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Zircon Lu-Hf Isotope of Granite in the Bianjiadayuan Pb-Zn-Ag Deposit, Inner Mongolia with Petrogenetic Implications

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Abstract: Series of late Mesozoic A-type granite and related polymetallic deposits located in the Southern Great Xing'an Range, NE China. The Bianjiadayuan Pb-Zn-Ag deposit serves a typical example and consists of quartz-sulfide vein-type mineralization within extensional faults related to granite. In situ LA-ICP-MS Hf isotopic analysis was conducted on zircons from ore-related granite. The zircons are characterized by εHf(t) of +2.3-+4.9 with average of +3.08 and T_{DM2} of 788-952Ma, indicating that the granite was derived from a juvenile crust that originated from depleted mantle and contaminated by some ancient continental crust. In term of mineralization,contamination with crust may play an important role in formation of the deposit.

Keywords: *Lu-Hf isotope; zircon;A-type granite; petrogenesis; Bianjiadayuan; NE China*

1. Introduction

The Southern Great Xing'an Range (SGXR), located in the southeastern part of Inner Mongolia, is considered to be one of the most important polymetallic metallogenic provinces in northern China [1-3]. Series of late Mesozoic A-type granite and related polymetallic deposits have been discovered in recent decades and the Bianjiadayuan Pb–Zn–Ag deposit serves a typical example. It is considered a mesothermal magmatic hydrothermal vein-type deposit controlled by fractures and related to A2-type granite in response to the tectonic/magmatic/hydrothermal activity in late Jurassic [4]. The A-type granite exposed in the SGXR has affinity with mineralization. The petrogenesis of ore-related granite have been discussed, however, the origin of granite in Bianjiadayuan require answering. In this paper, a systematic description of petrology of granite is first. Then the CL imaging and in situ Hf isotope analysis are conducted. At last, the origin of granite has been discussed using the Hf composition combined with data of other intrusions in the SGXR.

2. Geological background

The Bianjiadayuan Pb-Zn-Ag deposit is located in the south of the SGXR and north of the Xar Moron deep fault (Fig. 1). The SGXR forms the eastern section of the Central Asian Orogenic Belt (CAOB) between the Siberian Craton and the North China Craton (NCC). CAOB, the most significant region of Phanerozoic crustal growth and collision on Earth [5], witnessed the evolution of the Paleo-Asian Ocean during the Paleozoic and is characterized by multiple stages of accretion and collision. Regional extension began at Late Mesozoic and resulted in widespread volcanic rocks and granitoids, as well as large scale polymetallic minerallization. At the same time, westward subduction of the Pacific Plate caused the E– W and NE–SW trending tectonic framework.

The oldest formation in this region is the Precambrian metamorphic basement, including the Archean to Neoproterozoic metamorphic complex known as the Xilinhot massif, with gneiss and schist. The Late Paleozoic lithostratigraphic units, predominantly including Carboniferous detrital metasedimentary rocks, volcanic and Permian volcano-sedimentary rocks, are widely distributed and commonly constitute the host rocks for several mineral deposits [3, 6]. The Mesozoic rocks are composed of Jurassic and Cretaceous continental intermediate-felsic volcanic and sedimentary rocks. Widespread NE trending magmatism took place across the SGXR in Mesozoic, the most important period for magmatic activity in northern China. The Mesozoic granitoids in this region are mostly I and A-types [7]. Late Yanshanian granitoids including granite, granodiorite, and syengranite, with ages of 150−131 Ma, result in magmatic hydrothermal vein type deposits [8-10]. The late Yanshannian magmatic hydrothermal activity in extensional setting are believed to be closely associated, both temporally and spatially, with polymetallic mineralization [3, 4, 6, 11].

The exposed strata consist of Permian sedimentary rocks including siliceous slate and siltstone that are NNW dipping at 50–55° (Fig. 2) and Quaternary sediments. The Bianjiadayuan deposit is located in the south part of the Zhesi-Linxi synclinorium. Faulting developed in the district consists of two fault sets with various orientations: F1 (NW-trending) and F2 (NE-trending). F1 is approximately 500 m long, strikes NW 310°, and serves as the major ore-controlling extensional structure by providing room for emplacement of intrusions and subsequent mineralization. F2 is approximately 200 m long, strikes NE 15–30°, plunges 50–70° NW and crosscuts F1. Alteration and mineralization also occurs within F2, whereas the degree of alteration is less than in F1.

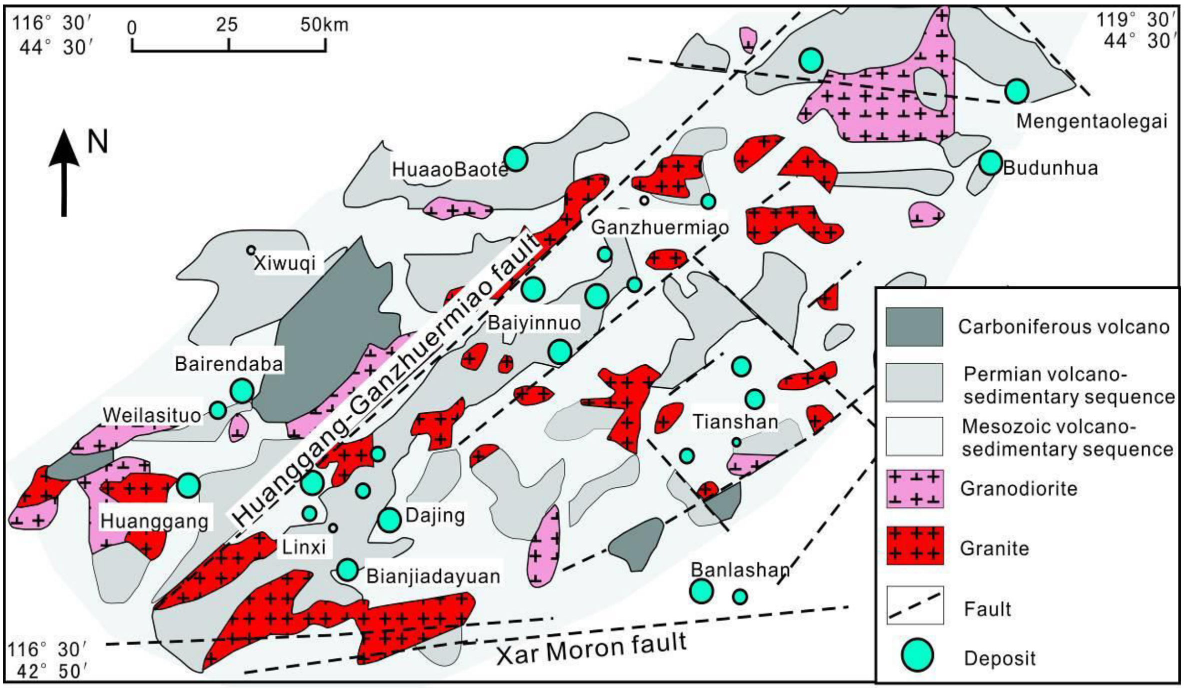

***Fig. 1** Sketch geological map showing distribution of mineral deposits in the South Great Xing'an Range (SGXR; modified after Chu et.al [12]*

Intrusive rocks are distributed discontinuously and can be grouped into two different episodes: the earlier diorite and gabbro and the later granite. Granite overlies gabbro and diorite. Gabbro is almost invisible on the surface, and the majority is observed in underground workings, which are clearly cut by orebodies. The main constituents are plagioclase, pyroxene, mafic hornblende and a small amount of mica. The exposed area of granite is 5–8% of ore district. The main minerals consist of quartz, plagioclase, K-feldspar, hornblende, with small amounts of biotite and pyrite and exhibit a medium-coarse granular texture.

The mineralization is more closely related to granite rather than gabbro on account of geology and geochemistry. The orebodies occur as veins in fractures within granite and in contact zone between granite and surrounding rocks. The granite have higher Ag, Pb, Sn content than gabbro and surrounding rocks, though the gabbro have more Zn content (Table 1).

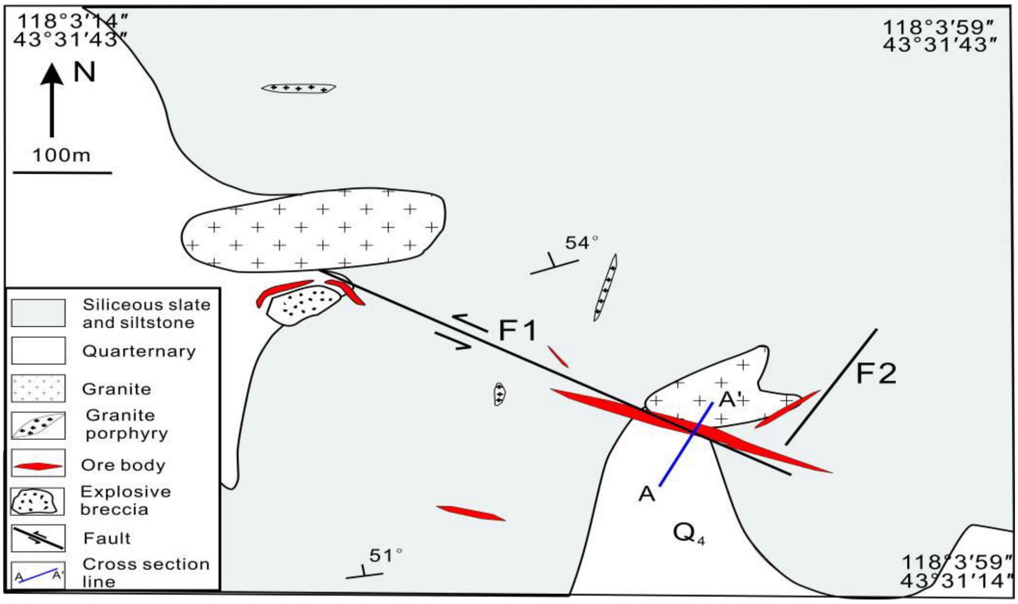

***Fig. 2** Geological map of the Bianjiadayuan Pb–Zn–Ag deposit*

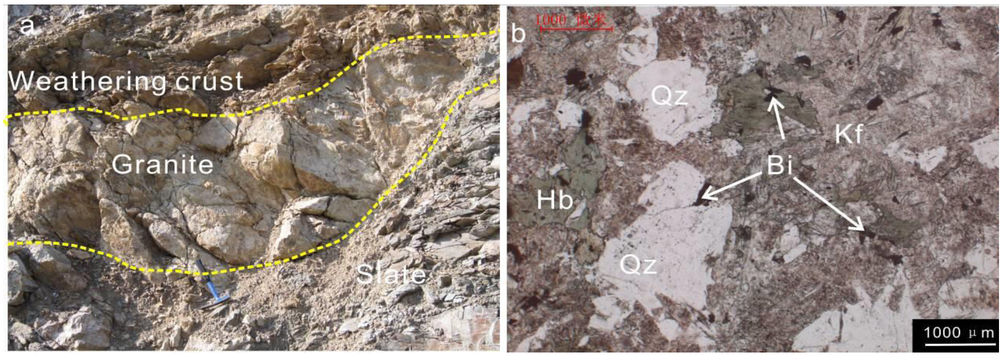

Fig. 3 *The granite of the Bianjiadayuan deposit (a) Granite intruding the slate; (b) The granite composed of quartz (Qz), K-feldspar (Kf) hornblende (Hb) and biotite (Bi)*

3. Methods

Zircons were separated from one sample of ore-related granites (BJYYT-10) using conventional heavy liquid and magnetic techniques at the Langfang Regional Geological Survey, Hebei Province, China. Representative grains were hand-picked under a binocular microscope, mounted in an epoxy resin disc, and then polished and coated with gold film. Zircons were documented with transmitted and reflected light as well as cathodoluminescence imagery (CL), using JXA-8100 plus MonoCL3 with the condition of acceleration voltage ranging from 1KV to 30KV and spectrum varying from 200 to 900 nm, to reveal their external and internal structures. The CL imaging and the following Hf isotopic analyses were conducted at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan, China.

Table 1 *Ore-forming elements content (ppm) of surrounding rocks and intrusive rocks*

Number	Rock	Ag	Pb	Zn	Cu	Sn
Zk0806-8	Siltstone	0.22	13	67	24	<5
Zk2806-3	Siltstone	0.07	18	79	7	27
Zk1206-3	Slate	0.22	58	143	57	<5
QT-13	Slate	0.04	37	93	155	17
Zk2001-4	Gabbro	<1	28	234	19	1
Zk2004-3	Gabbro	<1	17	58	8	11
Zk2806-7	Gabbro	<1	20	110	37	12
YT-10	Granite	1	114	36	<5	52
Zk2806-2	Granite	1	50	10	<5	29
Zk2806-1	Granite	<1	52	79	12	25

After LA-ICP-MS dating of zircon for U-Pb age, In situ Hf isotopic analyses were conducted on corresponding zircon using a Neptune Plus MC-ICP-MS, in combination with a Geolas 2005 excimer ArF laser ablation system. During the analysis, a laser repetition rate of 20 Hz at 200 mJ was used with the spot sizes of 44 μm. During the analysis, the $^{176}Hf/1^{177}Hf$ ratios of the standard zircon (GJ-1) were 0.282013 ± 0.000022 (2 σ, n = 276) [13], agreeing with the recommended values (0.282172 ± 0.000042 [14], within 2σ error.

4. Results

The zircons from granite are euhedral elongated grains, 0.3-1.5 mm in diameter, and show clear oscillatory zoning and no inherited cores in CL images (Fig. 4) with a stable Th/U ratio (0.39-0.53) of zircon [4], all of which are indicative of a magmatic origin [15]. A total of 15 spot analyses were obtained for the zircon and the results are listed in Table 2. Most zircons have $^{176}Lu/^{177}Hf$ ratios are less than 0.0025 except for BJY-5,11, manifesting that zircons have accumulated little radiogenic Hf after they formed. Therefore $^{176}Hf/^{177}Hf$ ratios represent isotopic composition of zircons when they formed [16]. Based on the LA-ICP-MS age of zircon (143.2Ma±1.5Ma [4] , The zircons have variable εHf(t) values of between +2.3 and +4.9. The εHf(t) have a normal distribution with an average value of +3.08 (Fig. 5). The zircon has one-stage model ages of 644−727 Ma and two-stage model ages of 788−954 Ma, and gives initial $^{176}Hf/^{177}Hf$ ratios ranging from 0.282740 to 0.282832. Zircons $f_{Lu/Hf}$ varies from −0.97 to −0.88, obviously less than $f_{Lu/Hf}$ value of mafic crust (−0.34) and salic crust (−0.72) [17]. Consequently, two-stage model ages T_{DM2} reflect the resident ages of source material in crust, suggesting an important event for crustal accretion occurred in this district in the Neoproterozoic.

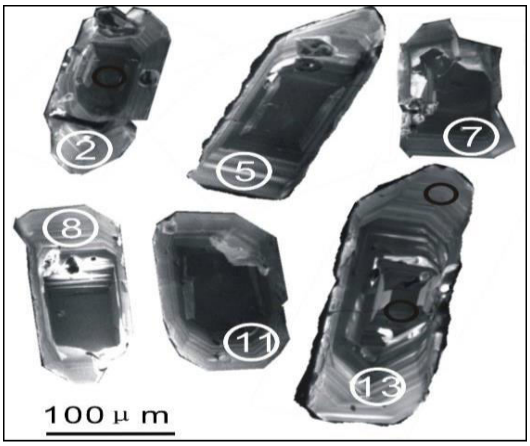

Fig. 4 *Representative CL images of zircon of granite in the Bianjiadayuan Pb-Zn-Ag deposit for in situ Hf isotope analysis*

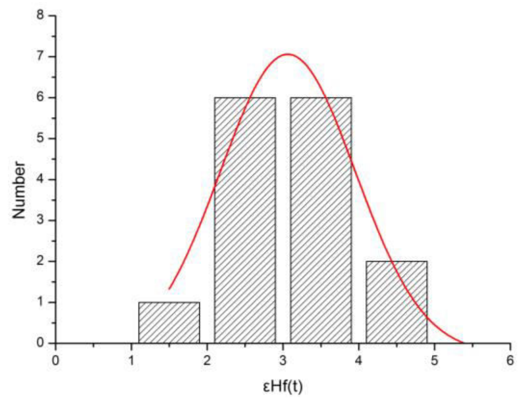

Fig. 5 *Weighted average εHf(t) of zircon (a) and dispersion degree to evaluate the data quality (b)*

5. Discussion

In situ Hf isotopic analysis is widely used to trace the source of magma in recent decades. It is an effective tool to discuss the origin and petrogenesis of intrusive rocks, especially for the phanerozoic Intermediate-felsic rocks. Zircon is a very stable mineral with higher sealing temperature (>850 ^{O}C) than other accessory minerals. Additionally, zircon have high Hf content and extremely low Lu content, leading a very low $^{176}Lu/^{177}Hf$ ratio. Zircons have accumulated little radiogenic Hf after they formed and have not been modified by later magmatic-hydrothermal activities, even in the advanced metamorphic facies such as granulite facies. Thus analytical $^{176}Hf/^{177}Hf$ ratio of zircon can generally represent the initial Hf composition when they formed. The zircon recorded the characteristic of source rock and also could be an important tool for crustal evolution.

Table 2 *Zircon Hf isotope compositions of ore-related granite in the Bianjiadayuan Pb-Zn-Ag deposit*

	Age (Ma)	$^{176}Hf/^{177}Hf$	$^{176}Lu/^{177}Hf$	$^{176}Yb/^{177}Hf$	εHf(0)	εHf(t)	T_{DM1}	T_{DM2}	$f_{Lu/Hf}$
BJY-1	146.6	0.282753	0.001509	0.042797	-0.7	2.4	717	932	-0.95
BJY-2	146.4	0.282749	0.001168	0.032212	-0.8	2.3	716	937	-0.96
BJY-3	142	0.282765	0.002675	0.074672	-0.2	2.6	722	915	-0.92
BJY-4	152	0.282759	0.000853	0.023188	-0.5	2.8	696	914	-0.97
BJY-5	151.2	0.282804	0.003322	0.09851	1.1	4.1	676	838	-0.90
BJY-6	142.4	0.282785	0.002423	0.069827	0.5	3.4	688	874	-0.93
BJY-7	144.3	0.282753	0.001181	0.035004	-0.7	2.4	710	930	-0.96
BJY-8	144.6	0.282791	0.002055	0.05844	0.7	3.6	673	860	-0.94
BJY-9	143.3	0.282776	0.001971	0.055905	0.1	3.1	692	889	-0.94
BJY-10	144.8	0.282796	0.002309	0.066226	0.8	3.8	670	851	-0.93
BJY-11	145.1	0.282832	0.003827	0.111592	2.1	4.9	644	788	-0.88
BJY-12	138.6	0.282799	0.002124	0.059979	0.9	3.8	662	847	-0.94
BJY-13	147	0.28274	0.001103	0.031616	-1.1	2.0	727	954	-0.97
BJY-14	137.5	0.282753	0.000985	0.028215	-0.7	2.3	707	932	-0.97
BJY-15	144.3	0.282773	0.001149	0.034499	0.0	3.1	681	890	-0.97

$\varepsilon Hf(0)=((^{176}Hf/^{177}Hf)/(^{176}Hf/^{177}Hf)_{CHUR,0}-1)*10000$; $\varepsilon Hf(t)=((^{176}Hf/^{177}Hf)-(^{176}Lu/^{177}Hf)*(e^{\lambda t}-1))/((^{176}Hf/^{177}Hf)_{CHUR,0}-(^{176}Lu/^{177}Hf)_{CHUR}*(e^{\lambda t}-1))-1)*10000$; $f_{Lu/Hf}=(^{176}Lu/^{177}Hf)/(^{176}Lu/^{177}Hf)_{CHUR}-1$; $T_{DM1}=1/\lambda*\ln[1+((^{176}Hf/^{177}Hf)-(^{176}Hf/^{177}Hf)_{DM})/((^{176}Lu/^{177}Hf)-(^{176}Lu/^{177}Hf)_{DM})]$; $T_{DM2}=T_{DM1}-(T_{DM1}-t)*((-0.55)-f_{Lu/Hf})/((-0.55)-(0.16))$; $(^{176}Hf/^{177}Hf)_{CHUR,0}=0.282772$; $(^{176}Lu/^{177}Hf)_{CHUR}=0.0332$; $(^{176}Hf/^{177}Hf)_{DM}=0.28325$; $(^{176}Lu/^{177}Hf)_{DM}=0.0384$; $\lambda=1.867*10^{-11}$ year^{-1}.

The depleted mantle source have higher $^{176}Hf/^{177}Hf$ ratio and εHf(t) than continental crust because Hf is inconsistent element and tends to remain in the source rocks. The granite with positive εHf(t) is considered to originated directly from depleted mantle or from partial melting of juvenile crust derived from depleted mantle. The negative εHf(t) imply melting of old crust. The zircon of granite in the Bianjiadayuan are characterized by εHf(t) of +2.3-+4.9 with average of +3.08 and $^{176}Hf/^{177}Hf$ of 0.282740 to 0.282832. In the εHf(t)/-Age plots, the sample located between depleted mantle line and chondrite developing line, but get close to chondrite. For granite, the T_{DM2} is more accurate to reflect the remelting of crust. The T_{DM2} of 788-952Ma indicate the magma source came from a juvenile crust.

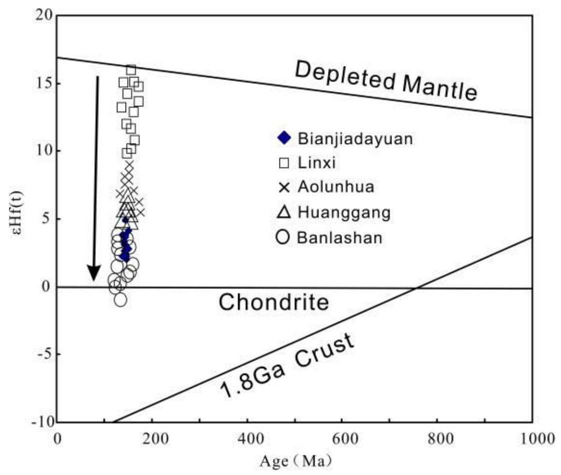

Fig. 6 *Hf isotopic compositions of zircons in ore-related granite from the Bianjiadayuan deposit and other granites in the SGXR (after Vervoort et.al [18]). The Hf isotopic data of other intrusions are after Mei et.al [19] and references therein*

A series of Hf compositions of A-type granite in the SGXR have been collected in this study. They have narrow age range from late Jurassic and early Cretaceous. These tightly cluster age of 130-150 Ma, implying that they probably were produced in similar geodynamic settings in Mesozoic. They have obvious positive εHf(t) of 0-+15 and Sr-Nd isotopic data ($(^{87}Sr/^{86}Sr)_i$ = 0.70211−0.70729, εNd(t) values range from −0.8 to +0.9. All of these data form a evolution line from depleted mantle to chondrite line, indicating the source rock have mantle origin and be assimilated by continental crust. Therefore ore-related granite was derived from a juvenile crust that originated from depleted mantle and contaminated by some ancient continental crust. The $^{176}Hf/^{177}Hf$-Age plot also supports the conclusion. This A-type granite in the SGXR have T_{DM2} from 1.7-0.7Ga, implying Phanerozoic crustal growth through mantle-derived underplating was significant in the NE China and that the growth of the continental crust in this region occurred from Meso-Neoproterozoic to the Phanerozoic [19, 20].

In term of the Bianjiadayuan granite, the mantle has undergone partial melting to produce juvenile crust in Neoproterozoic (0.8-0.9Ga). In the Late Jurassic (143.2Ma), the SGXR was in an intra-plate orogenic and extensional environment with the opening of the suture zone between the North China Craton and the Siberia Craton [21]. At the same time, lithospheric thinning and tectonic stress field transformation into extension from extrusion resulted in upwelling of magma of partial melting from the crust and subsequent emplacement of A-type granite.

Besides the petrogenesis, the Hf isotopic analysis can also be of implication for mineralization. The Bianjiadayuan, Aolunhua, Huanggang, Banlashan granite with low positive εHf(t) of 0-+10 and relative low $^{176}Hf/^{177}Hf$ (<0.2830) have larger scale mineralization than Linxi granitoids nothing with the mineralization. Moreover, most of Cu consist in slate and slate have more Zn than granite. Contamination with crust may play an important role in formation of a magmatic hydrothermal deposit.

6. Conclusion

The typical A-type granite in the Bianjiadayuan Pb-Zn-Ag deposit in the SGXR shows close affinity with mineralization. The zircons from the granite are characterized by εHf(t) of +2.3-+4.9 and T_{DM2} of 788-952Ma, indicating that the granite was derived from a juvenile crust that originated from depleted mantle and contaminated by some ancient continental crust. Contamination with crust may play an important role in formation of the deposit.

7. Acknowledgments

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