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ORE DEPOSITS

Rb-Sr Isotopic Geochronology and Geological Implications of Dongfeng Gold Deposit in Jiaodong Area

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ABSTRACT

The superlarge Dongfeng gold deposit is located in the Potouqing faults-alteration belt of the eastern part of the 'Zhao-Lai-gold ore belt', which belongs to the northwestern part of the Jiaodong area. Tectonically, ore bodies are controlled by faults and gold mainly occurs in the pyrite and polymetallic sulfide-bearing quartz vein. In this paper, Rb–Sr isotopic analysis is carried out with the beresite, which formed by hydrothermal metasomatism, and the Rb–Sr isochron age is 125.5±6.7Ma, indicating this deposit set up in the early Cretaceous of the late Yanshanian. Based on the relationship between the Dongfeng gold deposit and the Mesozoic granite, it is suggested that the formation of the gold deposit is a complex geological process of gradual enrichment and precipitation of the ore-forming elements. The initial ^{87}Sr/86Sr ratio of the beresite is 0.711502±0.000069, which indicates the ore-forming materials mainly come from the crust. Combined with the complex mineralization process of the Dongfeng gold deposit and the reported H-O isotopic data, it is suggested that the ore-forming materials are mainly derived from the crust with some mantle materials, while the ore-forming fluids are originated primarily from magmatic hydrothermal and mantle with some precipitate water.

Keywords: Rb–Sr isochron, (^{87}Sr/^{86}Sr) ratio, mineralization, Dongfeng gold deposit, Jiaodong gold-centralized area.

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1. Introduction

As one of the most significant gold concentration areas in China, Jiaodong area has special metallization background and metallogenesis (Goldfarb and Santosh, 2013). The great Linglong gold ore field is located in the northwest of the Jiaodong area, the eastern part of the 'Zhao-Lai-gold ore belt', including Linglong, Jiuqu, Dakaitou, Dongfeng and Dongshan ore blocks or fields. Previous researchers have carried out many studies of all types of gold deposits in the Jiaodong area. Yiao et al. (1990), Miao et al. (1999) and Hu et al. (1998) suggested the gold mineralization was closely correlated with the Mesozoic granites. Based on the studies of the gold deposit geochronology, Yang et al. (2000), Wang et al. (2000) and Chen et al. (2004) implied that gold mineralization occurred in the Mesozoic and concentrated from 128 to 115 Ma. Regarding the ore-forming fluids, Fan et al. (2005) suggested that ore-forming fluids of gold deposits were consistent throughout the whole Jiaodong area under similar mineralizing temperature and pressure conditions and the fluids were characterized by H_2O-CO_2-NaCL±CH_4, with low salinity and low-to-moderate temperature. Moreover, Mao et al. (2005) pointed out that mantle fluids were associated with the gold mineralization. Sun et al. (2000), Wan et al. (2000), Zhai et al. (2002), Zhai et al. (2004), Lv et al. (2007), Song (2008), Song et al. (2013) and Yang et al. (2014a) have comprehensively studied and reviewed the mineralizing setting and mineralization model of the gold deposits in the Jiaodong area.

Since the Dongfeng deposit has been found at the end of 1980's, some studies have been implemented in this reservoir. Xu et al. (2013) established the deposit database and ore grade distribution model for the Dongfeng deposit based on the Surpac software and applied the ordinary Kriging to estimate the orebody resources. Feng et al. (2009) studied the ore-forming conditions, ore body characteristics and wall rock alteration about the No.171 gold vein of Dongfeng gold deposit. Jiang et al. (2011) primarily discussed the metallogenic regularity of the Dongfeng gold deposit. However, the research of the metallogenic geochronology and the source of minerogenic substances is relatively weak. In this paper, Rb and Sr isotopic analysis has been carried out with the beresite, which has a close relationship with the mineralization of the Dongfeng gold deposit. The purpose of this study is to determine the mineralization age and discuss the source of ore-forming materials of the Dongfeng gold deposit. This study also put forward a new understanding of the mineralization for the Dongfeng gold deposit.

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2. Geological background and deposit geological characters

The Dongfeng gold deposit is located in the uplift of the northwestern part of Jiaodong area, which belongs to North China Craton. The regional strata in the studying area consist mainly of metamorphic rocks in Jiaodong rock group, in Archaean era and Quaternary. The metamorphic rocks are composed of biotite-granulite and amphibolite. Faults are well-developed in the Dongfeng area. The faults are mainly NE- and NNE-trending. The NE-trending faults are present at the Potouqing fault. The NE-trending faults are represented by the Luanjiahe fault. The intersection of two sets of faults controls the morphology and distribution of the Dongfeng gold deposits (Fig 1). The intrusions in the studying area mainly include the Linglong biotite adamellite, Guojialing granodiorite, and Luanjiahe monzonitic granite. The Linglong biotite adamellite occurs as batholiths or stocks, with SHRIMP zircon U-Pb age of 160.45±0.83Ma (Wan, 2014). The Guojialing granodiorite occurs as batholiths or stocks, with SHRIMP zircon U-Pb age of 131.86±0.99Ma (Wan, 2014). The Luanjiahe monzonitic granite also occurs as batholiths or stocks, with SHRIMP zircon U-Pb age of 154~152Ma (Luo and Miao, 2002). The recent data of geophysical prospecting, drilling project, and deep exploration reveals that there is a giant Guojialing granodiorite batholith in the deep of the studying area, overlain by the Linglong biotite adamellite (Feng et al., 2009).

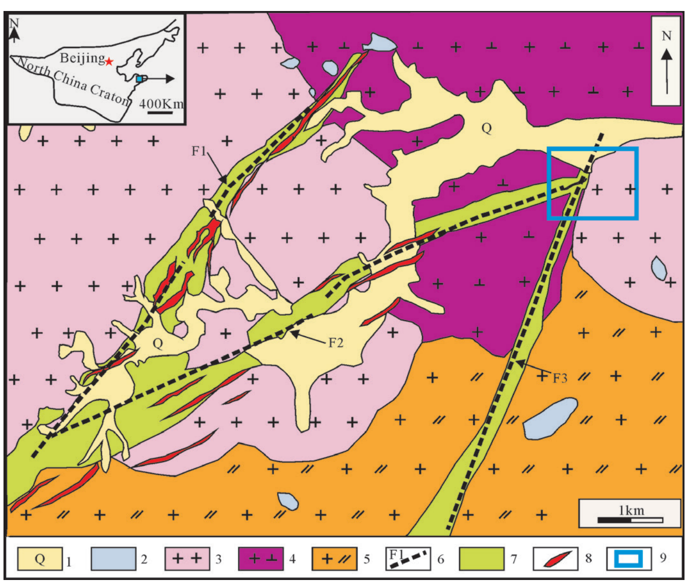

Figure 1. Regional geological sketch map of Dongfeng deposit in Jiaodong area

1. Quaternary; 2. Jiaodong Group; 3. Linglong Granite; 4. Guojialing Granite; 5. Luanjiahe Granite; 6. Faults; 7. Fractured belt; 8. Gold body; 9. Gold deposit range; F1. Jiuqujiangjia Faults; F2. Potouqing Faults; F3. Luanjiahe Faults.

The main vein of the Dongfeng gold deposits is No. 171 vein. The shape of the vein is simple, the vein strikes 60° 70°NE and dips SE. (Fig. 2). The ore minerals are mainly pyrite, galena, and sphalerite. The ores mainly comprise cataclastic, idiomorphic or hypidiomorphic granular, and gric textures. The structures of the ores can be disseminated, massive, vein, or veinlet (Fig. 3). The alteration assemblage includes beresitization, potash feldspathization, chloritization, and carbonatization, occurring as bands in the ore-bearing faults and pervasive alteration of nearby wall rocks. The dominant alteration related to the Au mineralization is beresitization. Gold mainly exists in polymetallic sulfide.

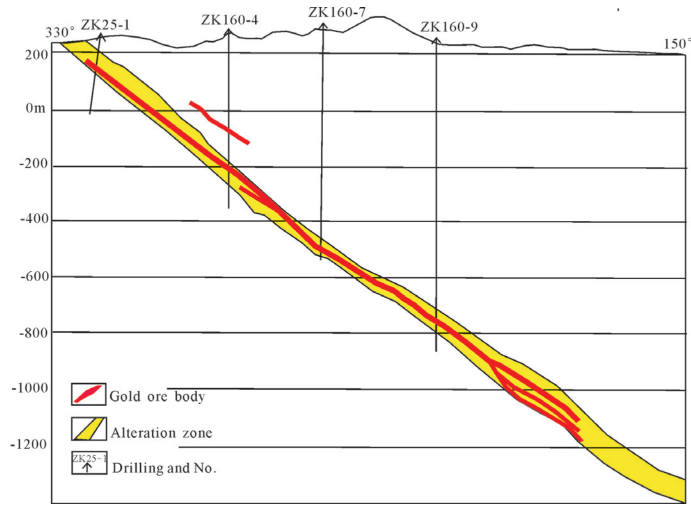

Figure 2. No. 160 vertical cross section of the No.171 vein of Dongfeng gold deposit.

3. Sampling and analytical methods

The five samples for the Rb and Sr isotopic analysis were beresite which formed by hydrothermal metasomatism and closely related to metallogenesis. The samples were collected at the -350m level in orebody No. 171 of the Dongfeng gold deposits. The sampling location of each sample and detailed characteristics of the five samples are shown in the Table 1 and Figure 3.

Table 1. The sampling locations and the characteristics of five samples

No.	The sampling locations	The features of the samples
K11-2	The West No. 1 Chuan at the -350m level of the Dongfeng deposit	The five samples are located in or nearby the ore-bearing faults. The color of the beresite is celandine green. The beresite mainly comprises cataclastic, granoblastic textures. The structures of the beresite can be massive, taxitic. The main minerals are quartz, sericite, and pyrite. The late sugar granular quartz closely coexists with the scaly sericite. The pyrite mainly distributes in the quartz veins, with the fine vein and dissemination structure (Fig. 3).
K12-2	The West No. 2 Chuan at the -350m level of the Dongfeng deposit	
K15-2	The West No. 6 Chuan at the -350m level of the Dongfeng deposit	
K17-2	The West No. 7 Chuan at the -350m level of the Dongfeng deposit	
K18-2	The West No. 9 Chuan at the -350m level of the Dongfeng deposit	

The crushing work of the samples was carried out in the analytical laboratory of CNNC Beijing Research Institute of Uranium Geology. The Rb and Sr isotopic analysis of 5 samples were performed at the IGGE of Chinese Academy of Geological Sciences. The steps of the Rb and Sr isotopic analysis are as follows: 1) According to "The specification of testing quality management for geological laboratories" (DZ/T0130-2006), the beresite samples were crushed up to 200 meshes without contamination. 2) The sample powder (ca. 0.1–0.2 g) was separated for the Rb-Sr analysis. Samples were dissolved in Teflon bombs with $HF+HNO_3+HClO_4$ acid (24h). 3) After completely dissolved, the samples were followed by drying.4) Then, the samples were treated with 6mol/L HCl and completely converted to chlorate, then dried. 5) Samples were dissolved by 0.5mol/L HCl. Following the centrifugal separation, the solution has been into cation exchange column and cleared by 1.75mol/L HCl with Rb. Then, the drying was carried out; the dissolve was cleared by 2.5mol/L HCl with Sr; at last, the drying was carried out.

The Rb and Sr isotopic analysis were performed on a PHOENIX ISOPROBE-T thermal ionization mass spectrometer. The relative humidity and temperature are 45% and 20Cº respectively. During the analysis, reproducibility and accuracy of Sr isotope running have been periodically checked by running the Standard Reference Material NBS 987, with a measured $^{87}Sr/^{86}Sr$ ratio of 0.710250±7 (2 σ mean). Both of the total procedure blanks for Rb and Sr were 2×10^{-10} g.

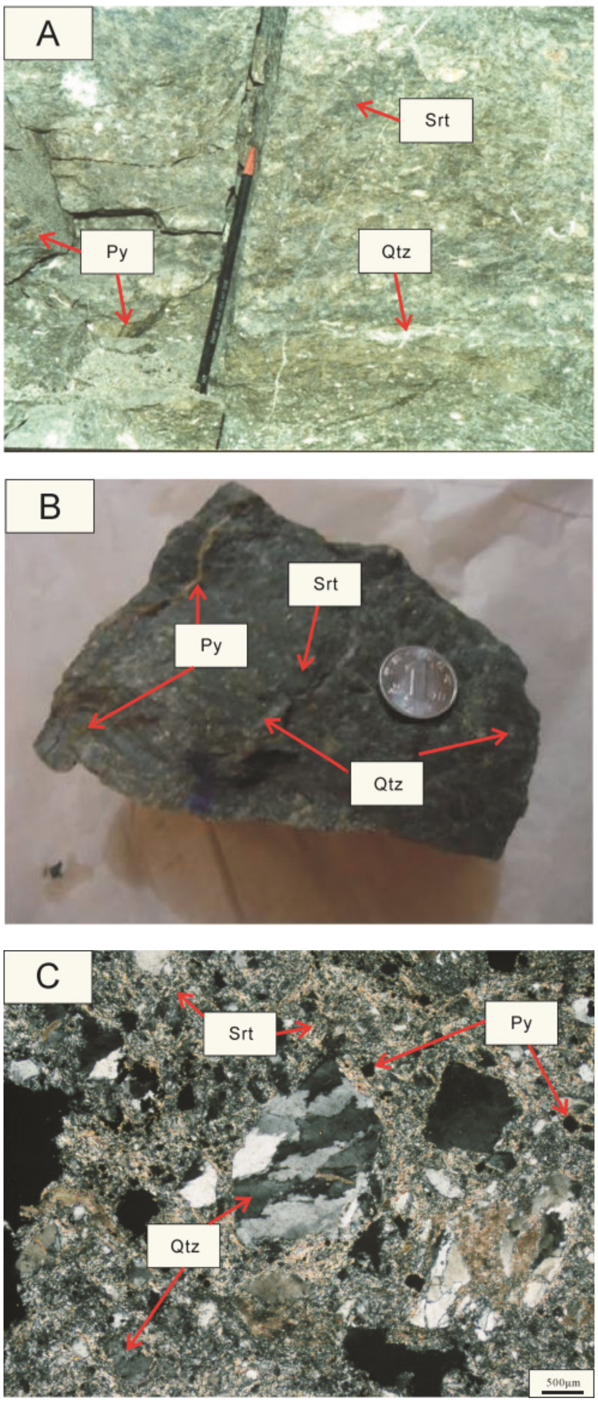

Figure 3. The characteristics of beresite samples of the Dongfeng gold deposit

A- celandine green beresite; B- massive beresite ores, pyrite distributes in the quartz veins, with the fine vein and dissemination structure;
C- quartz closely coexists with sericite under the cross-polarized light; Qtz-quartz; Srt-sericite; Py-pyrite

4 Analytical results

The Rb and Sr isotopic compositions of the five beresite samples in the Dongfeng deposit are presented in Table 2. The isochron age was calculated with the ISOPLOT program (Ludwing, 1998). The Rb and Sr concentrations of 5 beresite samples range from 71 to 171 Ug/g and 114 to 1269 Ug/g, respectively. The isotope ratios of $^{87}Rb/^{86}Sr$ range from 0.3891 to 3.4915, averaging 1.76702, and the isotope ratios of $^{87}Sr/^{86}Sr$ vary from 0.712201 to 0.718079, with an average of 0.7146836. Five beresite samples yield a Rb–Sr isochron age of 125.5±6.7 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.711502±0.00006 and an MSWD of 0.96 (Fig. 4). These results indicate that the Dongfeng gold deposit was formed at 125.5±6.7 Ma.

Table 2. Rb–Sr isotopic analysis of beresite from the Dongfeng gold deposit.

Deposit	No. of samples	Rock type	Rb[Ug/g]	Sr[Ug/g]	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Std err
Dongfeng deposit	K11-2	beresite	111	190	1.6874	0.714427	0.000011
	K12-2	beresite	113	188	1.7412	0.714555	0.000016
	K15-2	beresite	71	135	1.5259	0.714156	0.000014
	K17-2	beresite	171	1269	0.3891	0.712201	0.000019
	K18-2	beresite	137	114	3.4915	0.718079	0.000011

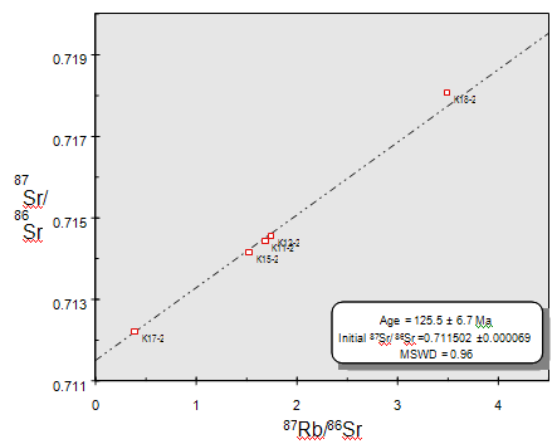

Figure 4. Rb–Sr isochron for the beresite from the Dongfeng gold deposit.

5 Discussion

5.1 Mineralization age

Endogenic gold deposits were developed among hydrothermal metasomatic alteration, granulating relatively small alteration minerals which were in a fair preservation of Rb and Sr. Moreover, Rb-Sr isochron method of altered minerals has been widely used in the study of the mineralization age of gold deposits (Jager, 1979; Andre and Deutsch, 1986; Wei et al., 1997; Yang and Zhou, 1999; Xie and Hu, 2000; Wang et al., 2002). However, as we know, under the effect of the crystal chemical conditions, Rb and Sr occur as the isomorph in the crystal lattice of the potassium-bearing and calcium-bearing minerals, respectively. Therefore, coinstantaneous enrichment of Rb and Sr in the same kind of mineral seems impossible. Also, a part of the Sr will be lost in the process of single mineral selection. Meanwhile, the purity of the single mineral can notbe ensured because of the tedious separation work. Therefore, the hydrothermal metasomatic system of total rocks, with good sealing ability, has been used in the Rb-Sr isotopic analysis. Based on the above theoretical foundation, the beresite which formed by strong hydrothermal metasomatism was collected to be employed in the Rb-Sr isotopic analysis to obtain the formation of the mineralization age of the Dongfeng gold deposit.

In recent studies, by using Rb-Sr, Ar-Ar, and SHRIMP U-Pb isotope system of ore minerals, the ages of the representative deposits in the Jiaodong gold-centralized area have been obtained (Table 3). The statistical results show that the ages of representative deposits are similar and range from 128 to 115Ma, indicating these deposits mainly formed from the late Jurassic to early Cretaceous, which is consistent with the previous conclusions of the time of the large scale gold metallogeny in the Jiaodong area (Fan et al., 2005; Chen et al., 2004). The Rb-Sr isochron age of the beresite from the Dongfeng gold deposit in this study is 125.5±6.7 Ma. This result is consistent within the age range showed in Table 3, indicating the mineralization age of the Dongfeng gold deposit is similar to other gold deposits in the Jiaodong area. This fact suggests that the gold deposits in the Jiaodong area are formed in a relatively short time and under the same mineralization background, and related with the Mesozoic tectonic transition. Thus, this age (125.5±6.7Ma) can be considered as the mineralization age of the Dongfeng gold deposit.

Table 3. Representative isotopic ages of the gold deposits in the Jiaodong gold-centralized area since 2000

Deposits	Analytical minerals	Analytical methods	Ages（Ma）	Data from
Xincheng	beresite	Rb-Sr	116.6±5.3	Yang et al., 2000
Linglong	pyrite	Rb-Sr	121.6±8.1	Yang and Zhou., 2000
Linglongjiuqu	pyrite	Rb-Sr	123±3	Yang and Zhou., 2001
Jiaojia	Sericite, muscovite	Ar-Ar	120.5±0.6~119.2±0.2	J. Li et al., 2003
Dongji	potash feldspar	Ar-Ar	116.3±0.8	H. Li et al., 2003
Dazhuangzi	quartz	Ar-Ar	115.6±1	Zhang et al., 2003a
Fayunkuang	pyrite	Rb-Sr	128.2±7	Zhang et al., 2003a
Pengjiakuang	Quartz and biotite	Ar-Ar	117.5±0.3~118.4±0.3	Zhang et al., 2003a
Cangshang	sericite	Ar-Ar	121.3±0.2	Zhang et al., 2003b
Rushan	Hydrothermal zircon	SHRIMP U-Pb	117±3	Hu et al., 2004
Dayigezhuang	sericite	Ar-Ar	130±4	Yang et al., 2014b
Dongfeng	beresite	Rb-Sr	125.5±6.7	This study

5.2 Relationship between the Mesozoic magmatism and the Dongfeng gold metallization

The Mesozoic Linglong biotite monzonitic granite, Guojialing granodiorite, and Luanjiahe monzodiorite are extensively distributed in the Jiaodong gold concentration area, which was closely related to the gold deposit mineralization. Therefore, research on isotope chronology for these Mesozoic granites is introduced in great detail. Based on the reported Zircon SHRIMP dating results of granites (Table 3), combined with the Rb-Sr isochron ages of the Dongfeng gold deposit, this paper discussed the relationship between the Mesozoic magmatism and the Dongfeng gold mineralization.

As shown in Table 3, Linglong biotite monzonitic granite, Luanjiahe monzodiorite and Guojialing granodiorite formed from 160 to 153 Ma, 154 to 152 Ma and 131 to 126 Ma, respectively, which indicate that Mesozoic granites are mainly formed in two phases: 160 to 152 Ma and 131 to 126 Ma. These results are a coincidence with the mineralization ages (128 to 115 Ma) of the representative gold deposits of the Jiaodong gold concentration area and the ore-forming age (125.5±6.7M) of the Dongfeng gold deposit. Furthermore, the mineralization of the Dongfeng gold deposit is contemporaneous with the formation of the Guojialing granodiorite, but later than the formation of the Linglong biotite monzonitic granite and Luanjiahe monzodiorite (Fig. 5). There is 155±3Ma inherited zircon in the Guojialing granodiorite, which indicates that the Guojialing granodiorite is considered to be the partial melting product of the Jiaodong Group and early granites. Also, the $\delta^{34}S$ values of the gold-bearing pyrite in the Dongfeng gold deposit and the Guojialing granodiorite are consistent, while the Pb isotopic values（$^{208}Pb/^{206}Pb$） show an increasing trend from Linglong biotite monzonitic granite to Guojialing granodiorite, then to gold deposits, which reveals an inheritance evolution trend (Wan, 2014).

Therefore, it could be ascertained that the Dongfeng gold deposit should go hand in hand with the Mesozoic magmatism. This can be embodied in the following respects: (1) During the emplacement of the Linglong granite during the Late Paleoproterozoic–Neoproterozoic period, the rock mass not only carried a gold element of itself but also gave rise to the activation and migration of the ore-forming elements disseminated in the Archean metamorphic rocks in Jiaodong area. Then these elements could be enriched in the favorable place for mineralization. (2) During the Indosinian-Early Yanshanian period, the tectonic-magmatic activity was extensively active, the intense interaction between crust and mantle materials occurred, with the formation of the Guojialing granodiorite. During the emplacement, the Guojialing granodiorite further activated and extracted the gold elements disseminated in the early metamorphic basement and granites. Also, the NE- and NNE-trending brittle fracture activities were intense, which provided the migration pathway and ore-forming space for the ore-forming fluids, while the ore fluids continuously interacted with the wall rocks. Under a favorable physicochemical condition, the ore-forming materials could precipitate and form the deposit in the convenient place. As a result, the Dongfeng gold mineralization was eventually completed.

Table 4. The SHRIMP zircon U-Pb ages of Mesozoic Granites in gold concentration area of Jiaodong

No.	geologic bodies	Major ages（Ma）	Inherited zircon ages(Ma)	Data from
1	Linglong Granite	153±4（19）	200～300	Luo and Miao, 2002
		157±4（11）	3400；200～300	
		160±3（23）	200～300	
		158±3（7）	180～300	
		158.53±0.79（18）	——	Lin and Li,, 2013
		160.45±0.83（18）	1040；2459	Wan, 2014
2	Luanjiahe Granite	154±4（9）	180～400	Luo and Miao, 2002
		152±10（5）	180～240	
3	Guojialing granodiorite	128±2（19）	1900～2700；155±3	Luo and Miao, 2002
		126±2（19）	2500；200～300	
		130±3（14）	1860±15；230±5	
		129±3（5）	1555	
		127.9±1.3（16）	——	Chen et al., 2014
		131.86±0.99（15）	2163；1470	Wan, 2014

Note: "——" means no data; data in brackets mean the number of analysis spots.

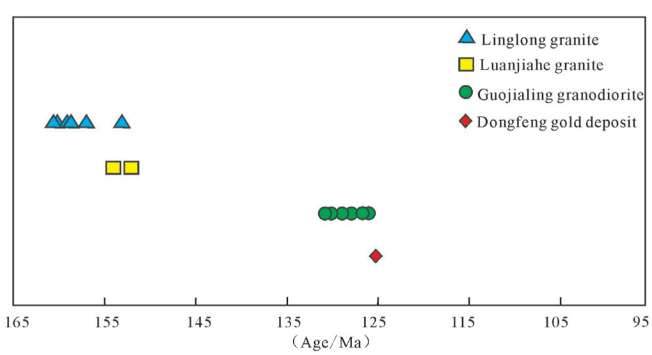

Figure 5. The collective age diagram of Mesozoic granites diagenesis and Dongfeng gold mineralization in Jiaodong area.

5.3 Sources of ore-forming materials and ore fluids

The Rb and Sr isotopic analysis are an effective tool to discuss the source of ore-forming materials (Fan et al., 2005; Medford et al., 1983; Bell et al., 1989; Darbyshire et al., 1996). Also, the Isr value is considered as an important indicator to discriminate the properties of the source of ore-forming materials (Tu et al., 1982; Wang and Zhou, 2002); the I_{sr} value is less than 0.705 for the mantle source, the Isr value is more than 0.709 for the crustal source. While the I_{sr} value is between 0.705 and 0.709 for the mixture of the mantle and crust sources. However, the indicators of different areas are variable due to the different geological background. In this study, we apply this indicator to discuss the origin of ore-forming materials. The（$^{87}Sr/^{86}Sr$）$_i$ ratio of beresite in this paper is 0.711502±0.000069（Fig. 4); it is thought to be reliable due to the reliability of the Rb-Sr isochron age of beresite. As mentioned above, the（$^{87}Sr/^{86}Sr$）$_i$ ratio of beresite is more than 0.709, appearing to indicate that the ore-forming materials are mainly from crust or dominant crust.

According to the results of previous researchers, the($^{87}Sr/^{86}Sr$)i ratios of the Linglong granite were from 0.710498 to 0.712286 (Deng et al., 2011), the ($^{87}Sr/^{86}Sr$)i ratios of the Guojiaing granodiorite were from 0.71071 to 0.71172 (Wang et al., 2014). By the above discriminant indicator, the Linglong granite and the Guojialing granodiorite were both from the crust. Moreover, there was inherited zircon (155±3Ma) in the Guojialing granodiorite; the age of the inherited zircon was consistent with the diagenetic age of early granites. So we can infer that the Guojialing granodiorite is the partial melting product of the early Linglong granite, which indirectly supports the view that the two kinds of granites are both from crust sources.

As discussed above, the formation of the gold deposit is a complex geological process of gradual enrichment and precipitation for the ore-forming elements. Especially, during the Indosinian-Early Yanshanian period, tectonic-magmatic activities caused the upwelling of the mantle materials, the mantle materials interacted with the previous crust materials (such as the rock series of Archean Jiaodong Group and Neoproterozoic Linglong granite) existing in the lithosphere, then formed a crust-mantle mixed-source type of magma, i.e. Guojialing granodiorite. Based on the above evidence, it is inevitable that there will always be the mantle material involved in the ore-forming materials and ore fluids.

Therefore, this article suggests that the ore-forming materials of the Dongfeng gold deposit are mainly from the crust. Meanwhile, some mantle materials also participate in mineralization of gold deposit. The previous studies also confirmed this judgment (Zhou et al., 2002; Liu et al., 2003). The Rb and Sr isotopic analysis of the gold-bearing mineral (pyrite), the carbonate minerals in gold ores, the contemporary magmatic rocks with gold mineralization and basement metamorphic rocks from the typical gold deposits, suggested that the Rb and Sr isotopic compositions of the gold ore minerals were similar with that of the mantle-derived magmatic rocks, and had a certain connection with that of the basement metamorphic rocks and the contemporary magmatic rocks with gold mineralization, which indicated that the ore-forming materials of the gold deposits were of multi-sources, including contemporary magmatic rocks, basement metamorphic rocks, and mantle-derived magma.

Also, based on the Hydrogen and Oxygen isotopic data of the fluid inclusions in quartz of the Dongfeng deposits (Wan, 2014), this article uses Sheppard 's diagram to discriminate the sources of ore-forming fluids (Fig. 5). In the Hydrogen and Oxygen isotopic diagram, the plotted points of the Linglong granite and Guojialing granodiorite samples are partly located in the usual range of magmatic water. However, another part of the plotted points is close to the range of water in the mantle, which implies that there may be some mantle materials participated in the process of granites diagenesis. Moreover, the plotted points of the ore samples of Dongfeng deposit are on the left of the range of magmatic water, and near the range of precipitation water, indicating that the ore-forming fluids are possibly mainly from magmatic hydrothermal and mantle with some precipitate water.

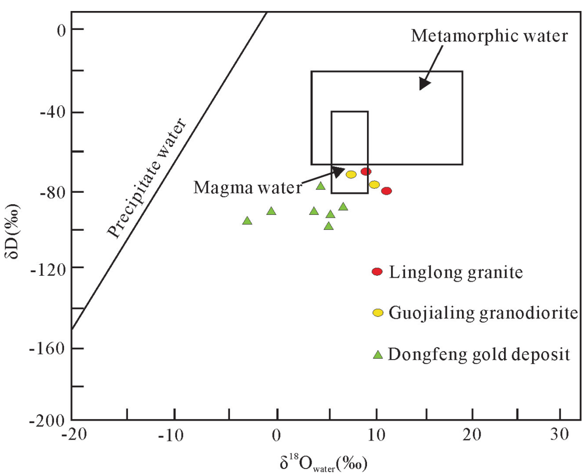

Figure 6. The Hydrogen and Oxygen isotopic diagram (base map from Sheppard, 1977, and data from Wan, 2014)

6 Conclusions

1) The Rb–Sr isochron age of beresites for the Dongfeng gold deposit in Jiaodong gold concentration area is 125.5±6.7Ma, indicating this deposit formed in the early Cretaceous of the late Yanshanian.

2) It could be ascertained that the Dongfeng gold deposit should go hand in hand with the Mesozoic magmatism. The formation of the gold deposit is a complex geological process of gradual enrichment and precipitation for the ore-forming elements.

3) The ore-forming materials of the Dongfeng gold deposit are mainly from the crust. Meanwhile, some mantle materials also participate in mineralization of gold deposit. The ore-forming materials of the gold deposits are of multi-sources, including contemporary magmatic rocks, metamorphic basement rocks, and mantle-derived magma. Moreover, the ore-forming fluids are possibly mainly from magmatic hydrothermal and mantle with some precipitate water.

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