17 Insights into the Ore Genesis of the Giant Bayan Obo REE-Nb-Fe Deposit and the Mesoproterozoic Rifting Events in the Northern North China Craton

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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. 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, coexisting dolomite–calcite, and calcite type, corresponding to different evolutionary stages of carbonatitic magmatism, and the latter always has higher LREE 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 and field interspersed relationship 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 former one. The ore bodies, distributed along an E-W striking belt, occur as large lenses and underwent more intense fluoritization and fenitization with wall rocks. The first episode mineralization is characterized by disseminated mineralization in the dolomite. The second or main-episode is banded 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-CO_2-NaCl-H_2O 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 the supercontinent Columbia. Some remobilization of REE occurred due to subduction of the Palaeo-Asian oceanic plate in the Early Paleozoic, forming weak vein-like mineralization.

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Geochemistry • Geochronology • Carbonatite • Dolomite • Bayan Obo REE-Nb-Fe deposit

17.1 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. 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, 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, particularly with regard to the mechanism of REE enrichment, still remains intense debated (Yuan et al. 1992; Wang et al. 1994, 2002a; Bai et al. 1996; Le Bas et al. 1997, 2007; Li 2007; Smith et al. 2000, 2015; Yang et al. 2000, 2003, 2009, 2011a, b, 2012; 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).

The main arguments have focused on the genesis of the ore-hosting dolomite marble. Chao et al. (1992, 1997) proposed that the dolomite marble is a sedimentary formation and the REE mineralization formed from fluids associated with granitic magmatism and metamorphism during the Paleozoic. Wang et al. (1992), Yuan et al. (1991) and Bai et al. (1996) suggested that the ore-hosting dolomite marble is a volcano-sedimentary formation and that the REE mineralization was derived from a mantle fluid. Drew et al. (1990), Le Bas et al. 1992, 1997, 2007), Yang and Le Bas (2004) and Yang et al. (2003, 2011a, b) argued that the ore-hosting dolomite marble is a carbonatite intrusion and that the REE mineralization was derived from a Mesoproterozoic carbonatitic magma. However, recent studies (Campbell et al. 2014; Lai et al. 2015; Ling et al. 2013; Smith et al. 2015; Xu et al. 2010, 2012; Yang et al. 2009) appear to favor the model of multiple mineralization.

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

17.2 Regional and Ore Geology

The Bayan Obo deposit is located in the northern margin of the North China Craton (NCC), bordering on the Central Asian Orogenic Belt to the north (Xiao et al. 2003; Xiao and Kusky 2009) (Fig. 17.1). Gentle fold structures, composed mostly of the low grade meta-sedimentary units of the Mesoproterozoic Bayan Obo Group, are distributed from south to north in the region (Fig. 17.1). The famous Bayan Obo giant REE-Nb-Fe deposit, hosted in the massive dolomite, occurs in one of the syncline cores (Fig. 17.2). 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. 17.2). 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. 2008a, b; 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 (H_9 term) and extended 18 km from east to west with approximately 2 km width (Fig. 17.1), was once considered as a component of Bayan Obo Group, called H_8 term. The origin of the dolomite 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 (Yuan et al. 1992; Le Bas et al. 1992, 1997, 2007; 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 Neoarchean 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. 17.1). These plutons were once regarded as intruding from Devonian to Jurassic. New geochronology

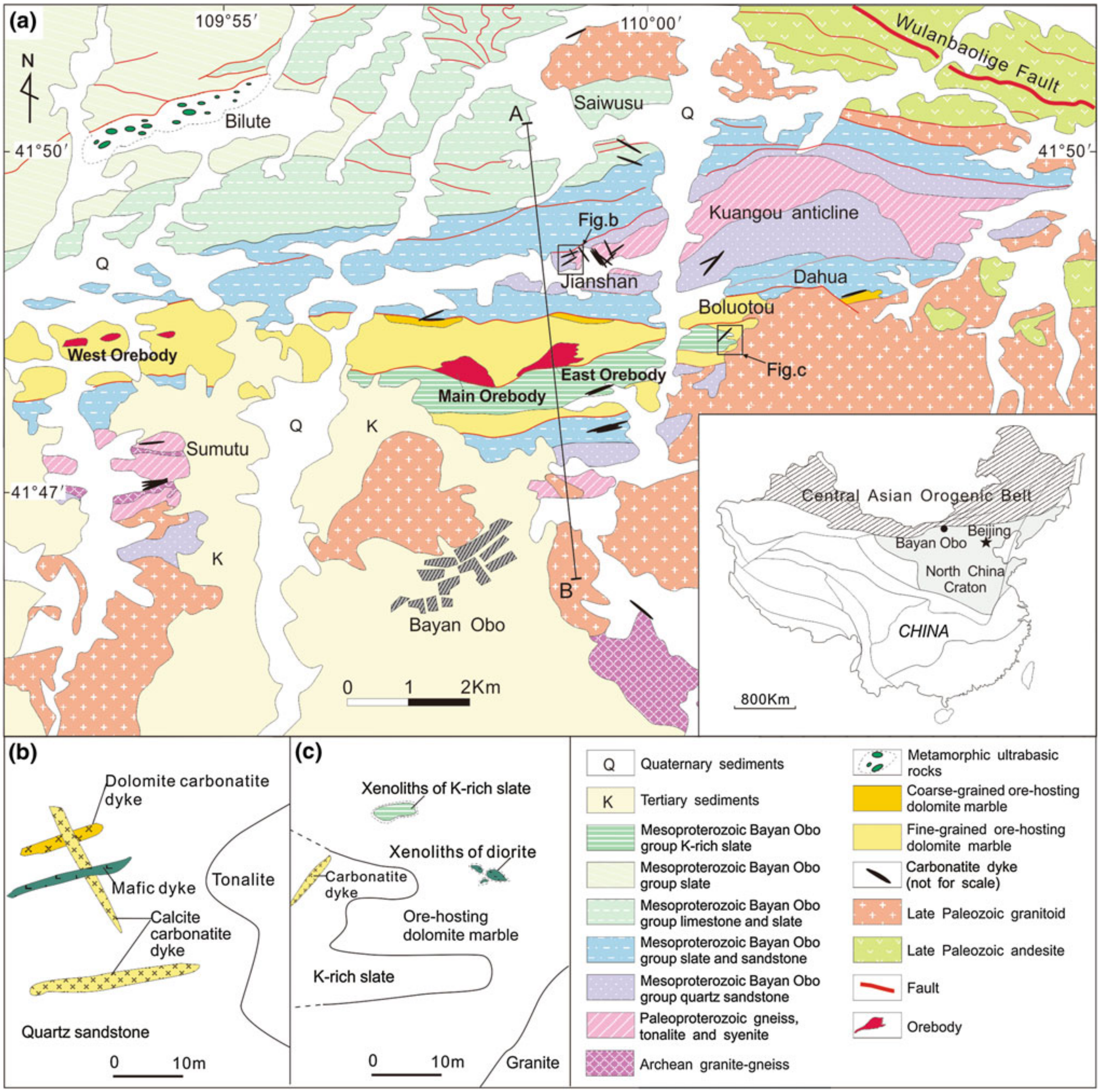

Fig. 17.1 Geological map of the Bayan Obo deposit (**a**). Intrusive contact between dolomite and calcite carbonatite dykes (**b**). Xenoliths of K-rich slate and diorite in fine-grained ore-hosting dolomite marble with extensive fenitization and flow structure around them (**c**), modified after Yang et al. (2011a)

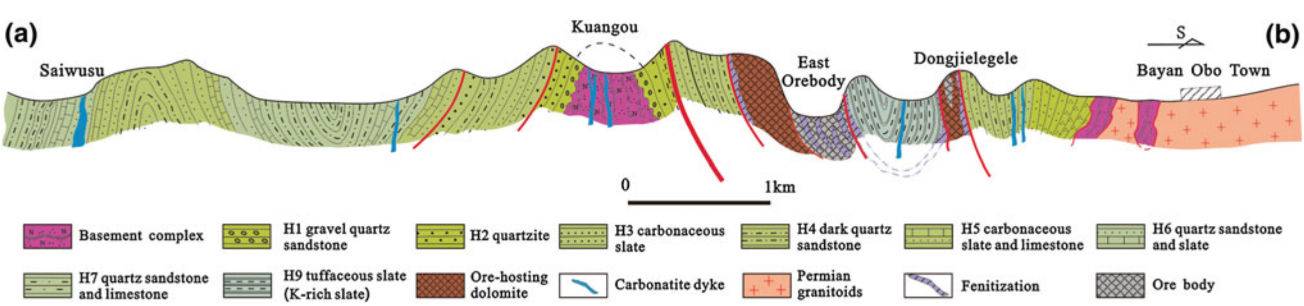

Fig. 17.2 Geological section of line *A*–*B* in Fig. 18.1, showing location of ore bodies

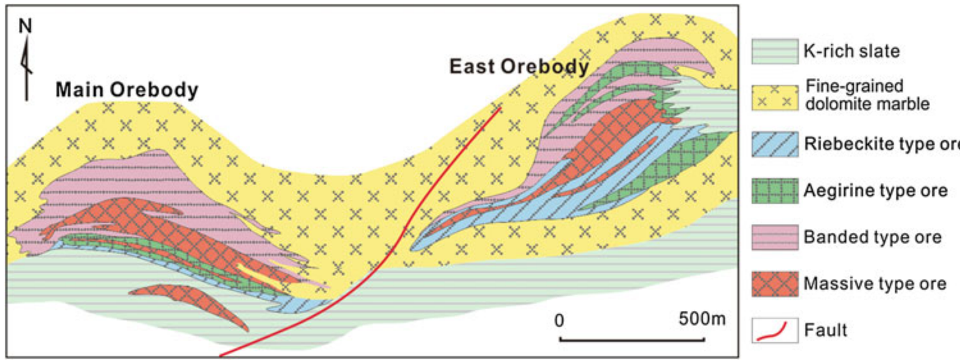

Fig. 17.3 Geological map of the main and east Orebody at Bayan Obo, modified after Institute of Geology and Guiyang Geochemistry, Chinese Academy of Sciences (1988)

Fig. 17.4 Outcrop of mafic and carbonatite dykes at Bayan Obo. **a**, **b** Carbonatite dykes in the Dongjie and Dulahala showing strong fenitization developed around the wallrock quartz conglomerate; **c**, **d** mafic dykes cutting banded ore body in the Bayan Obo REE deposit

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 to 281 Ma with peak age of 269 Ma (Fan et al. 2009), which is consistent with 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).

Detailed geological mapping showed that there are nearly one hundred carbonatite dykes occur in the vicinity of the Bayan Obo deposit (Figs. 17.1 and 17.4a). 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 (Fig. 17.4b) (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. 17.1). 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. 17.3), underwent more intense fluoritization, fenitization, and hosted more abundant REE and Nb resource. 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. 17.3). The principal REE minerals are bastnaesite-(Ce) and monazite-(Ce), and accompanied with a various kinds of REE and Nb minerals, such as huanghoite, aeschynite-(Ce), felgusonite, apatite, and columbite. Iron minerals are magnetite and hematite. Main gangue minerals include fluorite, barite, alkali amphibole, 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 cross-cutting relations, three important REE mineralizing episodes can be indentified at the simplest level (Fig. 17.5). The first episode is characterized by disseminated mineralization which contains monazite associated with ferroan dolomite, ankerite, and magnetite, concentrated along grain boundaries in the relatively unaltered/massive dolomite (Fig. 17.5a). The second or main-episode is banded and/or massive mineralization (Fig. 17.5b), which shows a generalized 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. 17.5c, d).

17.3 Genesis of Carbonatite Dyke and Ore-Hosting Dolomite

Abundant carbonatite dykes occur adjacent to the eastern and southern of the Bayan Obo mine and particularly within the Kuangou anticline (Fig. 17.1). 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. 17.4a, b). Wang et al. (2002a) mentioned that carbonatite dykes at Bayan Obo can be divided into three types: dolomite, coexisting dolomite–calcite and calcite type. The latter always has higher LREE 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. 17.1b), showing that the emplacement of the calcite dyke is later than the dolomite one. Geochemical data (Yang et al. 2011a) show 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 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, 2004). 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 (Fig. 17.1c) (Le Bas et al. 1997, 2007; Yang et al. 2011a). 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 Sailinhudong micrite mound. They show that the Bayan Obo ore-hosting dolomite marbles are strongly enri-

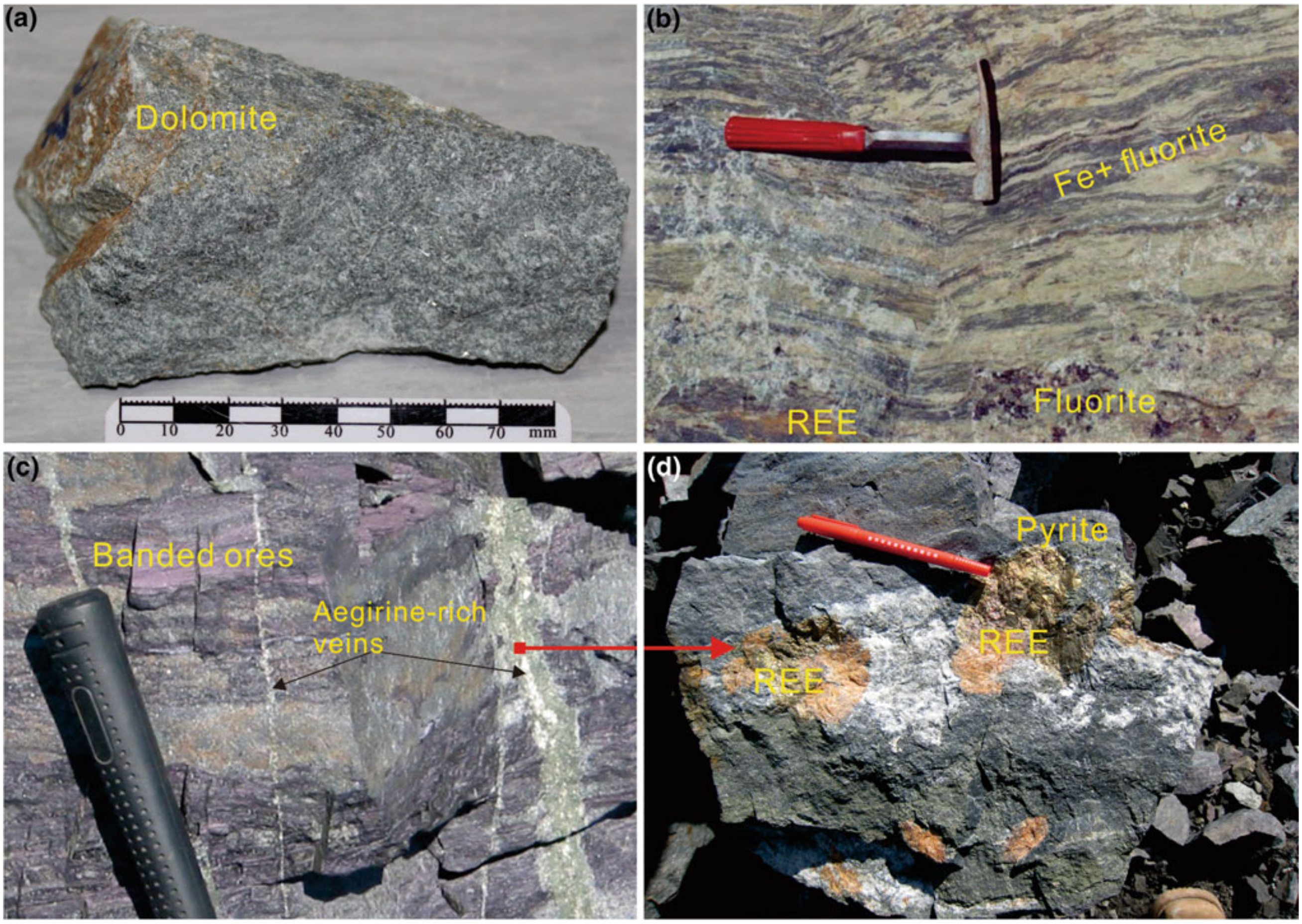

Fig. 17.5 Major mineralization types from the Bayan Obo deposit. **a** Fine-grained dolomite with disseminated mineralization; **b** banded REE–Nb–Fe mineralization; **c**, **d** late-stage vein cross-cutting banded REE–Nb–Fe ore

ched in LREEs, Ba, Th, Nb, Pb, and Sr, and have very different (PAAS)-normalized REE patterns, while Sailinhudong micrite carbonates have higher $\delta^{13}C_{PDB}$ and $\delta^{18}O_{SMOW}$ 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 $\delta^{26}Mg$ values of the Sailinhudong 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 $\delta^{26}Mg$ 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 (Fig. 17.6a). 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 carbonatite dykes at Bayan Obo. Data from those samples overlap within the magnesio-carbonatite

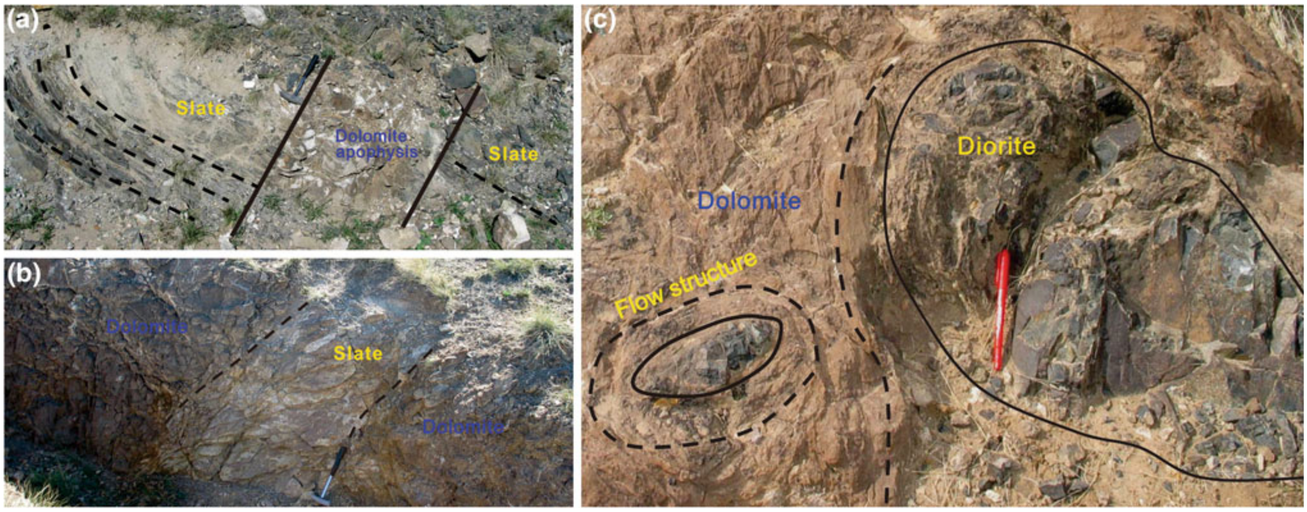

Fig. 17.6 Intrusion contact between dolomite and wallrocks. **a** A small apophysis, emanating from the dolomite, apparently intruded into the Bayan Obo group H_9 slate; **b** xenolith of H_9 slate in the ore-bearing dolomite; **c** xenoliths of diorite in the ore-bearing dolomite, and the flow structure around them

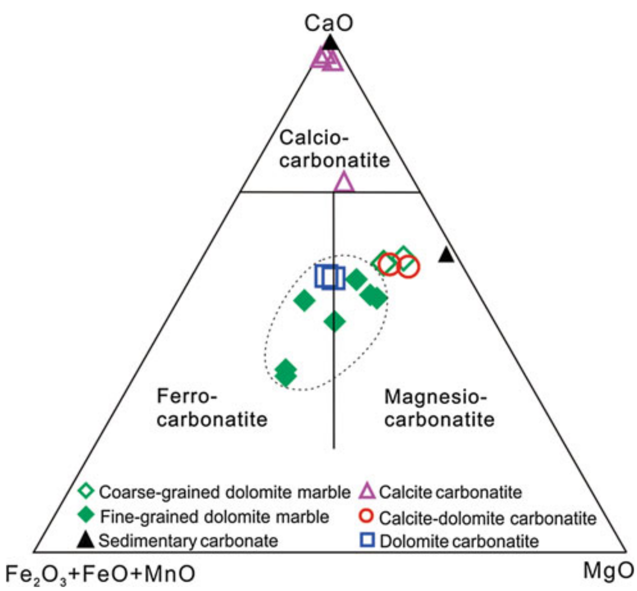

Fig. 17.7 CaO-MgO-(FeO + Fe_2O_3 + MnO) classification diagram (Woolley and Kempe 1989) for the carbonatite dykes, ore-hosting dolomite marble and sedimentary carbonate rocks from Bayan Obo district

region on the CaO-MgO-(FeO + Fe_2O_3 + MnO) classification diagram (Fig. 17.7) (Yang et al. 2011a), and show similar REE contents and distribution patterns on the chondrite-normalized abundance diagram (Yang et al. 2011a; Fig. 17.8a, 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 (Fig. 17.6), 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 Orebody 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 + Fe_2O_3 + MnO) classification diagram (Fig. 17.7) (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. 17.8a, 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 carbonatitic magma.

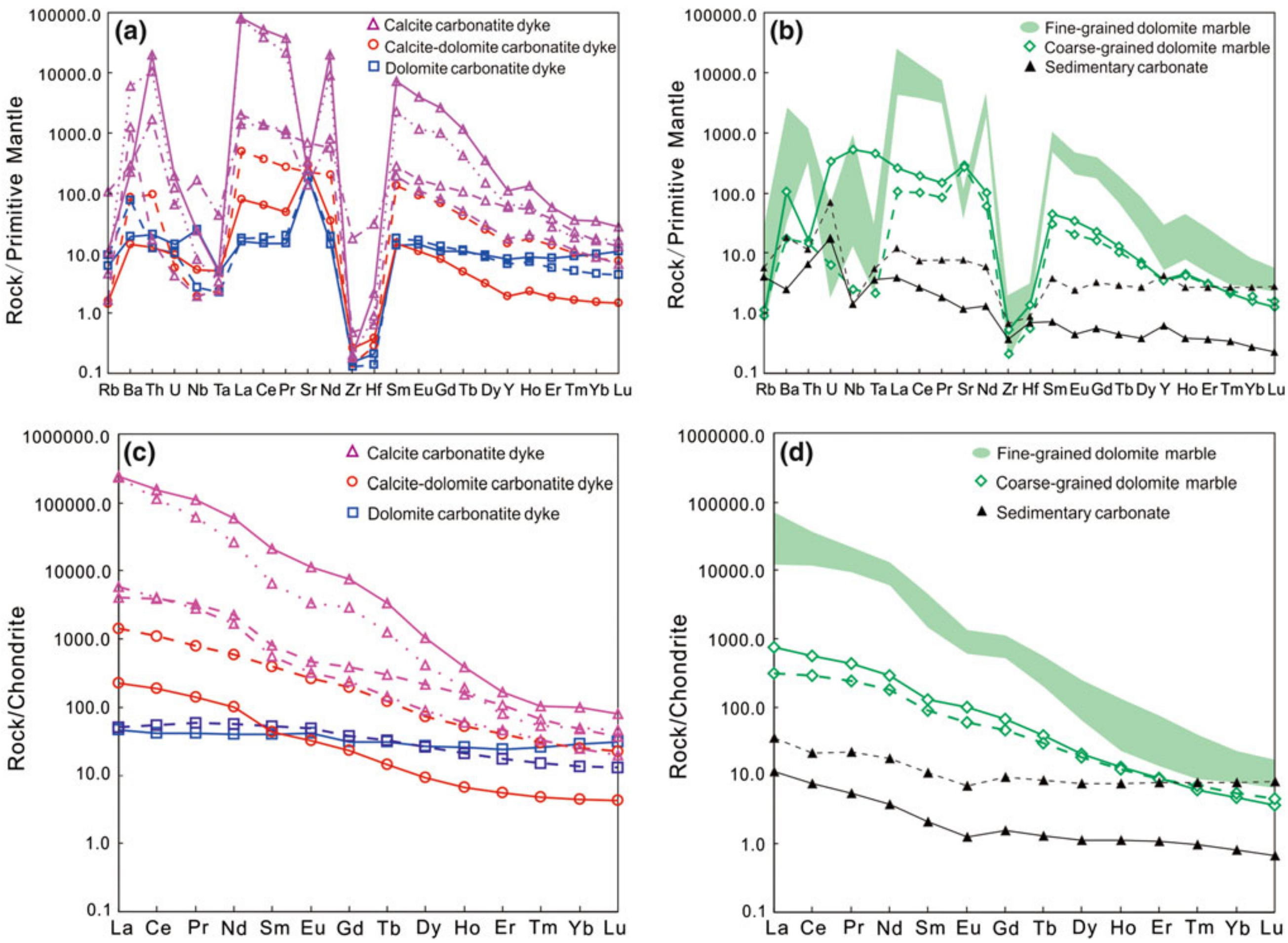

Fig. 17.8 **a**, **b** Primitive mantle-normalized trace element abundance pattern for carbonatite dykes, ore-hosting dolomite marble and sedimentary carbonate rocks at Bayan Obo; **c**, **d** chondrite-normalized REE abundance diagram for carbonatite dykes, ore-hosting dolomite marble, and sedimentary carbonate rocks at Bayan Obo, modified after Yang et al. (2011a)

17.4 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, 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 17.1; Fig. 17.9), 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.

17.4.1 Mesoproterozoic Mineralization

Nakai et al. (1989) first reported REE mineral La-Ba and Sm–Nd isochron date of 1350 ± 149 Ma 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 Ma and 1305 ± 78 Ma, respectively. Yang et al. (2011a) reported a whole-rock Sm–Nd isochron from of nine carbonatite dykes 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

Table 17.1 A brief geochronology overview in the Bayan Obo deposit

Type	Material	Sample location	Methods	Age (Ma)	References
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)
	Zircon in carbonatite	Dulahala	U–Pb	1418	Fan et al. (2014)
Ore-hosting dolomite marble, banded REE–Nb–Fe ore	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 bastaesite	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)
	Bastaesite	Dolomitic ore	Th–Pb	555	Liu et al. (2005)
	monazite	ore	Th–Pb	1231	
	Apatite	Main and East Orebodies	U–Pb	1588	Institute of Geology and Guiyang 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	

(continued)

Table 17.1 (continued)

Type	Material	Sample location	Methods	Age (Ma)	References
	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 re	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)

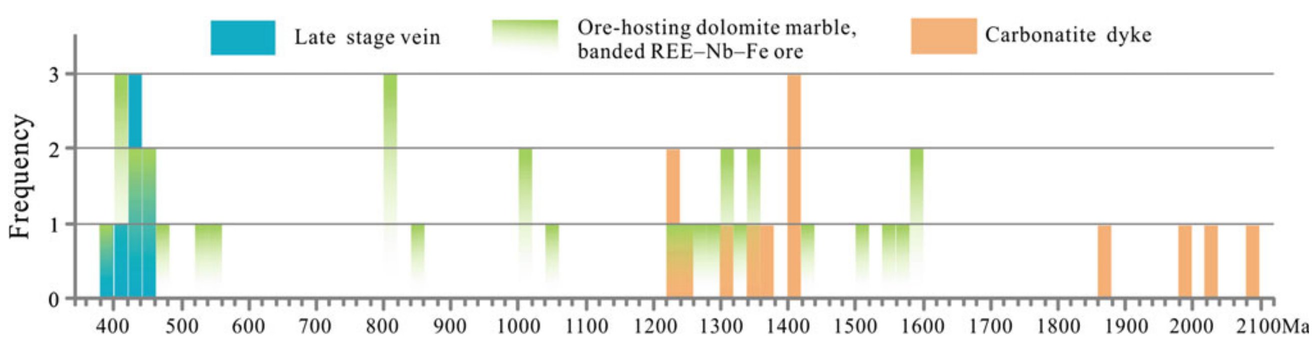

Fig. 17.9 Summary of published geochronological results of carbonatite dyke, ore-hosting dolomite marble, banded REE–Nb–Fe ore, and late-stage REE vein at Bayan Obo

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

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

17.4.3 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 Ma and 445 ± 11 Ma from carbonatite veins at Bayan Obo. SHRIMP analysis of monazite in the dolomite by Qiu (1997) gave average $^{206}Pb/^{238}U$ age of 802 ± 35 Ma and average $^{208}Pb/^{232}Th$ 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.

17.5 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). The 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 sedimentary carbonates provided original REEs and were metasomatized by REE-rich hydrothermal fluids to form the giant REE deposit. This result is obviously different from that of above Fe isotope composition measurements, which imply a multiple process and hydrothermal fluids resources for REE mineralization.

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).

17.6 Ore Genesis and Mesoproterozoic Rifting Events

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 is located in the north margin of the NCC, which experienced a major rifting event (the Langshan-Bayan Obo rift) in the Mesoproterozoic (Wang et al. 1992). The large Langshan-Bayan Obo continental rift, together with Yan-Liao rift in the east and Xiong'er rift in the south of NCC (Fig. 17.10), marked by swarm of mafic dykes between 1.75 and 1.79 Ga (Li et al. 2007; Peng et al. 2007; Santosh et al. 2010), correlate with the fragmentation of the Columbia supercontinent (Zhai et al. 2004; Zhao et al. 2004; Santosh et al. 2009).

The Bayan Obo deposit was likely associated in space and time with large-scale carbonatitic magmatic activity (ca. 1400–1300 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). Moreover Yang et al. (2011a) reported the coexistence of carbonatite and alkalic mafic rocks in the Bayan Obo region (Fig. 17.4c, d), which is usually related to continental rift environment. Extensive continental breakup and mantle-derived mafic and alkali magmatism during the middle Mesoproterozoic has been widely reported from various parts of the NCC in addition to the Bayan Obo region. Zhang et al. (2009) identified large volumes of 1.35 Ga diabase sills, emplaced into the Mesoproterozoic Wumishan Formation, indicates that the northern NCC underwent strong extension and mafic magmatism during the middle and late Mesoproterozoic (1.4–1.2 Ga), probably related to the final breakup of the supercontinent Columbia.

The mid–late Mesoproterozoic rifting within the NCC can be correlated to similar worldwide events associated with the breakup of the Columbia supercontinent (Rogers and Santosh 2002, 2009; Kusky and Li 2003; Kusky et al. 2007; Santosh et al. 2009). During its prolonged breakup history from ca. 1.8 to 1.2 Ga, the supercontinent probably witnessed two major episodes of fragmentation (e.g., Zhao et al. 2004, 2006). The early stage (1.8–1.6 Ga) is represented by the formation of several continental rifts accompanied by the emplacement of abundant mafic dyke swarms (Halls et al. 2000; Zhai et al. 2004; Li et al. 2006, 2007; Peng et al. 2007; Hou et al. 2008a, b). The second stage marked the final breakup (1.4–1.2 Ga), and witnessed the formation of several large mafic dyke swarms and anorogenic magmatic activity (Rogers and Santosh 2002; Zhao et al. 2004, 2006; Hou et al. 2008a).

The global anorogenic magmatism during Mesoproterozoic (mostly represented by alkaline mafic and ultramafic rocks) also include the kimberlites and carbonatites (1.6–1.2 Ga) in the margin of the Kaapvaal Craton (Phillips et al. 1989), the kimberlites (1.4–1.2 Ga) in the southwest margin of the West African (Haggerty 1982), the kimberlites

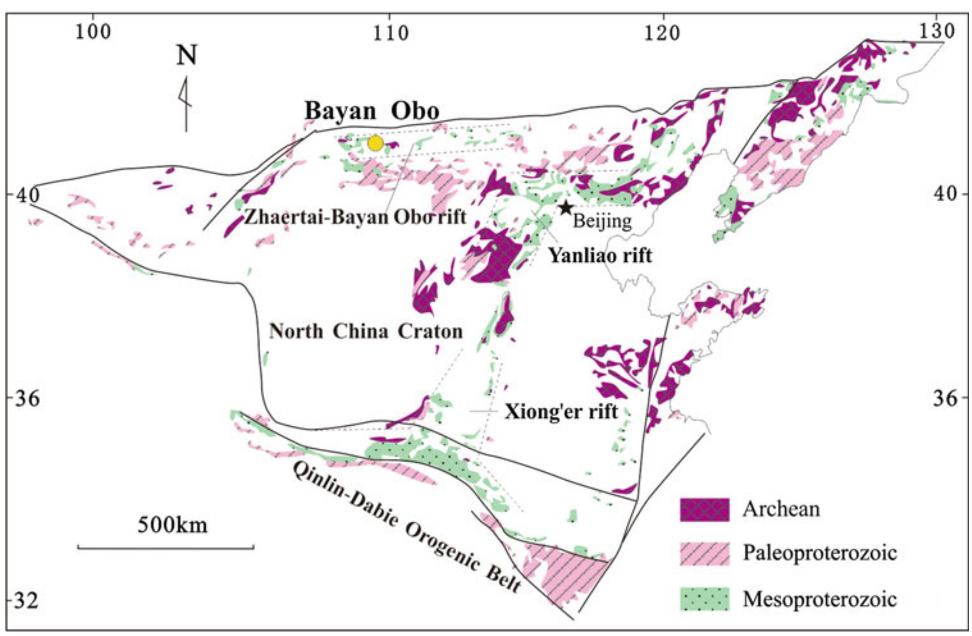

Fig. 17.10 Geological map of the North China Craton modified after Xiao et al. (2003), Peng et al. (2007) and Kusky et al. (2007)

(1.2 Ga) of Kimberley area in the western Australia (Pidgeon et al. 1989), and the kimberlites and lamproites (1.38–1.22 Ga) in the Indian Shield (Paul et al. 1975; Chalapathi Rao et al. 1996, Chalapathi Rao 2007). The Bayan Obo carbonatites described in this study closely correlate to most of the above examples in terms of tectonic setting and formation age.

Yang et al. (2011b) obtained similar whole-rock Sm–Nd isochron ages of the mafic dyke (1227 ± 60 Ma) and carbonatite (1354 ± 59 Ma) from Bayan Obo. The comparable Sr-Nd isotope characteristics and Nb/Ta ratios also suggest their close petrogenetic relationship. Furthermore, the Zr/Y versus Zr composition also suggests their formation within a continental rift (Yang et al. 2011b). This suggests that the generation of the parent mafic–carbonatitic magma was related to the initiation of the Bayan Obo continental margin rift. The massive carbonatitic–mafic magmatism in the Bayan Obo region during the middle to late Mesoproterozoic (1.4–1.2 Ga) is approximately coeval with the worldwide rifting events at this time that are associated with the final breakup of the supercontinent Columbia.

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.

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).

17.7 Conclusion

The giant Bayan obo deposit suffered repeated tectonic-magmatic reworking at the north margin of the NCC. The deposit is hosted in the massive dolomite, and nearly one hundred carbonatite dykes occur in the vicinity of the deposit, which were resulted from different evolutionary stages of carbonatitic magmatism from dolomite type to calcite type based on the REE and trace element data. The latter always has higher LREE content. The 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. Compilation of available data suggests that the mineralization age 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 and the breakup of the Columbia supercontinent. 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-CO_2-NaCl-H_2O 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. 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 the supercontinent Columbia. Some remobilization of REE occurred due to subduction of the Palaeo-Asian oceanic plate during the Early Paleozoic forming weak vein-like mineralization.

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