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REE Characteristics of the Kalatongke Cu-Ni Deposit, Xinjiang, China

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Abstract On the basis of the study on the REE geochemistry of the ore minerals and host rocks of the Kalatongke Cu-Ni deposit, Xinjiang, it is indicated that the major ore minerals, sulfides, were sourced from the host mafic-ultramafic magma. Characterized by low REE content of sulfide, such a Cu-Ni sulfide deposit occurring in the orogen is obviously different from that on the margin of the craton. Because the mafic-ultramafic rocks from the Cu-Ni sulfide deposit occurring in the orogen is water-rich and the REEs of some sulfides show a particular "multiple-bending" pattern, which suggests coexistence of multiple liquid phases (fluid and melt), the sulfide melt possibly contains a great deal of hydrothermal fluids and increasingly developed gases and liquid-rich ore-forming fluids after the main metallogenic epoch (magmatic segregation stage).

Key words: Cu-Ni sulfide deposit, rare earth elements, water-rich mafic-ultramafic rock, Xinjiang

1 Introduction

The Kalatongke deposit, about 30 km southeast of Fuyun county, northern Xinjiang, is a large-scale copper-nickel deposit associated with such elements or elemental combinations as Co, PGE, Au and Ag. It belongs to the magmatic liquation type as many typical sulfide Cu-Ni deposits in China as well as in the world. The deposit, however, possesses some distinct features as follows: (1) It occurs within an orogen or taphrogeosyncline and is far from the craton and (2) the host mafic-ultramafic rock contains hydrous silicates like amphibole and biotite (Hao et al., 1992; Tu, 1993). The authors systematically selected samples from different ore types, analyzed their REE contents, and discussed the REE characteristics based on the analytic data of mafic-ultramafic rocks. It is expected that this study would provide helpful information about the metallization in such a peculiar geological setting.

2 Geological Setting

The Kalatongke mining area is situated on the northern margin of the Junggar orogen, about 20 km from the Irtysh fault. The northern area of the fault belongs to the Siberian plate and the south belongs to the Junggar-Kazakhstan massif. The mining area is near the core of a synclinorium (Fig. 1). There mainly occurs the Lower Carboniferous Nanmingshui Formation within the Kalatongke mining area. This set of strata is composed of carbonaceous sedimentary tuff/slate and intermediate to felsic vitric crystal tuff, and might be divided into three lithologic members. Four groups of faults, striking NW, NE, nearly E-W and nearly N-S, are developed in the area.

The deposit occurs in Cu-Ni mineralized mafic-ultramafic complex intrusions intruding into the top of the Nanmingshui Formation. Eleven such ore-bearing intrusions have been discovered within approximately 12.5 km^2 in the mining area and the isotopic ages range mainly from 285 to 298 Ma (Wang et al., 1991; Zhao, 1991). Minable mineralization was discovered in the Nos. 1, 2, 3 and 7 intrusives, which are named the Nos. 1, 2, 3 and 7 ore blocks respectively. The No. 1 ore block, the only exploited block at present, has the best mineralization and the Nos. 2 and 3 bodies are unexposed. It is supposed that the Nos. 1, 2 and 3 intrusives are probably conjoined at a depth lower than 300 m (Yuan et al., 1993), and the acidity increases from west (No. 1) to east (No. 3). Most of the ore-bearing intrusions are composed of three lithofacies: biotite hornblende hyperite facies (central facies), biotite hornblende norite facies and gabbro-diabase facies (border facies), and diorite facies, which can be partly developed on the top of a intrusion.

The No. 1 intrusion has an irregular lenticular shape in plane and is sphenoid in cross section (Fig. 2). The principal minable ore bodies are classified into two types. Ore bodies of the first type are irregular shaped with large scales and composed mainly of sparse to dense disseminated ores formed by autochthonous liquation of late-stage magmas, or composed of veinlet-disseminated ores formed by postmagmatic hydrothermal

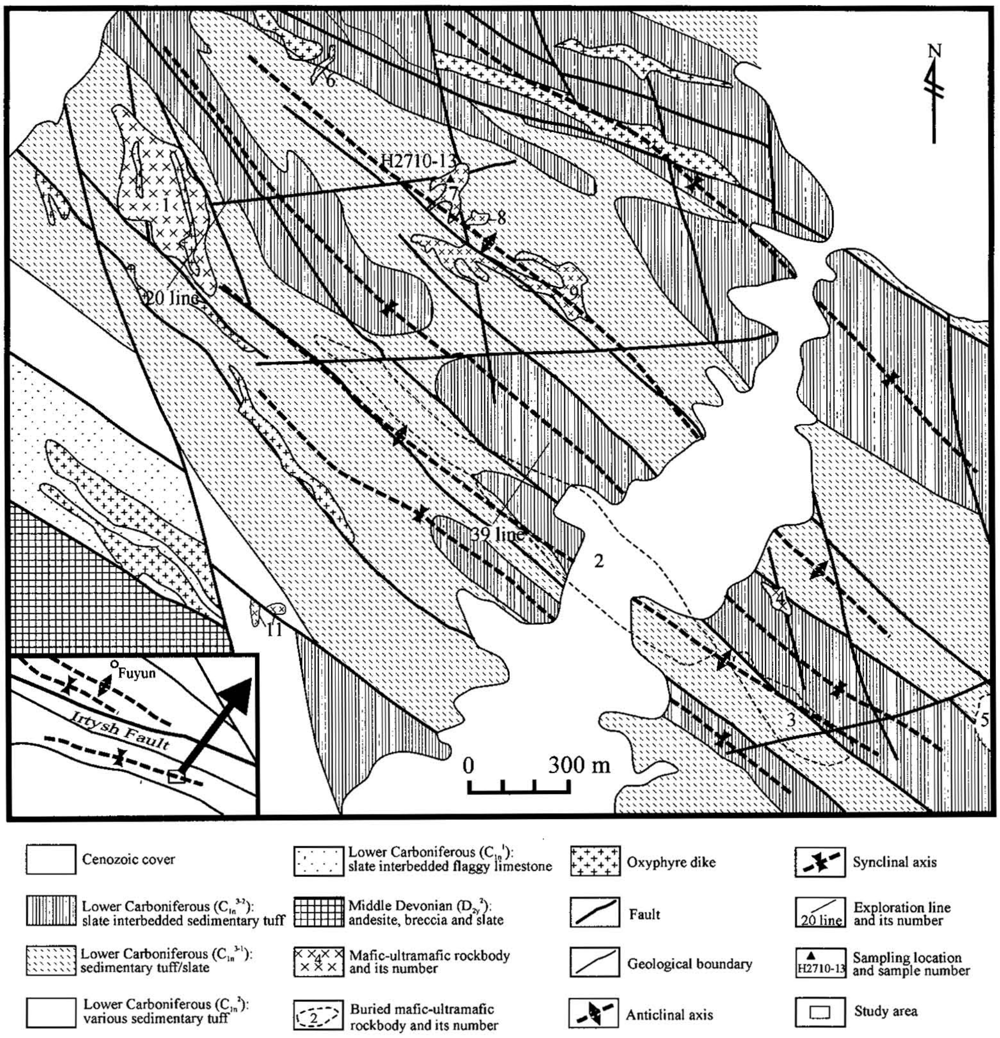

Fig. 1. A sketch map showing the geology of the Kalatongke mine (modified after Wang et al., 1991).

metasomatism; whereas those of the second type are vein-like and composed chiefly of massive and secondarily of brecciated ore formed by liquation and injection. The former distribute in rocks with high basicity near the bottom of the intrusive rock, while the latter occur mainly in the middle or on the bottom of the intrusive body. More than 70 kinds of mineral have been recognized in the deposit. The gangue minerals are the same as rock-forming minerals and their altered minerals in the host rock. The major ore minerals are pyrrhotite, chalcopyrite and pentlandite, and other common but minor ore minerals are pyrite, violarite, and magnetite etc. Two metallogenic epochs, the magmatic epoch and the ore magmatic epoch, are identified.

3 Sampling, Processing and Analysis

Representative samples of massive ore and disseminated ore in ultramafic rocks and veinlet ore in sedimentary tuff were selected from the Nos. 1, 2 and 7 ore blocks. Four major ore minerals, pyrrhotite, chalcopyrite, pentlandite and pyrite, were picked up under the binocular. They were treated with ultrasonic cleaning under room temperature and heat-drying before grinding to –200 mesh. The sulfides were analyzed with the ICP-MS method at the ICP-MS Laboratory of the Geological Research Institute of the National Nuclear Cooperation (Beijing) where the indium standard solution was adopted. The precision accuracy of this method is 3%± and the detection limit is from 0.002 (La) to 0.02 ppm (Ce). The bulk compositions of rock and ore were collected from previous works.

4 Characteristics of Rare Earth Elements

The REE Characteristics of the sulfides and ore from different ore types and host rocks are listed in Tables 1 and 2.

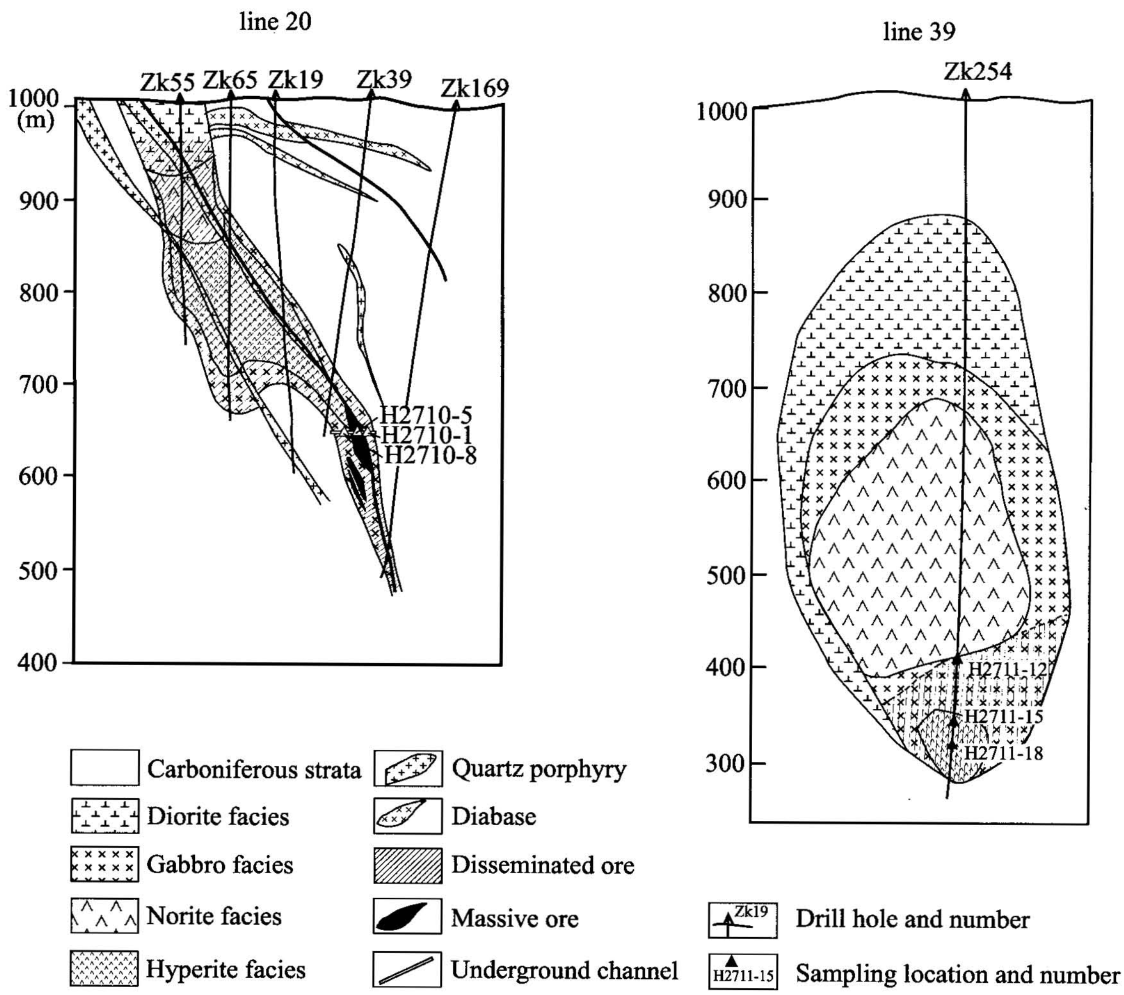

Fig. 2. A sketch map showing cross sections of the Nos. 20 and 39 exploration lines for the Kalatongke deposit (simplified from the No. 4 Geological Team of Xinjiang Bureau of Geology and Mineral Resources, 1985).

4.1 REE content

The REE content (ΣREE) of sulfide has a large range from 0.58 to 47.51 ppm, which is related to the ore type. It is higher when the sulfide disseminates in more acidic rock (e.g., diorite of the No. 2 ore block, sample H2711-12); on the contrary, lower ΣREE of sulfide is in the case of less acidic wall rocks. In the same way, the ΣREE of sulfide in massive ore is lower than that in disseminated ore. The ΣREE of ore and host rock are directly proportional to the SiO_2 content, i.e., $\Sigma REE_{host\ rock} > \Sigma REE_{disseminated\ ore} > \Sigma REE_{massive\ ore}$. For the host rock, the ΣREE in the No. 2 block is higher than that in the No. 1 block, and the higher the acidity, the higher the ΣREE will be. Different sulfide species in a single ore sample are very slightly different in ΣREE, which suggests that the REEs have similar distribution coefficients in sulfides during the magmatic mineralizing process. The ΣREE of sulfide in veinlet ore hosted in sedimentary tuff from the No. 1 block is close to that in massive ore.

4.2 REE fractionation

All sulfide, ore and host rock of this deposit are attributed to LREE enrichment. However, the degree of REE fractionation is different, and the fractionation features might be classified into the following three types. (1) Sulfide minerals and massive ores have the highest degree of REE fractionation with relatively high ΣLREE/ΣHREE ratios (>8.0) and La/Yb ratios (>11.0), (2) olivine-gabbro from the No. 1 block has the weakest REE fractionation with relatively low ΣLREE/ΣHREE ratios (<5.0) and La/Yb ratios (<8.0) and (3) other host rocks and disseminated ore have moderate REE fractionation with the ΣLREE/ΣHREE ratios ranging from 5.0–8.0 and the La/Yb ratios ranging from 8.0–11.0. It is obvious that the REE fractionation of sulfide is more intensive than that of silicate minerals. In disseminated ore, sulfides have lower REE contents and take a smaller proportion (less than 30%) compared with silicates, thus it is impossible to generate much more intensive effect on the REE fractionation of the ore, and thus the disseminated ore and the host rock have

Table 1 REE contents of sulfide and ore of different ore types in the Kalatongke deposit

Ore block		No. 1 ore block						No. 2 ore block			No. 7 ore block	No. 1 ore block					
Ore type		Veinlet ore in tuff	Disseminated ore in hyperite			Massive ore		Disseminated ore in gabbro-diorite	Disseminated ore in gabbronorite		Brecciated ore	Disseminated ore in hyperite			Disseminated ore in gabbronorite		Massive ore
Sulfide/Ore		Chalcopyrite	Chalcopy-rite	Pyrite	Pyrrhotite	Chalcopyrite	Pyrrhotite	Pentlandite	Pyrrhotite	Chalcopyrite	Pyrite	Ore			Ore		Ore
Sample No.		H2709-1	H2710-1-1	H2710-1-2	H2710-8	H2710-5-1	H2710-5-2	H2711-12	H2711-15	H2711-18	H2710-13						
Ser. No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ppm	La	0.283	0.766	0.381	0.296	0.113	0.135	9.894	1.017	1.085	0.449	13.73	4.14	1.56	6.31	9.72	0.33
	Ce	0.487	1.595	0.844	0.624	0.252	0.303	21.289	2.273	2.234	1.654	28.79	8.79	3.53	14.59	21.2	0.89
	Pr	0.058	0.188	0.100	0.080	0.031	0.037	2.400	0.276	0.255	0.084	3.66	1.12	0.55	2.13	3.06	0.14
	Nd	0.211	0.765	0.427	0.326	0.110	0.152	9.023	1.126	0.921	0.282	15.54	5.13	1.93	8.18	11.54	0.39
	Sm	0.037	0.156	0.089	0.070	0.022	0.028	1.792	0.202	0.171	0.047	3.03	1.03	0.45	2.01	2.7	0.08
	Eu	0.027	0.070	0.041	0.025	0.010	0.012	0.511	0.059	0.035	0.012	1.171	0.403	0.176	0.689	0.887	0.029
	Gd	0.042	0.141	0.075	0.066	0.018	0.024	1.303	0.172	0.150	0.051	2.569	0.888	0.414	1.83	2.41	0.052
	Tb	0.006	0.018	0.011	0.009	0.002	0.003	0.139	0.019	0.020	0.007	0.371	0.17	0.076	0.276	0.331	0.007
	Dy	0.034	0.097	0.059	0.048	0.010	0.009	0.570	0.091	0.097	0.037	2.4	0.872	0.398	1.77	2.27	0.038
	Ho	0.008	0.020	0.012	0.010	0.002	0.002	0.093	0.016	0.019	0.007	0.448	0.162	0.075	0.326	0.435	0.008
	Er	0.025	0.057	0.032	0.029	0.005	0.006	0.245	0.046	0.049	0.017	1.3	0.451	0.21	0.978	1.247	0.022
	Tm	0.004	0.007	0.004	0.005	0.001	0.001	0.030	0.005	0.006	0.003	0.184	0.065	0.032	0.145	0.175	0.003
	Yb	0.030	0.046	0.029	0.037	0.008	0.011	0.195	0.034	0.039	0.025	1.259	0.446	0.175	0.922	1.165	0.017
	Lu	0.005	0.006	0.004	0.005	0.001	0.001	0.030	0.006	0.005	0.003	0.176	0.064	0.027	0.131	0.168	0.003
	Σ REE	1.253	3.930	2.103	1.625	0.581	0.720	47.511	5.338	5.082	2.676	74.628	23.731	9.603	40.287	57.308	2.009
ΣLREE/ΣHREE		7.295	9.050	8.430	6.905	12.045	12.202	17.252	12.810	12.286	17.020	7.571	6.611	5.825	5.317	5.988	12.393
La/Yb		9.576	16.652	13.351	7.986	15.000	12.810	50.869	30.343	28.182	17.960	10.905	9.283	8.914	6.844	8.343	19.412
δEu		2.115	1.422	1.477	1.116	1.514	1.397	0.977	0.939	0.655	0.718	1.252	1.259	1.226	1.079	1.043	1.291
δCe		0.868	0.985	1.023	0.962	1.016	1.023	1.022	1.015	0.990	1.916	0.959	0.965	0.916	0.955	0.930	0.996
(La/Yb)n		6.456	11.227	9.001	5.384	10.113	8.636	34.295	20.457	19.000	12.109	7.352	6.258	6.010	4.614	5.625	13.087
(La/Sm)n		4.869	3.099	2.689	2.675	3.291	3.077	3.474	3.173	4.003	6.009	2.850	2.528	2.181	1.975	2.265	2.595

Note: Nos. 1–10 samples are analyzed by the authors; Nos. 11–16 samples are collected from Parat (1991).

Table 2 REE contents of ore-bearing mafic-ultramafic rocks from the Kalatongke deposit

Ore block		No. 1			No. 2			
Rock type		Hornblende norite	Hornblende hyperite	Olivine gabbro	Hornblende hyperite	Hornblende norite	Hornblende gabbro	Quartz diorite
Number of samples		2	1	1	2	5	2	3
Ser. No.		1	2	3	4	5	6	7
ppm	La	10.61	9.37	7.31	10.95	13.57	17.91	22.22
	Ce	24.97	21.97	16.92	24.36	28.86	37.25	48.45
	Pr	2.98	2.55	2.14	2.74	3.13	4.00	5.23
	Nd	12.26	10.18	10.7	12.06	13.59	17.82	24.59
	Sm	2.77	2.06	3.04	2.51	2.78	3.75	5.08
	Eu	0.70	0.51	1.13	0.70	0.73	1.02	1.36
	Gd	2.46	1.76	3.44	2.13	2.35	3.33	4.55
	Tb	0.54	0.34	0.58	0.35	0.38	0.55	0.74
	Dy	2.35	1.62	3.93	1.83	2.12	2.98	4.02
	Ho	0.47	0.3	0.79	0.36	0.42	0.59	0.78
	Er	1.24	0.84	2.18	0.98	1.19	1.64	2.14
	Tm	0.13	0.10	0.33	0.16	0.20	0.26	0.33
	Yb	1.18	0.75	2.15	0.92	1.23	1.58	1.95
	Lu	0.18	0.10	0.32	0.14	0.20	0.27	0.30
	ΣREE	62.81	52.45	54.96	60.16	70.75	92.92	121.73
ΣLREE/ΣHREE		6.367	8.028	3.006	7.775	7.742	7.304	7.218
La/Yb		9.026	12.493	3.400	11.897	11.050	11.332	11.414
δEu		0.804	0.799	1.065	0.904	0.851	0.862	0.846
δCe		1.054	1.064	1.018	1.044	1.030	1.018	1.047
(La/Yb)n		6.085	8.423	2.292	8.021	7.450	7.640	7.696
(La/Sm)n		2.413	2.861	1.513	2.748	3.070	3.007	2.753

similar REE fractionation. However, the olivine-gabbro from the No. 1 block probably belongs to late-stage dykes which were derived from a source different from that of the No. 1 host intrusive body (Ni et al., 1995).

4.3 Europium anomaly (δEu)

All sulfides and ores from the No. 1 block are characterized by positive Eu anomalies. The δEu value of massive ore is higher than that of disseminated ore, and the δEu value of sulfide is higher than that of ore. The host rock of the No. 1 block has moderate negative anomalies or almost no Eu anomaly (δEu values varying from 0.80 to 1.07). All sulfides from the Nos. 2 and 7 blocks and host rock of the No. 2 block have negative Eu anomalies, and particularly the sulfides have fairly high negative Eu anomalies (δEu values varying from 0.66 to 0.72).

4.4 Cerium anomaly (δCe)

Most sulfides, ore and host rock have no Ce anomaly except for one sample, pyrite collected from the open pit of the No. 7 ore block, which has a comparatively high positive Ce anomaly (δCe=1.92). It is easy to understand that Ce enrichment in pyrite results in high δCe values because Ce^{3+} is oxidized to Ce^{4+} very easily under a dry and oxidizing condition at surface.

4.5 REE pattern

The REE patterns of sulfide, ore and rock are shown in Figs. 3 and 4, from which one can see the following features. (1) Most REE patterns of sulfide, ore and host mafic-ultramafic rocks are shown as steeply declined smooth curves with similar slopes. The (La/Yb)n values vary from 6 to 13 and the LREE and the HREE have approximately equivalent fractionation. (2) The REE pattern of olivine-gabbro from the No. 1 block is shown as a smooth and gently aslope curve ((La/Yb)n=2.29) and the LREE and the HREE also have approximately equivalent fractionation. (3) REEs of some sulfide show a "multiple-bending" pattern, e.g., the No. 1 curve (pyrite from the No. 7 block), the No. 5 curve (chalcopyrite of veinlet ore in tuff from the No. 1 block), the No. 6 curve (chalcopyrite of massive ore from the No. 1 block) and the No. 10 curve (pyrrhotite of massive ore from the No. 1 block) in Fig. 3. The common feature of these curves is steep for the LREE but gentle for the HREE ((Gd/Yb)n≈1). Particularly, the HREE shows a downward bending pattern (relatively low Tb to Tm values) with obvious Eu, Ce or Yb anomalies in most cases. The REE of the hornblende norite and hornblende hyperite from the No. 1 block also show a "multiple-bending" pattern more or less.

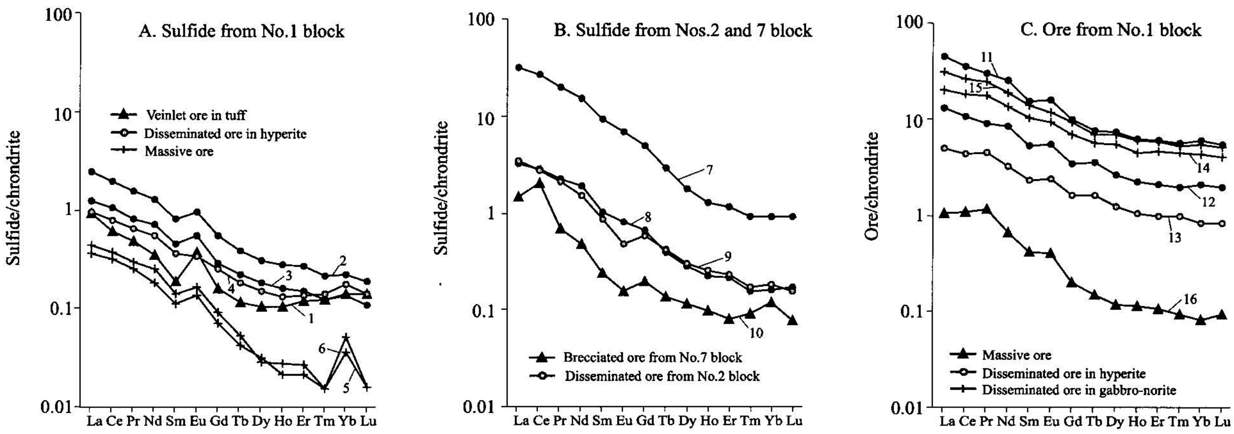

Fig. 3. Chondrite-normalized REE patterns of sulfide (A and B) and ore (C). Figures attached to the curves denote the sample numbers given in Table 1.

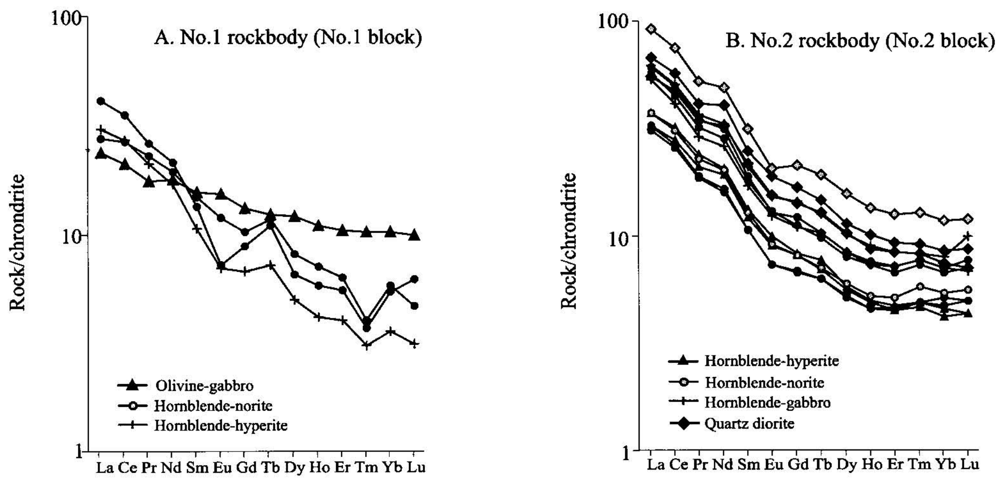

Fig. 4. Chondrite-normalized REE patterns for the host rocks of No. 1 ore block (A) and No. 2 ore block (B) in the Kalatongke deposit.

5 Discussion

5.1 REE characteristics of the Cu-Ni sulfide deposit in the orogen

It is well known that meta-peridotite of the ophiolite suite from the orogen has extremely low ΣREE values (0.26–0.63 ppm) and an "U"-shaped REE pattern, i.e., weak LREE fractionation ($(La/Yb)_n$=0.33–3.16, (Gd/Yb)n =0.63–0.92) (Frey, 1984). On the contrary, the intrusive ultramafic rocks related to the Cu-Ni sulfide deposit are characterized by higher ΣREE values and enrichment of LREE (ΣREE=10–40 ppm, $(La/Yb)_n$=2–10, (Gd/Yb)n =1.3–4.4) in the Noril'sk Cu-Ni deposit, Russia (Hawkesworth et al., 1995). Although the Kalatongke Cu-Ni deposit occurs within the orogen, the REE characteristics of its host ultramafic rock are distinctly different from those of the ophiolite from an orogen, but rather close to those of the melanocratic rock series.

The REE content of the sulfide, except for the disseminated pyrrhotite of diorite from the No. 2 block, is quite low (ΣREE=0.58–5.34 ppm), which is similar to that of the massive ore in the orogen, e.g., 0.69 ppm for the Baimazhai Cu-Ni deposit from Sichuan province (Tang and Liu, 1998), but much lower than that of the massive ore on the margin of the craton, e.g., 12.78–25.21 ppm for the Jinchuan Cu-Ni deposit in Gansu province (Tang and Liu, 1998).

5.2 Homological relationship between sulfide and host rock

Compared with the REE pattern of sulfide, ore and host mafic-ultramafic rock (Figs. 3 and 4), it is obvious that the sulfide and host rock have similar REE patterns, particularly very close LREE and HREE fractionation, but some differences in ΣREE and δEu values. It is indicated by the similarity of REE patterns between the host silicate and sulfide that the REE is distributed selectively in the above two phases during the magmatic process, and thus the sulfide equally absorbs each rare earth element from the parental magmas. This is similar to its geochemical behavior in ore-forming solutions (Wang et al., 1991). Because of its lithophile feature, the REE is selectively enriched in the silicate phase during immiscible separation between silicate magma and Cu-Ni sulfide ore magma and therefore the REE content in the sulfide phase is much lower than that in its parent rock, i.e. silicate rock. Difference of the Eu anomaly is related to the metallogenitic environment such as temperature and oxygen fugacity. It is evidenced by not only Drake's experiment (Drake, 1975) but also the REE feature of ore itself (Lettermoster, 1991) that europium is easily enriched in a low-fo_2 environment. Despite of insufficient fo_2 data about the Kalatongke deposit at present, it is presumed that the fo_2 value in ore magma for sulfide enrichment is much higher than that in magma dominated by a single silicate phase, and thus the δEu value of sulfide is higher than that of the parent rock.

5.3 Coexistence of fluid and melt in mineralization process

Some REE patterns of the sulfides in the Kalatongke deposit display a "multiple-bending" feature. It has ever been reported that some geological bodies in nature have a "tetrad effect" of rare earth elements, i.e. La–Nd, Pm–Gd, Gd–Ho and Er–Lu construct four upwards-convex curves respectively and the important controlling factors include coexistence of different liquid phases and formation of complexes of REE (Zhao et al., 1992). The features of REE, especially HREE, of the sulfide in this deposit are quite similar to this case, which might be related with hydrothermal activity. Studies of helium and argon isotopes in recent years suggest that copper-nickel ore of the Kalatongke deposit was derived from slow degasification of the mantle plume tail (Wang et al., 2001). Multistage, especially late hydrothermal activity is extraordinary notable in the deposit and the late chalcopyrite veinlets in tuff just represent the postmagmatic hydrothermal activity. The sulfide melt possibly contained a lot of hydrothermal fluids and liquid-rich ore-forming fluids were gradually generated after the main metallogenic epoch (the magmatic segregation stage). It is the coexistence of fluid and melt, that results in the multiple-bending model of REE, similar to the "tetrad effect" of REE.

6 Conclusions

The following conclusions can be reached in regard to the REE characteristics of the Kalatongke Cu-Ni sulfide deposit.

(1) Sulfide and the host rock have similar REE patterns, but the former has relatively low ΣREE values, which indicates that REE is selectively enriched in the silicate phase during the magmatic immiscible process, and thus the sulfide was derived from the host mafic-ultramafic magma.

(2) Distinguished from the Cu-Ni deposit on the margin of a craton, the Cu-Ni sulfide deposit of this area occurs in an orogen. It is characterized by low REE content and was partially contaminated by the host strata.

(3) The "multiple-bending" pattern of REE of the sulfides suggests coexistence of multiple liquid phases (fluid and melt). The sulfide melt possibly contained a lot of hydrothermal fluids, and liquid-rich ore-forming fluids were gradually generated after the main metallogenic epoch (magmatic segregation stage).

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