Geochemistry and chronology of Se' ertengshan greenstone, Inner Mongolia *

LIU Jianzhong (刘建忠)[1], WANG Lili (王莉莉)[2], ZHANG Fuqin (张福勤)[3], LI Chunlai (李春来)[1], ZOU Yongliao (邹永廖)[1], OUYANG Ziyuan (欧阳自远)[1,4], and XU Lin (徐 琳)[1,4]

[1] *National Astronomical Observatories, Chinese Academy of Sciences, Beijing* 100012, *China*

[2] *Zhengzhou Railway Vocational and Technical College, Zhengzhou* 450052, *China*

[3] *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing* 100101, *China*

[4] *Institute of Geochemistry, Chinese Academy of Sciences, Guiyang* 550002, *China*

Abstract This paper deals with the meta-mafic volcanic rocks of the Gongyiming iron deposit at Baotou, Inner Mongolia. The major and trace elements and REE data indicate that the meta-mafic volcanic rocks occurred in the environment similar to a modern continental rift. Sm-Nd and Rb-Sr isotopic studies indicated that the meta-basic rocks were formed during the Early Neoarchean from 2800 Ma to 2900 Ma and reworked during the Late Neoarchean (2500 Ma) by metamorphism. Because of the separation of the North China Craton from the Siberia Craton during the Middle Proterozoic (1600 Ma), the Rb-Sr systematics of the rocks has been changed. The Se' ertengshan greenstone seems to occur during the Middle Archean. A stable continental crust may have existed during the Paleoarchean.

Key words greenstone; chronology; geochemistry

1 Introduction

The Se' ertengshan region is situated on the northern margin of the North China Continental Platform. In the long past different researchers had different opinions on the metamorphic series in this region. Regional geological survey (1∶ 200000 on scale) (Compiling Group of Stratigraphic Tables for the Inner Mongolia Autonomous Region, 1978) has divided the metamorphic series in the region studied into the Wulashan Group, the Wutai Group, the Erdaowa Group and the Sanheming Group. According to the Geological Research Team of Inner Mongolia (Bureau of Geology and Mineral Resources, Inner Mongolia Autonomous Region, 1991), the metamorphic series was defined as the Dongwufenzi Group, belonging to Late Archean or Early Proterozoic. According to Li Shuxun et al. (1987), granites are widespread in this region and metamorphic layered series are of scattered distribution, where tectonic deformation is unusually complicated. The rocks belong respectively to different rock assemblages of the greenstone belt and overlapped due to the influence of tectonic deformation. So this is a typical granite greenstone belt. Wang Ji et al. (1995) conducted detailed chronological tectonic-framework studies of the rock formations in the region studied. As no precise age data for the rocks in this region have been obtained because of their having been influenced by later intensive erosion, the age (2500 Ma) of the top boundary can be estimated merely on the basis of the zircon U-Pb age of the granite, but no age data have been acquired for the bottom boundary. At present there still exists much controversy on the geotectonic position of the greenstone terrain. Therefore, more detailed chronological studies are extremely urgent and necessary.

2 Geology and sample description

The granite-greenstone belt in this region is composed predominantly of linear greenstone belt materials and granitic rocks, compositionally similar to those typical granite-greenstone belts throughout the world.

The greenstone belt can be divided into three rock assemblages and be compared to those in other parts of the world (Li Shuxun et al., 1987). In the lower part are ultramafic and mafic volcanic rock assemblages intercalated with calc-alkaline volcanic rocks and minor amounts of banded siliceous-ferruginous rocks. Although reformed by low-grade amphibolite facies metamorphism, the volcanic rocks in some segments still exhibit primary structures such as amygdamoidal and pillow structures. In the middle part are the calc-alkaline felsic volcanic rock and pyroclastic assemblages in-

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tercalated with tholeiites and minor amounts of argillaceous silty rocks. In the upper part are the felsic pyroclastic rock and immature clastic sedimentary rock assemblages. Because of slight reworking by low-grade greenschist facies metamorphism, some structures and textures of the protolith still remain unchanged, such as clastoporphyritic structure, palimpsest crystal debris, palimpsest rock debris, fumarole amygdamoidal structure, pilotaxitic structure, etc., as well as sedimentary grain-sequence bedding structures.

2.1 Granitic rocks

Although granitic rocks in the region studied are diverse in type, they can be precisely designated to two categories, i.e., tonalites and K-feldspar granitoids.

The tonalities, belt- and tongue-shaped, intruded into the lower levels of the greenstone belt and exposed mainly along the northern margin of the greenstone belt, though scattered along the southern margin. The zircon U-Pb ages are within the range of 2420 – 2470 Ma (Bureau of Geology and Mineral Resources, Inner Mongolia Autonomous Region, 1991). The schistosity of the rock massifs is well developed and a great number of xenoliths, which are of oriented distribution, are found in the country rocks. They are generally consistent with the country rocks (metamorphic rocks) with respect to the attitude of gneissose bedding. The common rock types include trondjemties, with granodiorite, quartz diorite and diorite coming next. It is hard to distinguish the lithofacies zones or independent rock massifs of the above rock types in the field because of their transitional relationships. In addition, no thermal contact phenomenon has been observed in the country rocks, though there have developed soda migmatitization and its products, which are directly genetically connected with the rock massifs, indicating that granitic rocks of this kind are the product of partial melting of greenstone.

The K-feldspar granites, elongated, elliptical and banded in shape, intruded the rock assemblages in the upper part of the cooled, consolidated greenstone belt. Tectonically, they are distributed nearly east-westwards along the core of the greenstone belt, constituting the low-moderate mountain ranges, in contrast to the surrounding gently hilly landforms. The zircon U-Pb ages are within the range of 1770 – 1650 Ma (Li Shuxun et al., 1987). Weakly gneissose structure is observed at the edges of the rock massifs, just in consistency with the gneissose attitude of the country rocks. Many country-rock xenoliths, diverse in type (e.g. mylonite, mafic rock, granulite, etc.), are observed in the rock massifs. Close to the edges of the rock massifs, the xenoliths are increased in number, are orientationally distributed, and are in consistency with the strike of the mylonite belt along the long axis. The rocks are simple in petrological character, with K-feldspar accounting for 50% – 60%, plagioclase < 10%, quartz 30% – 35%, and biotite 3%. Local potassic metasomatism is remarkable, and generally the rocks exhibit porphyroid texture, for example, the Changheshan and Zhangzigou rock massifs at Ba Yong. It is obvious that their country rocks (regionally metamorphic rocks and mylonite) have been strongly reworked by thermal contact metamorphism, and the porphyroid textures of the rock massifs indicate that the rocks were formed at shallower levels of the crust.

2.2 Metamorphic characteristics of the greenstone belt

According to the fabrics of the rocks and the conversion-reaction relations among minerals, it is indicated that the regional metamorphism in this terrain can be divided into two stages. The first stage is a low pressure-type regionally enhanced metamorphism, during which there was formed an enhanced metamorphic belt ranging from low-grade greenschist facies to low-grade amphibolite facies. The metamorphic reactions from low-grade green schist facies to high-grade green schist facies in the mafic rocks of this region are described as: Act + Chl + Ep + Qz→Hb + Ab + H_2O; Chl + Ep + Qz→Hb + Ab + H_2O. According to Thompson and Norton (1968), the temperature of the above reactions is 500℃, and the pressures are estimated to be 0.2 – 0.3 GPa. The critical reactions from high-grade greenschist facies to low-grade amphibolite facies are: $Hb_{(bluish\text{-}green)}$/Act + Ep + Chl→Di + Pl + $Hb_{(brown)}$ + H_2O; $Hb_{(bluish\text{-}green)}$ + Ep + Chl→Gt + Pl + $Hb_{(brown)}$ + H_2O. The temperature and pressure conditions for the above reactions are: 550℃ and 0.2 – 0.3 GPa, and the geothermal gradients are estimated to be 34 – 35℃/km and the *PTt* path is clockwise in form. The second-phase regional metamorphism is characterized by retrograsive metamorphism, and its maximum temperature is 450℃ and its maximum pressure is 0.58 GPa, with the geothermal gradient being 23℃/km.

The samples examined in this study were collected from the Gongyiming iron deposit in the western part of Guyang. The iron deposit is located in the lower part of the greenstone belt, closely against siliceous-ferruginous rocks. All are the plagiolcase amphibolites.

3 Geochemical characteristics of the samples

Systematic studies of the major elements, trace elements and REEs in the rocks will provide much information about the provenance of the rocks and also are an important key to explore the cycling of materials in the deep interior of the earth. In this paper the meta-mafic volcanic rocks in the lower part of the Se'ertengshan greenstone were systematically sampled and analyzed and the results are presented in Table 1.

Table 1. Chemical analyses of major (%) and trace (μg/g) elements and REE (μg/g) in the Se'ertengshan greenstone

	1	2	3	4	5	6	7	8
	S97-11	S97-19	S97-20	S97-22	S97-23	S97-26	S97-25	S97-29
SiO_2	45.94	46.87	47.91	56.87	55.74	48.46	57.82	51.03
Al_2O_3	17.55	13.24	6.5	16.14	16.52	17.66	5.90	16.7
Fe_2O_3	6.87	5.76	2.37	3.97	3.74	2.51	2.04	2.12
FeO	5.67	6.67	8.47	3.64	3.67	5.5	12.87	5.23
MgO	5.38	6.71	18.5	3.95	3.96	8.22	7.26	7.07
CaO	9.61	11.8	10.42	6.28	6.01	8.31	4.90	7.98
Na_2O	3.4	2.34	0.49	4.88	5.34	3.07	0.06	3.55
K_2O	1.45	0.31	0.32	1.51	1.46	1.50	0.32	1.69
MnO	0.16	0.18	0.19	0.13	0.13	0.14	0.12	0.14
TiO_2	1.18	1.06	0.42	0.49	0.8	1.40	0.75	1.38
P_2O_5	1.01	0.09	0.22	0.2	0.43	0.27	0.29	0.26
CO_2	0.07	1.97	0.36	0.1	0.1	0.26	3.38	0.16
H_2O^+	1.39	2.77	3.44	1.55	1.78	2.46	4.06	2.46
La	60.44	7.01	11.96	20.25	25.83	9.25	10.15	11.53
Ce	176.6	20.35	35.91	48.08	55.80	24.63	26.12	30.97
Pr	21.8	2.72	3.63	6.18	7.01	3.34	3.21	3.53
Nd	92.86	12.22	14.32	26.08	28.60	14.40	14.12	14.79
Sm	16.35	2.98	2.86	4.93	5.22	3.52	3.18	3.52
Eu	3.71	1.03	0.89	1.05	0.96	1.21	1.07	1.27
Gd	11.41	3.16	2.38	3.82	3.94	3.87	3.01	3.75
Tb	1.44	0.52	0.36	0.54	0.54	0.66	0.49	0.63
Dy	6.88	3.45	2.11	2.82	2.82	4.15	2.95	4.05
Ho	1.24	0.68	0.41	0.54	0.53	0.81	0.57	0.78
Er	2.76	1.77	1.09	1.36	1.27	2.21	1.47	2.05
Tm	0.38	0.27	0.17	0.21	0.19	0.36	0.24	0.32
Yb	2.28	1.70	1.03	1.21	1.09	2.04	1.38	1.93
Lu	0.37	0.27	0.17	0.18	0.18	0.35	0.24	0.32
Y	30.73	18.13	10.81	14.10	13.35	21.77	14.77	20.96
Eu/Eu^*	0.9515	1.1758	1.195	0.8475	0.8415	1.2005	0.1484	1.2245
ΣREE	429.24	76.28	88.11	131.33	147.32	92.58	82.97	100.42
Rb	25.3	1.0	1.1	21.9	21.5	39.6	14.2	40.4
Sr	1509	658	32.0	717	714	522	170	498
Ba	971	132	82	1002	1338	339	137	409
V	203	157	104	128	125	161	140	124
Cr	34	216	2422	122	73	166	849	186
Sc	17.2	33.3	22.1	19.6	17.1	25	26	26.9
Co	30.7	37.7	50.7	21.8	25.5	31.7	21.8	26.2
Ni	33.2	101.6	473	57.5	58.3	112.1	90.5	83.1
Ga	29.9	16.5	10.7	18.6	21.9	15.6	13.9	15.9
Zr	113.2	52.3	78.3	48.2	77.7	172.9	84.8	142.2
Hf	5.1	2.4	2.8	2.1	2.9	4.6	2.6	4.2
Ta	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.2
Th	3.2	0.2	0.3	0.2	0.7	0.6	0.3	0.6
U	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Pb	19.2	14.3	4.6	9.2	11.2	12.8	13.3	8.9
Mo	0.39	0.27	0.17	0.22	0.23	0.2	0.24	0.55
Nb	12.2	6.4	5.6	4.0	8.1	10.1	5.9	9.1

Note: The samples were all analyzed at Wuhan Institute of Analysis and Test, Ministry of State Land Resources.

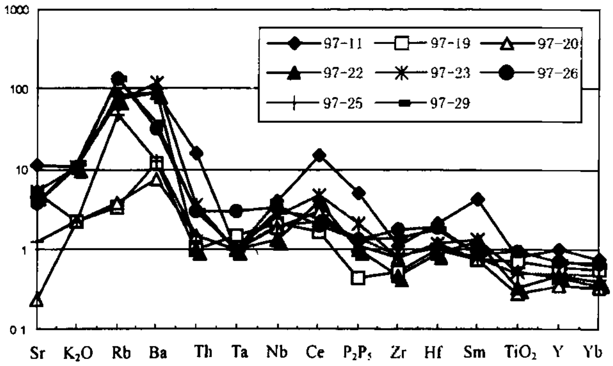

Fig. 1. N-MORB-normalized trace element spidergrams of the meta-mafic rocks in the Se' ertengshan region.

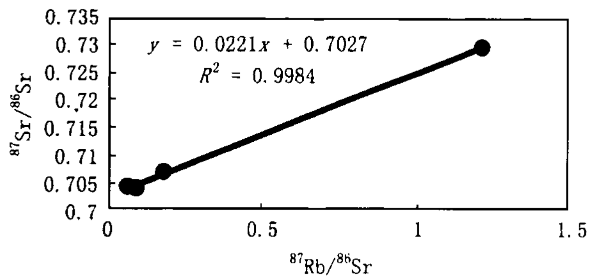

Fig. 2. Chondrite-normalized REE distribution patterns of the meta-mafic volcanic rocks in the Se' ertengshan region.

3.1 Major elements

According to the results of major element analyses and the data provided by Li Shuxun (1987) and Wang Ji et al. (1995), the Se' ertengshan greenstone contains abundant SiO_2, mostly within the range of 43% - 55%. From the bottom upwards, the basic rocks tend to decrease, whereas detrital rocks tend to increase, reflecting that the geotectonical environment changed from active to stable. The contents of MgO are highly variable, with an average value of 8.67%, reflecting the Mg index for magmatic differentiation degree, Mg'[$Mg' = 100 \times MgO/(MgO + FeO + Fe_2O_3)$] is within the range of 6 - 39. As compared with metamorphic basalts in the Archean greenstone belt (Condie, 1981), the Se' ertengshan greenstone is close to the TH2 type, as is reflected by its REE composition. On the AFM diagram they all fall within the field of tholeiites (the figure is omitted).

3.2 Trace elements

Trace elements, especially incompatible elements, are one of the important indicators to reveal the process of formation of the rocks and they can be used to discriminate the geotectonic environment at the time of rock formation. The meta-mafic volcanic rocks in the region studied are all projected into the field of basalts, as shown in Ti/100-Zr-Y and Zr/Y-Zr diagrams (omitted). In the Ta/Yb-Th/Yb diagram the rocks generally fall within the region of intraplate mantle evolution trend (omitted). The MORB-normalized trace element distribution patterns (Compiling Group of Stratigraphic Tables for Inner Mongolia Autonomous Region) (Fig. 1) generally show a "rise" trend, and the rock is strongly enriched in K, Rb, Ba and Ce, indicating that the meta-mafic rocks in this region would probably be formed in an environment like modern continental rift rather than in the oceanic environment. According to the rock assemblages and geochemical characteristics, it is judged that the Se' ertengshan greenstone appears to have formed in the active continental-margin fault trough environment.

Shown in Fig. 2 are the REE distribution patterns of the meta-mafic volcanic rocks. It can be seen from the figure that the samples all show LREE enrichment right-inclined patterns with no negative Eu anomaly, very similar to the distribution patterns of the TH2 tholeiites presented by Condie. This demonstrates that these rocks are identical in origin. The total amount of REE in the rocks is highly variable.

4 Isotope geochemistry and chronology

Till up to now, there have not yet been obtained highly reliable age data for the greenstone belt itself owing to the strong influence of later alteration processes. In this work we tried to collect those less altered rock samples as the subjects of study for isotope chronological and geochemical studies (Tables 2 and 3). Isotopic measurements of the samples were accomplished at the Open Lab. of Isotopes, Institute of Geology, Chinese Academy of Geological Sciences. For the analytical procedure and parameters, please refer to Zhang Zongqing and Ye Xiaojiang (1988). The age calculation was conducted by using the software ISOPLOT (1992). Results of the study have shown that samples S97-22, S97-23 and S97-25 may constitute an ideal isochron (Fig. 3), which gave an isochron age of 2892 ± 680 Ma, with $I_{Nd} = 0.509211 \pm 12$ and $\varepsilon_{Nd} = 6.5$. This age is the oldest one acquired in this region, which may represent the forming age of meta-mafic volcanic rocks in the lower part of the Se' ertengshan greenstone. The Nd isotope geochemical characteristics of this region are reflected by relatively high ε_{Nd} values. The values for some individual samples are 4.362 (except S97-26). According to the statistics data on samples S97-11, -20, -22, -23, and -26, the Rb-Sr isochron ages can be obtained to be 1546 ± 129 Ma, with the initial Sr isotopic ratio I_{Sr} = 0.7026 ± 5 (Fig. 4). Lower initial Sr isotopic ratios indicate that the rocks have experienced a lower degree of crustal contamination.

Table 2. Sm-Nd isotopic analyses of meta-mafic volcanic rocks

Seq. No.	Sample No.	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$①	T_{CHUR} (Ma)②	$T_{(DM10)}$ (Ma)③	I_{Nd}	$\varepsilon_{Nd(T_{DM})}$
1	S97 - 11	0.1092	0.511473	2.02239	2.434318	0.509721	4.694707
2	S97 - 20	0.1212	0.511622	2.043916	2.505194	0.50962	4.538349
3	S97 - 22	0.1175	0.511458	2.261329	2.665974	0.509391	4.183169
4	S97 - 23	0.1101	0.511308	2.330463	2.694757	0.50935	4.119516
5	S97 - 25	0.1364	0.511812	2.080306	2.62402	0.509451	4.275916
6	S97 - 26	0.1502	0.512787	-0.490741	0.871599	0.511928	8.109636

Note: ① Mass fractionation corrected with $^{143}Nd/^{144}Nd = 0.72190$; ② the calculating formula: T_{CHUR} (Ma) = $1/\lambda \ln[(^{143}Nd/^{144}Nd - 0.51264)/(^{147}Sm/^{144}Nd - 0.1967) + 1]$; ③ calculating formula: T_{DM} (Ma) = $1/\lambda \ln[(^{143}Nd/^{144}Nd - 0.51315)/(^{147}Sm/^{144}Nd - 0.2137) + 1]$. All the samples were analyzed by Zhang Zongqing, Tang Suohan, and Wang Jinhui with the Institute of Geology, Chinese Academy of Geological Sciences.

Table 3. Rb-Sr isotopic analyses of meta-mafic volcanic rocks

Seq. No.	Sample No.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	I_{Sr}	$\varepsilon_{Nd(T_{DM})}$	T_{DM}
1	Y97 - 11	0.06818	0.704595	0.70421	81.4238	0.39389
2	Y97 - 20	1.211	0.729445	0.70278	81.0684	1.53340
3	Y97 - 22	0.0966	0.704312	0.70817	82.4045	-2.8747
4	Y97 - 23	0.09251	0.704386	0.70956	82.7454	-4.0562
5	Y97 - 25	0.2675	0.711632	0.70136	80.7124	2.65245
6	Y97 - 26	0.1828	0.707191	0.70244	80.9824	1.80587

Note: T_{DM} = the model age of the rocks derived from the upper mantle characterized by Rb/Sr = 0.03, where $\lambda(^{87}Rb) = 0.0142\ Ga^{-1}$. All the samples were analyzed by Zhang Zongqing, Tang Suohan and Wang Jinhui with the Institute of Geology, Chinese Academy of Sciences.

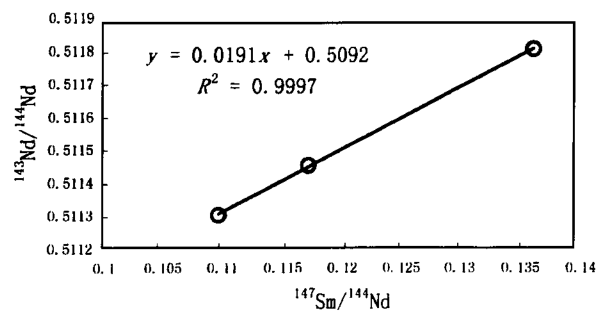

Fig. 3. Whole-rock Sm-Nd isochron diagram of the Se' ertengshan greenstone.

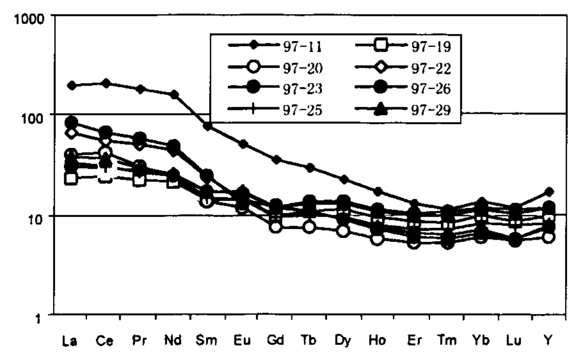

Fig. 4. Whole-rock Rb-Sr isochron diagram of the Se' ertengshan greenstone.

5 Results and discussion

The major element, trace element and REE geochemical characteristics and Sm-Nd and Rb-Sr isotope geochemical characteristics of meta-mafic volcanic rocks in the region studied indicated that meta-mafic volcanic rocks at Se' ertengshan belong to continental tholeiites, which are Middle Archean in age (2892 Ma), generally in accord to the age of the Xinghe complex (Wang Ji et al., 1995). What is worth notice is that the ε_{Nd} values reported from this region are significantly different from those of the Xinghe complex. The Se' ertengshan greenstone has an obviously high initial Nd isotopic ratio ($\varepsilon_{Nd} = 6.5$) as compared with the Xinghe complex ($\varepsilon_{Nd} = 0.6$). So, it should not be simply considered that both the Se' ertengshan greenstone and Xinghe complex were formed in a unified tectonic environment. They may have been formed during the same period but in different small continental cores. Statistics data of the isotopic ages indicated that the peak isotopic ages of mafic gneisses in the central-western parts of the North China Craton are concentrated within the three ranges, i. e., 2860 - 2880 Ma, 2640 - 2710 Ma and 2400 - 2520 Ma. The Sm-Nd isochron age of 2892 Ma is corresponding to the peak age value of 2860 - 2880 Ma, implying there had occurred a great crust/mantle differentiation event at the end of the Middle Archean in this region, while the zircon U-Pb age of 2500 ± Ma (Li Shuqin et al., 1987; Wang Ji et al., 1995) appears to represent the metamorphism which had occurred at the end of Neoarchean in the North China Craton. The isochron Rb-Sr ages of 1546 ± 129 Ma obtained in this work may be related to the process of splitting of the Middle Proterozoic North China Craton and the Siberia Craton in response to their south-northward expansion (Bai Jing, 1996). The initial Sr isotopic ratio is $I_{Sr} = 0.7026 \pm 5$ (Fig. 4). It can be seen clearly that the lower initial Sr isotopic ratio indicates a lower degree of crustal contamination for the Se'ertengshan greenstone.

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