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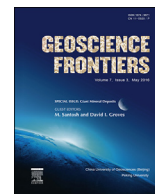


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Research paper

The giant Bayan Obo REE-Nb-Fe deposit, China: Controversy and ore genesis



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ABSTRACT

Bayan Obo ore deposit is the largest rare-earth element (REE) resource, and the second largest niobium (Nb) resource in the world. Due to the complicated element/mineral compositions and involving several geological events, the REE enrichment mechanism and genesis of this giant deposit still remains intense debated. The deposit is hosted in the massive dolomite, and nearly one hundred carbonatite dykes occur in the vicinity of the deposit. The carbonatite dykes can be divided into three types from early to late: dolomite, co-existing dolomite-calcite and calcite type, corresponding to different evolutionary stages of carbonatite magmatism based on the REE and trace element data. The latter always has higher REE content. The origin of the ore-hosting dolomite at Bayan Obo has been addressed in various models, ranging from a normal sedimentary carbonate rocks to volcano-sedimentary sequence, and a large carbonatitic intrusion. More geochemical evidences show that the coarse-grained dolomite represents a Mesoproterozoic carbonatite pluton and the fine-grained dolomite resulted from the extensive REE mineralization and modification of the coarse-grained variety. The ore bodies, distributed along an E–W striking belt, occur as large lenses and underwent more intense fluoritization and fenitization. The first episode mineralization is characterized by disseminated mineralization in the dolomite. The second or main-episode is banded and/or massive mineralization, cut by the third episode consisting of aegirine-rich veins. Various dating methods gave different mineralization ages at Bayan Obo, resulting in long and hot debates. Compilation of available data suggests that the mineralization is rather variable with two peaks at ~1400 and 440 Ma. The early mineralization peak closes in time to the intrusion of the carbonatite dykes. A significant thermal event at ca. 440 Ma resulted in the formation of late-stage veins with coarse crystals of REE minerals. Fluids involving in the REE-Nb-Fe mineralization at Bayan Obo might be REE-F-CO₂-NaCl-H₂O system. The presence of REE-carbonates as an abundant solid in the ores shows that the original ore-forming fluids are very rich in REE, and therefore, have the potential to produce economic REE ores at Bayan Obo. The Bayan Obo deposit is a product of mantle-derived carbonatitic magmatism at ca. 1400 Ma, which was likely related to the breakup of Columbia. Some remobilization of REE occurred due to subduction of the Palaeo-Asian oceanic plate during the Silurian, forming weak vein-like mineralization.

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1. Introduction

Bayan Obo ore deposit is the largest rare-earth element (REE) deposit, the second largest niobium (Nb) deposit in the world, and also a large iron (Fe) deposit in China. According to USGS (2015), China now hosts 42% of the world's total REE reserve base, and the

Chinese REE production accounted for 86% of the total world production in 2014. More than 80% light REE (LREE) resources in China are distributed in the Bayan Obo region, Inner Mongolia, Northern China (Wu et al., 1996; Yang and Woolley, 2006; Fan et al., 2014). Since the discoveries of Fe ores in the Main Orebody in 1927 by Mr. Daoheng Ding and REE minerals in 1935 by Mr. Zuolin He at Bayan Obo, many studies have been carried out, particularly in the recent two decades, on the geological background, mineral constituents, geochronology and geochemistry. However, due to the complicated element/mineral compositions and several geological activity events at Bayan Obo, the genesis of this giant REE ore deposit,

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including its potential ore-forming sources, particularly with regard to the mechanism of REE enrichment, still remains intense debate (Yuan et al., 1992; Wang et al., 1994; Bai et al., 1996; Le Bas et al., 1997, 2007; Smith et al., 2000, 2015; Yang et al., 2000, 2003, 2009, 2011a,b, 2012; Wang et al., 2002a; Fan et al., 2004a,b, 2014; Yang and Le Bas, 2004; Smith, 2007; Liu et al., 2008; Ling et al., 2013; Zhu et al., 2015).

In this paper, combined with accumulation of the broad scientific research results, especially those large numbers of petrochemistry, stable and radiogenic isotopic data, we review the geological features of this giant deposit, focusing on the geochronology, formation of ore-hosting dolomites and carbonatite dykes, and ore-forming fluids at Bayan Obo, and propose a possible process for the giant Bayan Obo REE-Nb-Fe deposit.

2. Regional and ore geology

The Bayan Obo deposit is located approximately 90 km south of the China and Mongolia border, at 109°58'E and 41°48'N, and just situated at the northern margin of the North China Craton (NCC), bordering the Central Asian Orogenic Belt to the north (Xiao et al., 2003; Xiao and Kusky, 2009) (Fig. 1). Gentle fold structures, composed mostly of the low grade metasedimentary units of the Mesoproterozoic Bayan Obo Group, are distributed from south to north in the region (Fig. 1). The famous Bayan Obo giant REE-Nb-Fe deposit, hosted in the massive dolomite, occurs in one of the syncline cores (Fig. 2). To the north of the ore body, a complete sequence of Bayan Obo Group is exposed in the Kuangou anticline,

which is developed on the Paleoproterozoic basement rocks with a distinct angular unconformity (Fig. 2). The low grade clastic sequences of the Bayan Obo Group represent the sedimentary units deposited within the Bayan Obo marginal rift (Wang et al., 1992), which correlated with the Mesoproterozoic continental breakup event of the NCC (Zhai, 2004; Zhao et al., 2004; Li et al., 2006; Hou et al., 2008; Yang et al., 2011b; Zhai and Santosh, 2011). The Bayan Obo REE-Nb-Fe deposit is just located in the Bayan Obo continental margin rift in the north of the NCC. The ore-hosting dolomites, covered by K-rich slate (H9 term) and extended 18 km from east to west with approximately 2 km width (Fig. 1), was once considered as a component of Bayan Obo Group, called H8 term. The origin of the dolomites is still disputed, and it has been proposed to be either sedimentary (Meng, 1982; Chao et al., 1992; Yang et al., 2009; Lai et al., 2012), or carbonatite related (Le Bas et al., 1992, 1997, 2007; Yuan et al., 1992; Yang et al., 2000, 2003, 2011a,b; Hao et al., 2002; Wang et al., 2002a; Zhu et al., 2015).

Basement rocks at Bayan Obo are composed of Neoproterozoic mylonitic granite-gneiss (2588 ± 15 Ma), Paleoproterozoic syenite and granodiorite (2018 ± 15 Ma), and biotite granite-gneiss and garnet-bearing granite-gneiss (~ 1890 Ma) (Wang et al., 2002b; Fan et al., 2010). Dioritic-granitic plutons, composed of gabbro, gabbroic diorite, granitic diorite, adamellite, and biotite granite, are distributed within a large area in the south and east Bayan Obo mine (Fig. 1). These plutons were once regarded as intruding from Devonian to Jurassic. New geochronology data reveal that these plutons were formed in a post-collisional tectonic regime at convergent margins in the late Paleozoic at a narrow time from 263

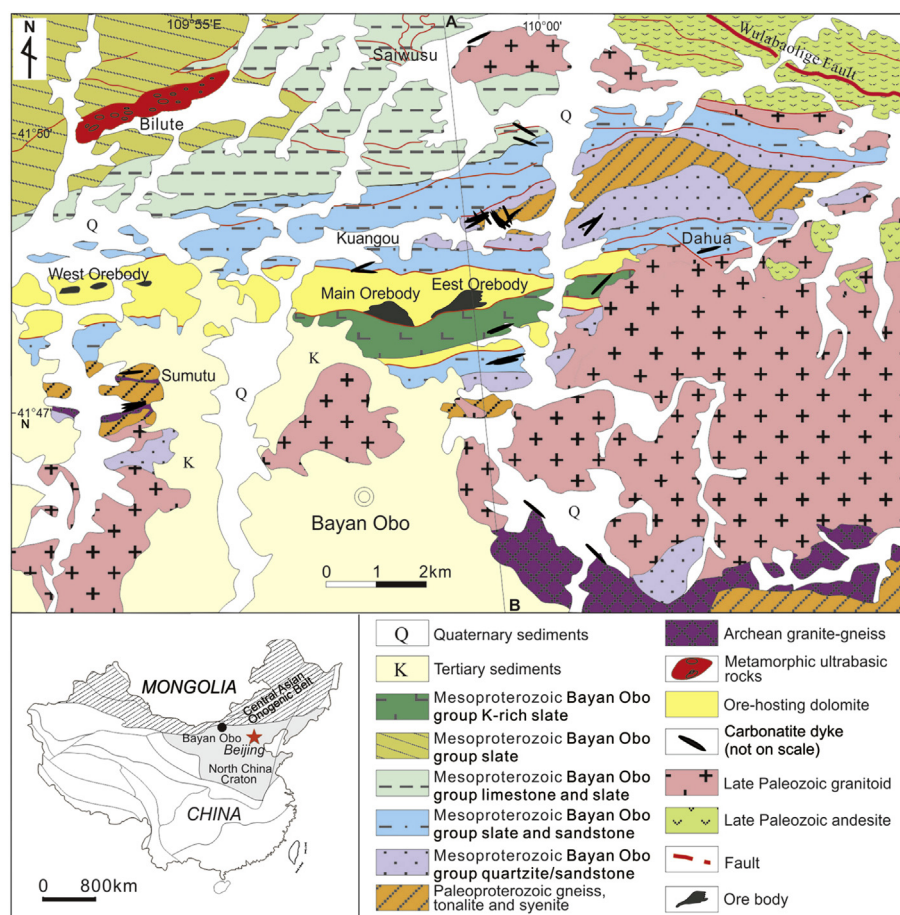


Figure 1. Geological sketch map of the Bayan Obo area, northern China. Modified after Yang et al. (2011a).

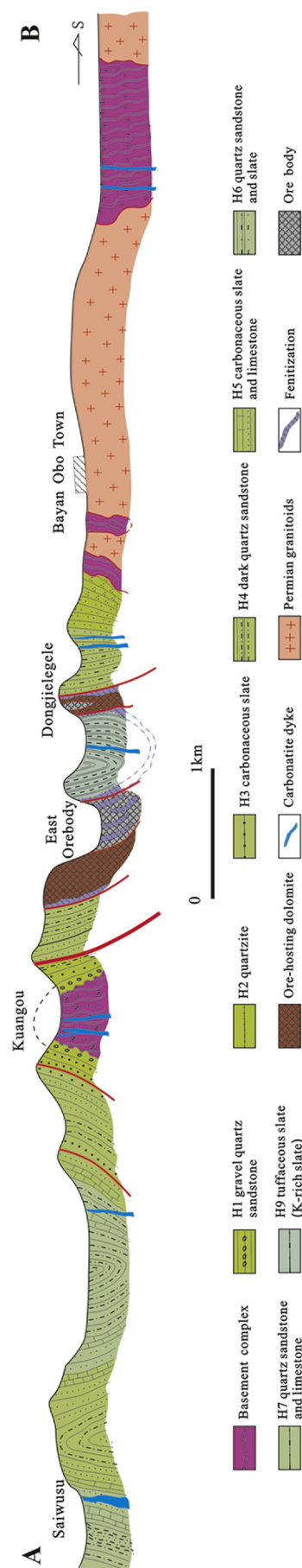


Figure 2. Geological section of line A–B in Fig. 1, showing location of ore bodies.

to 281 Ma with peak age of 269 Ma (Fan et al., 2009), which is consistent with plate subduction during the closure of the Palaeo-Asian Ocean (Ling et al., 2014). It has been proved that REE mineralization at Bayan Obo has no direct relation with these late Paleozoic granitoids (Fan et al., 2004b; Yang and Le Bas, 2004).

REE reserves in the Bayan Obo ore deposit are 57.4 million metric tons (Mt) with an average grade of 6% RE₂O₃, Nb reserves are expected at 2.2 Mt with an average grade of 0.13% Nb₂O₅, and total Fe reserves are at least 1500 Mt with an average grade of 35% (Drew et al., 1990; Bai et al., 1996; Hao et al., 2002). Rare-earth elements in the ores at Bayan Obo are rich in LREE, mostly are Ce, La and Nd, which occupy >90% LREE (Fig. 3). Element and mineral compositions at Bayan Obo are complicated. 71 elements and >190 minerals have been identified. Among them, 30 REE minerals, 20 Nb and Ta minerals, and particularly 18 new minerals like REE mineral Huanghoite (BaCe[F(CO₃)₂]), Baiyuneboite (NaBaCe₂[F(CO₃)₄]) and Nb mineral Baotite (Ba[Nb,Ti]₂SiO₇) were found.

Detailed geological mapping showed that there are nearly one hundred carbonatite dykes occur in the vicinity of the Bayan Obo deposit (Fig. 1). They intruded into the basement rocks and/or the Bayan Obo Group. The carbonatite dykes are usually 0.5–2.0 m wide and 10–200 m long, and strike generally to northeast or northwest (Le Bas et al., 1992; Tao et al., 1998; Yang et al., 2011a; Fan et al., 2014). It is significant that some dykes have metasomatized the country rocks on both sides of the contact zones, producing fenites characterized by the presence of sodic amphiboles and albite (Le Bas et al., 1992; Yang et al., 2003; Yang and Le Bas, 2004; Fan et al., 2014). The major constituent minerals in the dykes are dolomite and calcite, which are associated with subordinate apatite, monazite, barite, bastnaesite, and magnetite (Yang et al., 2003; Yang and Le Bas, 2004). The REE contents in the different carbonatite dykes vary from ca. 0.02 to ca. 20 wt.% (Tao et al., 1998; Yang et al., 2003).

The mine is composed of three major ore bodies: East, Main and West orebodies (Fig. 1). The East and Main orebodies are distributed between the boundary of ore-hosting dolomite and Bayan Obo group K-rich slate. The West Orebody, including many small ore bodies, locates mainly in the massive dolomite. Relative to the West Orebody, the East and Main orebodies occur as larger lenses (Fig. 4), underwent more intense fluoritization, fenitization and hosted more abundant REE and Nb mineralization. Fluorite appears in the fenitized dolomite, and riebeckite and phlogopite are observed in the K-rich slate. The ores are distributed along an E–W striking belt. From south to north in the East and Main orebodies, the REE ores are defined to be four types, namely the riebeckite, aegirine, massive, and banded types (Fig. 4). The principal REE minerals are bastnaesite-(Ce) and monazite-(Ce), and accompanied with a various kind of REE and Nb minerals, such as huanghoite, aeschynite-(Ce), fergusonite, and columbite. Iron minerals are

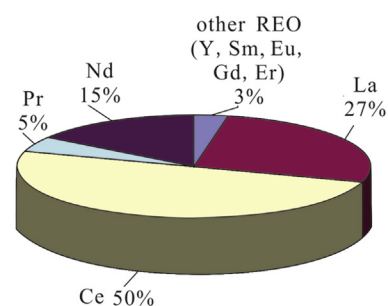


Figure 3. Rare earth elements contents in the Bayan Obo deposit.

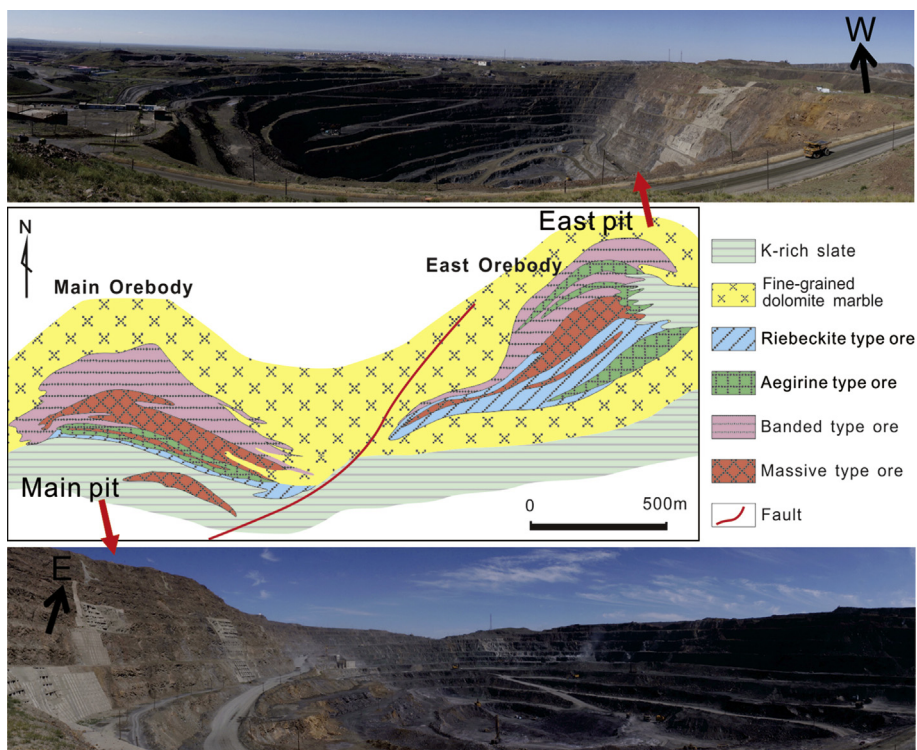


Figure 4. Geological map of the Main and East orebodies at Bayan Obo. Modified after Institute of Geochemistry, Chinese Academy of Sciences (1988).

magnetite and hematite. Main gangue minerals include fluorite, barite, alkali amphibole, apatite, quartz and aegirine.

The paragenesis of the deposit is complex, according to [Chao et al. \(1992\)](#), with at least 11 stages from syngenetic sedimentary deposition, through metamorphism and mineralization, to the intrusion of late Paleozoic granitoids mainly to the southeast of the deposit. Based on ore occurrences and crosscutting relations, three

important REE mineralizing episodes can be identified at the simplest level ([Fig. 5](#)). The first episode is characterized by disseminated mineralization which contains monazite associated with ferroan dolomite, ankerite and magnetite, concentrated along fractures and grain boundaries in the relatively unaltered/massive dolomite ([Fig. 5a](#)). The second or main-episode is banded and/or massive mineralization ([Fig. 5b](#)), which shows a generalized

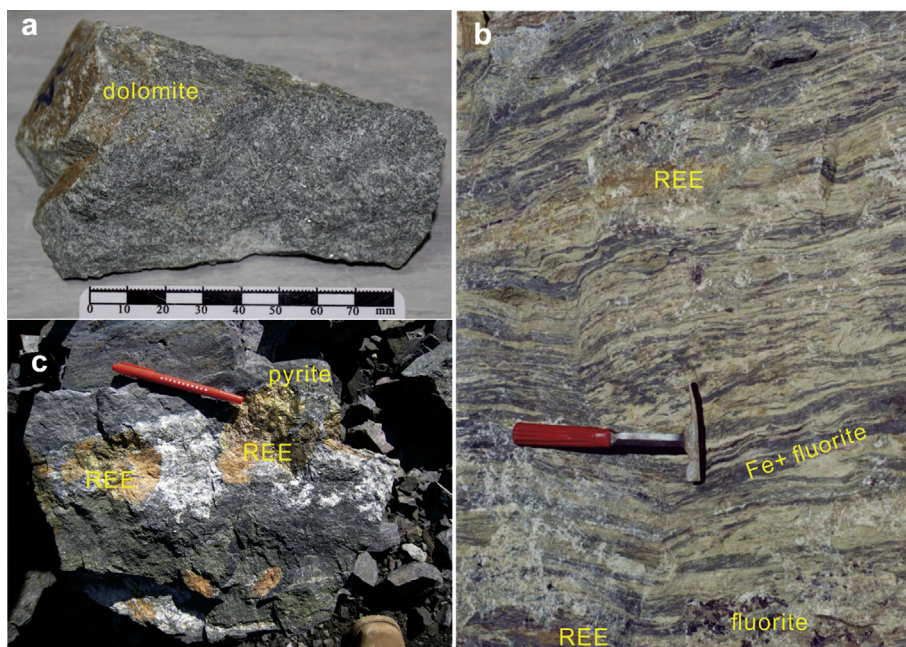


Figure 5. Major mineralization types from the Bayan Obo deposit. (a) Fine-grained dolomite with disseminated mineralization; (b) banded REE-Nb-Fe mineralization; (c) late-stage vein cross-cutting banded REE-Nb-Fe ore.

paragenetic sequence of strongly banded REE and Fe ores showing alteration to aegirine, fluorite and minor alkali amphibole. The banded and massive ores are cut by the third episode consisting of aegirine-rich veins containing fluorite, huanghoite, albite, calcite, biotite, and/or pyrite with coarser crystal (Fig. 5c).

3. Genesis of carbonatite dyke and ore-hosting dolomite (H8)

Abundant carbonatite dykes occur adjacent to the eastern and southern of the Bayan Obo mine and particularly within the Kuangou anticline (Fig. 1). These dykes intruded into the Bayan Obo Group of low grade meta-sedimentary rocks, as well as the basement rocks, with fenitization of the wall rocks (Fig. 6a). Wang et al. (2002a) mentioned that carbonatite dykes at Bayan Obo can be divided into three types: dolomite, co-existing dolomite-calcite and calcite type. The latter always has higher REE content. Wang et al. (2002a) also argued that these three types of carbonatite dykes might correspond with different evolutionary stages of carbonatitic magmatism based on the REE and trace element data. Yang et al. (2011a) found the outcrop of incision contact between dolomite type and calcite type dykes at Jianshan to the north of the East Orebody. Field evidence of incision contact shows that a dolomite carbonatite dyke was cut by a calcite one (Fig. 6b), showing that the emplacement of the calcite dyke is later than the dolomite one. Geochemical data (Yang et al., 2011a) showed that Sr and LREE contents in the dykes gradually increase from dolomite type, through calcite-dolomite type, to calcite type. This trend might be resulted from the crystal fractionation of a carbonatitic magma.

The origin of the ore-hosting dolomite at Bayan Obo has been addressed in various models, ranging from a normal sedimentary carbonate rocks (Chao et al., 1992) to volcano-sedimentary sequence (Wang et al., 1992), and a large carbonatitic intrusion (Le Bas et al., 1997, 2007; Yang et al., 2003). The possible presence of fossils (Meng, 1982) has been cited to support the first argument, and the contact relationships and some internal features have been used to support the third one (Le Bas et al., 1997, 2007). All arguments have been supported with reference to the trace element and isotopic composition of the dolomite. It should be pointed that carbonate rocks with fossils are not found in the Bayan Obo area. Sun et al. (2012, 2014) systematically analyzed elemental

geochemistry, and C, O, and Mg isotopic geochemistry of the ore-hosting dolomite and compared that with the nearby Sailinhu-dong micrite mound. They show that the Bayan Obo ore-hosting dolomite marbles are strongly enriched in LREEs, Ba, Th, Nb, Pb, and Sr, and have very different (PAAS)-normalized REE patterns, while Sailinhu-dong micrite carbonates have higher $\delta^{13}\text{C}_{\text{PDB}}$ and $\delta^{18}\text{O}_{\text{SMOW}}$ values, falling into the typical sedimentary field. The Bayan Obo ore-hosting dolomites are isotopically intermediate between primary igneous carbonatite and typical sedimentary limestone. The $\delta^{26}\text{Mg}$ values of the Sailinhu-dong micrite carbonates are lighter than those of normal Mesoproterozoic sedimentary dolostone, while those of the Bayan Obo ore-hosting dolomite marble are isotopically heavier, similar to $\delta^{26}\text{Mg}$ of mantle xenoliths and Bayan Obo intrusive carbonatite dyke. Sun et al. (2012, 2014) gave clear evidences that the ore-hosting dolomite at Bayan Obo was mainly derived from the mantle.

A relatively small volume of coarse-grained dolomite occurs in the Bayan Obo deposit mainly in the West Orebody, as well as in the northern part of the Main Orebody. The rocks are composed predominantly of coarse-grained euhedral–subhedral dolomite, associated with evenly distributed fine-grained apatite, magnetite, and monazite (Zhu et al., 2015). The fine-grained dolomites are distributed widely and constitute the main part of the deposit. It commonly also appears massive in outcrops, and consists predominantly of dolomite or ankerite, which is mostly fine-grained, ranging from 0.05 to 0.1 mm in diameter. The coarse-grained and fine-grained facies of the dolomite occurring at Bayan Obo introduced additional complexities in the interpretation of their genesis.

Le Bas et al. (2007) proposed that the coarse-grained dolomite represents a Mesoproterozoic carbonatite pluton and the fine-grained dolomite resulted from the extensive REE mineralization and modification of the coarse-grained variety. Yang et al. (2011a) showed the field observations in the northern part of the Main Orebody, and revealed that the coarse-grained dolomite intruded into the Bayan Obo group quartz sandstone as apophyses. However, the geochemical characteristics of the coarse-grained dolomite are not consistent with those of the fine-grained ones (Yang et al., 2011a). The major and trace element contents of the coarse-grained dolomite are very similar to the calcite-dolomite

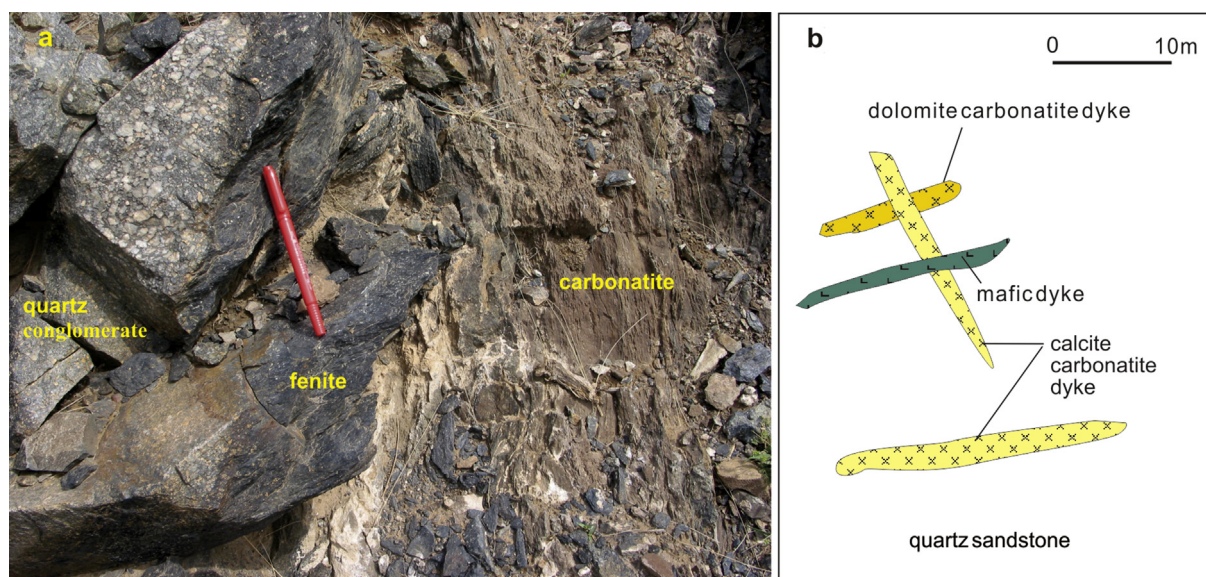


Figure 6. Outcrop of carbonatite dykes at Bayan Obo. (a) A carbonatite dyke in the Dulahala showing strong fenitization developed around the wallrock quartz conglomerate; (b) intrusive contact between dolomite and calcite carbonatite dykes in the Jianshan.

carbonatite dykes at Bayan Obo. Data from those samples overlap within the magnesio-carbonatite region on the CaO-MgO-(FeO+Fe₂O₃+MnO) classification diagram (Yang et al., 2011a), and show similar REE contents and distribution patterns on the chondrite-normalized abundance diagram (Yang et al., 2011a, Fig. 7a,b). The similar geochemical characteristics of coarse-grained dolomite and calcite-dolomite carbonatite dykes, and the intrusive contact between the coarse-grained dolomite and wallrocks, indicate that the coarse-grained dolomite is likely an earlier phase of calcite-dolomite carbonatite stock, which did not witness the subsequent mineralization event from the residual carbonatitic melts, probably because it is located far from the main mineralized zone. The fine-grained dolomite from the Main, East and West orebodies differs from the coarse-grained dolomite in their major, trace element and REE characteristics. The fine-grained dolomite shows major element compositions comparable to that of the dolomite carbonatite dykes. All the samples fall in the field of dolomite carbonatite dykes on the CaO-MgO-(FeO+Fe₂O₃+MnO) classification diagram (Yang et al., 2011a). The REE content and distribution patterns of the fine-grained dolomite samples, however, are similar to those of the calcite carbonatite dykes (Fig. 7a,b). Therefore, the fine-grained dolomite cannot be compared with any specific type of carbonatite dykes at Bayan Obo as mentioned by Yang et al. (2011a).

The REE content in the dolomite carbonatite dykes is relatively low, as compared to the extreme accumulation in the calcite carbonatite dykes at Bayan Obo. Chao et al. (1992) noted that the REE minerals in the fine-grained dolomite occur as ribbon or aggregates. Wang et al. (2010) also found that the REE minerals are

distributed around dolomite phenocryst in the fine-grained dolomite. Therefore, the REE minerals formed later than the formation of the dolomite phenocryst. These observations lead us to believe that the fine-grained dolomite represents an early stage large-scale dolomite carbonatite pluton, and the superposed REE mineralization was derived from the later calcite carbonatite magma.

4. REE mineralizing time

According to the occurrences of rocks/veins related with mineralization in the Bayan Obo deposit, the four types of REE mineralization are identified, including carbonatite dyke, ore-hosting dolomite marble, banded REE-Nb-Fe ore, and late-stage REE vein. Geochronology on these four type mineralizations, using U-Th-Pb, Sm-Nd, Rb-Sr, K-Ar, Ar-Ar, Re-Os, and La-Ba methods, have been reported in the last two decades (Nakai et al., 1989; Chao et al., 1992; Bai et al., 1996; Liu et al., 2004, 2008; Hu et al., 2009; Yang et al., 2011a,b; Campbell et al., 2014; Fan et al., 2014; Zhu et al., 2015). However, various dating methods gave different mineralization ages (Table 1, Fig. 8), resulting in long and hot debates. The compiled age data on Bayan Obo REE mineralization are rather variable, ranging from >1800 to ~390 Ma, with two peaks at ~1400 and 440 Ma. The earliest ages, reported from zircons in the carbonatite dykes by SHRIMP or ID-TIMS with ages >1.8 Ga, are largely thought to be inherited zircons derived from the Palaeoproterozoic basement in the area (Liu et al., 2008; Fan et al., 2014). There are three main opinions on mineralization ages.

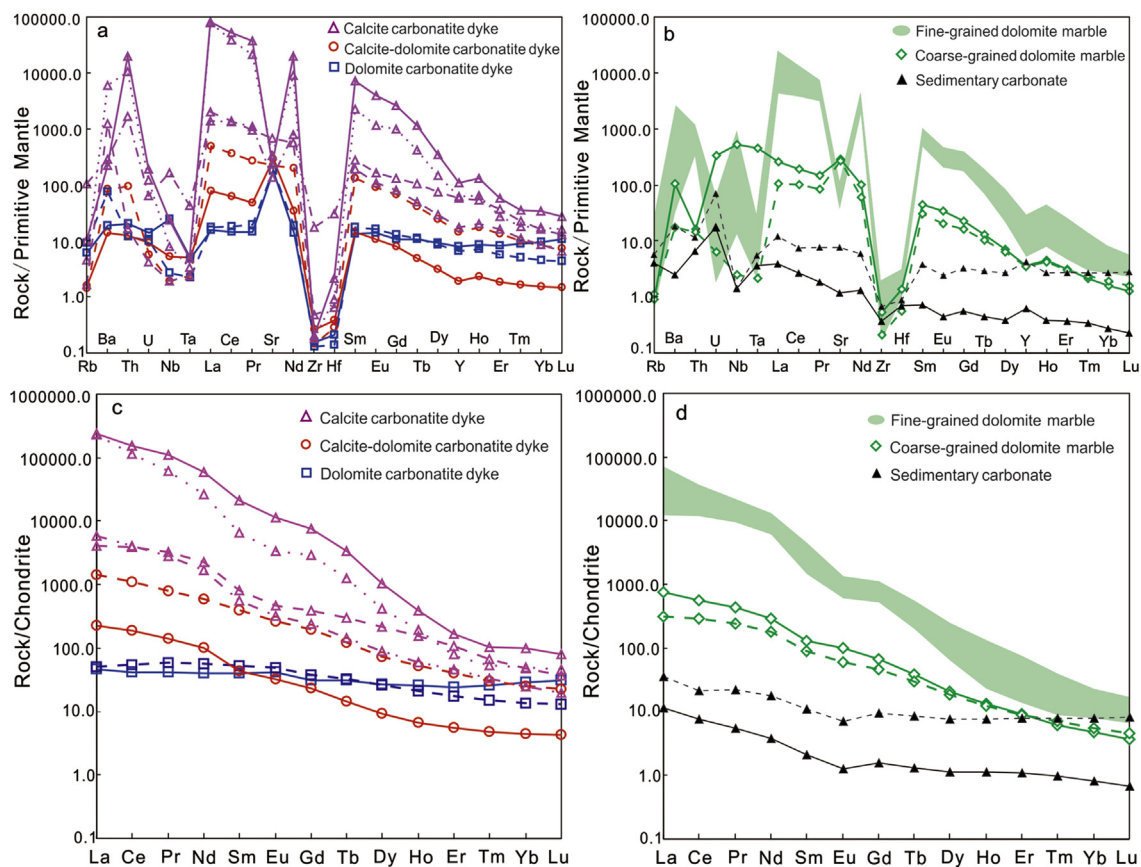


Figure 7. (a, b) Primitive mantle-normalized trace element abundance pattern, and (c, d) chondrite-normalized REE abundance diagram for carbonatite dykes, ore-hosting dolomite marble and sedimentary carbonate rocks at Bayan Obo (after Yang et al., 2011a).

Table 1

A brief geochronology overview in the Bayan Obo deposit.

Type	Material	Sample location	Methods	Age (Ma)	Reference
Carbonatite dyke	Carbonatite	Dulahala	Sm-Nd	1223	Zhang et al., 2003
	Carbonatite dykes	Jianshan	Sm-Nd	1354	Yang et al., 2011a
	Zircon in carbonatite	North of Main Orebody	U-Pb	1984	Liu et al., 2008
	Zircon in carbonatite	—	U-Pb	1416	Campbell et al., 2000
			U-Pb	2085	
			U-Pb	2035	
			U-Pb	1366	
	Carbonatite dykes	North of Main Orebody	U-Pb	1260	Liu et al., 2008
			Pb-Pb	1236	
	Monazite in carbonatite	Dulahala	Sm-Nd	1320	Yang et al., 2008
Ore-hosting dolomite marble, banded REE-Nb-Fe ore	Zircon in carbonatite	Dulahala	U-Pb	1418	Fan et al., 2014
	Dolomite	Main and East orebodies	Sm-Nd	1341	Yang et al., 2011a
	Whole rock of ore	Main and East orebodies	Sm-Nd	1592	Yuan et al., 1992
	Monazite and bastnaesite	Main Orebody	Sm-Nd	1580	Ren et al., 1994
		North of Main and East orebodies	Sm-Nd	1313	
	REE minerals	—	Sm-Nd	402	Cao et al., 1994
	Allanite and riebeckite	—	Sm-Nd	422	Zhang et al., 2001
	Dolomite	Main and East orebodies	Sm-Nd	1273	
	REE minerals in dolomite	Main and East orebodies	Sm-Nd	1250	Zhang et al., 1994
	Whole rock	Main and East orebodies	Sm-Nd	1286	
	Whole rock	Main and East orebodies	Sm-Nd	1305	Zhang et al., 2003
	Monazite	East Orebody	Sm-Nd	1013	Liu et al., 2005
		West Orebody	Sm-Nd	809	
		Ore	Sm-Nd	1060	
	REE minerals	Main and East orebodies	Sm-Nd	1426	Nakai et al., 1989
	Monazite	North of Main Orebody	Th-Pb	445	Ren et al., 1994
	Monazite	Main and East orebodies	Th-Pb	461	Wang et al., 1994
			Th-Pb	398–555	
	REE minerals	Main and East orebodies	Th-Pb	407	Chao et al., 1991
	Monazite	Dolomitic ore	Th-Pb	419	Chao et al., 1997
	Bastnaesite	Dolomitic ore	Th-Pb	555	Liu et al., 2005
	Monazite	Ore	Th-Pb	1231	
	Apatite	Main and East orebodies	U-Pb	1588	Institute of Geochemistry, Chinese Academy of Sciences, 1988
	Whole rock	Main and East orebodies	U-Pb	523	Zhang et al., 2003
	REE minerals	East Orebody	SHRIMP U-Pb	820	Nakai et al., 1989
		Contact zone	SHRIMP U-Pb	1002	
		Main and East orebodies	La-Ba	1350	
	Whole rock	Main and East orebodies	Pb-Pb	1500	Liu et al., 2001
	Whole rock	West Orebody	Rb-Sr	391	Zhang et al., 2003
	Alkali amphibole	Main and East orebodies	Ar-Ar	820	Chao et al., 1991
	Ore and dolomite	Main and East orebodies	Nd DM model age	1544	Philpotts et al., 1991
	Monazite in dolomite	Main and East orebodies	Nd DM model age	1656	Yang et al., 2008
		East Orebody	Sm-Nd	860	
	Bastnaesite	Main Orebody	U-Th-Pb	425	Chao et al., 1991
	Overgrowth of zircon in quartz dolomite	East Orebody	U-Pb	1325	Campbell et al., 2014
	Overgrowth of zircon in quartz dolomite	East Orebody	U-Pb	455	Campbell et al., 2014
Late stage vein	Pyrite	—	Re-Os	439	Liu et al., 2004
	Gangue mineral	Main Orebody	Sm-Nd	442	Hu et al., 2009
	Gangue mineral	East Orebody	Rb-Sr	459	Hu et al., 2009
	Huanghoite and aeschynite in aegirine vein	Main Orebody	U-Th-Pb	438	Chao et al., 1991
	Huanghoite and aeschynite	—	Sm-Nd	420	Chao et al., 1991
	Riebeckite vein	East of East Orebody	Ar-Ar	389	Lai et al., 2015
	Molybdenite	—	Re-Os	439	Liu et al., 1996

4.1. Mesoproterozoic mineralization

Nakai et al. (1989) first reported REE mineral La-Ba and Sm-Nd isochron date of 1350 ± 149 and 1426 ± 40 Ma, respectively. In addition, Zhang et al. (2003) obtained mineral Sm-Nd isochron date from ores at Main and East orebodies of 1286 ± 91 and 1305 ± 78 Ma, respectively. Yang et al. (2011a) reported a whole-rock Sm-Nd isochron from nine carbonatite dyke samples yielding a slightly older age of 1354 ± 59 Ma. Fan et al. (2014) analyzed zircons from a carbonatite dyke by conventional isotope dilution thermal ionization mass spectrometry (ID-TIMS), got an upper intercept age of 1417 ± 19 Ma. This age is confirmed by their SHRIMP U-Pb analysis

of zircon from the same carbonatite dyke, which gave a $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean age of 1418 ± 29 Ma.

4.2. Early Paleozoic mineralization

Wang et al. (1994) and Chao et al. (1997) made numerous Th-Pb dating of monazite and bastnaesite samples at Bayan Obo, and provided isochron ages for monazite mineralization ranging from 555 to 398 Ma. They proposed that intermittent REE mineralization of the Bayan Obo deposit started at about 555 Ma, and the principal mineralization occurred between 474 and 400 Ma. Hu et al. (2009) used Sm-Nd dating of REE mineral huanghoite and single-grain

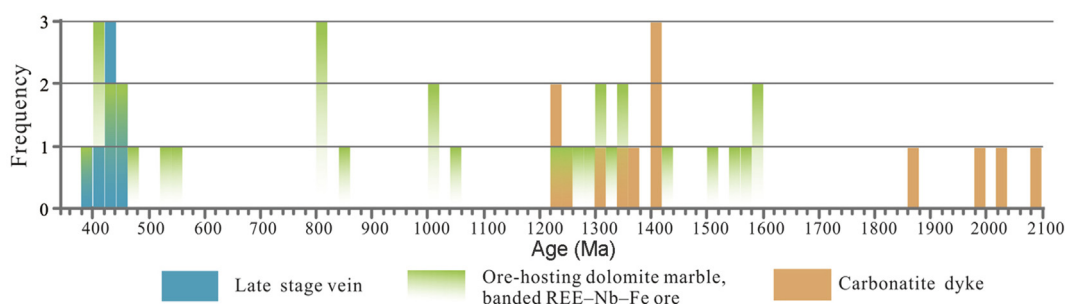


Figure 8. Summary of published geochronological results of carbonatite dyke, ore-hosting dolomite marble, banded REE-Nb-Fe ore, and late-stage REE vein at Bayan Obo.

biotite Rb-Sr dating, showing concordant isochrons corresponding to 442 ± 42 and 459 ± 41 Ma, respectively.

4.3. Two-stage mineralization

Ren et al. (1994) obtained monazite and bastnaesite Sm-Nd isochron of 1313 ± 41 Ma from Main and East Orebody ores, and monazite Th-Pb isochron of 461 ± 62 and 445 ± 11 Ma from carbonatite veins at Bayan Obo. SHRIMP analysis of monazite in the dolomite by Qiu (1997) gave average $^{206}\text{Pb}/^{238}\text{U}$ age of 802 ± 35 Ma and average $^{208}\text{Pb}/^{232}\text{Th}$ age of 498.8 ± 2.9 Ma. Campbell et al. (2014) reported SHRIMP dating of extremely U-depleted (<1 ppm) zircons from banded ores in the East Orebody. Their ^{232}Th - ^{208}Pb geochronological data reveal the age of zircon cores with Mesoproterozoic ages as 1325 ± 60 Ma and a rim alteration event with Caledonian ages as 455.6 ± 28.27 Ma. Zhu et al. (2015) reviewed Sm-Nd isotopic measurements which were undertaken to constrain the chronology of REE mineralization events at Bayan Obo, and considered that a series of ages between ca. 1400 and 400 Ma were resulted from thermal disturbance and do not imply the existence of additional mineralization events. They proposed that the earliest REE mineralization event was at 1286 ± 27 Ma using a Sm-Nd isochron of coarse-grained dolomite and the carbonatite dikes in their vicinity, and a significant thermal event at ca. 0.4 Ga resulted in the formation of late-stage veins with coarse crystals of REE minerals.

5. Nature of ore-forming fluids and sources

The study of the nature of ore-forming fluids at Bayan Obo is limited by the post depositional history of the ores, particularly in the earliest stages of the paragenesis like banded ores. Several possible sources of ore-forming fluids have been proposed for the Bayan Obo deposit, including deep source fluids (Institute of Geochemistry, Chinese Academy of Sciences, 1988), anorogenic magma (Wang et al., 2002a), magmatic and metamorphic fluids (Chao et al., 1997), mantle fluids (Cao et al., 1994), and carbonatite magma/fluids (Bai et al., 1996; Le Bas et al., 2007). Which source of ore-forming fluids best favor for REE mineralization is still disputed.

The available data on the oxygen, carbon, strontium and niobium isotope composition of the carbonatites, dolomites and obviously sedimentary limestones at Bayan Obo are taken to indicate that the large and coarse-grained dolomite was an igneous carbonatite, and that the finer grained dolomite recrystallized under the influence of mineralizing solutions which entrained groundwater (Philpotts et al., 1991; Le Bas et al., 1997). Sun et al. (2013) systematically investigated the Fe isotope compositions of different types of rocks from the Bayan Obo deposit and related geological formations, such as carbonatites, mafic dykes, and

Mesoproterozoic sedimentary iron formation and carbonates. The Fe isotope fractionation between magnetite and dolomite, and between hematite and magnetite at Bayan Obo is small, indicating that they formed in very high temperature conditions. Sun et al. (2013) proposed that the Fe isotope systematics for the Bayan Obo deposit is consistent with those of magmatic products, but different from those of sedimentary or hydrothermal products reported previously. They concluded that the Bayan Obo ore deposit is of magmatic origin. Huang et al. (2015) obtained trace elemental compositions of the magnetite and hematite from various ore types of the Bayan Obo deposit, using in situ LA-ICP-MS. Two generations of magnetite from Fe ores of the Bayan Obo deposit were identified, showing different trace element contents and origins. Magnetite of the first generation was sedimentary in origin and is rich in REEs, whereas that of the second generation was hydrothermal in origin and is relatively poor in REEs. Huang et al. (2015) concluded that the Bayan Obo REE deposit was most likely formed by further enrichment of REEs from REE-rich sedimentary carbonate rocks by metasomatism of hydrothermal fluids. This result is obviously different from that of above Fe isotope composition measurements.

Nature of ore-forming fluids is studied on fluid inclusions trapped in banded and vein ores at Bayan Obo (Smith et al., 2000; Fan et al., 2004a, 2006). Three types of fluid inclusions have been recognized: two or three phase CO_2 -rich, three phase hypersaline liquid-vapor-solid, and two phase aqueous liquid-rich inclusions. Microthermometry measurements indicate that the carbonic phase in CO_2 -rich inclusions is nearly pure CO_2 . Fluids involving in the REE-Nb-Fe mineralization at Bayan Obo might be REE-F- CO_2 -NaCl- H_2O system. Coexistences of hypersaline brine inclusion and CO_2 -rich inclusion with similar homogenization temperatures give evidence that immiscibility was happened during REE mineralization. An unmixing of an original H_2O - CO_2 -NaCl fluid with higher REE contents probably derived from carbonatite magma. The presence of REE-carbonates as an abundant solid in the ores shows that the original ore-forming fluids are very rich in REE, and therefore, have laid a foundation to produce economic REE ores at Bayan Obo (Fan et al., 2006).

6. Possible ore genesis

Genesis of the Bayan Obo giant ore deposit has been subject to debate for over several decades. Several possible models of ore genesis have been proposed for the deposit as reviewed by Wu et al. (1996), including syngenetic sedimentary deposition (Meng, 1982), metasomatism associated with granitic magmatism (Wang and Li, 1973), and deposition from exhalative, possibly carbonatite related, hydrothermal fluids (Yuan et al., 1992). Chao et al. (1992) demonstrated an epigenetic origin for the deposit via multistage hydrothermal metasomatism. On this basis models involving metasomatism by fluids derived from either subduction (Chao et al., 1992; Wang et al., 1994), or carbonatite, or alkaline,

magmatism (Drew et al., 1990; Hao et al., 2002; Yang et al., 2003; Ling et al., 2013; Sun et al., 2013) have been proposed. The link between carbonatite magmatism and the Bayan Obo mineralization now seems firmly established. The interpretation of the carbonatite source for the metasomatic fluids is supported by the presence of carbonatite dykes cutting the metamorphic and sedimentary rocks around the deposit and the apparent carbonatitic affinities of the host dolomites (Le Bas et al., 1992, 1997, 2007; Yang et al., 2000, 2003, 2011a).

The Bayan Obo deposit was likely associated in space and time with large-scale carbonatitic magmatic activity (ca. 1400 to 1300 Ma) in response to the long-term rifting and magma evolution in the north margin of North China Craton (Wang et al., 1992; Xiao and Kusky, 2009). The depleted mantle model age (T_{DM}) from the Nd isotope data on carbonatite dyke and ore-hosting dolomite samples range from 1.61 to 1.79 Ga, which coincide with the initiation of the Bayan Obo rift (ca. 1.75 Ga, Li et al., 2007). Along with the prolonged and slow extension of the Bayan Obo rift, the mantle lithosphere underwent low degree of partial melting leading to the production of carbonatite magma at the final stage of break up the supercontinent Columbia (ca. 1.4–1.2 Ga, Zhao et al., 2006; Hou et al., 2008). Through continuous evolution (crystal fractionation), abundant LREE accumulation occurred in the terminal calcite carbonatite magma, which was then superposed on the early dolomite carbonatite pluton, thus resulting in the formation of the giant Bayan Obo REE deposit.

As the Bayan Obo ore deposit are LREE and Th enriched, U depleted, with very lower Sm/Nd and U/Pb values, and low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, it is difficult to obtain high resolution Sm–Nd, U–Pb ages for banded and massive REE mineralization in the East and Main orebodies (Zhu et al., 2015). The zircons in the carbonatite dyke at Bayan Obo have provided a unique record of the early mineralization history of the region (Yang et al., 2011b). The timing of the early episode of REE mineralization of Bayan Obo deposit obtained from REE minerals and ore-hosting dolomite, ca. 1400–1300 Ma, is consistent with the reported ages of REE-rich carbonatite dykes, implying a genetic connections. Geochemical evidence of element content and Nd isotope composition also imply that ore-hosting dolomite and the carbonatite dykes have a close relationship to a magmatic origin (Yang et al., 2011b). A significant thermal event at ca. 440 Ma resulted in the formation of late-stage veins with coarse crystals of REE minerals. This event is also indicated by SHRIMP Th–Pb analyses of hydrothermal overgrowths on ore body zircon at Bayan Obo, which indicate ages of 455 ± 28 Ma (Campbell et al., 2014). However, the REE mineralization developed during this event resulted from remobilization of REE within the orebodies, and any potential contribution from external sources was minimal. Thus, this late mineralization event might make no significant contribution to the existing ore reserves (Zhu et al., 2015). The ages of ca. 440 Ma may be related to subduction of the Palaeo-Asian oceanic plate during the Silurian (Wang et al., 1994; Chao et al., 1997).

It can be concluded that the Bayan Obo giant deposit is a product of mantle-derived carbonatitic magmatism at ca. 1400 Ma, which was likely related to the breakup of Columbia. Some remobilization of REE occurred due to subduction of the Palaeo-Asian oceanic plate during the Silurian, forming weak vein-like mineralization.

7. Concluding statement

The giant Bayan obo deposit suffered repeated tectonic-magmatic re-working at the north margin of the NCC. Recent researches had given some evidences that the REE mineralization at Bayan Obo was a product of mantle-derived carbonatitic magmatism. But more ambiguous explanations are still existed. Where the

REE come from? How the REE transport and deposit from ore fluids? The Bayan Obo mine is also a large Nb deposit, the scale and mineralizing style of Nb are still unclear. Where can we find another giant LREE deposit like Bayan Obo in China or in the World? Understanding of the Bayan Obo deposit would be enhanced by recent-advanced *in-situ* micro-analytical studies of the geochemical and isotopic signature of the mineralization and more-detailed geological works.

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