

Rb-Sr and U-Pb isotopic systematics of pyrite and granite in Liaodong gold province, North China: Implication for the age and genesis of a gold deposit

JUN-HAO WEI,^{1,2*} CONG-QIANG LIU² and HONG-FENG TANG²

¹China University of Geosciences, Wuhan 430074, China

²Institute of Geochemistry, Chinese Academy of Science, Guiyang 550002, China

(Received November 27, 2002; Accepted May 26, 2003)

The Liaodong gold province, along the eastern margin of the North China craton, is a large productive base of gold in China. The Wulong gold deposit hosted in granitoid is a famous Au-bearing quartz vein gold deposit in this region, and located at the northern side of Sanguliu granite. The ages of Sanguliu granite determined by the conventional Rb-Sr isochron and U-Pb zircon methods are 131 ± 4.5 Ma and 129 ± 2.9 Ma respectively, thus the comprehensive isotopic age of Sanguliu granite is 130 Ma. Lode gold deposits commonly consist of pyrite and lesser amounts of galena and sphalerit sulfides accompanied by quartz and calcite. Here we use direct Rb-Sr dating of pyrite from Wulong gold deposit, and determined the age of Wulong gold deposit. A positive correlation between present-day $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rr}/^{86}\text{Sr}$ ratios of pyrite from the Wulong gold deposit corresponds to an age of 120 ± 3 Ma, which dates the age of gold mineralization. The Sr initial ratios (0.714816 to 0.7148927 of Sanguliu granite and 0.715280 to 0.715504 of pyrites in Au-bearing quartz veins) and Pb isotopic compositions in pyrites and Sanguliu granite indicates that lead was derived partially from the similar magmatic source, and the liner array of Pb isotope composition in pyrite show a incorporation of two end members (may be incorporation of basic and acid wall rocks). The studies of H and O isotopes of fluid inclusions in auriferous quartz veins demonstrate that the magmatic water predominates in ore fluids, and also reflect a little formation waters.

INTRODUCTION

A lot of many gold deposits hosted in granodiorite are distributed in eastern part of China. Thus accurate timing of mineralization and diagenesis is fundamental in studying and contrasting the genesis of these gold deposits. In recent decade years or more, with development of determinable technology, many dating methods have been developed and widely used in age determination of gold deposit, e.g., $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr dating of altered minerals such as sericite (Luo and Wu, 1987; Zhang *et al.*, 1994), Rb-Sr dating of fluid inclusions in quartz (Böhlke and Kistler, 1986; Li *et al.*, 1993), Rb-Sr, Sm-Nd, U-Pb, and Re-Os methods of scheelite (Frei *et al.*,

1998; Hart *et al.*, 2002), and dating of Rb-Sr isochron and U-Pb zircon methods of granitoid rocks (Li and Gui, 1990). However direct determination of the ages of hydrothermal mineral deposits has been hampered by the lack of minerals that are suitable conventional radiometric methods. Thus, most attempts to determine the age of lode gold deposits have been indirect.

The ideal way to determine the age of gold deposits is to analyze minerals that are thought to have formed coevally with the gold. One such mineral is pyrite (FeS_2), which is commonly associated with gold in many mines. Recent analyses of trace-element abundances in pyrite (Chen *et al.*, 1989) show relatively high levels of Rb, Sr, and rare earth elements (REEs). This characteris-

*Corresponding author (e-mail: weijh@cug.edu.cn)

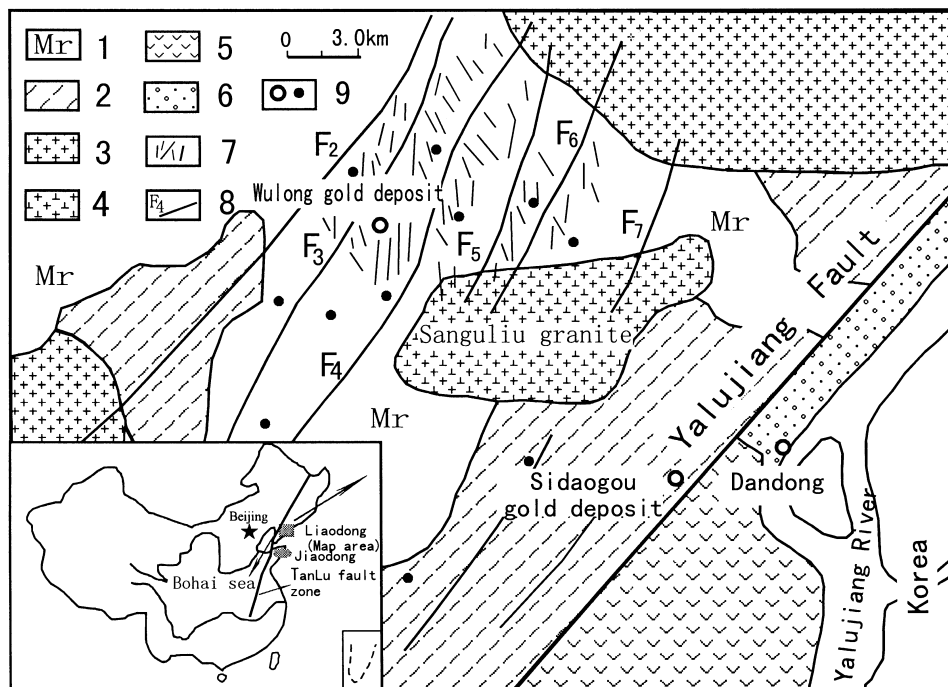


Fig. 1. Regional geological map of Liaodong region; 1-Indo-Sinian Dandong biotite granite; 2-Metamorphic rocks of Liaohe group; 3-Early Yanshanian granite; 4-Sanguliu granite; 5-Jourassic volcanic rocks; 6-Quaternary deposition; 7-Fault containing ore and dyke; 8- Main fault; 9-Gold ore deposit (occurrence).

tic may suggest that Sr and Nd isotopes could be used to monitor the source of the ore-forming materials and fluids from which the pyrites were deposited. Variation in the concentrations of Rb and Sr and their ratios in pyrites show the potential for direct dating (Yang and Zhou, 2001). In this paper, the ages of Sanguliu granite and Wulong gold deposit in Liaodong region, eastern China have been determined by using Rb-Sr isochron and U-Pb zircon methods respectively, and the sources of the materials and fluids associated with gold mineralization have also been defined by multiple isotopic tracers including Sr, Pb, H, and O isotopic data.

GEOLOGICAL SETTING

Liaodong area is situated in the eastern margin of the North China craton. It is bounded by the northeast-southwest trending Yalujiang fault zone in the east (Fig. 1), the Wulong gold deposit

is limited by the northeast-southwest trending second order faults (fault F_2 – F_6). The F_2 and F_5 faults are the border faults of west and east side of Wulong gold deposit, and faults controlling ore-bodies are the smallest north-south and/or northwest-southwest trending faults which are trending from 200 m to 2000 m in length (Fig. 1). Supracrustal rocks in the Liaodong district comprise both metamorphic Precambrian sequences and Mesozoic volcanic rocks and intrusions (Ni and Xu, 1993). The Precambrian sequences are composed of the low-grade metamorphic rocks of the Early Proterozoic Liaohe group. Rocks of the group such as metamorphic siltstone, phyllite, marble, graphitic schist, which form the basement of the Liaodong gold mineralization area. The metamorphic siltstone in the Liaohe group was determined to be as old as 2200 Ma by conventional Rb-Sr isochron methods (Zhang, 1988). Plutonic rocks, which intruded into the early Proterozoic Liaohe group in the Liaodong area,

have been traditionally divided into two suits, the Dandong and Sanguliu. The Dandong suite consists of medium-grained and peraluminous biotite granite with high content of SiO_2 (%), its age determined by conventional U-Pb zircon method is as old as 198 Ma (Mu *et al.*, 1989). This suite (exposure area of 3800 km² in Liaodong region) is an area of predominantly low strain and transected by anastomosing shear and high-strain deformation zones. The Sanguliu suite consists of medium-coarse-grained porphyritic granite. Gold deposits (Wulong, Sidaogou gold mines etc.) are located at outside contact of the Sanguliu suite (Fig. 1). In gold deposits, there are well developed various kind of dykes, mainly including fine-grained diorite dykes and granite porphyritic dykes in pre ore-forming stage, and lamprophyre dykes and diorite dykes etc. in post ore forming stage. The former dykes are closely associated with orebodies in space and show intense alteration. The dykes and auriferous quartz stringers are found cutting through marginal phase of the Sanguliu granite (Liu, Y. D., 1987). Two main phases of deformation occurred in the region during the Mesozoic; the first stage, northwest-southeast oblique compression, produced prominent northeast-southwest trending brittle ductile shear zones with sinistral oblique reverse movements, and the second stage involved the development of brittle structure, accompanied by hydrothermal alteration and gold mineralization (Wei *et al.*, 2001).

GEOLOGICAL CHARACTERISTICS OF GOLD MINERALIZATION

Historical production data indicate that the Liaodong region was a large repository of gold in China, and the details of the heterogeneous distribution of gold were stated by Liu (1994) and Peng (1994). The mineralization is mainly structurally controlled. Ore bodies are found mostly in third-order steeply inclined strike-slip brittle faults, which have two main orientations of Au-bearing brittle faults; (1) faults striking near S-N or 10°NE and controlling the greater part of the ore bodies of the main auriferous quartz vein, (2) faults strik-

ing N20°~40°W, and less controlling ore bodies. According to our field investigation, the above two group ore-bodies are not continuous along the strike, and composed of several en echelon ore bodies near to fine-grained diorite dykes.

Four stages of mineralization are recognized. Stage 1 is presented by non-metallogenic coarse-grained pyrite and quartz veins; Stage 2 shows a mineral assemblage of native gold, disseminated fine-grained pyrite, bismuthinite and lesser amount of galena and sphalerite; Native gold and very fine sulfide minerals, such as pyrite, galena, sphalerite, and chalcopyrite, and dark quartz veins formed stage 3; and stage 4 mainly involves the formation of minor amounts of gangue minerals, such as quartz, calcite, sericite and chlorite. Stage 2 contains the main gold source in the four metallogenic stages of Wulong gold deposit.

The gold is both free and sulfide hosted (usually pyrite, bismuthinite and galena). Bismuthinite is a common constituent in some Au-bearing quartz veins in this area, occurring as finely crystalline concentrations or scattered small grains. The relationship between gold abundance and bismuthinite concentration show a positive correlation.

SAMPLING AND ANALYTICAL TECHNIQUES

A total of 17 samples (7 samples for whole rock Rb-Sr isochron age, 4 samples for U-Pb zircon age, and 6 K-feldspar samples for Pb isotope data) of Sanguliu granite were collected from the surface different quarry. All samples are fresh, unaltered, and far away from fault zones. Whole rock samples for Rb-Sr isochron and separates of single minerals (K-feldspar) of Sanguliu granite accepted conventional disposal methods (Li *et al.*, 1993; Li and Li, 1997). The transparent, colorless or light yellow zircon crystals from Sanguliu granite possess perfect crystal form of tetragonal bipyramid, with short or long column, showing principally combinatory forms of (100), (110), and (111), 0.15~0.35 mm long, 0.05~0.15 mm wide. Crackless zircon separates with perfect crystal form, varying shape, granularity, and color were

handpicked out under a binocular microscope, then they were analyzed by a single separate or multiple separates. Besides, a post-air-abrasion analysis was applied to bigger zircon separates.

Five specimens of auriferous quartz veins for ore-forming age were collected from the mineralization stage 2 in the Wulong gold deposit underground. Pure pyrite separates were hand-picked under a binocular microscope to select grains similar in appearance from auriferous quartz. Every specimens from different locations (several to tens of meters apart) were analyzed.

Chemical treatment and U-Pb analysis of zircons were carried out in an ultra-clean laboratory in Tainjun institute of geology and mineral resources. Pb blank values of reagents were as follows: HCl and HF 2~5 pg/ml, ultrapure water 1~3 pg/ml, 7N HNO₃ 10~20 pg/ml. Mean blanks of total process were: Pb 40 pg and U 2 pg. Details of zircon dissolution and U-Pb separation and determination were given elsewhere (Lu and Li, 1991). U and Pb isotope data were determined with a VG-354 mass spectrometer on single Re filaments at the temperature of 1200~1300°C and 1300~1450°C, respectively. The raw data were corrected for instrumental mass fractionation using factors of 0.12%/amu (atomic mass unit) for U and 0.3%/amu for Pb.

Sr and Pb isotope analyses are as follows: Rock or mineral samples weighing ~550 mg were transferred into Teflon vessels, after being washed ultrasonically in Millipore water, and dissolved using a mixture of HCl and HNO₃ in a ratio of 1:3. Subsample solutions were dried and redissolved in HCl for Rb, Sr, and in HBr for Pb, and loaded on quartz columns. Separation of the required elements for isotope analysis was made by cation exchange. Rb, Sr concentrations were obtained by isotopic dilution. Isotopic ratio measurements were made on a multicollector MAT-261 mass spectrometer as described by Ling *et al.* (1998). Sr isotope data were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and the $^{87}\text{Sr}/^{86}\text{Sr}$ of the Sr standard NBS-607 during this study was 1.200395 ± 8 (2σ , $n = 8$). Errors are quoted throughout as two standard deviations from measured or calculated values.

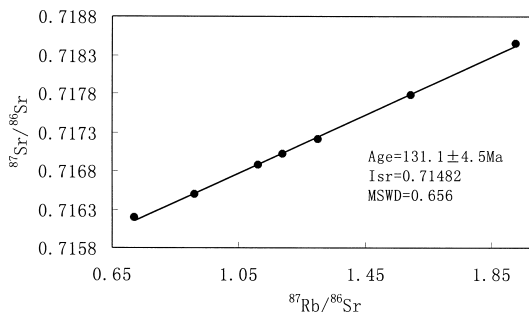


Fig. 2. Rb-Sr isochron of Sanguliu granite. *Isr* is initial ratio; MSWD is of mean square of weighed deviate.

Analytical uncertainties are estimated to be <0.5% for $^{87}\text{Rb}/^{86}\text{Sr}$. The decay constant used in the age calculation is $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11}/\text{yr}$. For Pb isotopes, in-run precision for typical individual analysis was better than 0.1% at the 2σ level. A fractionation correction of 0.1%/amu was applied on the basis of analysis of standard NBS981. Blanks during the course of this study averaged 0.4 ng for Rb, 0.2 ng for Sr, and 0.3 ng for Pb. The Rb-Sr isochron ages and U-Pb zircon age were calculated by using the ISOPLOT (2.9 version) program (Ludwig, 1996).

Nine Au-bearing quartz vein samples from the levels between +80 and -40 m (Table 5) were systematically analyzed for oxygen and hydrogen isotope data, at Yichang Institute of Geology and Mineral Resources using a Nuclide 3-inch 600 ratio mass spectrometer. Separation of quartz from ores (auriferous quartz vein) was accomplished by handpicking without any chemical treatment. The quartz separates were analyzed for $\delta^{18}\text{O}$ and extracted fluid inclusion waters were analyzed for δD . To ensure adequate fluid for analyses, 5–8 g of quartz separate were crushed in copper tubes under vacuum. The analytical techniques used are the same as those described in Li *et al.* (1993) and involve the reaction of ground quartz powders with BrF₅. Results were reported in delta notation relative to SMOW. The overall analytical errors are on the order of 0.1 and 1‰ for oxygen and hydrogen isotopes, respectively.

Table 1. Rb-Sr isotopic compositions of Sanguliu granite

Sample	Rock type	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr} (\pm 2\sigma)$	$(^{87}\text{Sr}/^{86}\text{Sr})_i$
Sgy-1	Sanguliu granite	145.2	285.4	1.5951	0.71779 ± 0.00003	0.714843
Sgy-2	Sanguliu granite	86.7	346.6	0.7204	0.71619 ± 0.00004	0.714859
Sgy-3	Sanguliu granite	154.2	386.9	1.1102	0.71688 ± 0.00002	0.714829
Sgy-4	Sanguliu granite	172.9	501.4	1.2958	0.71721 ± 0.00007	0.714816
Sgy-5	Sanguliu granite	169.4	254.8	1.9256	0.71845 ± 0.00004	0.714892
Sgy-6	Sanguliu granite	89.5	283.1	0.9088	0.71650 ± 0.00005	0.714821
Sgy-7	Sanguliu granite	188.1	558.3	1.1874	0.71702 ± 0.00003	0.714826

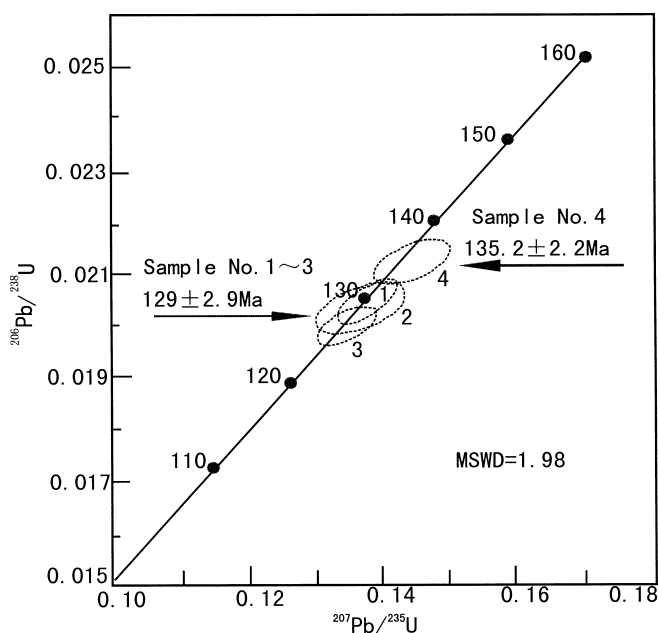


Fig. 3. U-Pb zircon age of Sanguliu granite.

DATING OF SANGULIU GRANITE AND PYRITE ASSOCIATED WITH GOLD MINERALIZATION

Rb and Sr concentrations of seven samples from Sanguliu granite were listed in Table 1, the scatter observed reflect probably homogeneity of the initial Sr isotope compositions, and the homology of seven samples. Seven samples yielded the Rb-Sr age of 131.1 ± 4.5 Ma, with a low MSWD (mean square of weighted deviates) of 0.656 and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.71482 (Fig. 2).

Isotopic compositions and ages of U-Pb in zircons from Sanguliu granite were present in Table

2. It can be seen that the difference of the ages are in the order of $t_{206} < t_{207} < t_{206-207}$. The probable explanation is that radiogenic lead of zircons has been lost to a varying degree in the late geological events. The change scope of the four group U-Pb zircon ages ($^{206}\text{Pb}/^{238}\text{U}$ age) is 127.5~135.3 Ma, with a MSWD of 1.98, which also show a little lost of radiogenic lead. The scope of former three group ages and its weight average age are of 127.5~130.3 Ma and 129 ± 2.9 Ma, respectively (Fig. 3), above ages may be approximate to zircon crystal age and approach the emplacement age of Sanguliu granite. The No. 4 zircons in transparent would be reworked by later geological ther-

Table 2. U-Pb isotopic compositions in zircons from Sanguliu granite

No.	Concentration		Atomic ratios of isotopes ^{a)}						Age/Ma	
	U ($\mu\text{g/g}$)	Pb ($\mu\text{g/g}$)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$
1	497	11	4069	0.2056	0.0204 [34]	0.1378 [37]	0.04893 [95]	130.3	131.1	144.7
2	390	10	363	0.1963	0.0203 [40]	0.1368 [55]	0.04885 [165]	129.6	130.2	140.6
3	438	12	247	0.2048	0.0199 [31]	0.1348 [37]	0.04896 [102]	127.5	128.4	145.7
4	325	8	751	0.2168	0.0212 [35]	0.1446 [48]	0.03945 [132]	135.2	137.1	169.4

^{a)} $^{206}\text{Pb}/^{204}\text{Pb}$ has been corrected by diluting reagent and experimental blank ($\text{Pb} = 0.040 \text{ ng}$, $\text{U} = 0.002 \text{ ng}$). Isotopic atomic ratios of Pb are all radiogenic. Data in brackets above Table 2 are absolute errors (2σ), e.g., 0.0204 [34] is equal to 0.0204 ± 0.00034 (2σ).

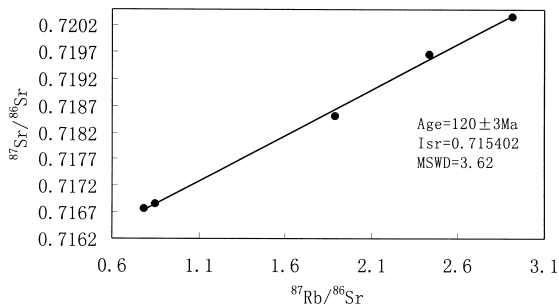


Fig. 4. Rb-Sr isochron of pyrites in Au-bearing quartz from ore-forming stage 2 of Wulong gold deposit. Isr is initial ratio; MSWD is of mean square of weighed deviate.

mal event, its age of $^{206}\text{Pb}/^{238}\text{U}$ is 135.2 Ma, show a little older age. Perfect crystal form of analyzed zircons rules out the possibility of relict zircons from paleostrata. Thus comprehensive isotopic age of Sanguliu granite emplacement is 130 Ma.

In the Wulong gold deposit, compositions of Rb-Sr isotope of five pyrite samples are listed in the Table 3. Rb (0.823~1.988 ppm) and Sr (1.923~3.024 ppm) concentrations are variable. Five pyrite samples (Table 3) yielded the Rb-Sr age of 120 ± 3 Ma, with a lower MSWD of 3.62 and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.715402 (Fig. 4).

Previous efforts on determining the age of Sanguliu granite, based on K-Ar method used on biotite and K-feldspar in Sanguliu granite, gave the age range of 91~136 Ma (Peng, 1994). The age of granite porphyry dykes mineralized is 78.6 Ma, i.e., ore-forming age of Wulong gold deposit is later than the age of emplacement of granite porphyry dykes, whereas the age of altered sericite in the ores is 134 Ma (Liu, 1987), thus previous researches provide different metallogenic ages of Wulong gold deposit. Field geological reconnaissance show that the Au-bearing quartz veins cut the magmatic phase of the Sanguliu granite, i.e., the mineralization is later than the emplacement of Sanguliu granite. Therefore this study provides that the ages of Sanguliu granite and Wulong gold deposit are 130 Ma and 120 ± 3 Ma respectively.

The Liaodong and Jiaodong gold concentration regions are located in the same metallogenic

Table 3. Rb-Sr isotopic compositions of pyrites in Au-bearing quartz

No.	Mineral	Rb ($\times 10^{-6}$)	Sr ($\times 10^{-6}$)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (1σ)	$(^{87}\text{Sr}/^{86}\text{Sr})_i$
76-1	Pyrite	1.620	1.923	2.431	0.71965 ± 5	0.715504
76-2	Pyrite	1.998	1.976	2.919	0.72037 ± 1	0.715392
76-3	Pyrite	0.8232	3.024	0.7856	0.71677 ± 15	0.715430
76-4	Pyrite	0.8759	2.985	0.8468	0.71686 ± 3	0.715416
76-5	Pyrite	1.3190	2.016	1.888	0.71850 ± 4	0.715280

Table 4. Pb isotopic compositions of pyrites in Au-bearing quartz vein, Sanguliu granite, and Dandong biotite granite

No.	Geological bodies	Mineral	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
A ₁	Dandong biotite granite	Plagioclase	17.288	15.565	38.694
A ₂	Dandong biotite granite	Plagioclase	17.467	15.566	38.220
A ₃	Dandong biotite granite	Plagioclase	17.406	15.586	38.472
A ₄	Dandong biotite granite	Plagioclase	17.432	15.542	38.283
A ₅	Dandong biotite granite	Plagioclase	17.389	15.489	38.376
A ₆	Dandong biotite granite	Plagioclase	17.325	15.473	38.421
A ₇	Dandong biotite granite	Plagioclase	17.193	15.464	38.342
B ₁	Sanguliu granite	K-feldspar	17.712	15.595	38.739
B ₂	Sanguliu granite	K-feldspar	17.717	15.580	38.749
B ₃	Sanguliu granite	K-feldspar	17.649	15.556	38.521
B ₄	Sanguliu granite	K-feldspar	17.675	15.552	38.659
B ₅	Sanguliu granite	K-feldspar	17.582	15.621	38.725
B ₆	Sanguliu granite	K-feldspar	17.496	15.617	38.698
W ₁₀₇	Au-bearing quartz vein	Pyrite	17.569	15.572	38.533
W ₇₉	Au-bearing quartz vein	Pyrite	17.628	15.627	38.738
W ₁₂₃	Au-bearing quartz vein	Pyrite	17.596	15.587	38.598
W ₂₃	Au-bearing quartz vein	Sphalerite	17.639	15.660	38.836
W ₂₆	Au-bearing quartz vein	Pyrite	17.560	15.610	38.688
W ₆	Au-bearing quartz vein	Pyrite	17.487	15.514	38.269
W ₉	Au-bearing quartz vein	Pyrite	17.625	15.659	38.831
W ₂₁	Au-bearing quartz vein	Pyrite	17.694	15.736	39.121
W ₂₉	Au-bearing quartz vein	Pyrite	17.793	15.860	39.521
W ₄₆	Au-bearing quartz vein	Pyrite	17.689	15.704	38.985

A₁~A₇, W₁₀₇~W₄₆ after Peng (1994), other data from this work.

zone (Fig. 1). It is bounded by the north-north-east-trending Tanlu fault belt in the west, and the Jiaodong gold province is at south side of the Bohai Sea. The ages of SHRIMP U-Pb method for Mesozoic intrusion in this region is about 160~126 Ma (Qiu *et al.*, 2002; Wang *et al.*, 2002), and the age of lode gold deposits in this area are from 122~123 Ma (Yang and Zhou, 2001). This effort in Liaodong area interprets the identity on diagenetic and metallogenic ages between Liaodong and Jiaodong region.

SOURCE OF METALLOGENIC MATERIALS AND FLUIDS

Pb isotope compositions of 23 samples were listed in Table 4. Several K-feldspars in the Sanguliu granite were examined for Pb isotope data in this study. Pyrites in gold-bearing quartz veins contain visible gold or have a high gold content, and their characteristics provide convincing evidence that gold and pyrite are genetically associated (Peng, 1994). The Pb isotope data from

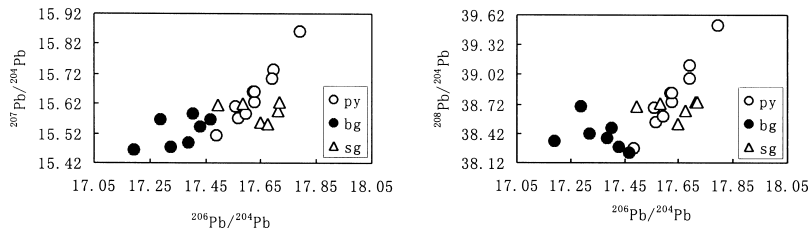


Fig. 5. Pb isotopic variation diagram, py: pyrites in Au-bearing quartz veins; bg: Dandong biotite granite; sg: Sanguliu granite.

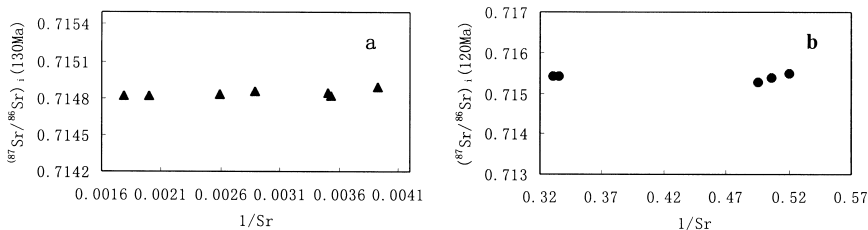


Fig. 6. $(^{87}\text{Sr}/^{86}\text{Sr})_i - 1/\text{Sr}$ map of Sanguliu granite and pyrites in gold-bearing quartz veins. a: Sanguliu granite; b: Pyrites in Au-bearing quartz vein.

Table 5. Oxygen and hydrogen isotope data of fluid inclusions in quartz from Au-bearing quartz vein

Sample	Sample description	$\delta^{18}\text{O}_{\text{quartz}}$ (‰)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰)	$\delta\text{D}_{\text{H}_2\text{O}}$ (‰)
Vein 76-1	Auriferous quartz vein in Stage 2 at 80 m level	12.69	5.33	-67.54
Vein 76-2	Auriferous quartz vein in Stage 2 at 80 m level	13.44	6.08	-72.13
Vein 76-3	Auriferous quartz vein in Stage 2 at 80 m level	11.98	4.62	-62.32
Vein 76-4	Auriferous quartz vein in Stage 2 at 80 m level	11.56	4.20	-75.85
Vein 76-5	Auriferous quartz vein in Stage 2 at 40 m level	13.69	6.33	-82.32
Vein 76-6	Auriferous quartz vein in Stage 2 at 40 m level	12.98	5.62	-67.73
Vein 76-7	Auriferous quartz vein in Stage 2 at -40 m level	11.36	4.00	-82.73
Vein 76-8	Auriferous quartz vein in Stage 2 at -40 m level	14.45	7.09	-82.12
Vein 76-9	Auriferous quartz vein in Stage 2 at -40 m level	11.24	3.88	-89.58

Quartz-water fractionation equation: $1000\ln \alpha_{\text{Q-H}_2\text{O}} = 3.306 \times 10^{-6} T^{-2} - 2.71$ (Zhang, 1989), temperature used is 300°C in ore stage 2.

Dandong biotite granite, Sanguliu granite, and pyrites in the auriferous quartz veins of Wulong gold deposit can be used to shed light on the source of ore-forming materials, and their compositions are within rather narrow ranges of 17.193~17.467, 17.496~17.717, 17.487~17.793 for $^{206}\text{Pb}/^{204}\text{Pb}$, 15.464~15.586, 15.552~15.621, 15.514~15.860 for $^{207}\text{Pb}/^{204}\text{Pb}$, 38.220~38.694, 38.521~38.749, 38.269~39.521 for $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. The $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ values and $^{208}\text{Pb}/$

^{204}Pb versus $^{206}\text{Pb}/^{204}\text{Pb}$ values (Fig. 5) of Dandong biotite granite, Sanguliu granite, and pyrites in Au-bearing quartz veins also show that pyrites plot within the partial area of the Sanguliu granite, which indicates that the lead in pyrites and Sanguliu granite was derived partially from the similar magmatic source, and the linear array of Pb isotope composition in pyrite show a incorporation of two end member (may be incorporation of basic and acid rocks), but there are obvi-

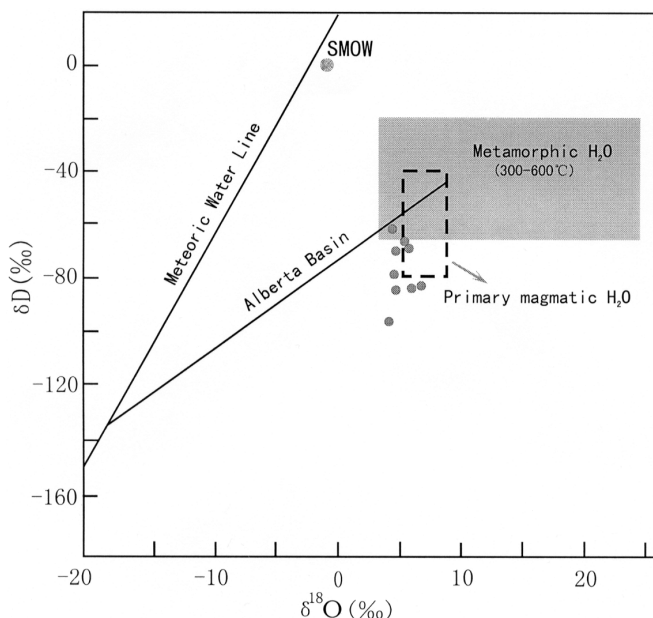


Fig. 7. Diagram of δD versus $\delta^{18}O$ for the fluid inclusions in quartzs in ore-forming stage 2 of Wulong gold deposit (map outline after Taylor, 1974).

ous difference in Pb isotopic characteristics between pyrites and Dandong biotite granite. The initial $^{87}Sr/^{86}Sr$ ratios of Sanguliu granite (0.714816 to 0.714892) and pyrites (0.715280 to 0.715504) in gold-bearing quartz veins, also suggest a possibility that a little higher $^{87}Sr/^{86}Sr$ ratios of pyrites reflect the incorporation of Sr from surrounding metamorphic wall rocks (Fig. 6).

The analytical results of H and O isotope compositions are presented in Table 5. The δD values of the inclusion fluids range from -89.58 to -62.32‰ . These values are similar to those of magmatic fluid (Taylor, 1974). The $\delta^{18}O$ values of the ore fluid can be calculated using the quartz-water fraction equation (Zhang, 1989). Nine quartz samples yielded $\delta^{18}O$ values from 11.24 to 14.45‰ (Table 5). Based on the homogenization temperature (average temperature of main stage 2 is $300^{\circ}C$) from microthermometric study of the fluid inclusions, the calculated average $\delta^{18}O$ values of water in equilibrium with the quartz would be 3.88 to 7.09‰, near to the magmatic water area (Taylor, 1974) (Fig. 7), and also reflect a little formation waters.

CONCLUSIONS

Rb-Sr isochron age (131.1 ± 4.5 Ma) and U-Pb zircon age (129 ± 2.9 Ma) of Sanguliu granite reported in this paper are reliable, thus the comprehensive isotopic age of Sanguliu granite is 130 Ma.

Rb-Sr isochron age (120 ± 3 Ma) of pyrites in Au-bearing quartz veins from the Wulong gold deposit represent the direct dating of a lode gold deposit using pyrites as the Rb-Sr geochronometer. Results for pyrite document not only the feasibility of using pyrite as the Rb-Sr geochronometer, but also the applicability of Rb-Sr geochronology to various types of hydrothermal pyrite-rich orebodies and rocks elsewhere.

Combined Sr and Pb isotopic data of pyrites, Dandong biotite granite, and Sanguliu granite, this study can be used to interpret that the ore-forming and diagenetic materials of Sanguliu granite come near the magmatic source, the liner array of Pb isotope composition in pyrite show a incorporation of two end member of basic and acid rocks, but there are obvious difference in Pb isotopic

characteristics between Pb in pyrites and in Dandong biotite granite.

Oxygen and hydrogen isotope characteristics suggest that the ore-forming fluid came near magmatic water, and also reflect a little formation waters.

Acknowledgments—This work was financially supported by the Chinese National Ministry of Science and Technology (grant 95-P-39), outstanding young scientists foundation (grant No: 49625304), and foundation of Open laboratory of deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences.

REFERENCES

- Böhlke, K. K. and Kistler, R. W. (1986) Rb-Sr, K-Ar and stable isotope evidence for the ages and sources of fluid components of gold-bearing quartz veins in the northern Sierra Nevada Foothills metamorphic belt, California. *Econ. Geol.* **81**, 296–322.
- Chen, G. Y., Shao, W. and Sun, D. S. (1989) *Genetic Mineralogy of Gold Deposits in Jiaodong Region with Emphasis on Gold Prospecting*, 234–280, Chongqing Publishing House, Chongqing, China (in Chinese with English abstract).
- Frei, R., Nagler, T. F., Schonberg, R. and Kramers, J. (1998) Re-Os, Sm-Nd, U-Pb, and stepwise lead leaching isotope systematics in shear-zone hosted gold mineralization: Genetic tracing and age constraints of crustal hydrothermal activity. *Geochim. Cosmochim. Acta* **62**, 1925–1936.
- Hart, C. J. R., Goldfarb, R. J. and Qiu, Y. M. (2002) Gold deposits of the northern margin of the North China craton: multiple late Paleozoic-Mesozoic mineralizing events. *Mineralium, Deposita* **37**, 326–351.
- Li, H. M. and Li, H. K. (1997) Determination of age of gold mineralization of Dongping gold deposits by U-Pb dating hydrothermal zircon from ore veins. *Acta Geoscientia Sinica* **18**(Supp.), 176–179 (in Chinese with English abstract).
- Li, H. Q., Liu, J. Q. and Wei, L. (1993) *The Isochronology of Inclusions of Hydrothermal Deposits and Its Geological Application*, 10–25, Geological Publishing House, Beijing, China (in Chinese).
- Li, X. H. and Gui, X. T. (1990) Dating of granitoid rocks—A brief methodological discussion. *Geochemica* **4**, 303–311 (in Chinese with English abstract).
- Ling, W. L., Gao, S. and Zhang, H. F. (1998) Study on Sm-Nd isotopic geological chronology of Kongling complex in Huangling area, Yangtze craton. *Chinese Science Bulletin* **43**, 86–89 (in Chinese).
- Liu, G. Z. (1994) Typomorphic characteristics of quartz in auriferous quartz vein and exploration significance in Wulong gold deposit. *J. Shenyang Institute of Gold Technology* **37**, 10–16 (in Chinese with English abstract).
- Liu, L. D. (1987) Discussion on genesis of main lode gold deposit in china. *J. Changchun College of Geology* **17**, 373–381 (in Chinese with English abstract).
- Liu, Y. D. (1987) Discussion on the geological characteristics and genesis of Sangulin granite, Liaodong. *Liaoning Geology* **3**, 245–260 (in Chinese with English abstract).
- Lu, S. N. and Li, H. M. (1991) Zircon U-Pb dating of volcanic rocks from Dahongyu group, Changcheng system, Jixian, Hebei province. *J. Chinese Academy of Geosciences* **22**, 139–143 (in Chinese with English abstract).
- Ludwig, R. K. (1996) ISOPLOT: A plotting and regression program for radiogenic-isotope data (version 2.9). U.S. Geological Survey Open-File Report, 91-445, 47.
- Luo, W. C. and Wu, Q. S. (1987) Dating of the mineralization age of gold deposit in Jiaodong Peninsula using the altered minerals. *Chinese Science Bulletin* **16**, 1245–1248.
- Mu, K. M., Ling, J. Q. and Zou, Z. R. (1989) *Genesis of Granitoid Rocks in North Platform*, 120–195, Jinling Publishing House of Science and Technology, Jilin, China (in Chinese).
- Ni, P. and Xu, K. Q. (1993) Geological evolution of Liaodong peninsula and genesis of gold deposits. *Mineral Deposits* **12**, 231–243 (in Chinese with English abstract).
- Peng, Y. D. (1994) Study on Genesis of Wulong gold deposit in Liaoning province. *J. Precious Metallic Geology* **3**, 21–31 (in Chinese with English abstract).
- Qiu, Y. M., Groves, D. I. and McNaughton, N. J. (2002) Nature, age, and tectonic setting of granitoid-hosted, orogenic gold deposits of the Jiaodong Peninsula, eastern North China craton, China. *Mineralium Deposita* **37**, 283–305.
- Taylor, H. P. (1974) The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition. *Econ. Geol.* **69**, 843–883.
- Wang, L. G., Qiu, Y. M. and McNaughton, N. J. (2002) Constraints on crustal evolution and gold metallogeny in the Northwestern Jiaodong peninsula, China, from SHRIMP U-Pb zircon Studies of granitoids. *Ore Geology Reviews* **37**, 275–291.
- Wei, J. H., Li, Z. D. and Zhao, Y. X. (2001) Evidences from characteristic compositions of fluid inclusions

- and altered rocks for fluid/rock interaction: As exemplified by the Wulong gold deposit. *Acta Mineralogical Sinica* **21**, 710–706 (in Chinese with English abstract).
- Yang, J. H. and Zhou, X. H. (2001) Rb-Sr, Sm-Nd, and Pb isotope systematics of pyrite: Implications for the age and genesis of lode gold deposits. *Geology* **29**, 711–714.
- Zhang, L. G. (1989) Oxygen isotope fractionation in quartz-water-salt system. *Econ. Geol.* **84**, 1643–1650.
- Zhang, Q. S. (1988). *Early Crust and Deposits in Liaodong Peninsula*, 243–288, Geological Publishing House, Beijing, China (in Chinese).
- Zhang, Z. H., Zhang, J. X. and Ye, S. Z. (1994) *The Isotopic Age of Gold Deposits in Liaodong Peninsula*, 12–67, Seismology Press, Beijing, China (in Chinese).