Nd-Sr isotopic determination of the ore-bearing Proterozoic ultramafic rocks in Jinchuan, China

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Sm-Nd isotopic study for the ore-bearing Jinchuan ultramafic rocks in Gansu province, China, reveals the age of 1508 ± 31 Ma, which is obtained by Sm-Nd internal isochron method. The Rb-Sr isotopic system of the Jinchuan rocks have been contaminated by crustal materials, but little influence of crustal materials disturbed their Sm-Nd isotopic system. The determined results for acid-washed pyroxenes show that the source region of the Jinchuan ultramafic rocks may possess the following features: relatively homogeneous negative $\epsilon_{\text{Nd}}(T)$ values, relatively dispersed $\epsilon_{\text{Sr}}(T)$ values (generally larger than +60), and exhibiting a horizontal distribution in Nd-Sr correlation diagram.

INTRODUCTION

The largest Cu-Ni sulphide ore in China occurs in the Jinchuan ultramafic rocks, which are considered to have come initially from the sub-continental mantle. Because very few radiometric age data were published, the age of the Jinchuan rock body remains equivocal until now.

The major aims of the present study are: to determine age of the Jinchuan rock body using Sm-Nd method, which is, in generally, difficult to establish using other methods, and to obtain their initial Nd and Sr isotopic information.

GEOLOGICAL SETTING AND SAMPLING LOCATIONS

The Jinchuan rock body is located in about 30 km northeast of Yongchang city, Gansu province, China. This area is on the upwarped district of margin of Alashan Platform at southwest Sino-Korean Block and it belongs to the middle belt, inner of the Block being in its north and the corridor transition belt of the Qilian fold system being in its south (Sixth Team, 1984). The development

of deep rifts in southern and northern flanks of the upwarped district formed two large rift zones. The upwarped district is mostly covered by the Precambrian strata consisting of the lower Baijiazui Formation and the upper Tamagouzi Formation. The Jinchuan ultramafic rock body has intruded in the Lower Proterozoic Baijiazui Formation with shape of dyke along the rift in northern flank, and is in discordant contact with gneiss, marble and migmatite. The rock body is 6500 m in length and 30 to 500 m in width, emerging an area of 1.34 km², and composed mostly of peridotites with high abundance Ni (Fig. 1). Some researchers thought that the Jinchuan rocks were derived initially from mantle, rose along a supercrust fault zone and then reached a magma chamber in crust. Finally, they went into the present position under action of pulsating tectonic stress (Sixth Team, 1984).

The minerals in the ultramafic samples are mostly olivines (mainly chrysolytes) and pyroxenes (mainly clinopyroxenes) with a small amount of plagioclases, sulfides and metallic minerals. Under microscope, olivines are generally altered into serphites and fibred taxoites, and a part of py-

Fig. 1. Geological map of the Cu-Ni sulphide ore district of Baijiazui. 1: Quaternary system, 2: Precambrian migmatites, 3: ultramafic rocks, 4: emerged area of ore bodies, 5: deep rifts, 6: faults.

Table 1. Mineral compositions of the Jinchuan ultramafic rocks

Sample No.	Rock type	Olivine (wt.%)	Pyroxene (wt.%)	Plagioclase and others (wt.%)
JA-9	lherzolite	65	30	5
JA-9b	augite-peridotite	60	36	4
JA-9c	augite-peridotite	65	30	5
JA-7a	lherzolite	55	40	5
JII-1	lherzolite	55	40	5
JII-36	olivine pyroxenite	30	70	0
JII-37	pyroxenolite	7	90	3
JII-50	lherzolite	55	30	15
JII-66	augite-peridotite	55	40	5
JII-69	lherzolite	50	35	15
JII-73	augite-peridotite	55	35	10

roxenes were altered into amphiboles. The mineral compositions of the Jinchuan ultramafic rocks is listed in Table 1.

EXPERIMENTAL METHOD

The whole rock samples (about 5 kg each) were split into small fragments (about 1 cm). After ultrasonically cleaned in distilled water, they were crushed and sieved. A portion of 0.1 to 1 mm in size was used for mineral separation, which was executed repeatedly by heavy liquid and magnetic separation techniques. The separates were further purified by hand-picking under a binocular microscope and rejecting those grains showing signs

of alteration.

It has been shown repeatedly that the acid-washed method can successfully remove Nd and Sr not hosted in the pyroxene structure, which are predominantly of crustal origin. The superficial contaminant should not affect the isotopic compositions of clean clinopyroxene separates, even in highly altered rocks of spinel and garnet facies (Zindler *et al.*, 1983; Reisberg, 1988; Reisberg *et al.*, 1989). So, in the present study, the key analyses were performed on hand-picked, acid-washed pyroxene separates from samples JA-9, JII-50, JII-66 and JII-69.

The acid-washed procedure is as the following: Samples were placed in 3N HCl for 3 hours. Two

times during this period the HCl leachate was changed and samples were agitated for about 15 minutes in an ultrasonic bath. Next, they were leached in 10% HF in an ultrasonic bath for several minutes and then washed in ultrapure water several times. After treated as above, sample weights were only about one half of the original untreated samples.

Nd, Sr, Sm and Rb concentrations were determined using the MSID method. Sample powders (<200 mesh) for isotopic analysis were spiked with ^{145}Nd , ^{149}Sm , ^{84}Sr and ^{87}Rb tracers prior to digestion to ensure spike equilibration. Following the initial open beaker evaporation, they were decomposed with HF + HClO_4 in teflon bombs for two days at a temperature of about 200°C. After the samples were removed from the oven, HClO_4 was added and evaporated to dryness. 6N HCl was added several times until samples were completely dissolved and solution showed clear.

Two sets of cation exchange columns (AG50 WX-8 resin, 200–400 mesh) were used in chemical procedure. Sr, Rb and total REE were separated and collected in the first set. The separation of Sm and Nd were carried out using the second set and 0.23 M α -hydroxyisobutyric acid at pH 4.43 as eluant. Rb and Sr were loaded onto single Ta filaments, while Sm and Nd onto Ta-Re-Ta triple filaments for analysis on a VG 354 mass spectrometer with 5-collector at Nanjing University. Fractionations were corrected by normalizing to a $^{86}\text{Sr}/^{88}\text{Sr}$ value of 0.1194 and $^{146}\text{Nd}/^{144}\text{Nd}$ value of 0.7219. $^{147}\text{Sm}/^{144}\text{Nd}$ value was limited to $<5 \times 10^{-4}$ when Nd isotopic ratios were measured. Nd isotopic ratios of each sample were directly determined using the unspiked samples. Uncertainties in concentrations of Sm and Nd were $\leq 0.1\%$. During this study, an average obtained for NBS 987 $^{87}\text{Sr}/^{86}\text{Sr}$ ratios was 0.71023 ± 1 . The results measured for BCR-1 and La Jolla are $^{148}\text{Nd}/^{144}\text{Nd} = 0.512662 \pm 9$ and 0.511860 ± 4 , respectively. Typical total-procedure blank levels are 0.06 ng for Nd and 1 ng for Sr. The experimental details have been described by Wang *et al.* (1988).

$\varepsilon_{\text{Nd}}(T)$ and $\varepsilon_{\text{Sr}}(T)$ were calculated using the equations as previously defined by DePaolo and

Wasserburg (1976, 1977). The present-day bulk earth (CHUR) values used were: $^{148}\text{Nd}/^{144}\text{Nd} = 0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ (Jacobsen and Wasserburg, 1980; Wasserburg *et al.*, 1981). The present-day total earth (UR) values used were: $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$ and $^{87}\text{Rb}/^{86}\text{Sr} = 0.0827$ (DePaolo, 1981). The decay constants used were: $6.54 \times 10^{-12} \text{ a}^{-1}$ for ^{147}Sm and $1.42 \times 10^{-11} \text{ a}^{-1}$ for ^{87}Rb . Isochrons were statistically calculated using the computer program of two-error regression with reciprocal of square of error as weight (Model 2) in the book of Faure (1988).

RESULTS AND DISCUSSION

Age of the Jinchuan ultramafic rock body

Sm-Nd and Rb-Sr isotopic results for the Jinchuan rocks are listed in Tables 2 and 3, respectively.

Because of the newly-proven ability of the Sm-Nd radiometric system to provide precise chronological information for mafic and ultramafic rocks that have suffered severe Rb-Sr redistribution, the Sm-Nd internal isochron method was used in the present study. From Table 1, the whole rock samples have very close Sm/Nd and Nd isotopic ratios and they can not yield a reliable isochron. However, the mineral separates and their whole rocks from which the minerals were isolated show a sufficient variation in Sm/Nd and Nd isotopic ratios to obtain isochrons. Four internal isochrons consisting of the whole rocks and pyroxenes (PY(G) and PY(B)) from samples JA-9, JII-50, JII-66 and JII-69 are plotted in Fig. 2, respectively, which give very close ages of $1540 \pm 45 \text{ Ma}$, $1534 \pm 32 \text{ Ma}$, $1488 \pm 77 \text{ Ma}$ and $1515 \pm 97 \text{ Ma}$. By combining JII-50, JII-66 and JII-69 of the second group (lherzolite), all eight points give a well defined isochron with the age of $1508 \pm 31 \text{ Ma}$, with relative coefficient of 0.999 and MSWD of 0.33 (Fig. 3). The age of combining eight points of the second group (lherzolite) is in correspondence with four ages obtained respectively. Each acid-washed pyroxene has the same $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{148}\text{Nd}/^{144}\text{Nd}$ ratios as that of unwashed pyroxene, and they all fall on the original isochrons. So, the

Table 2. *Sm-Nd isotopic results of the Jinchuan rocks*

Sample No.	Rock type ^a	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd ^b	$\epsilon_{Nd}(T)^c$	Group
JA-9	lherzolite	0.6211	2.948	0.1270	0.511800 ± 10	-2.9	1
	Py (G)	1.984	7.658	0.1562	0.512095 ± 9	-2.8	
	awp	1.811	7.592	0.1498	0.512021 ± 11	-3.0	
JA-9b	augite-peridotite	0.1251	0.597	0.1266	0.511780 ± 50	-3.2	1
JA-9c	augite-peridotite	0.2163	1.005	0.1282	0.511801 ± 27	-3.1	1
JA-7a	lherzolite	0.1810	0.836	0.1302	0.511810 ± 42	-3.3	2
JII-1	lherzolite	0.5931	2.849	0.1258	0.511790 ± 17	-2.8	2
JII-36	olivine						2
	pyroxenite	1.705	7.970	0.1288	0.511826 ± 22	-2.7	
JII-37	pyroxenolite	2.044	9.350	0.1318	0.511830 ± 36	-3.2	2
JII-50	lherzolite	1.584	6.985	0.1366	0.511854 ± 10	-3.7	2
	Py (G)	2.660	10.37	0.1550	0.512039 ± 8	-3.6	
	Py (B)	2.496	10.31	0.1466	0.511948 ± 9	-3.7	
	awp	2.511	10.12	0.1477	0.511955 ± 12	-3.6	
	augite-peridotite	1.886	8.317	0.1366	0.511859 ± 7	-3.6	
JII-66	Py (G)	2.607	10.24	0.1540	0.512032 ± 7	-3.6	2
	Py (B)	2.427	9.713	0.1511	0.511993 ± 9	-3.7	
	awp	2.461	9.921	0.1553	0.512004 ± 11	-3.6	
	lherzolite	1.537	6.778	0.1366	0.511860 ± 10	-3.6	
JII-69	Py (G)	3.627	13.73	0.1598	0.512091 ± 11	-3.5	2
	awp	3.583	13.41	0.1606	0.512122 ± 9	-3.1	
	augite-peridotite	1.102	5.102	0.1306	0.511827 ± 11	-3.0	
JII-73	augite-peridotite	1.102	5.102	0.1306	0.511827 ± 11	-3.0	2

^aG: high-quality separates, awp: acid-washed pyroxenes, B: slightly poor separates, Py: pyroxenes.^bData normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219, error: 2σ m.^cCalculated for T = 1508 Ma.Table 3. *Rb-Sr isotopic results of the Jinchuan rocks*

Sample No.	Rock type ^a	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr ^b	(⁸⁷ Sr/ ⁸⁶ Sr) _i	$\epsilon_{Sr}(T)^c$	Group
JA-9	lherzolite	5.61	27.0	0.600	0.71689 ± 4	0.70390	+17.0	1
	awr	3.10	19.8	0.489	0.71481 ± 2	0.70423	+21.6	
	awp	0.51	2.60	0.471	0.71736 ± 50	0.70716	+63.4	
JII-36	olivine							2
	pyroxenite	9.61	49.4	0.563	0.71472 ± 2	0.70254	-2.3	
JII-50	awr	5.91	47.0	0.363	0.71252 ± 2	0.70465	+27.7	2
	lherzolite	10.0	178	0.166	0.71044 ± 2	0.70685	+58.9	
	awr	7.11	157	0.130	0.70914 ± 2	0.70632	+51.4	
	awp	2.13	67.2	0.102	0.71027 ± 2	0.70806	+76.2	
JII-66	augite-peridotite	18.5	108	0.496	0.71329 ± 6	0.70256	-2.1	2
	awr	6.41	78.5	0.236	0.71217 ± 11	0.70707	+62.0	
	awp	3.21	104	0.089	0.71072 ± 2	0.70879	+86.1	
JII-69	lherzolite	10.0	162	0.179	0.71220 ± 6	0.70832	+80.8	2
	awr	8.71	183	0.138	0.70947 ± 3	0.70650	+53.9	
	awp	1.61	37.5	0.123	0.71200 ± 5	0.70933	+94.1	
JII-73	augite-peridotite	3.80	26.8	0.410	0.71321 ± 2	0.70433	+23.1	2
	awr	2.20	20.1	0.316	0.71321 ± 2	0.70628	+50.9	

^aawr: acid-washed whole rocks, awp: acid-washed pyroxenes.^bData normalized to ⁸⁶Sr/⁸⁸Sr = 0.1194, error: 2σ m.^cCalculated for T = 1508 Ma.

Fig. 2. Sm-Nd internal isochrons for samples JA-9, JII-50, JII-66 and JII-69.

Fig. 3. Sm-Nd isochron defined by combining samples JII-50, JII-66 and JII-69 of second group.

combining age of 1508 ± 31 Ma can be considered to represent the crystallization age of the Jinchuan ultramafic rock body.

Nd-Sr isotopic correlativity

In Table 2, Sm and Nd concentrations of the whole rocks are obviously lower than those of pyroxenes, meaning that pyroxenes are the main minerals rich in REE. From the calculation with time (T) of 1508 Ma, the $\epsilon_{\text{Nd}}(T)$ values of all samples, whatever are the whole rocks, unwashed pyroxenes or acid-washed pyroxenes, are very

close, falling within -2.7 and -3.7 . Indeed, these values can be considered to be identical because the experimental errors are about ± 0.5 . The experimental results indicate that little influence of contamination of crustal source disturbed the Sm and Nd isotopic system of the Jinchuan samples. The $\epsilon_{\text{Nd}}(T)$ values of determined samples may reflect the Sm-Nd isotopic character of the source region of the Jinchuan rock body.

In contrast to the undisturbed evidence in the Sm-Nd system, Rb-Sr isotopic data (Table 3) demonstrate the following tendency for unwashed

Fig. 4. Nd-Sr isotopic distribution of pyroxenes in Jinchuan rocks in Nd-Sr correlation diagram ($T = 1508$ Ma).

Fig. 5. REE patterns for samples JA-9, JII-50, JII-66 and JII-69 normalized to chondritic values (Wakita *et al.*, 1971).

whole rocks (uwr) and acid-washed whole rocks (awr):

$$(\text{conc. of Rb, Sr})_{\text{uwr}} > (\text{conc. of Rb, Sr})_{\text{awr}},$$

$$(\text{Rb/Sr})_{\text{uwr}} > (\text{Rb/Sr})_{\text{awr}}, \text{ and}$$

$$(\varepsilon_{\text{Sr}}(T))_{\text{uwr}} < (\varepsilon_{\text{Sr}}(T))_{\text{awr}}.$$

This clearly indicates that the Rb-Sr isotopic system of the whole rocks has been subjected to contamination of crustal materials. The $\varepsilon_{\text{Sr}}(T)$ values of acid-washed pyroxenes are better values close to the true $\varepsilon_{\text{Sr}}(T)$ of source region from which the Jinchuan rocks were derived. The $\varepsilon_{\text{Sr}}(T)$ values of the source region certainly are positive and, in general, larger than +60.

The analysis of Nd-Sr isotopic correlation is one of the important methods to investigate nature of source. Figure 4 shows the distribution of four acid-washed pyroxenes, extracted from samples JA-9, JII-50, JII-66 and JII-69, respectively, in the Nd-Sr correlation diagram. The four points all fall in the quarter IV and they align on a horizontal line.

Rare earth elements for the four samples (JA-9, JII-50, JII-66 and JII-69) are plotted in Fig. 5. They show similar LREE-enriched patterns.

Through the discussion above, the Jinchuan ultramafic rocks may have come from a source region demonstrating these features of Nd-Sr isotopes:

- relatively homogeneous $\varepsilon_{\text{Nd}}(T)$ values (mostly in -3.2 ± 0.5),
- relatively dispersed $\varepsilon_{\text{Sr}}(T)$ values (mostly larger than +60),
- horizontal distribution in the Nd-Sr correlation diagram, and
- rich in LREE.

CONCLUSIONS

Three conclusions can be obtained from the present study. The first is that the age of the Jinchuan ultramafic rock body is 1508 ± 31 Ma, which is gained by the Sm-Nd internal isochron

method. The second is that Rb-Sr isotopic system of the Jinchuan rocks has been evidently contaminated by crustal materials, but little influence of crustal source disturbed their Sm-Nd isotopic system. The third is that the source region of the Jinchuan ultramafic rocks may possess the features of Nd-Sr isotopes: relatively homogeneous negative $\varepsilon_{\text{Nd}}(T)$ values, relatively dispersed $\varepsilon_{\text{Sr}}(T)$ values, in general, larger than +60, and exhibiting a horizontal distribution in the Nd-Sr correlation diagram.

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