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Ba-REE fluorcarbonate minerals from a carbonatite dyke at Bayan Obo, Inner Mongolia, North China

X.-M. Yang[1], **X.-Y. Yang**[1], **P.-S. Zhang**[2], and **M. J. Le Bas**[3,*]

[1] Department of Earth and Space Sciences, University of Science and Technology of China, P.R. China
[2] Institute of Geology, The Chinese Academy of Sciences, P.R. China
[3] Department of Geology, University of Leicester, United Kingdom

With 3 Figures

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Summary

The new occurrence in a carbonatite dyke at Bayan Obo, Inner Mongolia, North China, of the Ba-REE fluorocarbonate minerals cebaite, hunghoite and cordylite is presented, together with their chemical composition, rare earth element (REE) patterns, and syntaxial intergrowth relationships. These syntaxial textures, investigated by scanning and electron microprobe techniques, are interpreted in terms of the cooling history during the late-stage crystallization of the carbonatite magma or possible later events. The REE distribution patterns of the Ba-REE fluorocarbonate minerals in the dyke are similar to those of the corresponding minerals in the dolomite marble that hosts the giant REE-Nb-Fe ore body at Bayan Obo, providing evidence that the two may be cogenetic.

Zusammenfassung

Ba-SEE Fluorkarbonat-Minerale aus einem Karbonatitgang bei Bayan Obo, Innere Mongolei, Nord-China

Die Ba-SEE Fluorkarbonate Cebait, Huangoit und Cordylit kommen in einem Karbonatitgang bei Bayan Obo, Innere Mongolei, Nord-China, vor. Ihre chemische

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[*] Present address: School of Ocean and Earth Science, University of Southampton, United Kingdom

Zusammensetzung, SEE-Verteilungsmuster und syntaktische Verwachsungsbeziehungen werden vorgestellt. Letztere wurden mit Mikrosonden-Rastermethoden untersucht und im Zusammenhang mit der Abkühlungsgeschichte des Karbonatit-Magmas oder eventueller späterer Ereignisse interpretiert. Die SEE-Verteilungsmuster der Ba-SEE Fluorkarbonate im Gang ähneln denen entsprechender Minerale im Dolomit-Marmor in dem die Großlagerstätte Bayan Obo aufsitzt; dies weist darauf hin, dass beide kogenetisch sein könnten.

Introduction

Minerals of the Ba-REE fluorcarbonate series are a characteristic of the REE-Nb-Fe giant ore body at Bayan Obo, Inner Mongolia, China and have attracted much mineralogical attention (*Zhang* et al., 1986, 1995; *Zhang*, 1990; *Institute of Geochemistry*, 1988; *Jones* et al., 1996). The four species of this series at Bayan Obo are: cebaite ($Ba_3Ce_2(CO_3)_5F_2$), huanghoite ($BaCe(CO_3)_2F$), cordylite ($CaBa(Ce,La)_2(CO_3)_4F$), zhonghuacerite ($Ba_2Ce(CO_3)_3F$), of which cebaite and huanghoite dominate.

The cebaite occurs mainly in the aegirine type Nb-REE massive ore, together with apatite, fluorite, barite, calcite and dolomite, but sometimes also in the aegirine type massive Nb-REE-Fe ore in a fluorite-cebaite assemblage (*Yuan* et al., 1992) and rarely in late stage veins. Most huanghoite occurs in the late stage veins that cut across the massive or banded ores, while some is disseminated throughout the ores (*Zhang* et al., 1995). Cordylite and zhonghuacerite are relatively rare in the ore deposit. They also occur disseminated in dolomite type Nb-REE ore in the west ore bodies associated with cebaite, ankerite, magnetite and fluorite, and sometimes with bastnaesite and monazite.

Cebaite, huanghoite and cordylite have now been discovered in a cerbonatite dyke only 2 km north-north-east of the East ore body of the Bayan Obo deposit. It is named the Wu dyke after Mr. *Wu Zhanjiang*, the mining geologist at Bayan Obo who discovered it. Although all the Ba-REE fluorcarbonate minerals have different occurrences, the REE patterns of each have a degree of similarity which suggests formation by related processes (*Mariano*, 1989). In addition, carbon and oxygen isotopic compositions for REE fluorcarbonate mineral separates show a typical mantle signature (*Fang* et al., 1994), indicating a mantle origin for the mineralizing fluids (*Cao* et al., 1994). Nevertheless, there have never been any other reports of mantle fluids elsewhere in the world that produced such a giant REE deposit as at Bayan Obo, and the metallogenesis of the deposit requires further study.

The discovery of carbonatite dykes in the Bayan Obo area has provided new clues to the genesis of the giant Bayan Obo REE-Nb-Fe ore body. They compare well geochemically with the H8 dolomite marble that hosts the body, especially with respect to the REE and trace element distribution patterns in the apatite and monazite both from the carbonatite dykes and the H8 dolomite marble (*Le Bas* et al., 1992). The research by *Le Bas* et al. (1997) and *Yuan* et al. (1992) is interpreted to indicate that the ore-hosting dolomite marble is carbonatitic in origin, but several authors, including *Meng* (1982), *Hou* (1987) and *Chao* et al. (1992, 1993, 1997), consider the marble to be sedimentary in origin. One approach aimed at resolving the controversy has been the chemical study of rock-forming minerals common to both the marble and the carbonatite dykes (*Yang* et al., 1998a). Another has been the C-O-Sr isotope study of the marble (*Le Bas* et al., 1992, 1997; *Yuan* et al., 1992). Both these appear to point to the REE formation at Bayan Obo being related directly or indirectly to carbonatite.

Ba-REE fluorcarbonate minerals are also known from pegmatite dykes of the nepheline syenite of Mont St. Hilaire, Quebec (*Chen* et al., 1975), the Khibina carbonatite, Kola peninsula, Russia (*Kapustin*, 1973; *Zaitsev* et al., 1996, 1998), and the Qaquarssuk carbonatite, Greenland (*Knudsen*, 1991). *Wall* et al. (1996) describe these minerals as common carbonatitic late-stage products.

Since August 1988, we have systematically investigated the carbonatite dykes at Bayan Obo, made a 1:10,000 geological map of the dykes, collected over 300 samples and made 100 double-polished thin sections. This contribution investigates the chemical composition, REE patterns and syntaxy of the newly observed Ba-REE fluorcarbonate minerals in the Wu dyke, makes comparison with the corresponding minerals from the H8 dolomite marble hosting the Bayan Obo REE-Nb-Fe ore deposit, and presents a new interpretation.

Geological features of the carbonatite dyke

The carbonatite dyke studied is located at Dulahala, 2 km NNE of the East ore body of the Bayan Obo ore deposit (Fig.1). It cuts across H1 coarse quartz sandstone and H3 shales of the Proterozoic Bayan Obo group, and strikes north 20° east, dipping to the west at 85 ~ 89°. It is well exposed on the surface: 60 m long and 1.1–1.5 m wide. The dyke has sharp contacts with the H1 wall-rock on the western side and H3 wall-rock to the east, the bedding of both striking ENE-WSW and dipping northward. These field relationships indicate that the dyke was intruded up a fault which separates the H1 from the H3. There are well-developed fenite zones 10–20 cm wide on both sides. The fenite is characterized by the assemblage of riebeckite-arfvedsonite, albite and phlogopite. These alkaline minerals are also concentrated along fractures and joints along which fluids penetrated the wall-rocks for as much as 20–30 metres from the contacts with the carbonatite dyke, but contact metamorphism and fenitization beyond the 10–20 cm fenite zones is not immediately evident in the field.

Although the carbonatite is generally even-textured, it locally contains xenoliths and xenocrysts of quartz sandstone, quartzite, fenite and arfvedsonite from the wall-rocks. The dyke is strongly deformed and sheared parallel to the dyke margins by later tectonism, resulting in local alignment of rock-forming minerals, curved cleavage and wavy extinction of large calcite crystals. The dyke is composed mainly of euhedral to subhedral fine-grained crystals of calcite 0.2–0.4 mm across with some calcite phenocrysts up to 5–7 mm in diameter. Calcite forms interlocking grains producing a mosaic texture with triple junctions that is typical of igneous carbonatite. In addition, the dyke contains riebeckite, apatite, hematite, magnetite, monazite, allanite, quartz, fluorite, barite, albite and phlogopite. Being fine-grained, the carbonatite could be classified as alvikite.

The carbonatite also contains minor bastnaesite and parisite, most of which occurs as euhedral to subhedral crystals 0.01–0.07 mm across with some up to

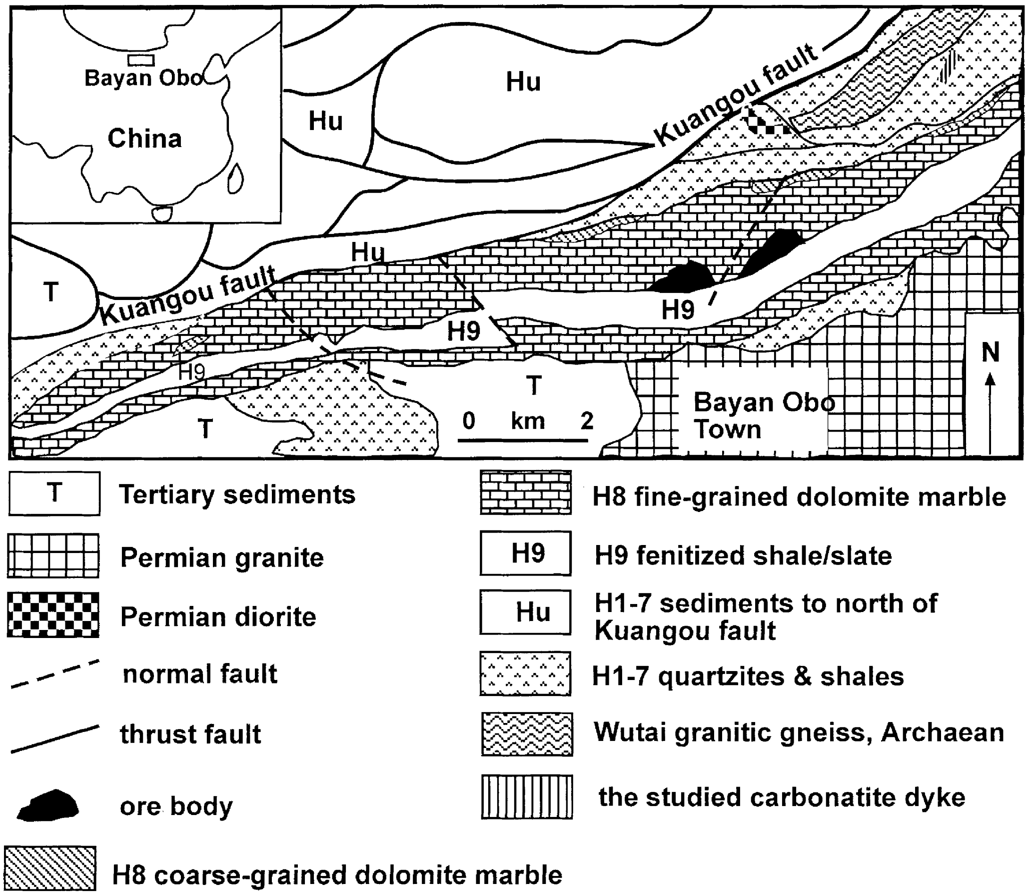

Fig. 1. Geological sketch map of the Bayan Obo region, North China, after *Le Bas* et al. (1997). The locality of the Wu carbonatite dyke is shown. It cuts across H1 coarse quartz sandstone and H3 shale of the Proterozoic Bayan Obo group

0.3–0.5 mm across. These minerals produce aggregates interlocked with calcite, and are thought to indicate that they are primary minerals crystallizing directly from carbonatite magma (*Yang* et al., 1998b). Under the polarizing microscope, bastnaesite and parisite are light brown to light yellow, weakly pleochroic, with high relief and high-order interference colours. Cebaite, huanghoite and cordylite are relatively rare in the alvikite, occurring randomly as fine aggregates. Their single crystals are subhedral-anhedral, with rims often dissolved by late stage solution, leaving irregular lobate shapes, but retaining regular syntaxial texture (Fig. 2a and b). Under the polarizing microscope, they are colourless or light-brown to light-yellow, weakly pleochroic, with high relief and high-order interference colours. They are optically negative unlike bastnaesite and parisite which are positive.

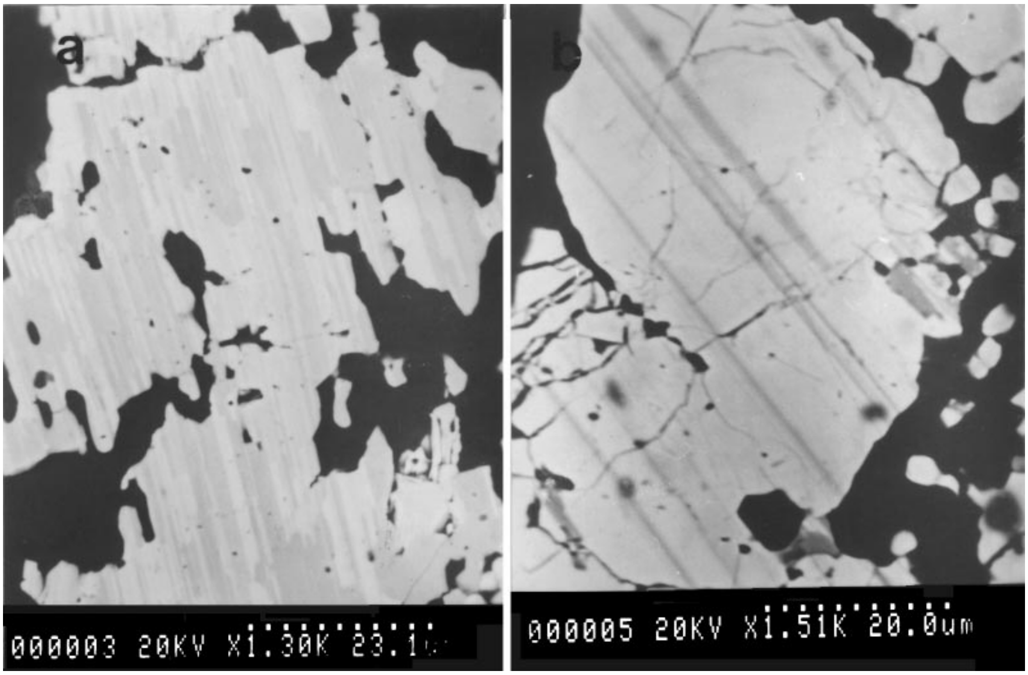

Fig. 2. SEM back-scatter images of Ba-REE fluorcarbonate minerals from Bayan Obo carbonatite dyke. **a** Host cebaite crystal (grey) in section parallel to c axis with microfine lamellae of cordylite (grey-white) distributed on (0001) plane, grain 2 of sample 90/39 in Table 1. **b** Host cordylite crystal (grey-white) in section parallel to c axis with lamellae of huanghoite daughter (grey) on (0001) plane; grain 10 of sample 90/39 in Table 1

Analytical procedures

The Ba-REE fluorcarbonate minerals, cebaite, huanghoite and cordylite, have been analysed from samples 90/39 and CD13(1) collected from the dyke and prepared as doubly-polished thin sections. The texture and composition of minerals were first investigated under the scanning electron microscope (SEM), and then selected mineral grains were quantitatively analyzed by electron microprobe analysis (EMPA). SEM observations were performed on a Hitachi S-520 with qualitative energy-dispersive analyser at the Department of Geology, University of Leicester. The working voltage was 20 kv and current was 18 mA. EMPA was conducted on a Cameca SX50 at the Natural History Museum, London. Ca, Sr, Y, Ba, La, Ce, Th and U were analysed with PET; F with PC1; Pr, Nd, Sm and Gd with LIF; Na, Mg, Al and Si with TAP. Experimental conditions were 15.0 kV and 20 nA, and electron beam size was set at 1 micron for microfine mineral phases and 5 micron for the larger homogeneous grains of the Ba-REE fluorcarbonate minerals. Standard samples used in analysis included natural minerals, synthetic glasses and metals. Peak overlap corrections were made for Ce-Ba, Sm-Ce, Gd-Ce and Gd-La pairs, using correction factors determined from the analysis of single REE standards (glasses) and other pure mineral standards. Raw data were corrected by the PAP

Table 1. *Representative microprobe analyses of Ba-REE fluorcarbonate minerals from the Bayan Obo carbonatite dyke*

Sample	90/39		90/39				90/39	90/39	90/39	
Grain no	1				1		2	10	5	
Mineral	Cb	Cd	Cb	Cb	Cd	Cd	Hh	Cd	Cd	Hh
Position	host	lamella	core	rim	lamella	host	lamella			
SiO_2	0.44	0.19	0.25	0.45	0.29	0.17	0.22	0.22	0.35	0.30
ThO_2	0.47	<0.1	<0.1	<0.1	0.65	0.30	0.13	0.41	0.57	0.48
UO_2	<0.1	<0.1	0.31	0.25	<0.1	<0.1	0.10	<0.1	0.18	<0.1
Al_2O_3	0.46	0.29	0.54	0.50	0.28	0.21	0.37	<0.1	<0.1	<0.1
Y_2O_3	0.17	0.08	0.08	0.14	0.19	<0.05	<0.05	0.62	0.63	0.48
La_2O_3	12.85	19.27	10.78	14.17	16.60	16.76	13.94	12.33	13.05	10.79
Ce_2O_3	15.52	23.08	14.22	16.62	22.23	23.19	19.54	24.18	25.97	21.94
Pr_2O_3	1.58	2.16	1.51	1.32	2.21	2.30	2.04	1.84	1.98	1.06
Nd_2O_3	2.76	3.79	2.74	2.99	4.44	4.58	4.11	7.89	8.19	6.06
Sm_2O_3	0.10	0.21	0.04	0.16	0.29	0.29	0.32	0.11	0.21	0.00
Gd_2O_3	<0.15	0.20	<0.15	<0.15	0.32	<0.15	0.22	0.76	0.76	0.55
MgO	0.11	0.00	0.08	0.05	0.00	0.00	0.00	0.07	0.03	0.09
CaO	8.37	7.18	5.42	8.57	9.11	13.55	7.48	10.72	7.80	10.88
SrO	2.37	1.89	3.43	2.87	2.21	1.30	2.46	1.11	0.70	0.99
BaO	31.36	17.45	37.63	28.42	16.00	11.76	24.96	13.73	12.57	20.80
Na_2O	0.17	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CO_2^*	21.65	21.90	20.78	21.85	22.04	22.82	21.51	22.42	22.03	22.29
F	2.55	4.74	2.80	2.93	5.03	3.90	4.01	4.63	5.91	4.15
total	101.02	102.45	100.67	101.54	101.98	101.27	101.42	101.04	100.92	100.91
$-O=F_2$	1.07	1.99	1.18	1.23	2.12	1.64	1.69	1.95	2.49	1.75
TOTAL	99.94	100.46	99.49	100.31	99.86	99.62	99.73	99.09	98.44	99.17
REE_2O_3	33.07	48.78	29.36	35.53	46.27	47.26	40.17	47.72	50.79	40.89
Si	0.075	0.025	0.045	0.076	0.038	0.022	0.015	0.029	0.047	0.019

(continued)

Table 1 *(continued)*

Th	0.018	0.000	0.000	0.000	0.020	0.009	0.002	0.012	0.017	0.007
U	0.000	0.000	0.012	0.009	0.000	0.000	0.002	0.000	0.005	0.000
Al	0.091	0.046	0.111	0.098	0.044	0.032	0.029	0.000	0.000	0.000
Y	0.015	0.006	0.007	0.012	0.014	0.000	0.000	0.043	0.045	0.000
La	0.802	0.950	0.701	0.876	0.814	0.794	0.350	0.594	0.640	0.262
Ce	0.961	1.130	0.917	1.020	1.082	1.090	0.487	1.157	1.264	0.528
Pr	0.097	0.105	0.097	0.081	0.107	0.108	0.051	0.088	0.096	0.025
Nd	0.166	0.181	0.173	0.179	0.211	0.210	0.100	0.368	0.389	0.142
Sm	0.006	0.010	0.002	0.009	0.013	0.013	0.008	0.005	0.010	0.000
Gd	0.000	0.009	0.000	0.000	0.014	0.000	0.005	0.033	0.034	0.012
Mg	0.027	0.000	0.020	0.014	0.000	0.000	0.000	0.014	0.005	0.009
Ca	1.517	1.029	1.024	1.538	1.297	1.864	0.545	1.501	1.112	0.766
Sr	0.233	0.146	0.350	0.279	0.170	0.097	0.097	0.084	0.054	0.038
Ba	2.079	0.914	2.599	1.866	0.833	0.592	0.666	0.703	0.655	0.535
Na	0.054	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$(CO_3)_2^-$	5	4	5	5	4	4	2	4	4	2
F	0.682	1.002	0.781	0.776	1.057	0.792	0.432	0.957	1.243	0.432

CO_2 calculated by stoichiometry. *Cd* cordylite; *Cb* cebaite; *Hh* huanghoite. Data for grains 5 and 7 are the average of three analysed points, grain 6 is average of two points program (*Bishop* et al., 1978). Details are given by *Williams* (1996). Detection limit was better than 0.1% (REE_2O_3 wt%) for most REE, 0.05% for BaO and SrO, and 0.1% for ThO_2 and UO_2. The results are presented in Table 1.

Results and discussion

SEM investigation showed that, while a few of the cebaite grains are single and homogeneous crystals, others contain microfine lamellae of cordylite in regular syntaxial intergrowths that are clearly seen in section parallel to the c axis (Fig.2a). In section perpendicular to the c axis, some perfect hexagons of unzoned bastnaesite were observed. Many of the bastnaesite grains occur as fine-grained aggregates interlocked with calcite producing a mosaic texture with some triple junctions such as occurs in igneous carbonatites (*Yang* et al., 1998b), and is interpreted as a primary igneous texture because no replacive relationships have been found in thin section. In the same rock, cordylite is seen to include regular syntaxial lamellae of huanghoite (grey) parallel to the (0001) plane of the host (Fig.2b).

The three common interpretations for the origin of syntaxy are: (1) formation during eutectic crystallization of the host carbonatite magma; (2) formation by exsolution of subsolidus phases during slow cooling of the carbonatite; (3) formation during later hydrothermal metasomatic reaction with the minerals. The finegrained texture of the carbonate and Ba-REE fluorcarbonate minerals in the carbonatite indicates that the cooling rate of the carbonatite dyke was relatively rapid even although that is dependent on the ambient temperature of the country rock into which the dyke was intruded.

The syntaxial texture seen in the cebaite and cordylite is that of lamellae of regular thickness distributed fairly uniformly throughout the grain and extending right across the grain (Fig. 2a,b). These are common characteristics of exsolution lamellae (*Putnis* and *McConnell*, 1980, p. 154). The latter authors further comment that "in slowly cooled rocks the scale of this exsolution is coarser than in rapidly cooled rocks" and note that, for pyroxenes, rapid cooling results in "lamellae on an electron-microscope scale". The lamellae in Fig. 2a are on such a scale. The occurrence of coarser exsolution lamellae in a rapidly cooled rock would be possible if that rock had, in a subsequent metamorphic event, undergone reheating to an appropriate subsolvus temperature long enough to allow the diffusion and nucleation necessary for unmixing.

The syntaxial intergrowths between the Ba-REE fluorocarbonate minerals cebaite, cordylite and huanghoite parallel to (0001) arise from the identical axes and similar REE-F structural layers of these minerals. Cordylite and huanghoite also have the same structural layers but different packing sequence. The former is packed as the sequence of -Ba-Ce-Ce-Ba-, while the latter as -Ce-Ba-Ce-Ba-. Although Ce and Ba are located along the same structural layer in cebaite, its *b* dimension is equal to *a* of cordylite and huanghoite, ca 5.07 Ångstroms (*Miyawaki* et al., 1987, 1988). An epitaxial texture between bastnaesite and parisite has been previously reported from Bayan Obo (*Yang* et al., 1998b). *Zaitsev* et al. (1998) described syntaxial intergrowth of synchysite, parisite and bastnaesite in the Khibina carbonatite and considered the texture to be late stage primary magmatic.

Using TEM, *Li* et al. (1983) reported that the structural layers of huanghoite from the Bayan Obo deposit contain parisite layers and that syntaxy occurred between Ba-REE fluorocarbonate and Ca-REE fluorocarbonate minerals. However, this kind of syntaxy requires to be further investigated because the crystal structures of these two mineral series contrast greatly, and it is difficult for them to form intergrowth relations (*Donnay* et al., 1953; *Miyawaki* et al., 1987, 1988; *Ni* et al., 1993; *Wang* et al., 1994; *Giester* et al., 1998).

Investigation using EMPA of the Ba-REE fluorocarbonate minerals confirms the above SEM results that host cebaite contain fine lamellae of cordylite (Table 1 and Fig. 2a) and that cordylite contains regular lamellae of huanghoite (Table 1 and Fig. 2b). The two analyses of core and rim cebaite in grain 2 of Table 1 show a slight but significant zonal increase in REEs from core to rim. This suggests that cebaite is part of the primary crystallization of the carbonatite although formation by progressive crystallization during subsequent phases of mineralization cannot be ruled out. The light REE enrichment patterns of cebaite with $Ce > La > Nd$ (Fig. 3a) are typical of minerals from carbonatities elsewhere (*Meyer*, 1984). La depletion and a Ce anomaly are common features of Ba-REE minerals in the metasomatic ore deposits at Bayan Obo (*Zhang* et al., 1995). Stronger depletion in light REE occurs in the Ca-Ba-REE minerals of the Khibina carbonatites (analysed on the same Cameca microprobe at the Natural History Museum, London) which *Zaitsev* et al. (1998) describe as having undergone subsolidus metasomatic alteration by alkaline hydrothermal fluids. The REE distribution patterns in Fig. 3a also show no La depletion or Ce anomaly which suggest that the cebaite has not been subjected to any appreciable alteration by fluids since its primary crystallization. Cordylite analysed from veins cutting the dolomite marble which hosts the ore body does show light REE depletion (Fig. 3b).

The cause of the variation in composition of cordylite in Table 1 is less clear. The Ca/Ba ratio is highest in host cordylite (grain 10, Table 1) and lowest in the lamellae of cordylite (grains 1 and 2, Table 1), and this could be corellated with relatively high and low temperatures respectively. Much lower Ca/Ba ratios are reported by *Zaitsev* et al. (1998) for the same minerals in the Khibina carbonatites which they consider to have undergone late stage low temperature alteration. Crystal chemistry indicates that Ca and Sr are able to substitute partly for Ba, and that Th can replace some REE in the structure of Ba-REE fluorocarbonate minerals, the substitution relation being $2(Sr^{2+}, Ca^{2+}) + Th^{4+} = Ba^{2+} + 2REE^{3+}$. This type of substitution relation was also used to explain the atomic proportions of Sr(Ca)-Th and REE-Ba in cordylite from Mont St. Hilaire, Quebec (*Chen* et al., 1975) and in parisite-(Ce) and bastnaesite-(Ce) from the Khibina carbonatites, Kola Penisula, Russia (*Zaitsev* et al., 1998).

In addition, all the F contents reported in Table 1 are lower than the theoretical values. They are ascribed to partial substitution of OH^- for F^-. This also applies to those minerals from the Bayan Obo ore deposit (*Zhang* et al., 1986, 1995), from Quebec (*Chen* et al., 1975; *Meyer*, 1984) and from the Khibina carbonatites (*Zaitsev* et al., 1996, 1998). The F^- deficiency in Ba-REE fluorocarbonate minerals is interpreted to indicate that $(OH)^-$ occurred in the crystallizing agents (i.e. carbonatite magma or hydrothermal fluid related to carbonatite) at relatively low temperature or at a subsequent hydrothermal event during metamorphism. This

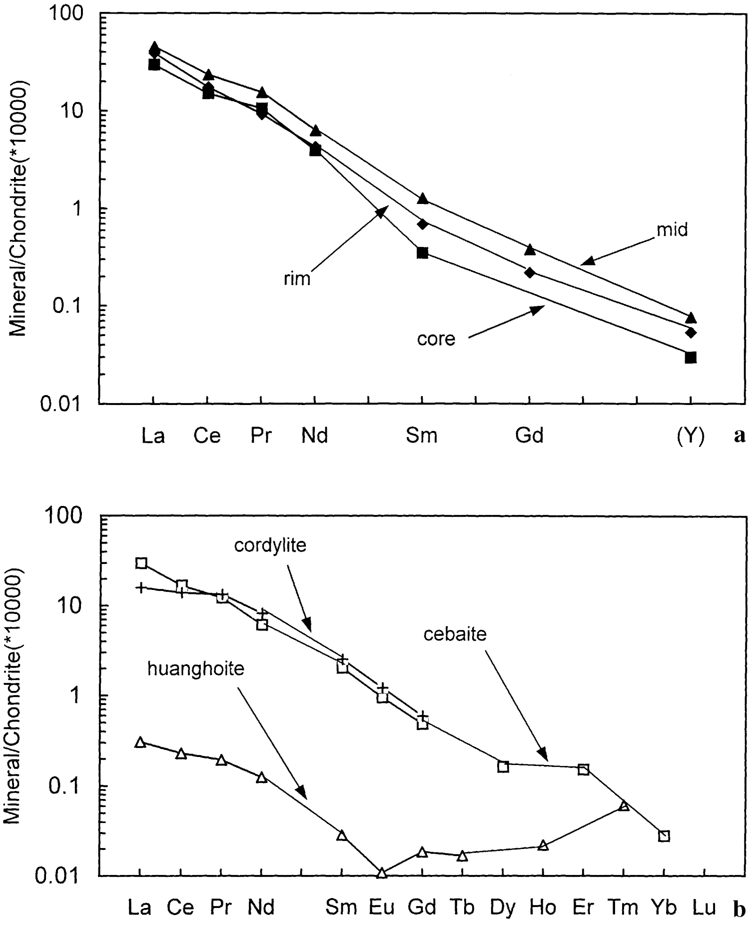

Fig. 3. Chondrite normalized REE patterns for Ba-REE fluorcarbonate minerals from Bayan Obo carbonatite dyke. **a** Ba-REE fluorcarbonate minerals from the carbonatite dyke, grain no. 2 in sample 90/39 (Table 1) with rim and core of cebaite crystal in Fig. 2a labelled and mid is cordylite lamella at the middle; no LREE depletion is evident. **b** Cordylite showing LREE depletion and cebaite in the dolomite marble which hosts the ore body, and huanghoite in fine veins that cross cut the banded ores; data are from *Zhang* et al. (1986)

agrees with the results of experimental investigations by *Hsu* (1992) of the stability fields of fluorocarbonates and hydroxylcarbonates of Ce and La. Hydroxylbastnaesite-(La) is stable up to 810 °C, and fluorobastnaesite-(La) is stable up to 860 °C. The corresponding minerals with Ce are stable up to 650 °C and 780 °C, depending on the oxygen fugacity. This experiment showed that bastnaesite could be stable from hydrothermal to magmatic conditions, and F-enriched species could form in an environment relatively low in F content. OH species are rare and occur only in low-temperature environments essentially devoid of fluorine. A recent review of experimental syntheses of bastnaesites made by *Wyllie* et al. (1996) indicated that primary bastnaesite group minerals could form at low temperatures in late stage carbonatite magma. This implies that the formation of fluorcarbonate minerals does not require the higher temperatures of early stage magmatic carbonatites.

It is significant that the chondrite-normalized REE distributions for cebaite and cordylite from the carbonatite dyke compare closely with those of the corresponding minerals in the dolomite marble host of the Bayan Obo ore deposit, where they are associated with ankerite, magnetite, quartz, fluorite, bastnaesite, and monazite (Fig. 3a and b). This similarity is interpreted to mean that the minerals both from the carbonatite and the dolomite marble hosting the ore deposit have a common REE source. This is supported by the results from the genetic mineralogy of carbonate minerals (*Yang* et al., 1998a) and O, and Sr isotopic geochemistry (*Le Bas* et al., 1992, 1997). However, the REE pattern for huanghoite from fine veins that cross-cuts the banded ores of the deposit is different and includes a negative Eu anomaly (Fig. 3b). Although its light REE distribution parallels that of the cebaite and cordylite, its heavy REE pattern shows an upward trend and interesects that of cebaite and cordylite (Fig. 3b). It is apparent that the fine vein of huanghoite was later than the dolomite marble hosting the ores, and had a hydrothermal origin. Sm-Nd isotope dating of this huanghoite gave an age of 422 Ma (*Zhang* et al., 1994) that could represent hydrothermal events caused by Caledonian subduction and metamorphism (*Chao* et al., 1993; *Wang* et al., 1994). Cebaite and cordylite with mantle O and C isotopic compositions (*Fang* et al., 1994; *Cao* et al., 1994) occur in the dolomite marble and might be primary minerals from carbonatites. The depletion of La in cordylite is most likely the product of a late stage hydrothermal transformation (Fig.3b). Apatite and monazite from the dolomite marble also show La depletion (*Le Bas* et al., 1992). These phenomena are ascribed to transformation of the primary Ba-REE fluorocarbonate minerals in the carbonatite by late-stage hydrothermal action probably related to Caledonian subduction and metamorphism as suggested by *Chao* et al. (1993) and *Wang* et al. (1994), or related to unexposed carbonatite intrusives at depth (*Campbell* and *Henderson*, 1997; *Campbell*, 1998).

Conclusions

The similarity between Ba-REE fluorocarbonate minerals from the carbonatite dyke and the corresponding minerals from the dolomite marble host of the Bayan Obo ore deposit implies a genetic linkage. The texture, zoning, exsolution lamellae and lack of light REE depletion all indicatie that the cebaite and cordylite hosting the lamellae belong to the late-stage primary crystallization of the carbonatite magma, with the lamellae being probably related to subsequent metasomatic events associated with the deformation of the region during Caledonian subduction and the formation of the ore deposit. Although the main REE mineralization of the Bayan Obo REE-Nb-Fe ore deposit is probably associated with hydrothermal fluids, the sources and nature of the metasomatic fluids that formed the ore deposit in the dolomite marble are still in dispute.

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Authors' addresses: *X.-M. Yang* and *X.-Y. Yang*, Department of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, P.R. China, e-mail: yxm@ustc.edu.cn; *P.-S. Zhang*, Institute of Geology, The Chinese Academy of Science, Beijing 100029, P.R. China; *M.J. Le Bas*, School of Ocean and Earth Science, University of Southampton, SO14 3ZH, United Kingdom