the gold_bearing veins Ⅰ ranges from 307 to 379 ℃ with an average of 353 ℃; and that of the gold_bearing veins Ⅱ from 260 to 318 ℃ with an average of 281 ℃. The formation pressures of both gold_bearing veins Ⅰ and Ⅱ are estimated to be at ~ 5 kbar. Thus, the Wulashan gold deposit is characterized as a meso_thermal ore deposit formed at high pressure. The equilibrium temperatures of alkali feldspars from regional metamorphic gneisses, migmatites and granites are 526, 465 and 497 ℃ at 8 kbar, respectively, which are lower by ~ 250 ℃ than the estimated temperatures using garnet_biotite geothermobarometer. The alkali feldspars in metamorphic gneisses, migmatites and granite may be re_equilibrated after they crystallized and experienced consequent geological events. This is consistent with the result of Hart *et al*. (2002), who concluded that a complex thermal history with numerous overprinting thermal / magmatic events occurred in this region. In fact, the equilibrium temperature of an alkali feldspar from migmatites is 846 ℃, which may represent the primary alkali feldspars without being replaced in this region.

It is well known that two_feldspar thermometer can give reasonably accurate estimation of equilibrium temperatures for feldspar pairs from metamorphic and volcanic rocks for which the normal formation temperature is > 700 ℃, but is not accurate in the estimation of equilibrium temperatures at lower temperatures (Stomer, 1975; Powell & Powell, 1977; Johannes, 1979; Heselton *et al*., 1983; Parsons & Brown, 1983). However, Fuhrman & Lindsley (1988), Lindsley & Nekvasil (1989) and Elkins & Grove (1990) two_feldspar thermometer all gave quite consistent and reasonable estimation for the temperature, T_{Ab}, of alkali feldspars from the Wulashan gold deposit, although the estimated T_{Or} and T_{An} are not very consistent, probably due to the fact that the content of Or in plagioclase feldspar and that of An in alkali feldspar are too low so that they are more severely affected by the analytical uncertainties. Furthermore, the estimated equilibrium temperature, T_{Ab}, of alkali feldspars from gold_bearing veins Ⅰ (K feldspar_quartz veins) and gold_bearing veins Ⅱ (quartz veins) in the Wulashan gold deposit are 353 and 281 ℃ at the pressure of 5 kbar, in good agreement with the estimated temperatures from carbonate, mica minerals and native gold geothermometers (Xue *et al.*, 2000), and the measured homogeneous temperatures of quartz and alkali feldspars from the same mineralized lodes (Gan *et al.*, 1994; Hart *et al.*, 2002).

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