Bull. Natl. Mus. Nat. Sci., Ser. C, **34**, pp. 1–26, December 22, 2008

A Reconnaissance Study on Minerals from the Bayan Obo Nb-REE-Fe Deposit, Inner Mongolia, China

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Introduction

The Bayan Obo ore deposit is a famous, world-class, giant Nb-REE-Fe deposit located in Inner Mongolia, China, situated in approximately 80 kilometers south of the border between China and Mongolia, at 109°57′E and 41°46′N. The deposit is contained within the sediments of the Proterozoic Bayan Obo Group, which consist predominantly of sandstones and slates, with the exception of the H8 dolomite marble unit, which hosts the vast majority of the ore. The paragenesis of the deposit is extremely complex, from deposition, through metamorphism and mineralization, to the intrusion of Hercynian granitoids to the south of the deposit (e.g. Chao *et al.*, 1997).

The size of the deposit is about 18 km long along east-west direction, and 0.5–5 km wide along north-south direction. It includes several orebodies, among which the Main and East orebodies are the two major Nb-REE-Fe orebodies. Based on the mineralization characteristics, all the ores can be classified into three main types: Nb-REE-Fe ore, Nb-REE ore, and Nb ore. More than 190 mineral species have been identified from the Bayan Obo deposit. The complicated mineralogy of the deposit has been described in detail by previous workers (e.g. Zhang and Tao, 1986). The main economic minerals include magnetite, hematite, bastnäsite-(Ce), monazite-(Ce), and pyrochlore.

Samples and Analytical Methods

Through one and half day survey on the Bayan Obo deposit in 2004, one of the authors (RM) collected about 30 samples. Among them, 26 samples were investigated in the present study mainly for mineral composition of each sample and chemical composition of constituent minerals. The samples were collected mostly in the Main and East orebodies, and in the surrounding areas of the deposit. The working number (TS), National Museum registration number, and rock name of each sample is listed in Table 1. Although the genesis of the deposit has been controversial for many years, the rock mainly consisting of carbonates with REE minerals and/or Nb minerals is tentatively named carbonatite in the present study.

A preliminary study of thin sections of samples was carried out for qualitative and semi-quantitative analysis of the constituent minerals using an electron microscope equipped with an energy dispersive spectrometer (JEOL 5400 with fully quantitative Link Systems model QX2000) employing an operating voltage of 15 kV and Faraday cup current of 1 nA. A quantitative analysis was consequently performed using an electron microprobe analyzer equipped with a wave length spectrometer (JXA 8800 of JEOL) employing an operating voltage of 15 kV and a current of 20 nA, with a beam diameter of about 2 μm. The following minerals and synthetic materials were used as standards: wollastonite for Si and Ca, anatase for Ti, sillimanite for Al,

Table 1. Working and registration numbers and rock names.

Working No.	Registration No.	Rock Name	Locality
TS-1	NSM-MF15339	Weathered carbonatite (?)	Northern erea
TS-2	NSM-MF15340	Carbonatite	North eastern erea
TS-3	NSM-MF15341	Carbonatite	Northern erea
TS-4	NSM-MF15342	Chert	Northern erea
TS-5	NSM-MF15343	Aegirine rock	Northern erea
TS-6	NSM-MF15344	Aegirine rock	Northern erea
TS-7	NSM-MF15345	Carbonatite	North eastern erea
TS-8	NSM-MF15346	Felsic alkali rock	North eastern erea
TS-9	NSM-MF15347	Carbonatite	South of East Orebody
TS-10	NSM-MF15348	Weathered carbonatite	Northern erea
TS-11	NSM-MF14696	Fluorite rock	South of East Orebody
TS-12	NSM-MF15349	Carbonatite	South of East Orebody
TS-13	NSM-MF15350	Carbonatite with huanghoite-(Ce) band	South of East Orebody
TS-14	NSM-MF15351	Carbonatite with monazite-(Ce) band	South of East Orebody
TS-15	NSM-MF15352	Cerium ore (Fluorite-bastnäsite rock)	East Orebody
TS-16	NSM-MF15353	Cerium ore (Fluorite-bastnäsite rock)	East Orebody
TS-17	NSM-MF15354	Carbonatite (?)	South of East Orebody
TS-18	NSM-MF15355	Carbonatite	Main Orebody
TS-19	NSM-MF15356	Phlogopite-richterite rock	South of East Orebody
TS-20	NSM-MF15357	Magnetite-apatite rock	East Orebody
TS-21	NSM-MF15358	Richterite-humite-group mineral-fluorite rock	South of East Orebody
TS-22	NSM-MF15359	Monazite-(Ce)-fluorite rock	Main Orebody
TS-23	NSM-MF15360	Magnetite-apatite rock	East Orebody
TS-24	NSM-MF15361	Carbonatite with huanghoite-(Ce) band	South of East Orebody
TS-25	NSM-MF15362	Carbonatite	South of East Orebody
TS-26	NSM-MF15363	Magnetite-barite rock	Main Orebody

Mg_2SiO_4 for Mg, Fe_2SiO_4 for Fe, rhodonite for Mn, albite for Na, CaF_2 for F, ScP_5O_{14} for Sc, YP_5O_{14} for Y, SnSe for Sn, ThO_2 for Th, $FeNb_2O_6$ for Nb, $MnTa_2O_6$ for Ta, LaP_5O_{14} for La, CeP_5O_{14} for Ce, PrP_5O_{14} for Pr, NdP_5O_{14} for Nd, SmP_5O_{14} for Sm, GdP_5O_{14} for Gd, DyP_5O_{14} for Dy, and ErP_5O_{14} for Er.

Some of grains analyzed by the electron microprobe were picked up from the thin sections for X-ray diffraction investigations. The X-ray powder diffraction patterns were obtained using a Gandolfi camera of 114.6 mm diameter employing Ni-filtered CuKα radiation, recorded on imaging plates, and processed with a Fuji BAS-2500 bio-imaging analyzer using a computer program by Nakamuta (1999).

Brief Description of Samples

The following is brief description of samples. Constituting minerals are listed in Table 2.

TS-1: Weathered carbonatite (?) (Plate 1-A). Sample TS-1 is a massive, dark brown rock mainly consisting of calcite. Small amounts of forsterite, iron oxide and sulfide are included.

TS-2: Carbonatite (Plate 1-B). Sample TS-2 is a massive, white carbonatite mainly consisting of calcite, with dark brown, irregular-shaped micaceous parts mainly consisting of phlogopite. Small amounts of barite, fluorapatite, clinopyroxene, fluorbritholite-(Ce), and pyrochlore are observed.

TS-3: Carbonatite (Plate 1-C). Sample TS-3 is a massive, brown carbonatite mainly consisting of calcite, with small amounts of phlogopite, magnesioriebeckite, barite, monazite-(Ce), pyrochlore, and allanite-(Ce). Fine-grained quartz is also observed as an alteration product of amphibole.

TS-4: Chert (Plate 1-D). Sample TS-4 is a massive, gray- to white-colored chert, mostly composed of quartz of variable grain sizes. Small amounts of K-feldspar, chlorite, zircon, pyrochlore, iron oxide, and ilmenite are ob-

Table 2. Mineral composition of samples.

Mineral Name		Chemical Composition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Fluorite		CaF_2 *Y-bearing					O				O		O		O*	O*	O	O	O*			O	O	O	O	O	O	O
Zhangpeishanite	☆	BaFCl											O															
Pyrrhotite-Pyrite		$FeS–FeS_2$	O								O			O			O	O		O	O		O			O	O	
Galena		PbS									O			O	O	O				O			O			O	O	
Sphalerite		(Zn, Fe)S									O						O				O		O					
Tetradymite (?)		Bi_2Te_2S																							O			
Magnetite-Hematite		$Fe_3O_4–Fe_2O_3$ *Goethite	O			O		O?	O	O	O	O,O*	O	O,O*	O	O	O	O	O		O,O*	O	O	O,O*	O	O,O*	O	O
Ilmenite		$FeTiO_3$				O						O		O							O			O	O			
Quartz		SiO_2			O	O	O			O		O							O					O	O			
Ilmenorutile		$(Ti, Nb, Fe)_3O_6$																O							O			
Thorianite		ThO_2									O										O					O		
Ferrocolumbite	☆	$FeNb_2O_6$ *Sc-bearing					O											O*							O*			
Fergusonite-(Ce)	☆	$(Ca, La, Y)NbO_4$							O							O							O					
Aeschynite-group	☆	$(Ce, Nd, Ca, Y)(Ti, Nb)_2(O, OH)_6$ *Niobo-																O				O	O	O,O*				
Pyrochlore	☆	$NaCaNb_2O_6(F,OH)$		O	O	O	O	O	O								O	O					O		O			
Calcite		$CaCO_3$	O	O	O		O	O	O	O	O	O		O	O	O		O	O	O	O	O	O			O		
Dolomite		$CaMg(CO_3)_2$							O				O	O	O	O		O	O	O	O		O	O	O	O	O	
Ankerite		$Ca(Fe, Mg, Mn)(CO_3)_2$									O												O	O				
Norsethite	☆	$BaMg(CO_3)_2$											O		O											O		
Bastnäsite-(Ce)	☆	$(Ce, La)(CO_3)F$									O	O		O	O		O	O	O	O		O	O	O	O	O	O	O
Parisite-(Ce)	☆	$(Ce, La)_2Ca(CO_3)_3F_2$										O						O	O			O	O		O	O		
Cordylite-(Ce)	☆	$(Na_{1-x}Ca_{x/2})Ba(Ce, La)_2(CO_3)_4F$													O								O			O	O	
Huanghoite-(Ce)	☆	$Ba(Ce, La)(CO_3)_2F$									O				O					O			O			O	O	
Cebaite-(Ce)	☆	$Ba_3Ce_2(CO_3)_5F_2$																					O					
Calcioancylite-(Ce)	☆	$(CeCa)(CO_3)_2[(OH)(H_2O)]$																									O	
Barite		$BaSO_4$ *Sr-bearing		O*	O		O	O	O		O	O	O	O	O	O		O	O	O	O	O	O	O	O	O	O*	O*
Monazite-(Ce)		$CePO_4$ *Th-bearing			O			O			O			O		O	O	O	O	O	O*	O	O	O	O	O		
Fluorapatite		$Ca_5(PO_4)_3F$ *REE-bearing		O*			O	O		O					O*	O	O	O	O	O		O		O	O	O*	O	O
Zircon		$ZrSiO_4$				O		O		O																O		
Thorite		$ThSiO_4$									O																O	
Humite-group		$nMg_2SiO_4 \cdot Mg(OH)_2$	O						O		O				O	O							O			O	O	
Fluorbritholite-(Ce)	☆	$(Ce, Ca)_5[(Si, P)O_4]_3(F, OH)$		O										O	O								O				O	
Titanite (sphene)		$CaTiO(SiO_4)$								O																		
Gadolinite-(Ce)	☆	$Ce_2FeBe_2Si_2O_{10}$												O														
Bafertisite	☆	$Ba(Fe, Mn)_2TiO(Si_2O_7)(OH, F)_2$																					O					
Chevkinite-Perrierite	☆	$(Ce, La, Ca)_4(Fe, Mg)_2Ti_3Si_4O_{22}$ *Sc-bearing												O								O*						
Allanite-(Ce)		$CaCeFe^{2+}Al_2(Si_2O_7)(SiO_4)O(OH)$			O							O																O
Baotite	☆	$Ba_4(Ti, Nb, Fe)_8O_{16}(Si_4O_{12})Cl$					O																					
Aegirine		$NaFeSi_2O_6$ *Sc-bearing					O	O									O*											
Clinopyroxene		$Ca(Mg, Fe)Si_2O_6$		O						O?																		
Tremolite-Richterite		$Na(CaNa)(Mg, Fe)_5Si_8O_{22}(OH)_2$												O	O						O		O			O		
Richterite-Arfvedsonite		$Na(CaNa)(Mg, Fe)_5–Na_3(Mg, Fe)_4Fe$									O?								O	O				O				O
Magnesioriebeckite		$Na_2(Mg, Fe)_3Fe_2Si_8O_{22}(OH)_2$			O		O	O		O																		
Phlogopite	☆	*with Kinoshitalite mol., ?silica-rich		O	O			O?	O*	O	O*			O*	O?		O		O*		O			O?		O?	O*	O*
Chlorite		$(Mg, Fe)_5Al(Si_3Al)O_{10}(OH)_8$				O																						
Paragonite		$NaMg_3AlSi_3O_{10}(OH)_2$																										O
K-feldspar		$KAlSi_3O_8$ *Ba-bearing				O		O		O,O*																		

☆ Occurrence and chemical composition of these minerals are given and discussed in the present paper.

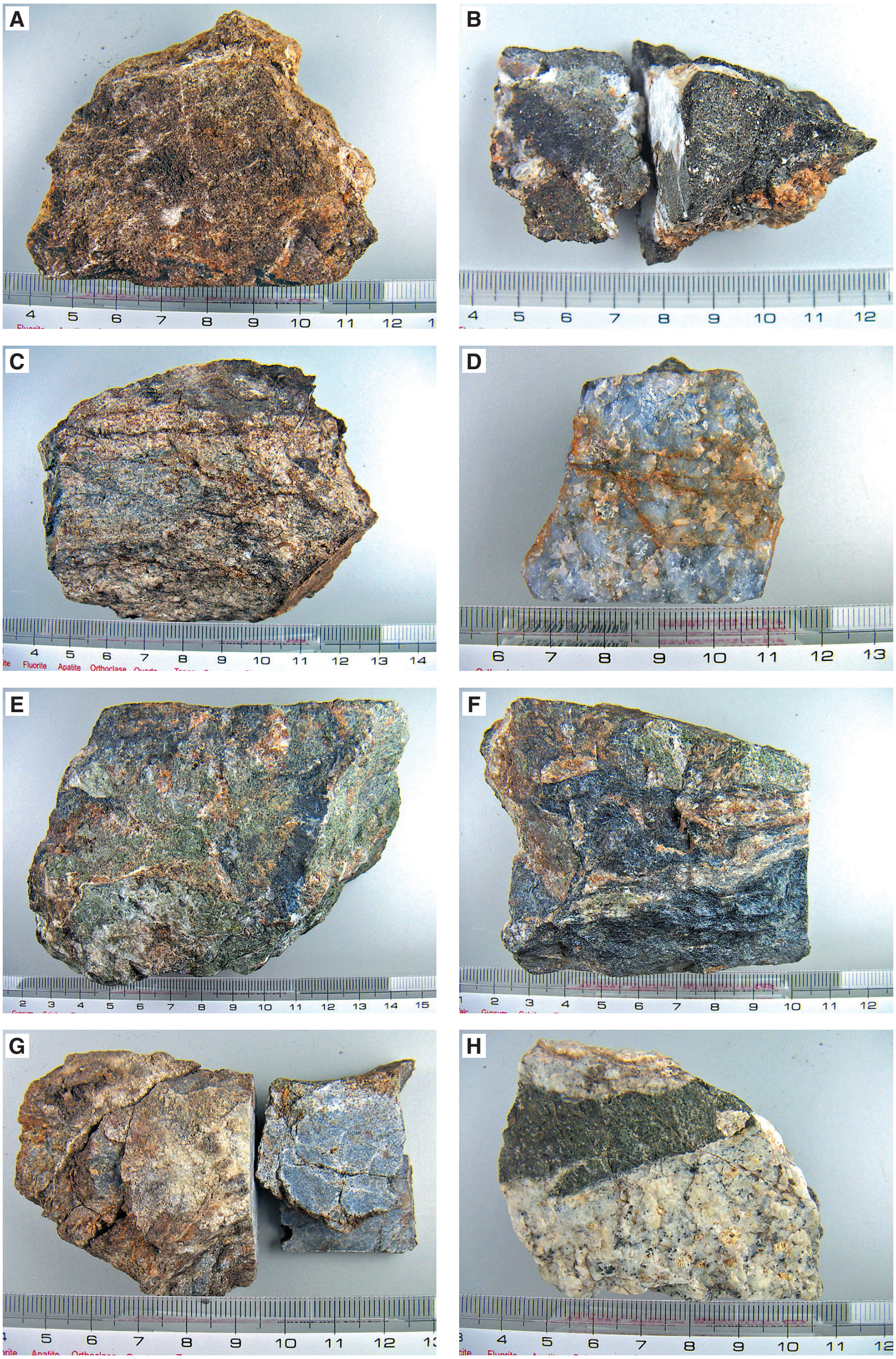

Plate 1 Photographs of samples. A to H correspond to the samples TS-1 to TS-8.

served.

TS-5: Aegirine rock (Plate 1-E). Sample TS-5 is a massive, pale green aegirine rock with irregular-shaped, light brown calcite-quartz aggregates and dark green to black magnesioriebeckite aggregates. Small amounts of barite, fluorapatite, fluorite, pyrochlore, ferrocolumbite, and baotite are observed.

TS-6: Aegirine rock (Plate 1-F). Sample TS-6 is a massive, pale green aegirine rock with irregular-shaped, yellow to light brown calcite aggregates, and dark green to black magnesioriebeckite aggregates. Small amounts of K-feldspar, barite, fluorapatite, phlogopite, iron oxide, pyrochlore, monazite-(Ce), and zircon are recognized.

TS-7: Carbonatite (Plate 1-G). Sample TS-7 is a massive, gray carbonatite, mainly composed of calcite and dolomite. Small amounts of phlogopite, pyrochlore, fergusonite-(Ce), humite-group mineral, barite, and iron oxide are recognized.

TS-8: Felsic alkali rock (Plate 1-H). Sample TS-8 is a massive, coarse-grained, gray rock with igneous texture. Large amounts of K-feldspar and quartz are present. Small amounts of aegirine-augite, magnesioriebeckite, phlogopite, fluorapatite, zircon, titanite (sphene), calcite and iron oxide are observed.

TS-9: Carbonatite (Plate 2-I). Sample TS-9 is a massive, gray carbonatite, composed of calcite and minor ankerite. Small amounts of fluorite, phlogopite, huanghoite-(Ce), barite, monazite-(Ce), bastnäsite-(Ce), thorianite, thorite, richterite-arfvedsonite (?), humite-group mineral, iron oxide and sulfide, galena, and sphalerite are recognized.

TS-10: Weathered carbonatite (Plate 2-J). Sample TS-10 is a massive, brown carbonatite mainly consisting of calcite. Small amounts of barite, bastnäsite-(Ce), parisite-(Ce), allanite-(Ce), ilmenite, iron oxide, goethite, and quartz are observed.

TS-11: Fluorite rock (Plate 2-K). Sample TS-11 is a massive, dark purplish-colored fluorite rock. Tiny grains of barite, norsethite, zhangpeishanite, and iron oxide are scarcely scattered in fluorite matrix. Thin dolomite veinlets cutting fluorite are recognized.

TS-12: Carbonatite (Plate 2-L). Sample TS-12 is a massive, gray carbonatite with phlogopite flakes. The matrix of the rock consists of major calcite and minor dolomite. Besides phlogopite, small amounts of tremolite-richterite, barite, chevkinite-perrierite-(Ce), monazite-(Ce), bastnäsite-(Ce), fluorbritholite-(Ce), gadolinite-(Ce), ilmenite, iron oxide and sulfide, goethite, and galena are recognized in the sample.

TS-13: Carbonatite with huanghoite-(Ce) band (Plate 2-M). Sample TS-13 is a massive, gray carbonatite with a reddish band of one centimeter width. The carbonatite consists of calcite and dolomite, with minor fluorbritholite-(Ce), bastnäsite-(Ce), cordylite-(Ce), humite-group mineral, barite, tremolite-richterite, phlogopite, fluorapatite, norsethite, iron oxide, and galena. The reddish band is composed of huanghoite-(Ce), fluorite, and humite-group mineral with its clayey alteration product. This clayey material causes reddish color of the band.

TS-14: Carbonatite with monazite band (Plate 2-N). Sample TS-14 is a massive, gray carbonatite with brown monazite-(Ce)-bearing bands of one centimeter width in maximum. The carbonatite consists of calcite and dolomite, with minor humite-group mineral, barite, fluorapatite, fergusonite-(Ce), iron oxide (magnetite), and galena. The brown band is composed of fluorite, monazite-(Ce), and humite-group mineral with serpentine as an alteration product. Thin calcite veinlets are also present in the sample.

TS-15: Cerium ore (Plate 2-O). Sample TS-15 is a massive fluorite-bastnäsite-(Ce) rock with dark purplish (fluorite) and greenish gray (bastnäsite-(Ce), phlogopite, and monazite-(Ce)) bands. Fluorite band is almost monomineralic with tiny pyrochlore grains, and fluorite grains show purplish color at their central parts under the microscope. REE-bearing band

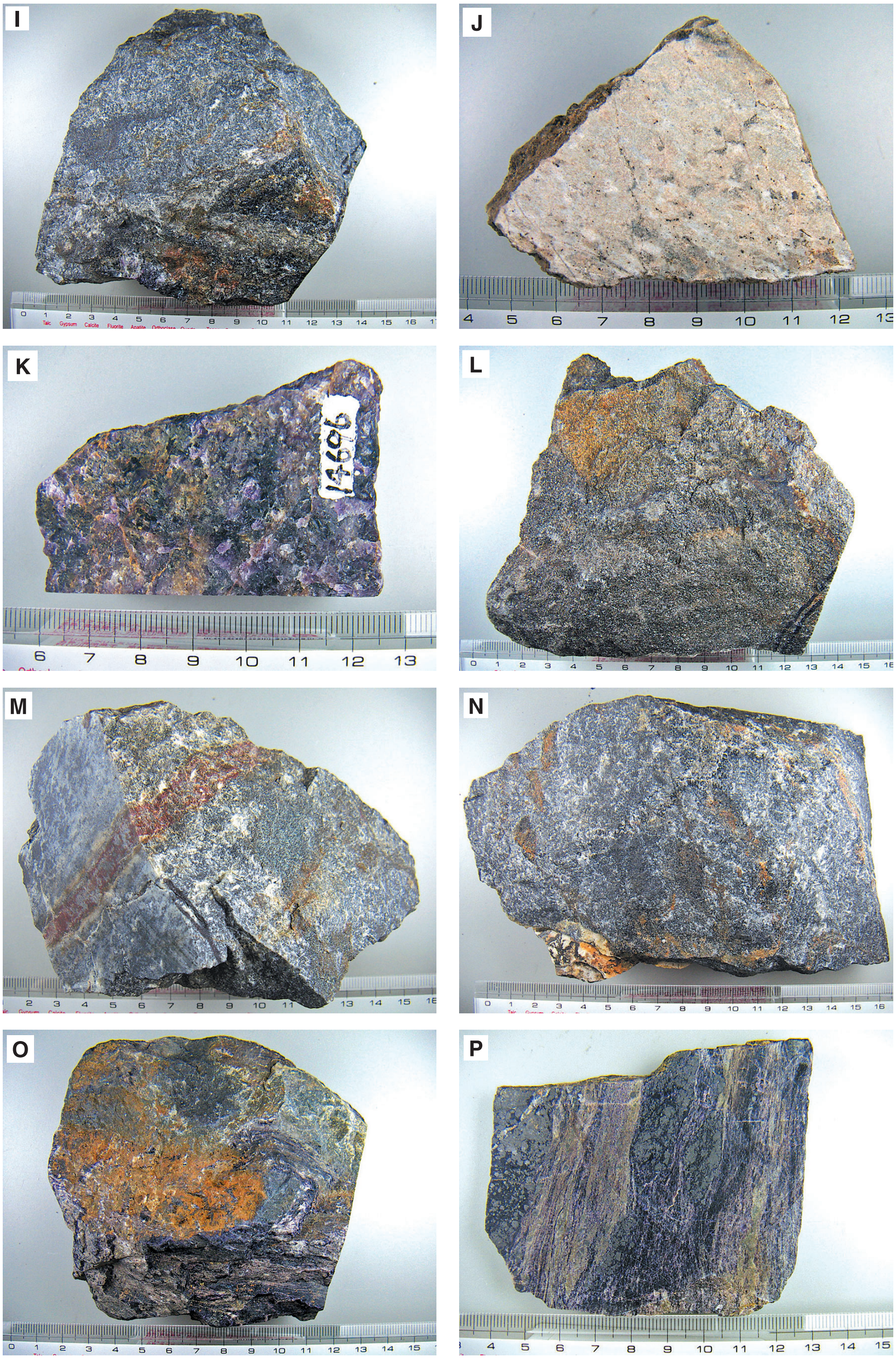

Plate 2 Photographs of samples. I to P correspond to the samples TS-9 to TS-16.

consists of bastnäsite-(Ce), phlogopite, and monazite-(Ce), with minor fluorapatite, aegirine, iron oxide and sulfide, and sphalerite.

TS-16: Cerium ore (Plate 2-P). Sample TS-16 is a banded fluorite-bastnäsite-(Ce) rock, with dark purplish (fluorite) and gray (bastnäsite-(Ce) and monazite-(Ce)) bands with thickness of one to several millimeters. Fluorite band consists of fluorite and rounded aggregates of iron oxide with tiny ferrocolumbite grains. REE-bearing band consists of bastnäsite-(Ce), with minor parisite-(Ce), monazite-(Ce), pyrochlore, aeschynite-group mineral, ilmenorutile, fluorapatite, barite, iron oxide, and iron sulfide. Thin veinlets of calcite with dolomite are present.

TS-17: Carbonatite (?) (Plate 3-Q). Sample TS-17 is a massive, greenish gray rock, mainly composed of dolomite with minor calcite. Quartz is observed in a part of the thin section, as fine, angular grains making aggregate of amoeba-like form in fine-grained carbonate matrix. This texture suggests that the rock could not be simply classified as carbonatite. Small amounts of fluorite, bastnäsite-(Ce), parisite-(Ce), barite, monazite-(Ce), fluorapatite, richterite-arfvedsonite, phlogopite, and iron oxide are present.

TS-18: Carbonatite (Plate 3-R). Sample TS-18 is a massive, gray carbonatite with fibrous, pale blue richterite-arfvedsonite vein of one centimeter width. Carbonatite consists of calcite and dolomite, with minor barite, fluorapatite, bastnäsite-(Ce), huanghoite-(Ce), monazite-(Ce), iron sulfide, and galena.

TS-19: Phlogopite-richterite rock (Plate 3-S). Sample TS-19 is a massive, black rock mainly consisting of phlogopite and tremolite-richterite. Calcite and dolomite make small aggregates in the silicate matrix. Small amounts of monazite-(Ce), thorianite, barite, iron oxide and sulfide, goethite, ilmenite, and sphalerite are recognized.

TS-20: Magnetite-apatite rock (Plate 3-T). Sample TS-20 is a weakly banded, black rock, mainly composed of magnetite-hematite and fluorapatite. Thin, mono-mineralic fluorite bands are observed. Small grains of monazite-(Ce) are also aggregated making thin bands. Small amounts of barite, bastnäsite-(Ce), parisite-(Ce), chevkinite-perrierite-(Ce), and aeschynite-group mineral are recognized. Fine calcite veinlets cut the banding structure of the rock.

TS-21: Richterite-humite-group mineral-fluorite rock (Plate 3-U). Sample TS-21 is a rock with weak banding structure. Tremolite-richterite makes dark green bands, and humite-group mineral makes brown-colored bands due to the color of its clayey alteration product. Fluorite, iron oxide, and iron sulfide are common. Small amounts of calcite, dolomite, ankerite, barite, pyrochlore, bastnäsite-(La), parisite-(Ce), cordylite-(Ce), huanghoite-(Ce), cebaite-(Ce), aeschynite-group mineral, fergusonite-(Ce), fluorbritholite-(Ce), monazite-(Ce), bafertisite, sphalerite, and galena are present.

TS-22: Monazite-fluorite rock (Plate 3-V). Sample TS-22 is a massive to weakly banded monazite-(Ce)-fluorite rock. Monazite-(Ce) makes white to light brown bands, whereas fluorite makes purple bands with small amounts of dolomite and ankerite. Magnetite and hematite also make discontinuous bands to lenses. These bands include small grains of bastnäsite-(Ce), aeschynite-group mineral, fluorapatite, tremolite-richterite, phlogopite, and ilmenite. Fine veinlets of quartz, barite, and goethite are observed.

TS-23: Magnetite-apatite rock (Plate 3-W). Sample TS-23 is a massive, black magnetite ore with gray bands mainly consisting of fluorapatite and monazite-(Ce). The latter bands also include small amounts of fluorite, quartz, and dolomite. Small amounts of barite, pyrochlore, bastnäsite-(Ce), aeschynite-group mineral, ferrocolumbite, ilmenite, ilmenorutile, and tetradymite (?) are recognized.

TS-24: Carbonatite with huanghoite-(Ce) band (Plate 3-X). Sample TS-24 is a massive, brown carbonatite with a huanghoite-(Ce) band. The

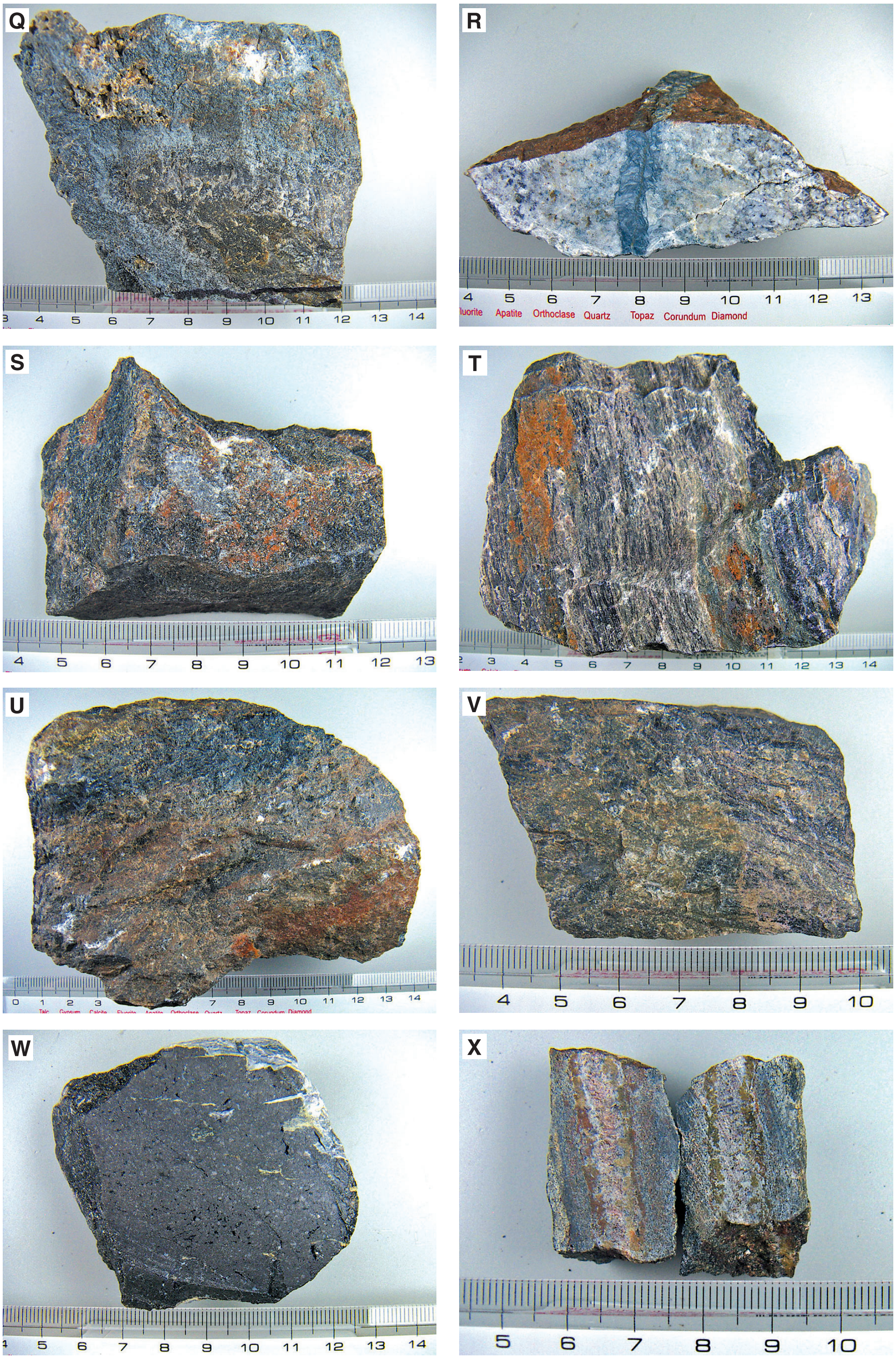

Plate 3 Photographs of samples. Q to X correspond to the samples TS-17 to TS-24.

sample is similar to TS-13 as to their mineral assemblages, and consists of calcite and dolomite, with minor fluorite, barite, fluorapatite, bastnäsite-(Ce), parisite-(Ce), cordylite-(Ce), monazite-(Ce), zircon, humite-group mineral (norbergite) with serpentine, which gives the sample brownish appearance, thorianite, norsethite, iron oxide and sulfide, and galena. The band of less than one centimeter width consists of huanghoite-(Ce), tremolite-richterite, and phlogopite, with minor barite, fluorapatite, norsethite, bastnäsite-(Ce), parisite-(Ce), and fluorite.

TS-25: Carbonatite (Plate 4-Y). Sample TS-25 is a massive, gray carbonatite mainly consisting of dolomite, with minor fluorite, barite, fluorapatite, phlogopite, tremolite-richterite, bastnäsite-(Ce), cordylite-(Ce), huanghoite-(Ce), calcioancylite-(Ce), fluorbritholite-(Ce), thorite, humite-group mineral, iron oxide and sulfide, and galena.

TS-26: Magnetite-barite rock (Plate 4-Z). Sample TS-26 is a massive, dark gray rock, mainly composed of magnetite, partly replaced by hematite, and barite. Minor amounts of fluorite, fluorapatite, bastnäsite-(Ce), phlogopite, allanite-(Ce), and paragonite are recognized.

Occurrence and Chemical Composition of Minerals

As given in the previous chapter, mineral composition of samples remarkably varies sample to sample, and shows rather complicated feature. About fifty mineral species were recognized in the studied samples as listed in Table 2. Among them, selected are eighteen species which seem worthy to be considered, and occurrence and chemical composition of these minerals will be presented in this chapter. Those minerals are shown in Table 2 with asterisk marks following mineral names.

1. Zhangpeishanite

This is a new mineral found in a sample (TS-11) during the present study. The mineral occurs sparsely as transparent, colorless, minute rounded grains smaller than 100 μm in diameter in purple-colored fluorite (Plate 4-1). Chemical composition of this mineral was determined as BaFCl. It is tetragonal with space group *P*4/*nmm*. Zhangpeishanite is a member of the matlockite group, and is the Ba-dominant analogue of matlockite (PbFCl) and rorisite (CaFCl). The name is for Professor Zhang, Peishan (born in 1925), a mineralogist, of Chinese Academy of Sciences, in recognition of his remarkable contributions to the mineralogy of Bayan Obo. The mineral and mineral name were approved by the IMA. Detailed description of the mineral is given by Shimazaki *et al.* (2008a).

2. Ferrocolumbite

Ferrocolumbite, $FeNb_2O_6$, is a relatively uncommon accessory mineral in Bayan Obo ores, and was found in three samples (TS-5, TS-16, and TS-23) in this study. Under the microscope, ferrocolumbites occur as small, reddish brown grains with a size of less than several tens to several hundreds of microns.

The analytical results of ferrocolumbites in the samples TS-5 and TS-23 are shown in Table 3. Standard deviation for the average value is given as one sigma throughout all tables in the present paper. Very small amounts of tantalum, yttrium, and tin were recognized. A marked variation in TiO_2 content was also identified.

It is worthy to note that small amount of scandium is present in ferrocolumbites of TS-16 and TS-23, whereas the ferrocolumbite of TS-5 is essentially Sc-free. The Sc_2O_3 content ranges from 0.20 to 0.25 wt% with an average value of 0.22% for TS-16 ferrocolumbites, whereas it ranges from 0.56 to 1.04 wt% with an average value of 0.67 wt% for TS-23 ferrocolumbites as shown in Table 3. Besides the elements presently exploited, such as Nb, REE, and Fe, scandium and thorium have been considered as possible byproducts from this deposit (Wang, 2004; Che *et al.*, 2006), and it is important to the mining activity to clarify in which minerals those elements are included. Some details on the distribution of scandium in

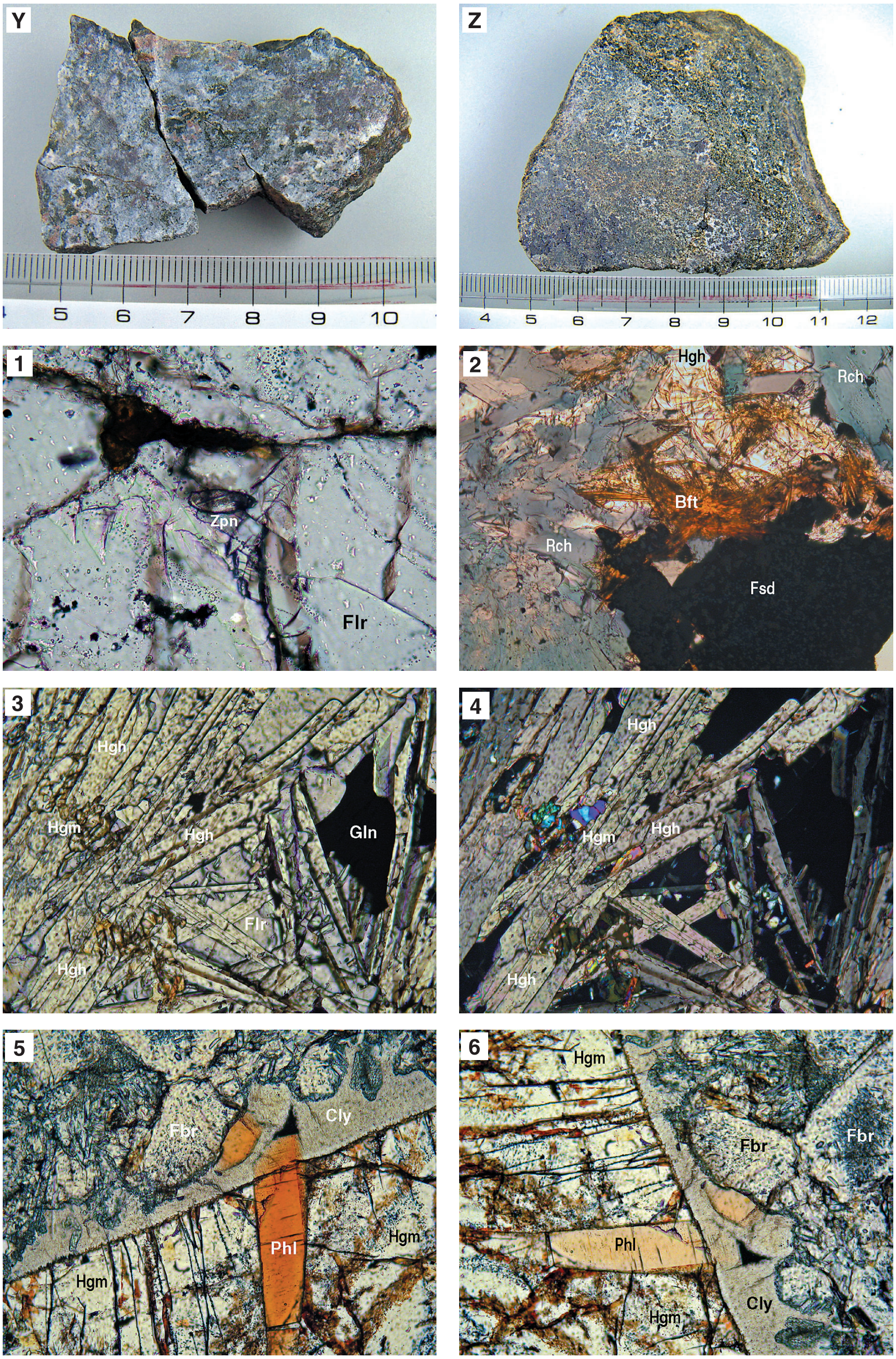
Y
Z
5 6 7 8 9 10
4 5 6 7 8 9 10 11 12
1
Zpn
Flr
2
Hgh
Rch
Bft
Rch
Fsd
3
Hgh
Hgm
Hgh
Gln
Flr
Hgh
4
Hgh
Hgm
Hgh
Hgh
5
Fbr
Cly
Phl
Hgm
Hgm
6
Hgm
Fbr
Fbr
Phl
Cly
Hgm

Table 3. Analytical results of Sc-free and Sc-bearing ferrocolumbites (TS-5, 11 analyses and TS-23, 15 analyses).

Sample	TS-5					TS-23				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=6)		Range (wt%)	Average	Std. dev.	No. of atoms (O=6)	
Nb_2O_5	67.66–76.12	72.65	2.35	1.822	2.04	68.89–78.19	71.73	2.22	1.795	2.05
TiO_2	1.56–9.52	5.12	2.34	0.214		2.96–7.91	6.08	1.43	0.253	
Ta_2O_5	0.00–0.25	0.14	0.09	0.002		0.00–0.30	0.12	0.09	0.002	
FeO	14.13–19.09	17.15	1.63	0.794	1.01	16.07–18.22	16.76	0.60	0.775	0.98
MnO	1.98–6.09	3.68	1.25	0.173		2.77–3.32	3.03	0.15	0.142	
MgO	0.30–0.44	0.36	0.04	0.030		0.08–0.17	0.13	0.02	0.011	
Sc_2O_3	0.00–0.04	0.01	0.02	0.001		0.56–1.04	0.67	0.13	0.032	
Y_2O_3	0.18–0.62	0.33	0.13	0.010		0.14–0.36	0.22	0.06	0.007	
SnO_2	0.00–0.03	0.01	0.01	0.000		0.14–0.66	0.38	0.13	0.008	
Total		99.45					99.12			

studied minerals are given in a separate paper (Shimazaki *et al.*, 2008b).

3. Fergusonite-(Ce)

Fergusonite-(Ce), (Ce, La, Y)NbO_4, tetragonal, is also a relatively uncommon accessory mineral in Bayan Obo ores, and was found in three samples (Samples TS-7, TS-14, and TS-21) in the present study. Fergusonite-(Ce) usually occurs as reddish brown-colored, tiny grains with several tens microns diameter, rimming pyrochlore aggregates (TS-7) or near the boundary planes of monazite-(Ce) bands (TS-21). Fergusonite-beta-(Ce), monoclinic, is a mineral firstly described from the Bayan Obo deposit, and the material called fergusonite-(Ce) in the present study is possibly fergusonite-beta-(Ce). Fergusonite-(Ce) in TS-7 is in the metamict state with no X-ray diffraction peaks. Fergusonite-(Ce) in TS-14 gave extremely broad and weak X-ray diffractions. Owing to the crystallographic natures, it was impossible to determine their crystal systems, tetragonal or monoclinic for the present materials.

The analytical results of Fergusonite-(Ce) of TS-7 and TS-14 are shown in Table 4. Remarkable differences are present between the minerals from the two samples as to yttrium and thorium contents. Fergusonite-(Ce) of TS-21 shows moderate yttrium contents (0.77–1.70 Y_2O_3) and low thorium contents (0.11–0.45 ThO_2). Large variation in thorium contents of Bayan Obo fergusonite-(Ce) is also recognized by Zhang *et al.* (1995). It is worth noting that fergusonite-(Ce) in the present study is associated with humite group minerals, and is concordant with the description that the mineral occurs in "magnesian skarn" in the Bayan Obo deposit by Zhang and Tao (1986).

Plate 4 Photographs of samples (Y and Z) and some representative photomicrographs of minerals (1 to 6). Y and Z correspond to the samples TS-25 to TS-26. 1: Photomicrograph of zhangpeishanite in TS-11, taken in plane-polarized light. The width of photo is about 250 μm. 2: Photomicrograph of bafertisite in TS-21, taken in plane-polarized light. The width of photo is about 1 mm. 3 and 4: Photomicrographs of huanghoite-(Ce) in TS-13, taken in plane-polarized light and under crossed polars. The width of photo is about 1 mm. 5 and 6: Photomicrographs of phlogopite with reverse pleochroism in TS-13, taken in plane-polarized light. The latter photo shows 90° clockwise rotated position of the former photo. Note that the phlogopite crystal elongates along c-axis with the trace of basal cleavage perpendicular to the elongation. The width of photo is about 1 mm. Mineral names abbreviation is as follows. Bft: bafertisite, Cly: clayey material, Fbr: fluorbritholite-(Ce), Flr: fluorite, Fsd: Fe-sulfide, Gln: galena, Hgh: huanghoite-(Ce), Hgm: humite-group mineral, Phl: phlogopite, Rch: richterite, and Zpn: zhangpeishanite.

Table 4. Analytical results of fergusonite-(Ce) (TS-7, 5 analyses and TS-14, 11 analyses).

Sample	TS-7					TS-14				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=4)		Range (wt%)	Average	Std. dev.	No. of atoms (O=4)	
Nb_2O_5	43.66–45.48	44.74	0.65	0.993	1.00	44.01–47.14	45.56	0.74	1.005	1.01
Ta_2O_5	0.00–0.57	0.26	0.23	0.003		—	—	—	—	
La_2O_3	11.00–12.47	11.63	0.58	0.211		4.03–7.29	6.05	1.03	0.109	
Ce_2O_3	26.63–28.18	27.24	0.51	0.490		20.53–25.41	23.61	1.51	0.423	
Pr_2O_3	3.35–4.11	3.69	0.25	0.066		3.26–4.03	3.58	0.22	0.064	
Nd_2O_3	10.66–12.25	11.42	0.57	0.201		11.11–16.27	13.74	1.77	0.240	
Sm_2O_3	0.01–0.40	0.26	0.15	0.004		0.21–1.44	0.78	0.32	0.013	
Gd_2O_3	0.00–0.48	0.13	0.18	0.002	1.01	0.24–1.16	0.62	0.29	0.010	0.95
Dy_2O_3	0.02–0.13	0.07	0.04	0.001		0.49–1.07	0.74	0.15	0.007	
Y_2O_3	0.19–0.33	0.26	0.06	0.003		1.45–5.48	2.89	1.30	0.038	
CaO	0.31–0.57	0.43	0.08	0.023		0.13–0.92	0.41	0.23	0.021	
FeO	0.00–0.13	0.06	0.05	0.002		0.01–0.44	0.17	0.14	0.007	
ThO_2	0.30–0.61	0.48	0.14	0.005		0.52–4.74	1.81	1.52	0.020	
Total		100.67					99.96			

4. Aeschynite-group minerals

Aeschynite-group minerals, AB_2X_6-type REE and Nb-Ti oxides, are found in four samples, TS-16, TS-20, TS-21, and TS-22. Aeschynite-group minerals occur usually as tiny, yellowish brown to reddish brown grains under the microscope.

In most analyses, the number of cerium exceeds the number of neodymium, and the number of titanium exceeds the number of niobium, and the minerals belong to aeschynite-(Ce). However, analyses for TS-16 show almost equal amounts of cerium and neodymium, and they are named aeschynite-(Ce) or aeschynite-(Nd) by the predominance of cerium or neodymium as given in Table 5-1. On the contrary, among analyses for TS-22, one analysis shows the excess of niobium over titanium, and indicates the presence of niobo-aeschynite-(Ce) in part. The analytical results of aeschynite-(Ce) and niobo-aeschynite-(Ce) of TS-22 are given in Table 5-2. Yttrium and thorium contents are variable as seen in these tables.

In the monograph on minerals from the Bayan Obo deposit, Zhang and Tao (1986) put one chapter titled "Some mineralogical problems of aeschynite-group minerals of Bayan Obo and other places", and discussed about complexity of their chemical composition and classification. They recognized five species in Bayan Obo samples as aeschynite-(Ce), aeschynite-(Nd), niobo-aeschynite-(Ce), niobo-aeschynite-(Nd), and titanian aeschynite-(Ce). The first three were also recognized in the present study. If niobo-aeschynite-(Nd) is confirmed, it will be a new mineral, and it is thought to be highly possible on the basis of compositional ranges obtained in the present study. Yang *et al.* (2001) also recognized these four members of aeschynite-group minerals from the Bayan Obo deposit, and discussed the correlation among cations and coupled substitution in these minerals. Zhang and Tao (1986) described that aeschynite-group minerals in the Bayan Obo deposit are transparent under the microscope, but are amorphous in X-ray diffraction analyses due to metamictization.

5. Pyrochlore

Pyrochlore, $NaCaNb_2O_6(F, OH)$, was found in ten samples, TS-2 to TS-7, TS-15, TS-16, TS-21, and TS-23. Pyrochlore occurs usually as colorless to pale yellow, rounded grains, and is isotropic under the microscope. It is a common mineral in Bayan Obo ores, and is the most important niobium mineral in the mine.

Table 5-1. Analytical results of aeschynite-(Ce) and aeschynite-(Nd) (TS-16).

Sample	Aeschynite-(Ce)			Aeschynite-(Nd)		
	Wt%	No. of atoms (O=6)		Wt%	No. of atoms (O=6)	
TiO_2	25.59	1.179	2.02	27.00	1.258	2.06
Nb_2O_5	30.24	0.838		28.59	0.801	
La_2O_3	0.78	0.018	1.04	0.54	0.012	1.00
Ce_2O_3	12.15	0.273		12.71	0.289	
Pr_2O_3	3.13	0.070		2.82	0.064	
Nd_2O_3	12.35	0.271		14.44	0.320	
Sm_2O_3	2.31	0.049		2.57	0.055	
Gd_2O_3	1.95	0.040		1.76	0.036	
Dy_2O_3	1.25	0.025		0.92	0.018	
Er_2O_3	0.29	0.006		0.14	0.003	
Y_2O_3	4.25	0.139		2.20	0.073	
CaO	1.60	0.105		1.11	0.074	
FeO	0.46	0.024		0.31	0.016	
ThO_2	1.18	0.016		3.05	0.043	
Total	97.53			98.16		

Table 5-2. Analytical results of aeschynite-(Ce) and niobo-aeschynite-(Nd) (TS-22, 8 analyses and 1 analysis).

Sample	Aeschynite-(Ce)					Niobo-aeschynite-(Ce)		
	Range (wt%)	Average	Std. dev.	No. of atoms (O=6)		Wt %	No. of atoms (O=6)	
TiO_2	22.28–28.88	26.10	2.26	1.197	2.06	21.25	0.966	2.01
Nb_2O_5	29.08–36.88	31.24	3.07	0.862		38.20	1.045	
La_2O_3	2.43–3.33	3.00	0.32	0.068	1.02	2.40	0.054	1.05
Ce_2O_3	18.80–21.07	20.10	0.84	0.450		18.96	0.421	
Pr_2O_3	2.64–3.52	3.08	0.23	0.068		2.81	0.062	
Nd_2O_3	9.44–10.62	9.90	0.35	0.216		8.95	0.194	
Sm_2O_3	0.67–1.18	0.94	0.17	0.020		1.07	0.022	
Gd_2O_3	0.21–0.58	0.40	0.12	0.008		0.57	0.011	
Dy_2O_3	0.06–0.36	0.23	0.10	0.005		0.21	0.004	
Er_2O_3	0.00–0.58	0.07	0.08	0.001		0.12	0.002	
Y_2O_3	0.44–0.98	0.72	0.20	0.023		1.13	0.036	
CaO	1.77–2.36	2.00	0.19	0.131		3.20	0.208	
FeO	0.34–0.46	0.39	0.04	0.020		0.67	0.034	
ThO_2	0.27–0.54	0.42	0.08	0.006		0.12	0.002	
Total		98.59				99.66		

Representative results of chemical analyses of pyrochlore are given in Table 6. Titanium contents are very variable from sample to sample. Fluorine contents are also variable. Certain amounts of REE are always contained in the mineral. These varieties are also described by Zhang and Tao (1986).

6. Norsethite

Norsethite, $BaMg(CO_3)_2$, is a relatively uncommon accessory mineral in the Bayan Obo deposit, and was recognized in three samples, TS-11, TS-13, and TS-24. Norsethite occurs as tiny grains in fluorite, similar to zhangpeishanite, in TS-11, and as aggregates of grains of several tens to one hundred microns diameter in carbonatite parts of TS-13 and TS-24.

Table 6. Analytical results of pyrochlore (TS-3, 3 analyses and TS-7, 10 analyses).

Sample	TS-3					TS-7				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=6.5)		Range (wt%)	Average	Std. dev.	No. of atoms (O=6.5)	
Nb_2O_5	55.41–57.38	56.54	0.83	1.580		67.78–69.58	68.84	0.57	1.886	
TiO_2	7.56–8.89	8.23	0.54	0.382	1.96	0.24–0.45	0.31	0.06	0.014	1.91
Ta_2O_5	0.00–0.10	0.03	0.05	0.001		0.05–0.70	0.42	0.21	0.007	
Na_2O	6.25–6.67	6.48	0.18	0.777		4.93–5.44	5.12	0.14	0.601	
CaO	14.26–15.35	14.90	0.47	0.989		17.38–18.50	18.26	0.31	1.186	
FeO	0.22–0.56	0.36	0.14	0.019		1.51–1.85	1.71	0.10	0.086	
MnO	—	—	—	—		0.12–0.19	0.16	0.02	0.008	
MgO	—	—	—	—		0.05–0.12	0.08	0.02	0.008	
Al_2O_3	—	—	—	—		0.11–0.17	0.15	0.02	0.011	
Y_2O_3	0.37–0.49	0.41	0.05	0.013		0.00–0.26	0.11	0.08	0.003	
La_2O_3	0.64–0.86	0.74	0.09	0.017	2.04	0.55–0.87	0.7	0.09	0.016	1.99
Ce_2O_3	5.10–6.06	5.58	0.39	0.126		1.94–2.33	2.14	0.15	0.047	
Pr_2O_3	0.65–1.06	0.88	0.17	0.020		0.00–0.34	0.16	0.11	0.004	
Nd_2O_3	2.16–3.24	2.73	0.44	0.060		0.36–0.69	0.52	0.09	0.011	
Sm_2O_3	0.14–0.36	0.26	0.09	0.006		0.00–0.19	0.06	0.07	0.001	
Gd_2O_3	—	—	—	—		0.00–0.46	0.09	0.17	0.002	
Dy_2O_3	0.13–0.21	0.17	0.03	0.003		—	—	—	—	
ThO_2	0.38–0.85	0.69	0.22	0.010		0.04–0.59	0.29	0.15	0.004	
F	3.80–4.17	4.03	0.17	0.788	0.79	4.13–4.42	4.26	0.08	0.817	0.33
O=F		−1.70						−1.79		
Total		100.33						101.59		

Table 7. Analytical results of norsethite (TS-24, 5 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms (O=2)	
BaO	50.17–51.48	50.91	0.42	0.846	
CaO	0.35–0.47	0.42	0.04	0.019	0.90
SrO	0.34–0.43	0.37	0.03	0.009	
Na_2O	0.16–0.26	0.20	0.04	0.017	
TiO_2	0.11–0.23	0.17	0.04	0.005	
MgO	15.57–16.86	16.20	0.41	1.024	1.11
FeO	0.94–1.40	1.15	0.16	0.041	
MnO	0.98–1.27	1.15	0.11	0.041	
CO_2*		34.50		2	
Total		105.07			

* Calculated on the basis of ideal formula (C=2).

Representative results of chemical analysis of norsethite are given in Table 7. Compared to the ideal composition, a relatively large amount of MgO was determined in the analysis.

7. Bastnäsite-(Ce)

Bastnäsite-(Ce), $(Ce, La, Nd)(CO_3)F$, was found in 15 samples, TS-9, TS-10, TS-12, TS-13, TS-15 to TS-18, and TS-20 to TS-26. Bastnäsite-(Ce) occurs usually as transparent, colorless grains with high indices and high birefringence under the microscope. It is a common mineral in Bayan Obo ores, and is one of the most important REE minerals in the mine.

Bastnäsite-(Ce) frequently occurs with other fluorocarbonate minerals like parisite, cordylite, and huanghoite. In particular, the assemblage of bastnäsite-(Ce) and parisite-(Ce) is common, and observed in half of samples which contain bastnäsite-(Ce).

Results of chemical analyses of bastnäsite-(Ce) in the sample TS-17 are given in Table 8-1. In the table, two kinds of bastnäsite-(Ce), “Ca-free” and “Ca-bearing”, are given. All analytical results of bastnäsite-(Ce) in the samples other than TS-17, are similar to that of “Ca-free” in Table 8-1. Only in TS-17, “Ca-bearing” bastnäsite-(Ce) is recognized as shown in the table. The phase has high CaO content with low F content and low total weight percents. This variation is interpreted as that some synchysite-(Ce), $CaCe(CO_3)_2F$, layers are regularly stacked in bastnäsite-(Ce) structure (e.g. Yang *et al.*, 1998). Following to this change, the La content decreases drastically, and those of other RE elements, such as Pr and Nd, markedly increase. In the sample TS-17, these two kinds of bastnäsite-(Ce) coexist without those of any intermediate compositions between them.

In the present study, bastnäsite-(La) was also recognized in sample TS-21. The analytical results are shown in Table 8-2. In this sample, the other REE carbonates, such as, parisite, cordylite, and huanghoite, are present. However, none of them showed the predominance of La over Ce.

As stated above, most analytical results show that the studied bastnäsite-(Ce) is “Ca-free”, and generally contain a relatively large amount La and a small amount of Nd. However, the La and Nd contents are variable sample to sample, and bastnäsite-(Ce) with relatively low La and high Nd contents is also present as shown in Table 8-2 (sample TS-12).

Zhang and Tao (1986) reported in detail bastnäsites-(Ce) from the Bayan Obo deposit. They recognized bastnäsite-(Ce) only, but neither bastnäsite-(La), bastnäsite-(Nd), nor bastnäsite-(Y). According to their description, the distribution of REE in their samples of bastnäsite-(Ce) is mostly Ce>La>Nd, whereas some of them show Ce>Nd>La.

8. Parisite-(Ce)

Parisite-(Ce), $CaCe_2(CO_3)_3F_2$, was found in eight samples, TS-10, TS-16, TS-17, TS-20, TS-21, TS-23 and TS-24. Parisite-(Ce) occurs usually as transparent, colorless small grains with high indices and high birefringence under the microscope. It is a relatively common REE mineral in Bayan Obo ores.

Representative results of chemical analyses of this mineral in the sample TS-24 are given in Table 9. In all analytical results of the mineral in the present study indicate that fluorine is strongly depleted, and only reaches to 4.5 wt% at the maximum. However, in the description by Zhang and Tao (1986), this kind of F depletion was not recognized.

9. Cordylite-(Ce)

Cordylite was defined previously as $BaCe_2(CO_3)_3F_2$ for a long time (e.g. Gains *et al.*, 1997), but redefined as $(Na_{1-x}Ca_{x/2})BaCe_2(CO_3)_4F$ by Giester *et al.* (1998). This mineral is common in the Bayan Obo deposit, and Fu and Su (1987) determined its chemical composition as $NaBaCe_2(CO_3)_4F$, and named it baiyuneboite. In addition, Shen and Mi (1991) determined crystal structure of the mineral with chemical composition of $(Ca_{0.5}\square_{0.5})BaCe_2(CO_3)_4F$ from this deposit, and they proposed in 1992 a general chemical formula of cordylite as $(Na_{1-x}Ca_{x/2})BaCe_2(CO_3)_4F$. Giester *et al.* (1998) checked the minerals from four localities, including those from type locality and the Bayan Obo deposit, and authorized this formula.

This mineral was found in four samples, TS-13, TS-21, TS-24, and TS-25 in the present study. The appearance under the microscope is quite similar to those of other fluorocarbonates like bastnäsite and parisite. The results of chemical analyses of cordylite-(Ce) from these four samples indicate that there are two significant characteristics on the chemical formula of this mineral. One is a deficiency of fluorine, and the other is an excess of calcium. The sample in TS-21 gave an X-ray diffraction pattern identical to

Table 8-1. Analytical results of bastnäsite-(Ce) (TS-17, 9 analyses for Ca-free and 6 analyses for Ca-bearing).

Sample	TS-17 (Ca-free)					TS-17 (Ca-bearing)				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=1.5)		Range (wt%)	Average	Std. dev.	No. of atoms (O=1.5)	
La_2O_3	29.78–39.76	33.10	3.12	0.446		12.38–13.70	13.23	0.45	0.172	
Ce_2O_3	29.93–36.39	33.92	1.96	0.453		30.12–33.60	32.14	1.15	0.415	
Pr_2O_3	1.43–2.37	2.00	0.29	0.027		3.84–4.46	4.23	0.20	0.054	
Nd_2O_3	3.56–5.97	5.13	0.78	0.067		12.56–14.57	13.75	0.66	0.173	
Sm_2O_3	0.04–0.32	0.22	0.08	0.003		0.79–1.30	0.96	0.17	0.012	
Gd_2O_3	0.00–0.38	0.09	0.13	0.001		0.18–0.89	0.40	0.23	0.005	
Tb_2O_3	—	—	—	—	1.00	—	—	—	—	1.07
Dy_2O_3	—	—	—	—		0.00–0.22	0.08	0.09	0.001	
Er_2O_3	—	—	—	—		—	—	—	—	
Y_2O_3	0.00–0.11	0.04	0.04	0.001		0.07–0.51	0.28	0.16	0.005	
ThO_2	0.00–0.09	0.02	0.03	0.000		0.91–1.28	1.15	0.12	0.009	
CaO	0.05–0.22	0.09	0.05	0.004		4.76–5.71	5.41	0.31	0.204	
SrO	0.00–0.04	0.01	0.01	0.000		0.81–1.12	0.98	0.11	0.02	
BaO	0.00–0.16	0.04	0.06	0.001		0.00–0.33	0.13	0.13	0.002	
F	8.28–8.72	8.48	0.16	0.979	1	6.79–8.29	7.61	0.46	0.849	1
H_2O*		0.09		0.021			0.64		0.151	
O=F		−3.57					−3.20			
CO_2*		20.07		1			20.77		1	
Total		99.73					98.56			

* Calculated on the basis of ideal formula (F+OH=1, C=1).

Table 8-2. Analytical results of bastnäsite-(La) (TS-21, 7 analyses) and bastnäsite-(Ce) (TS-12, 5 analyses).

Sample	TS-21					TS-12				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=1.5)		Range (wt%)	Average	Std. dev.	No. of atoms (O=1.5)	
La_2O_3	35.09–36.58	35.86	0.46	0.482		15.06–19.75	16.93	1.78	0.230	
Ce_2O_3	31.25–32.18	31.80	0.31	0.424		36.01–37.00	36.46	0.41	0.493	
Pr_2O_3	1.57–2.01	1.75	0.14	0.023		3.66–4.42	4.09	0.33	0.055	
Nd_2O_3	4.67–4.92	4.81	0.08	0.063		12.19–15.32	14.02	1.22	0.185	
Sm_2O_3	0.00–0.45	0.23	0.14	0.003		0.73–1.20	0.97	0.17	0.012	
Gd_2O_3	—	—	—	—		0.03–0.42	0.19	0.16	0.002	
Tb_2O_3	—	—	—	—		—	—	—	—	
Dy_2O_3	—	—	—	—	1.00	0.00–0.16	0.10	0.06	0.001	1.01
Er_2O_3	—	—	—	—		—	—	—	—	
Y_2O_3	—	—	—	—		0.15–0.34	0.25	0.08	0.005	
ThO_2	0.05–0.34	0.19	0.10	0.002		0.03–0.19	0.13	0.06	0.001	
CaO	0.06–0.25	0.13	0.06	0.005		0.26–0.91	0.50	0.25	0.020	
SrO	0.00–0.05	0.03	0.02	0.001		0.00–0.07	0.02	0.03	0.000	
BaO	—	—	—	—		0.00–0.39	0.13	0.16	0.002	
F	8.91–9.28	9.05	0.12	1.042	1.04	7.76–7.98	7.88	0.01	0.919	1
H_2O		—		0			0.33		0.081	
O=F		−3.81					−3.32			
CO_2*		20.11		1			19.857		1	
Total		100.15					98.54			

* Calculated on the basis of ideal formula (F+OH=1, C=1).

Table 9. Analytical results of parisite-(Ce) (TS-24, 8 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms (O=4)	
CaO	9.75–10.75	10.38	0.36	1.012	
SrO	0.09–0.48	0.29	0.12	0.015	1.03
BaO	0.00–0.19	0.07	0.07	0.003	
La_2O_3	13.72–14.96	14.24	0.43	0.478	
Ce_2O_3	29.28–30.62	29.80	0.42	0.992	
Pr_2O_3	3.19–3.75	3.38	0.16	0.112	
Nd_2O_3	10.57–12.05	11.24	0.46	0.365	
Sm_2O_3	0.49–0.74	0.60	0.08	0.019	1.98
Gd_2O_3	0.00–0.37	0.16	0.14	0.005	
Tb_2O_3	0.00–0.16	0.05	0.05	0.002	
Dy_2O_3	0.00–0.08	0.03	0.03	0.001	
Er_2O_3	0.00–0.17	0.06	0.05	0.002	
Y_2O_3	0.00–0.18	0.11	0.07	0.005	
F	4.18–4.53	4.40	0.13	1.266	2
H_2O*		1.21		0.734	
O=F		−1.85			
CO_2*		24.16		3	
Total		98.33			

* Calculated on the basis of ideal formula (F+OH=2, C=3).

the database (ICDD #27–34).

Representative analytical results are given in Table 10, and the number of atoms in the chemical formula is calculated on the basis of 4.5 oxygen atoms except CO_2. As shown in the table, fluorine occupies only about 76 to 85% of the site, and this is a common feature through all cordylites analyzed in the present study. The number of sodium is 0.4 to 0.45, and the number of calcium is always excess over the value given by (1−Na)/2 (Table 10). The latter feature indicates the necessity of re-definition of this mineral as to the calcium content, in particular, the mineral with more than 0.4 Ca in the (Na, Ca) site, as exemplified by TS-21 in Table 10.

The deficiency of fluorine and the excess of calcium bring the excess of positive charge. One solution is to suppose that oxygen could replace fluorine, such as $(Ca,Na)BaCe_2(CO_3)_4(O,OH,F)$. However, according to the results of TS-21 (Table 10), the excess of positive charge is possibly compensated by the deficiency of REE. Obviously further study is necessary on cordylites from the Bayan Obo deposit.

As to the distribution of REE in cordylites in the deposit, Zhang and Tao (1986) recognized two types, such as Ce>La>Nd and Ce>Nd>La. In the present study, this tendency is also noticed. For example, the mineral from TS-13 shows Ce>Nd>La (Table 10), but cordylites from other three samples show Ce>La>Nd. In particular, the sample TS-21 includes bastnäsite-(La), and shows relative enrichment of lanthanum in the sample (Table 10).

10. Huanghoite-(Ce)

Huanghoite-(Ce), $BaCe(CO_3)_2F$, is a common fluorocarbonate mineral in the Bayan Obo deposit, and found in six samples (TS-9, TS-13, TS-18, TS-21, TS-24, and TS-25) in the present study. The appearance under the microscope is similar to common carbonate minerals, and show parallel, elongated rectangular shape, indicating that the mineral makes parallel aggregates of platy crystals (Plates 4-3 and 4-4).

Representative results of chemical analyses are shown in Table 11. Most of obtained analyses are similar to that given in Table 11. The ratio of barium to REE is almost 1 : 1, but fluorine is always deficient, and occupies only 50 to 60% of the site. The rest could be OH radical. However, such a large deficiency of fluorine was not recognized

Table 10. Analytical results of cordylite-(Ce) (TS-13, 5 analyses and TS-21, 10 analyses).

Sample	TS-13					TS-21				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=4.5)		Range (wt%)	Average	Std. dev.	No. of atoms (O=4.5)	
BaO	23.63–25.77	24.59	0.77	1.094	1.09	23.75–26.39	25.52	0.84	1.096	1.10
Na_2O	1.80–2.22	2.00	0.14	0.439		1.73–2.17	1.89	0.14	0.401	
SrO	1.07–1.40	1.27	0.11	0.084	0.72	0.31–0.52	0.46	0.07	0.029	0.73
CaO	2.13–3.92	3.15	0.64	0.383		4.46–4.81	4.65	0.12	0.546	
La_2O_3	5.80–7.17	6.44	0.55	0.270		18.10–19.50	18.94	0.46	0.766	
Ce_2O_3	19.32–22.15	20.94	0.93	0.871		18.59–19.93	19.20	0.51	0.770	
Pr_2O_3	2.76–3.97	3.36	0.40	0.139		1.01–1.87	1.49	0.30	0.060	
Nd_2O_3	11.37–14.05	12.09	1.03	0.490		3.52–3.92	3.66	0.14	0.143	
Sm_2O_3	0.40–0.95	0.70	0.21	0.027	2	0.08–0.30	0.15	0.07	0.006	2
Gd_2O_3	0.02–0.34	0.17	0.14	0.006		0.00–0.15	0.05	0.05	0.002	
Tb_2O_3	—	—	—	—		—	—	—	—	
Dy_2O_3	0.00–0.14	0.03	0.06	0.001		—	—	—	—	
Er_2O_3	—	—	—	—		—	—	—	—	
Y_2O_3	0.00–0.13	0.04	0.05	0.002		0.00–0.14	0.07	0.05	0.004	
ThO_2	0.00–0.34	0.18	0.11	0.005		0.00–0.16	0.06	0.07	0.001	
F	2.17–2.72	2.36	0.19	0.847	1	2.13–2.23	2.18	0.04	0.755	1
H_2O*		0.20		0.153			0.33		0.245	
O=F		−0.99					−0.92			
CO_2*		25.80		4			26.73		4	
Total		102.33					104.46			

* Calculated on the basis of the general formula (Na, Ca, □)Ba(Ce, Ca)$_2$(CO_3)$_4$F

in previous works (e.g. Zhang and Tao, 1986).

As mentioned previously, the sample TS-21 is relatively enriched in lanthanum, and this nature is markedly indicated in huanghoite-(Ce) analyses, too (Table 11).

11. Cebaite-(Ce)

In addition to huanghoite, a rare earth fluorocarbonate with higher barium contents was recognized in the TS-21. It was identified as cebaite-(Ce), $Ba_3Ce_2(CO_3)_5F_2$, with the chemical composition and X-ray diffraction pattern. The deficiency of fluorine, ca. 1.2 in the empirical formula, indicates a replacement of F with (OH) in cebaite-(Ce) from Bayan Obo. Some grains showed La-dominance over Ce (Table 12) among the rare earth elements.

12. Calcioancylite-(Ce)

The mineral in the sample TS-25 with a considerable amount of strontium gives an X-ray diffraction pattern identical to those of ancylite-(Ce), calcioancylite-(Ce) and kozoite-(Nd). It is calcioancylite-(Ce) having a chemical composition of solid solution towards to ancylite-(Ce), indicating that more than 35% of the Ca site is replaced by Sr (Table 13). It is richer in rare earth elements in comparison to the ideal composition, [CaCe]$(CO_3)_2$[(OH)(H_2O)]. A part of (OH) is replaced with F suggesting a fluorine end member in ancylite group minerals, [CaCe]$(CO_3)_2$[F(H_2O)].

13. Fluorbritholite-(Ce)

Fluorbritholite-(Ce), (Ce, Ca)$_5$[(Si, P)O_4]$_3$(F, OH), is a relatively common accessory mineral in the Bayan Obo deposit, and appears with or without fluorapatite. The mineral is observed in five samples (TS-2, TS-12, TS-13, TS-21, and TS-25), as rounded, short prismatic grains, very similar to apatite in appearance under the microscope (Plate 4-5 and 4-6).

Representative results of chemical analyses are shown in Table 14. In most analyses, the number

Table 11. Analytical results of huanghoite-(Ce) (TS-21, 7 analyses and TS-24, 6 analyses).

Sample	TS-21					TS-24				
	Range (wt%)	Average	Std. dev.	No. of atoms (M=2)		Range (wt%)	Average	Std. dev.	No. of atoms (M=2)	
BaO	34.25–37.49	35.44	1.02	0.965		38.02–39.04	38.43	0.32	1.010	
CaO	0.08–0.29	0.17	0.09	0.012	0.99	0.08–0.14	0.11	0.02	0.008	1.02
Na_2O	0.00–0.08	0.05	0.02	0.007		—	0.00	—	0.000	
SrO	0.02–0.26	0.12	0.08	0.005		0.01–0.15	0.09	0.05	0.003	
La_2O_3	11.56–16.07	14.04	1.65	0.360		8.70–10.53	10.03	0.62	0.248	
Ce_2O_3	18.18–19.55	18.94	0.41	0.482		19.02–20.25	19.58	0.44	0.481	
Pr_2O_3	1.34–2.09	1.65	0.22	0.042		2.13–2.56	2.32	0.15	0.057	
Nd_2O_3	3.66–6.38	4.62	1.00	0.115		7.01–8.78	7.61	0.60	0.182	
Sm_2O_3	0.00–0.52	0.27	0.18	0.006	1.01	0.00–0.55	0.25	0.20	0.006	0.98
Gd_2O_3	0.00–0.34	0.08	0.12	0.002		0.02–0.23	0.11	0.08	0.002	
Tb_2O_3	—	—	—	—		—	0.00	—	—	
Dy_2O_3	—	—	—	—		—	0.00	—	—	
Er_2O_3	—	—	—	—		—	0.00	—	—	
Y_2O_3	0.00–0.28	0.11	0.11	0.004		0.00–0.13	0.03	0.05	0.001	
ThO_2	—	—	—	—	0.00	0.00–0.28	0.12	0.11	0.002	0.00
F	2.77–3.54	3.01	0.23	0.662	1	2.39–2.81	2.72	0.15	0.576	1
H_2O*		0.73		0.338			0.95		0.424	
O=F		−1.27					−1.14			
CO_2*		21.08		2			21.84		2	
Total		99.04					103.05			

* Calculated on the basis of an ideal formula (F+OH=1, C=2).

Table 12. Analytical results of cebaite-(La) (TS-21, 3 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms (M=5)	
BaO	42.47–43.07	42.84	0.26	2.847	
CaO	0.27–0.32	0.30	0.02	0.055	2.95
Na_2O	0.07–0.11	0.09	0.01	0.030	
SrO	0.17–0.33	0.23	0.07	0.022	
La_2O_3	13.89–16.93	14.94	1.41	0.934	
Ce_2O_3	13.10–15.22	14.24	0.87	0.884	
Pr_2O_3	0.85–1.42	1.12	0.23	0.069	
Nd_2O_3	1.84–2.79	2.44	0.43	0.148	
Sm_2O_3	0.00–0.17	0.06	0.08	0.003	2.05
Gd_2O_3	0.00–0.24	0.11	0.10	0.006	
Tb_2O_3	—	—	—	—	
Dy_2O_3	—	—	—	—	
Er_2O_3	—	—	—	—	
Y_2O_3	0.00–0.02	0.01	0.01	0.001	
F	2.19–2.38	2.29	0.08	1.228	1.95
H_2O*		4.42		0.726	
O=F		−0.96			
CO_2*		21.60		5	
Total		103.73			

* Calculated on the basis of an ideal formula (OH=(2−F)+(REE^{3+}−2), C=5).

Table 13. Analytical results of calcioancylite-(Ce) (TS-25, 8 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms (M=2)	
CaO	4.65–6.81	5.80	0.76	0.395	
SrO	5.76–8.69	7.13	0.96	0.262	0.67
BaO	0.26–0.70	0.47	0.14	0.012	
La_2O_3	17.03–22.09	19.40	1.48	0.454	
Ce_2O_3	26.11–30.10	28.59	1.32	0.665	
Pr_2O_3	2.14–2.91	2.48	0.22	0.057	
Nd_2O_3	5.21–7.65	6.33	0.72	0.143	
Sm_2O_3	0.03–0.49	0.30	0.15	0.006	1.33
Gd_2O_3	0.00–0.32	0.17	0.11	0.004	
Tb_2O_3	—	—	—	—	
Dy_2O_3	—	—	—	—	
Er_2O_3	—	—	—	—	
Y_2O_3	—	—	—	—	
ThO_2	0.00–0.27	0.10	0.10	0.001	
F	2.09–2.95	2.50	0.25	0.503	
O=F		−1.05			
CO_2*		23.07		2	
H_2O*		5.11		2.164	
Total		100.40			

* Calculated on the basis of ideal formula ($H_2O=M^{2+}$, $OH^-=REE^{3+}$, C=2).

of fluorine in the unit formula is nearly one or more, and confirms that the mineral belongs to fluorbritholite. As shown in Table 14 (TS-12), essentially P_2O_5-free fluorbritholites are present in the studied samples. The end-member of fluorbritholite-(Ce) could be expressed as $Ce_3Ca_2(SiO_4)_3F$, and the number of calcium in the unit formula could not be less than two. However, as shown in the table, some analyses show a deficiency of calcium, much less than two. Excess of positive charge by REE over three seems to be compensated by producing a vacant position, such as that the total number of Ca and REE are less than five.

In the monograph by Zhang and Tao (1986), two examples of britholite-(Ce) analyses are given. One has an excess, 4.50 wt%, fluorine, to be fluorbritholite-(Ce), and the other is F-free, obviously to be britholite-(Ce).

14. Gadolinite-(Ce)

Gadolinite-(Ce), $Ce_2Fe^{2+}Be_2Si_2O_{10}$, is usually found in alkali pegmatites and alkali granites, and has not yet been reported from the Bayan Obo deposit. Through the study on sample TS-12, some REE minerals are recognized as scattered around tremolite-richterite aggregates. Among them, a REE-bearing mineral with much amount of Si, with low amount of Ca, and actually free from Ti and P, is noticed as tiny grains. The chemical composition clearly indicates that the mineral could not be chevkinite-perrierite-(Ce), monazite-(Ce), bastnäsite-(Ce), or fluorbritholite-(Ce), but is possibly gadolinite-(Ce). The X-ray diffraction pattern of this grain gave a pattern of gadolinite-datolite group mineral. Although beryllium could not be analyzed at present, the analytical results are very consistent to the consideration that this is gadolinite-(Ce), the Ce-predominant member of the gadolinite-datolite group, as shown in Table 15.

15. Bafertisite

Bafertisite, $BaFe_2^{2+}TiOSi_2O_7(OH,F)_2$, was a rare mineral firstly described from the Bayan Obo deposit, and was found only in one sample (TS-21) in the present study. Under the microscope, the mineral occurs as brown, tiny, elongated crystals associated with huanghoite (Plate 4-2).

Table 14. Analytical results of fluorbritholite-(Ce) (TS-12, 11 analyses and TS-21, 9 analyses).

Sample	TS-12					TS-21				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=12.5)		Range (wt%)	Average	Std. dev.	No. of atoms (O=12.5)	
CaO	6.66–8.38	7.66	0.60	1.133		13.62–14.85	14.03	0.41	2.028	
FeO	0.14–0.40	0.24	0.04	0.028		0.09–0.30	0.18	0.07	0.020	
La_2O_3	12.08–19.13	15.89	0.85	0.807		13.71–16.70	15.44	1.66	0.766	
Ce_2O_3	32.55–35.02	33.41	1.33	1.687		29.12–30.44	28.78	3.17	1.420	
Pr_2O_3	3.46–4.60	4.03	0.18	0.202		2.89–3.67	3.18	0.24	0.156	
Nd_2O_3	10.64–16.84	13.61	1.01	0.671		8.76–10.35	9.57	0.45	0.461	
Sm_2O_3	0.59–1.79	1.07	0.25	0.051	4.63	0.61–1.10	0.83	0.14	0.039	5.05
Eu_2O_3	—	—	—	—		0.50–0.82	0.66	0.10	0.030	
Gd_2O_3	0.00–0.78	0.32	0.19	0.015		0.09–0.86	0.53	0.21	0.024	
Tb_2O_3	—	—	—	—		0.00–0.21	0.08	0.07	0.004	
Dy_2O_3	0.00–0.18	0.10	0.11	0.004		0.31–0.68	0.48	0.11	0.021	
Y_2O_3	0.07–0.57	0.27	0.15	0.020		0.86–1.20	1.04	0.10	0.074	
ThO_2	0.02–1.06	0.32	0.13	0.010		0.00–0.29	0.14	0.10	0.004	
SiO_2	21.53–22.58	22.20	0.59	3.065	3.07	18.50–20.01	19.34	0.48	2.607	2.90
P_2O_5	0.00–0.05	0.01	0.53	0.001		1.97–3.36	2.59	0.44	0.295	
F	1.93–2.69	2.39	0.39	1.042	1.04	2.29–3.57	2.57	0.40	1.094	1.09
O=F		−1.01					−1.08			
Total		100.51					98.36			

The results of chemical analyses are shown in Table 16. Some amounts of manganese are present in the mineral as Zhang and Tao (1986) described.

16. Chevkinite-Perrierite-(Ce)

Chevkinite-perrierite group minerals have relatively complicated chemical compositions, with a general formula of $A_4BC_4(Si_2O_7)_2O_8$, where A=Ca, REE, Th; B=Fe, Mn, Mg; and C=Ti, Mg, Fe, Al. The mineral seems relatively rare in the Bayan Obo deposit, and was found in two samples (TS-12 and TS-20) in the present study. Under the microscope, the mineral occurs as brown, tiny, elongated grains of several tens to 100 microns long, closely associated with other REE minerals like monazite-(Ce), bastnäsite-(Ce), and fluorbritholite-(Ce) (TS-12), or accompanied with magnetite aggregates (TS-20). The results of chemical analyses of the minerals in TS-12 and TS-20 are given in Table 17.

The relationship between chevkinite and perrierite, whether dimorphs or not, has been controversial for a long time. A single-crystal diffraction work is the conclusive determination of the type of crystal structure, chevkinite or perrierite, for these minerals (e.g., the crystal structure of rengeite with the perrierite structure; Miyawaki *et al.*, 2002). However, the X-ray diffraction technique could not be applied to a single crystal of the material due to its scarcity and fine grain size. According to the discrimination diagram with a criterion of the relative abundance of CaO and FeO* for distinguishing between the two minerals, which was proposed by Macdonald and Belkin (2002), Shimazaki *et al.* (2008b) assigned the minerals in TS-12 and TS-20 as chevkinite-(Ce) and perrierite-(Ce), respectively. These two minerals were also identified from the Bayan Obo deposit in previous works; chevkinite-(Ce) (Zhang and Tao, 1986) and perrierite-(Ce) (Zhang *et al.*, 1995).

17. Baotite

Baotite, $Ba_4(Ti,Nb,Fe^{3+})_8O_{16}(Si_4O_{12})Cl$, is also a rare mineral firstly found in the Bayan Obo area, and found in one sample (TS-5) in the present study. It occurs as tiny, brownish grains, and is pleochroic under the microscope.

The results of chemical analyses of the mineral

Table 15. Analytical results of gadolinite-(Ce) (TS-12, 7 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms*	
FeO	6.91–7.69	7.31	0.23	0.543	0.80
MgO	1.73–2.02	1.91	0.09	0.253	
La_2O_3	11.06–12.81	11.65	0.56	0.382	1.94
Ce_2O_3	26.70–28.85	27.62	0.73	0.899	
Pr_2O_3	3.27–3.78	3.48	0.20	0.113	
Nd_2O_3	11.15–13.43	12.70	0.71	0.403	
Sm_2O_3	0.78–1.46	1.14	0.18	0.035	
Gd_2O_3	0.00–0.48	0.17	0.17	0.005	
Dy_2O_3	0.46–0.64	0.57	0.06	0.016	
Y_2O_3	0.04–0.37	0.18	0.11	0.009	
CaO	0.61–1.09	0.76	0.15	0.072	
ThO_2	0.06–0.35	0.20	0.09	0.004	
SiO_2	22.73–24.19	23.21	0.50	2.062	2.06
BeO**		9.37		2	2
H_2O**		0.69		0.407	
Total		100.96			

* (Si+REE+Ca+Th=4)
** Calculated on the basis of ideal formula.

Table 16. Analytical results of bafertisite (TS-21, 3 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms (O=9)	
BaO	26.86–28.82	27.60	0.87	0.932	1.05
CaO	0.34–1.82	1.03	0.61	0.095	
Na_2O	0.10–0.15	0.12	0.02	0.020	
FeO	23.79–24.60	24.15	0.34	1.739	1.98
MnO	3.08–3.46	3.32	0.17	0.242	
TiO_2	12.93–13.90	13.45	0.40	0.872	0.92
Nb_2O_5	0.86–1.33	1.10	0.19	0.043	
Ta_2O_5	—	—	—	—	
SiO_2	23.73–24.43	24.00	0.30	2.067	2.07
F	1.81–1.91	1.86	0.04	0.505	2
H_2O*		2.60		1.495	
O=F		−0.78			
Total		98.45			

* Calculated on the basis of ideal formula (F+OH=−2).

in TS-5 are given in Table 18. An excess of number of atoms in the site for Ti, Nb, and ferric iron, is recognized. However, the presence of Ba, Si, and Cl, with adequate numbers of atoms, that is 4 : 4 : 1, confirms that this is baotite. It is reported that the mineral mainly occurs along quartz veins in siliceous sedimentary rocks, but occurs also in the Main and East orebodies with aegirine, richterite, and albite (Zhang and Tao, 1986), and the occurrence in TS-5 seems to correspond to the latter case.

18. Phlogopite-group minerals

Phlogopite, $KMg_3AlSi_3O_{10}(F, OH)_2$, and related minerals are common in the deposit, and observed in 15 samples in the present study, such as, in TS-2, TS-3, TS-6 to TS-9, TS-12, TS-13, TS-15, TS-17, TS-19, TS-22, and TS-24 to TS-26. Subhedral to euhedral, platy crystals of several tens to several hundreds microns are common,

Table 17. Analytical results of chevkinite-(Ce) (TS-12, 4 analyses) and perrierite-(Ce) (TS-20, 10 analyses).

Sample	TS-12				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=22)	
La_2O_3	13.74–18.02	15.90	1.881	1.231	
Ce_2O_3	23.47–25.97	24.64	0.885	1.895	
Pr_2O_3	1.81–2.45	2.18	0.238	0.167	
Nd_2O_3	6.07–7.53	7.05	0.969	0.529	
Sm_2O_3	0.05–0.51	0.31	0.168	0.022	3.99
Gd_2O_3	0.00–0.21	0.07	0.086	0.005	
Dy_2O_3	0.00–0.20	0.07	0.081	0.005	
ThO_2	0.00–0.20	0.07	0.082	0.003	
CaO	0.39–0.91	0.57	0.208	0.128	
Y_2O_3	0.00–0.12	0.05	0.052	0.006	
FeO	8.98–9.78	9.48	0.310	1.000 / 0.661	1.00
TiO_2	14.56–15.73	15.00	0.439	2.365	4.17
Al_2O_3	0.38–2.29	1.70	0.771	0.421	
MgO	1.45–1.61	1.53	0.057	0.722	
SiO_2	19.57–20.98	20.38	0.512	4.285	4.29
Total		99.00			

Sample	TS-20				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=22)	
La_2O_3	7.19–9.11	8.31	0.696	0.610	
Ce_2O_3	17.89–20.61	19.81	0.483	1.445	
Pr_2O_3	1.97–2.51	2.27	0.166	0.165	
Nd_2O_3	6.83–7.70	7.20	0.289	0.513	
Sm_2O_3	0.22–0.64	0.40	0.116	0.028	4.07
Gd_2O_3	0.00–0.45	0.15	0.135	0.010	
Dy_2O_3	0.00–0.17	0.05	0.061	0.003	
ThO_2	0.01–0.25	0.08	0.079	0.004	
CaO	3.95–5.19	4.73	0.407	1.010	
SrO	1.87–2.68	2.41	0.245	0.277	
FeO	5.23–8.61	6.68	0.925	1.000 / 0.110	1.00
TiO_2	17.01–18.34	17.70	0.061	2.647	
Nb_2O_5	0.16–0.92	0.49	0.220	0.044	3.84
Sc_2O_3	2.82–3.64	3.26	0.255	0.565	
Al_2O_3	1.30–2.59	2.03	0.356	0.476	
SiO_2	20.50–21.75	21.14	0.453	4.215	4.22
Total		96.71			

Table 18. Analytical results of baotite (TS-5, 5 analyses).

	Range (wt%)	Average	Std. dev.	No. of atoms (O=29)	
BaO	35.73–39.02	37.51	1.18	3.865	3.90
MnO	0.07–0.26	0.16	0.06	0.036	
TiO_2	27.70–31.45	30.14	1.43	5.939	
Nb_2O_5	13.02–14.70	13.75	0.80	1.630	8.21
Ta_2O_5	0.00–0.35	0.14	0.13	0.010	
Fe_2O_3	2.73–3.75	3.18	0.40	0.627	
SiO_2	15.30–16.11	15.57	0.28	4.091	4.09
Cl	2.08–2.14	2.12	0.03	0.941	0.94
O=Cl		−0.48			
Total		102.09			

and usually show colorless to light brown pleochroism under the microscope. It is worthy to note that phlogopites in a few specimens (e.g. TS-13, TS-24, and TS-25) show unusual, reverse pleochroism, that is, Z′=colorless and X′=light brown. Some grains are elongated along c-axis with the trace of basal cleavage perpendicular to the elongation (Plates 4-5 and 4-6). It is known that the phlogopite with this optical anomaly has been described from kimberlites and carbonatites (e.g. Shinno and Suwa, 1981), and reverse pleochroism in Fe^{2+}- and Fe^{3+}-bearing phlogopite is attributed to tetrahedrally coordinated ferric iron.

Chemical composition of phlogopites and related minerals in the studied samples shows rather complicated feature. Almost half of the analytical results show chemical composition close to normal phlogopite, $KMg_3AlSi_3O_{10}(OH,F)_2$. However, even in those analyses, some excess of silica and some deficiency of alumina are commonly observed as shown in Table 19-1, reflecting Al-depleted nature of the mineralization in Bayan Obo. The rest of analyses, of unusual phlogopite, could be divided into two groups, Ba-bearing group and Si-rich group.

The Ba-bearing phlogopite is known as kinoshitalite, and ideal chemical formula of the end-member is written as $BaMg_3Al_2Si_2O_{10}(OH)_2$. In the present study, grains of phlogopite with variable amounts of barium, up to 20 wt% BaO, are recognized in some samples as shown in Table 19-1. Table 19-1 shows an example of analyses with Ba more than 0.5 in the site for K (TS-17). Although due to Al-poor environments, the number of Al is less than the expected value to balance the excess positive charge by Ba instead of K, and the excess positive charge seems to be partly compensated by the deficiency of atoms in the site for K, this mineral could be called kinoshitalite.

The other group of analytical results is characterized by enrichment of Si, more than 3, up to 4, in the ideal formula, with strong depletion of Al. There seem to be two types present. One (Type 1) is iron-bearing phlogopite with reverse pleochroism. Chemical composition of an example from TS-24 is given in the first column of Table 19-2. A considerable amount of iron exists. Considering that the mineral shows reverse pleochroism, total iron was assigned to ferric and ferrous by the calculation to achieve that the total number of atoms of silicon, titanium, aluminum and ferric iron is four in the tetrahedral site. Alumina is almost completely depleted, and the tetrahedral site for aluminum in normal phlogopite unit formula is occupied by ferric iron and less silicon. In general, ferric-rich end-member is known as tetraferriannite, $K(Fe^{2+}, Mg)_3Fe^{3+}Si_3O_{10}(OH, F)_2$, and tetraferriphlogopite, $K(Mg, Fe^{2+})_3Fe^{3+}Si_3O_{10}(OH, F)_2$. The studied mineral could be the F-bearing tetraferriphlogopite, that is, $K(Mg, Fe^{2+})_3$-$(Fe^{3+}, Si, Al)Si_3O_{10}(OH, F)_2$.

The other type (Type 2) of Si-enrichment is associated with the void of octahedral Mg, as shown in the second column of Table 19-2. In this example, alumina is again much depleted, and the tetrahedral site is completely occupied by silicon. The excess positive charge is balanced by 0.5 void in octahedral site, and the end-member could be presented as $KMg_{2.5}\square_{0.5}Si_4O_{10}(OH, F)_2$. The mineral with a similar composition is known in muscovite subgroup as montdorite, $(K, Na)(Fe^{2+}, Mn^{2+}, Mg)_{2.5}\square_{0.5}Si_4O_{10}(F, OH)_2$. Thus, the studied mineral could be the Mg-analogue of montdorite, that is, $K(Mg, Fe^{2+})_{2.5}\square_{0.5}Si_4O_{10}(OH, F)_2$. The material with

Table 19-1. Analytical results of phlogopite and kinoshitalite (TS-17, 3 analyses and 16 analyses).

Sample	TS-17 Phlogopite					TS-17 Kinoshitalite				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=11)		Range (wt%)	Average	Std. dev.	No. of atoms (O=11)	
SiO_2	43.36–45.27	44.58	0.86	3.192	3.20	33.65–37.49	35.83	1.38	2.749	2.76
TiO_2	0.02–0.34	0.15	0.14	0.008		0.10–0.32	0.19	0.07	0.011	
Al_2O_3	9.30–10.28	9.72	0.41	0.819	0.82	11.84–13.63	12.84	0.47	1.159	1.16
MgO	21.63–22.24	22.00	0.27	2.363		21.25–25.01	23.25	0.03	2.675	
FeO	8.56–9.02	8.74	0.20	0.522	2.89	3.88–9.01	5.43	1.58	0.347	3.03
MnO	0.02–0.05	0.03	0.01	0.002		0.05–0.15	0.08	0.03	0.005	
CaO	0.09–0.35	0.17	0.12	0.013		0.02–0.26	0.17	1.31	0.014	
BaO	0.00–1.70	0.64	0.75	0.018	0.94	16.66–20.69	18.92	1.08	0.569	0.85
Na_2O	0.17–0.36	0.26	0.08	0.036		0.84–1.90	1.36	0.42	0.202	
K_2O	8.72–10.06	9.53	0.58	0.871		0.07–1.47	0.62	0.42	0.061	
F	2.96–3.43	3.21	0.19	0.726	0.73	2.85–3.63	3.18	0.25	0.770	0.77
O=F		−1.35					−1.34			
Total		97.68					100.53			

Table 19-2. Analytical results of phlogopites (TS-24, 5 analyses and 15 analyses).

Sample	TS-24 (Type 1)				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=11)	
SiO_2	45.04–46.83	45.98	0.733	3.000	3.00
				0.373	
TiO_2	0.00–0.04	0.01	0.016	0.001	1.00
Al_2O_3	0.05–0.97	0.31	0.352	0.027	
Fe_2O_3	12.39–16.23*	10.89	1.299*	0.599	
FeO		3.56		0.217	
MgO	22.83–24.33	23.49	0.584	2.585	2.81
MnO	0.06–0.21	0.16	0.053	0.01	
CaO	0.00–0.05	0.02	0.019	0.002	
BaO	0.21–0.46	0.27	0.096	0.008	1.00
Na_2O	0.07–0.13	0.09	0.022	0.013	
K_2O	10.04–10.81	10.40	0.258	0.974	
F	1.86–2.84	2.15	0.363	0.498	0.50
O=F		−0.91			
Total		96.42			

Sample	TS-24 (Type 2)				
	Range (wt%)	Average	Std. dev.	No. of atoms (O=11)	
SiO_2	56.04–60.57	58.39	1.400	4.003	4.00
TiO_2	0.00–0.06	0.01	0.016	0.001	
Al_2O_3	0.03–1.40	0.41	0.423	0.033	0.03
MgO	24.02–25.23	24.30	0.330	2.499	
FeO	0.40–2.42	1.17	0.480	0.067	2.57
MnO	0.00–0.05	0.02	0.015	0.001	
CaO	0.01–0.09	0.04	0.025	0.003	
BaO	0.00–0.15	0.03	0.043	0.001	0.75
Na_2O	0.03–0.11	0.06	0.023	0.008	
K_2O	7.96–9.06	8.44	0.339	0.739	
F	2.37–3.56	3.01	0.302	0.652	0.65
O=F		−1.27			
Total		94.61			

*: Range and standard deviation of iron analyses are given for Fe_2O_3 values.

The amounts of ferric and ferrous iron were calculated to satisfy that the total number of atoms in the tetrahedral sites is four.

this chemical composition is called tetrasilicic potassium fluor mica, $KMg_{2.5}\square_{0.5}Si_4O_{10}F_2$, and stably synthesized (e.g., Toraya *et al.*, 1976).

These two types of Si-enrichment are together recognized in one sample (TS-24). Both analytical results show low total weight percents, and the site for K is not fully occupied in the latter case. It is obvious that further precise study is necessary to establish the new end-members related to phlogopite above proposed.

In the monograph of Bayan Obo mineralogy by Zhang and Tao (1986), one example of chemical analysis of biotite is listed, and 1.57 wt% of BaO is reported in it. However, no description about kinoshitalite from the deposit is given. One example of phlogopite analysis shows 3.20 Si and 0.69 Al in the formula unit, indicating the Si-rich and Al-poor feature of the mineral. One example of the phlogopite with reverse pleochroism is also listed.

Conclusion

Through microscopic and EPMA analytical study on thin sections of 26 samples from the Bayan Obo deposit and its surrounding areas, many new data on the mineralogy of the deposit were obtained. Among them, main contribution of the present study to the Bayan Obo mineralogy is as follows.

1) Zhangpeishanite, BaFCl, a new mineral, was found.
2) The occurrence of bastnäsite-(La) was newly established from the deposit. Ca-bearing bastnäsite-(Ce), probably making mixed-layer structure with synchysite-(Ce), is present.
3) A Ca-rich cordylite-(Ce) (Ca>0.5 in the unit formula) was found, strongly suggesting the necessity of re-definition of cordylite-group minerals. The studied cordylites-(Ce) are mostly depleted in fluorine.
4) Fluorbritholite-(Ce) was confirmed. Essentially P_2O_5-free end-member fluorbritholite-(Ce), $Ca_2Ce_3(SiO_4)_3F$, is present. In this phase, however, Ca is much depleted, less than 2 in the formula unit, and the excess charge seems to be balanced by the excess of REE, more than 3.

5) Gadolinite-(Ce) is present in the deposit.
6) Both chevkinite-(Ce) and perrierite-(Ce) are concluded to be present on the basis of their chemical compositions. Small amounts of Sc are contained in perrierite-(Ce).
7) Rare minerals like bafertisite and baotite, both firstly described from the deposit, are recognized, and their chemical compositions were presented.
8) Among Ba-bearing phlogopite samples in the deposit, the presence of kinoshitalite was confirmed. On the basis of many analytical results of phlogopite in the deposit, two Si-enriched and Al-depleted phlogopites are recognized, tetra ferriphlogopite, $K(Mg, Fe^{2+})_3(Fe^{3+}, Si, Al)Si_3O_{10}(F, OH)_2$ and Mg-analogue of montdorite, $KMg_{2.5}\square_{0.5}$-$Si_4O_{10}(F, OH)_2$.

The present report is only results of a reconnaissance study of the 26 samples. The authors believe that these samples from the Bayan Obo areas are treasure boxes, and that further detailed and precise study on these samples brings great contribution to the world of mineralogy, as well as petrology and geochemistry.

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