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Mesoproterozoic mafic and carbonatitic dykes from the northern margin of the North China Craton: Implications for the final breakup of Columbia supercontinent

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ABSTRACT

The North China Craton (NCC) has figured prominently in recent reconstructions on the Paleoproterozoic supercontinent Columbia. Here we report abundant carbonatitic and mafic dykes from around the giant Bayan Obo rare earth element deposit in the northern margin of the NCC, and present geochemical and isotope geochronological data. The carbonatite (1354 ± 59 Ma) and mafic dykes (1227 ± 60 Ma) have comparable whole rock Sm–Nd isochron ages and Sr–Nd isotope compositions, suggesting a common source characteristic. Their geochemical characters including major and trace elements as well as REE patterns also attest to a common tectonic environment of magma generation and emplacement within a continental margin rift. The extensive mafic and carbonatitic magmatisms are associated with an extensional event that resulted in the formation of the Bayan Obo rift in the northern margin of the NCC, which we correlate with the final stages of fragmentation of the Columbia supercontinent amalgam.

1. Introduction

The late Mesoproterozoic globe witnessed extensive magmatic activity manifested in the form of mafic dyke swarms and related volcanic suites within a relatively short span of time ranging from ca. 1.35–1.21 Ga (Zhao et al., 2004, 2009; Ernst et al., 2008; Hou et al., 2008a) (Fig. 1). Imprints of this rift-related magmatic activity are preserved in various continents including North America (Le Cheminant and Heaman, 1989; Ernst et al., 1995, 2001; Ernst and Buchan, 2003), South America (Raposo and D'Agrella, 2000), Africa (Hunter and Reid, 1987), Greenland (Nielsen, 1987; Cadman et al., 2001), Australia (Mortimer et al., 1988; Pidgeon and Nemchin, 2001), India (Chalapathi Rao et al., 1996, 2010; Chalapathi Rao, 2007; Dharma Rao et al., 2010), and east Antarctica (Sheraton et al., 1990). One of the most widely distributed dyke swarms of this period is the Mackenzie swarm in northwest Canada (Ernst et al., 1995), which extends over an area of 2.7 million km^2 from a central domain comprising large ultramafic–mafic intrusions. Precise U–Pb dating has shown that these mafic dykes and intrusions were emplaced within a very short period of 1272–1267 Ma (Le Cheminant and Heaman, 1989). The other dike swarms with similar age in North America include the 1.24 Ga Sudbury dyke swarm and 1.25 Ga Mealy dike swarm (Ernst et al., 2008). These mafic dyke swarms are considered to signal the final breakup of the Columbia supercontinent in the late Mesoproterozoic (Rogers and Santosh, 2002, 2004, 2009; Hou et al., 2008a; Santosh et al., 2009; Hou et al., 2010). The North China Craton (NCC) has been considered as an integral part of the Paleoproterozoic supercontinent Columbia (Zhao et al., 2002; Kusky et al., 2007; Santosh et al., 2007a,b; 2010; Rogers and Santosh, 2009; Santosh, 2010). Among the various paleogeographic configurations of the NCC within the Columbia amalgam, the model proposed by Hou et al. (2008a,b) is based largely on the extensive mafic dyke swarms which traverse the NCC, and their robust correlation with similar suites in other crustal fragments of this supercontinent assembly. The NCC is traversed by a number of Mesoproterozoic continental rifts, both within the central part of the craton and at its margins (Fig. 2a). These include the Zhaertai–Bayan Obo rift in the north, Yanliao rift in the east, and Xiong'er rift in the south, with the timing of their formation since 1.8 Ga (Kusky and Li, 2003; Zhai, 2004; Zhao et al., 2004, 2009; Li et al., 2006; Peng et al., 2007). However, mafic dyke swarms of late Mesoproterozoic age, although common in many parts of the world, have seldom been reported from the NCC in previous studies.

In this study, we document abundant late Mesoproterozoic (1.35–1.21 Ga) mafic and carbonatitic dykes from the northern margin of the NCC (Fig. 2), associated with the famous Bayan Obo giant rare earth element (REE) ore deposit. Based on detailed investigations on the distribution and emplacement relationship of these dykes, as well as their petrology, geochemistry and isotope characteristics, we provide

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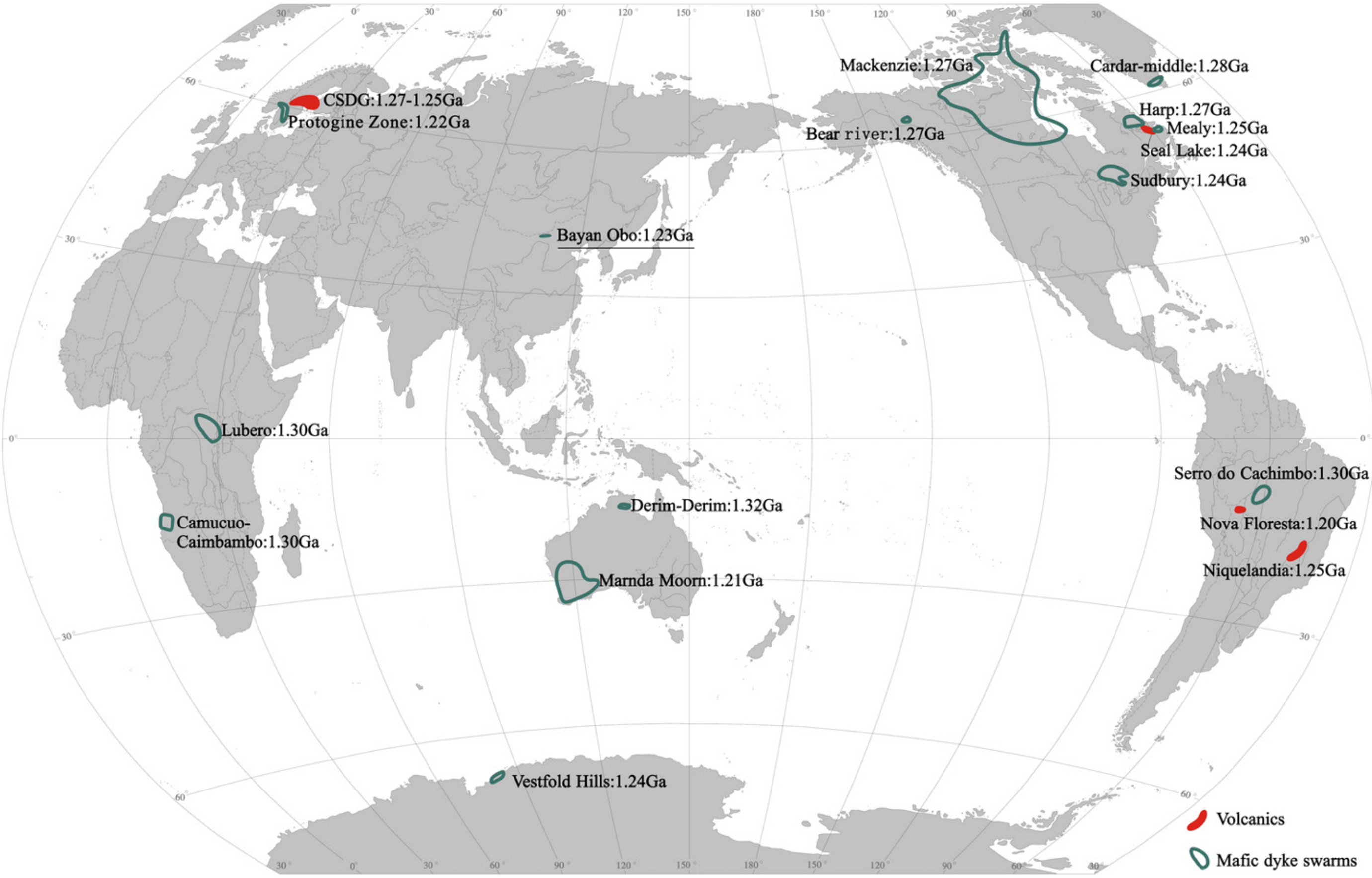

Fig. 1. Global distribution of mafic dyke swarms and volcanics between 1.35 and 1.20 Ga, (modified after Ernst et al., 2008).

new insights into mafic–carbonatitic magmatism associated with the final stages of the breakup of the Columbia supercontinent.

2. Geological background

The Bayan Obo district is located at the northern margin of NCC bordering the Central Asian Orogenic Belt to the north (Xiao et al., 2003, 2010; Xiao and Kusky, 2009) (Fig. 2a). Gentle fold structures, composed mostly of low grade metasedimentary units of the Mesoproterozoic Bayan Obo Group are distributed from south to north in the region (Fig. 2b). The famous Bayan Obo giant REE deposit occurs in one of the syncline cores. To the north of the ore body, a complete sequence of Bayan Obo Group is exposed in the Kuangou anticline, which developed on the Paleoproterozoic basement rocks with a distinct angular unconformity. The low grade clastic sequences of the Bayan Obo Group represent the sedimentary units deposited within the Bayan Obo marginal rift which developed during the Mesoproterozoic continental breakup event (Wang et al., 1992).

Adjacent to the giant REE deposit and especially within the Kuangou anticline, abundant carbonatite dykes are seen intruding the Bayan Obo Group of low grade metasediments, as well as the basement rocks (Fig. 2b). The dykes, almost vertically cutting the strata, are typically 0.5 to 2.0 m wide and 10 to 200 m long, and show a northeast or northwest strike. In addition, there are two small carbonatite stocks towards the northern domain of the ore body. Le Bas et al. (2007) considered them as a coarse-grained carbonatite which survived the extensive mineralization event in the Mesoproterozoic.

It is thought that the majority of continental carbonatites result from mantle magmatism following crustal stretching and thinning (Tilton and Bellk, 1994; Smithies and Marsh, 1998). Magmatism in such tectonic settings is often characterized by alkalic–basic anorogenic suites and may include kimberlite, lamprophyre and carbonatite (Dawson, 1989). The association of mafic magmatic dykes together with carbonatites in the Bayan Obo region therefore provides an excellent example of late Mesoproterozoic mantle magmatism and has therefore important implications on the rift tectonics associated with the NCC within the Columbia supercontinent.

3. Sampling and field relation

The mafic dykes are typically 1.0 to 2.0 m wide and 10 to 100 m long. In the Bayan Obo ore deposit, they incise the banded REE ore body as well as the overlying K-rich slate of the Bayan Obo group (Fig. 3a, b). The mafic dykes also cut through the carbonatite dykes at Jianshan (E109°59′10.2″, N41°49′02.9″) in the Kuangou anticline (Fig. 2c). We therefore infer that the emplacement of the mafic dykes might have post-dated the formation of the carbonatite dykes as well as the REE mineralization. In this study, the samples of the mafic dykes were collected from Dahua, Kuangou and the main Bayan Obo ore body. The locations and sample numbers are shown in Fig. 2b.

The carbonatite dykes, steeply cutting the strata, are typically 0.5 to 2.0 m wide and 10 to 200 m long, and show a northeast or northwest strike, the host rocks generally suffered extensive fenitization (Fig. 3d). Based on their mineralogical composition, the carbonatite dykes can be divided into three categories: dolomite type, coexisting dolomite–calcite type, and calcite type, with the calcite type showing higher REE content than the other two types (Wang et al., 2002). The carbonatite samples for this study were collected from around the ore body, especially in the Kuangou anticline, including two small carbonatite stocks and nine carbonatite dykes. The sampling locations and sample numbers are shown in Fig. 2b.

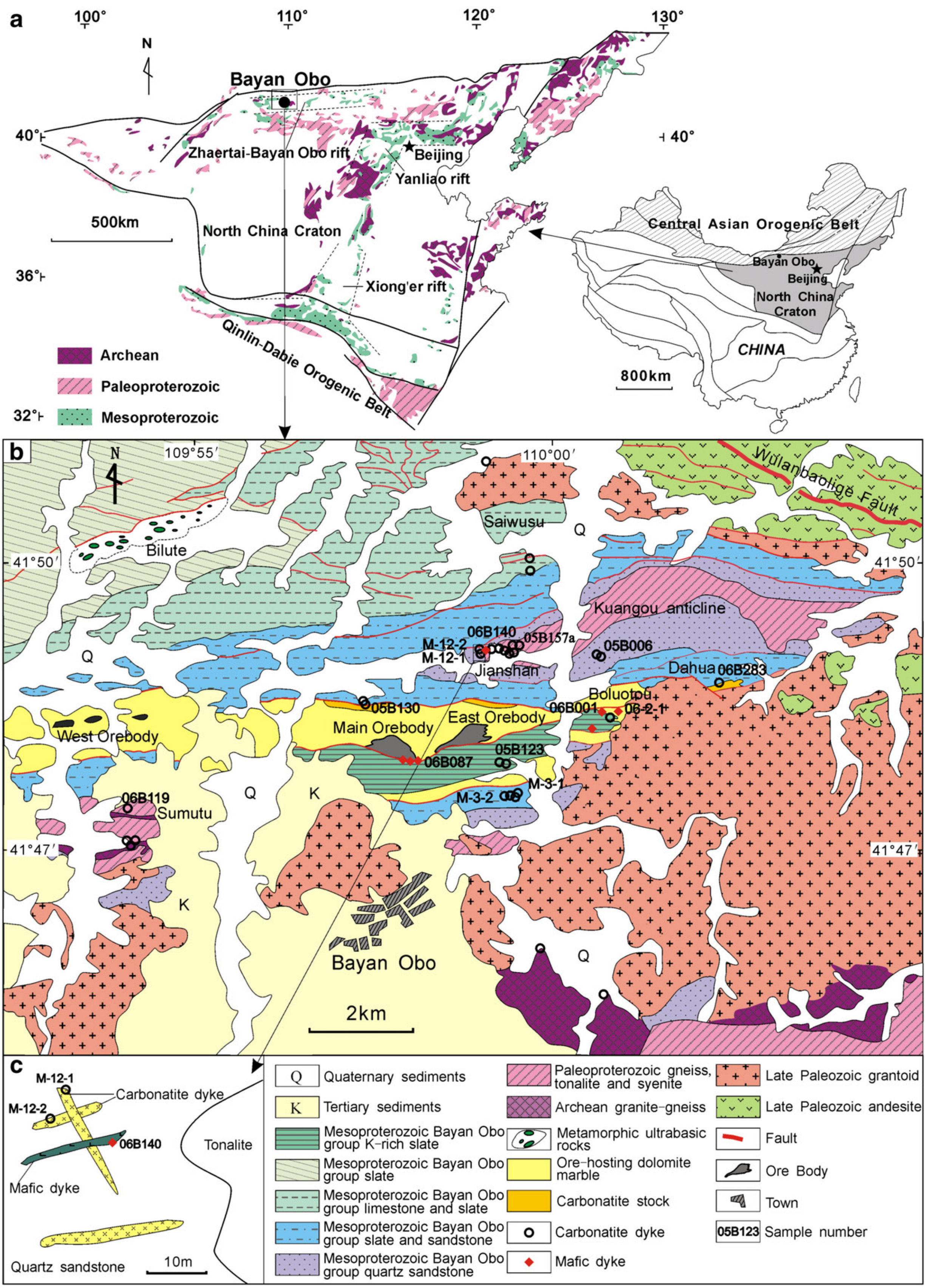

Fig. 2. Geological map of the North China Craton (a) and the Bayan Obo region (b), modified after Xiao et al. (2003), Peng et al. (2007), Kusky et al. (2007) and Le Bas et al. (2007). (c) Intrusive contact between carbonatite and mafic dyke.

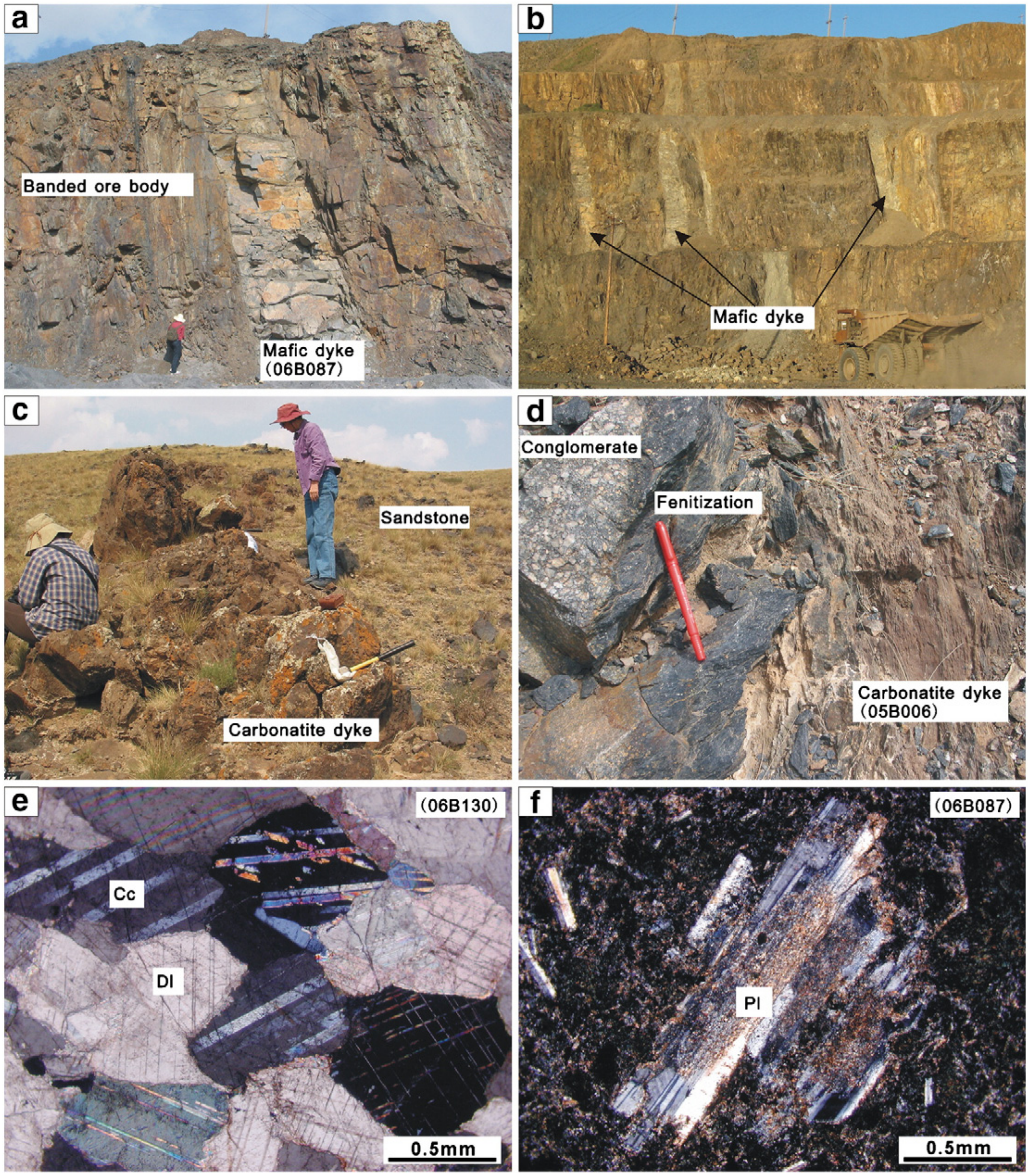

Fig. 3. Photograph of carbonatites and mafic dykes. (a)–(b) Mafic dykes cutting banded ore body in the Bayan Obo REE deposit. (c)–(d) Carbonatite dykes in Bayan Obo region. (e) Photomicrograph of carbonatite showing a mosaic of triple junction of calcite and dolomite. (f) Photomicrograph of mafic dykes showing a skeletal texture of diabase porphyrite. Symbols for minerals: Cc, calcite; Dl, dolomite; Pl, plagioclase.

4. Petrography

Lithologically, the mafic dykes are mainly composed of diabase (06B140) and diabase porphyrite (06B001, 06-2-1, 06B087). The rock samples are fine grained and show a dull green color with porphyritic texture defined by plagioclase phenocrysts. The main rock-forming minerals are plagioclase and clinopyroxene. Plagioclase grains occur as automorphic laths with a skeletal texture whereas clinopyroxenes are mostly xenomorphic granular, often showing alteration to sericite (Fig. 3f). The accessory minerals are mostly biotite, magnetite and apatite.

The dolomite carbonatite dykes (No. M-12-2, 05B157a), mainly composed of dolomite together with calcite and magnetite, are distributed chiefly in the Kuangou anticline, with a maroon color in the weathering surface and grayish white color in the fresh section. They usually have coarse-grained texture, and keep equal triple angle between dolomite and calcite.

The dolomite–calcite coexisted carbonatite dykes (No. M-3-2, 06B119) are mainly found in the south of the ore body. They appear brownish yellow in weathering surface and milk white in fresh section, and mainly comprise dolomite and calcite, together with apatite, magnetite and monazite. This type of dykes has medium–fine-grained texture, and fine-grained calcite is observed to surround coarse-grained dolomite under microscope (Wang et al., 2002). The coexisted carbonatite stocks (No. 05B130, 06B283) are mainly found in the north of the ore body. They have equigranular textures, where dolomite and calcite minerals are aligned being euhedral to subhedral with a mosaic of triple junction (Fig. 3e).

The calcite carbonatite dykes (No. M-3-1, 05B123, M-12-1, 05B006) are distributed around the ore body, and appear brownish yellow in weathering surface and green yellow in fresh section. They are mainly composed of dolomite and calcite, together with apatite, magnetite, monazite, bastnaesite, fluorite, and minor quartz. They show medium–fine-grained microporphyritic texture, with granular aggregate consisted of fine-grained REE minerals inlaying the clearance of calcite. These REE minerals are likely the primary mineral crystallized directly from the carbonatitic magma (Yang et al., 1998).

5. Analytical methods

For major element analysis, wafers made by TR-1000S Automatic Bead Fusion Furnace with a diameter of 2.5 cm were analyzed with the XRF-1500 Sequential X-Ray Fluorescence Spectrometer housed at the Laboratory for Elements Analysis, Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS).

Trace and rare earth elements were measured on Finnigan MAT ELEMENT Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) at the Laboratory for Elements Analysis, IGGCAS. Precision on concentrations reported is better than 8%.

Sr and Nd isotope ratios were measured on a Finnigan MAT-262 mass spectrometer at the Laboratory for Radiogenic Isotope Geochemistry, IGGCAS. The total procedural blanks for Rb–Sr and Sm–Nd were less than 100 pg and 50 pg. The error in concentrations is less than 0.5% of the quoted values (2σ). Average $^{87}Sr/^{86}Sr$ values of NBS987 standard were 0.710232 ± 12 (2σ, n = 10, relative to $^{86}Sr/^{88}Sr = 0.1194$) and average $^{143}Nd/^{144}Nd$ values of Ames standard were 0.512125 ± 8 (2σ, n = 12, relative to $^{146}Nd/^{144}Nd = 0.7219$) during this study. Data regression of isochron age calculation was performed with ISOPLOT ver. 3.0 software (Ludwig, 2003), conservatively using errors of 2% for $^{147}Sm/^{144}Nd$ and $^{87}Rb/^{86}Sr$ ratio, and errors of 0.01% for $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratio as an estimate for external precision. Detailed analytical procedures and isotope ratio measurements are given by Chen et al. (2000).

6. Results

6.1. Major elements

The major element concentrations of the carbonatites and mafic dykes from Bayan Obo are presented in Table 1. The mafic dykes show a narrow range in SiO_2 (46.3%–54.7%). The total alkalis ($K_2O + Na_2O$) show a range of 4.55%–7.30%, which are in general higher than those for normal gabbro (4%). In total alkalis versus SiO_2 diagram (Fig. 4), three samples of the dykes plot in the alkalic region (06B140, 06B087 and 06-2-1) and within the domain defined by the mafic dykes from south Greenland (Goodenough et al., 2002), and the other sample (06B001) plots in the subalkalic region, comparable with the composition of the mafic dykes from the Mackenzie dyke swarm in Canada (Schwab et al., 2004).

6.2. Trace and rare earth elements

The trace and rare earth element concentrations of the carbonatites and mafic dykes are presented in Table 1. The total REE contents of the mafic dykes (174.6–581.2 ppm) are comparable with the values for the carbonatites from Bayan Obo (244.4–393.2 ppm). The $(La/Yb)_N$ ratio of the mafic dykes (7.8–61.7) and carbonatites (51.5–55.0) shows a moderate variation. In the chondrite-normalized REE diagrams (Fig. 5), both rock types show a similar LREE enriched distribution pattern with no obvious negative Eu anomaly, except that the mafic dykes have slightly higher heavy rare earth element (HREE) as compared to the carbonatites. These features are comparable with the REE characteristics in mafic dykes and carbonatites of similar age elsewhere in the world (Woolley and Kempe, 1989; Windley, 1993; Schwab et al., 2004).

In the primitive mantle-normalized trace element diagram (Fig. 6), all the mafic dykes display a general enrichment in Ba and Th, and depletion in Rb, Zr, Hf, Nb and Ta. The mafic dykes from Bayan Obo show higher enrichment in Sr and Ba as compared to these elements in the Mackenzie dyke swarm, Canada (Fig. 6). In the (Zr/Y) versus Zr diagram (Fig. 7), all the four samples of mafic dykes plot in the Within Plate Basalt field, correlating well with their formation in an extensional tectonic setting at the craton margin rift in the Bayan Obo region. The geochemical features of the Bayan Obo mafic dykes

Table 1
Contents of major (wt.%) and trace (ppm) elements of carbonatite and mafic dykes.

Rock type	Mafic dyke				Carbonatite stock	Carbonatite dyke
Sample no.	06B001	06-2-1	06B087	06B140	05B130	06B119
SiO_2	51.85	51.45	52.04	46.32	0.84	0.60
TiO_2	0.80	0.90	1.01	1.01	0.01	0.01
Al_2O_3	14.90	15.36	17.38	16.85	0.03	0.02
$Fe_2O_3^T$	8.41	8.21	8.90	9.24	4.64	6.07
MnO	0.15	0.32	0.12	0.13	0.52	0.40
MgO	8.20	6.29	3.59	5.12	17.34	17.35
CaO	8.32	7.57	4.31	8.44	29.53	29.61
Na_2O	3.46	5.99	4.04	2.36	0.05	0.04
K_2O	1.55	1.08	3.26	2.19	0.04	0.02
P_2O_5	0.18	0.20	0.32	0.22	1.16	0.03
LOI	1.60	1.95	4.60	7.59	43.07	44.24
Total	99.41	99.33	99.57	99.47	97.23	98.39
Mg#	69.44	64.10	48.46	56.36	89.70	86.95
Rb	38.01	23.52	84.75	88.60	0.73	1.01
Ba	5806	9756	1922	1017	122.3	98.16
Th	6.87	5.98	6.21	3.72	1.25	1.06
U	1.24	1.22	1.29	0.71	0.13	0.20
Nb	11.19	13.78	17.11	6.73	1.80	3.76
Ta	0.52	0.65	0.75	0.32	0.09	0.21
La	218.5	136.1	40.21	23.94	72.50	53.82
Ce	249.6	177.2	71.72	48.81	179.3	112.8
Pr	21.49	19.43	8.83	6.04	23.14	13.20
Sr	544.4	923.2	656.9	756.1	5626	6021
Nd	61.87	55.33	31.44	23.57	82.24	46.27
Zr	147.1	159.2	144.2	129.6	2.38	3.01
Hf	3.83	4.43	3.66	3.47	0.17	0.12
Sm	8.06	8.22	5.60	5.20	13.77	6.57
Eu	1.84	2.72	1.47	1.34	3.48	1.84
Gd	7.24	7.00	4.51	4.33	9.59	4.69
Tb	0.84	0.90	0.66	0.66	1.11	0.54
Dy	4.67	5.08	3.81	3.91	4.63	2.33
Y	24.32	25.44	21.03	20.32	15.97	8.88
Ho	0.97	0.97	0.87	0.82	0.70	0.37
Er	2.75	2.63	2.40	2.26	1.47	0.90
Tm	0.38	0.38	0.37	0.34	0.18	0.12
Yb	2.54	2.46	2.35	2.19	0.95	0.75
Lu	0.40	0.37	0.36	0.34	0.12	0.11
∑REE	581.2	418.8	174.5	123.7	393.2	244.4
Eu/Eu*	0.74	1.09	0.90	0.87	0.93	1.01
$(La/Yb)_N$	61.73	39.69	12.28	7.84	55.03	51.47
Nb/Ta	21.72	21.16	22.91	20.77	20.68	17.91

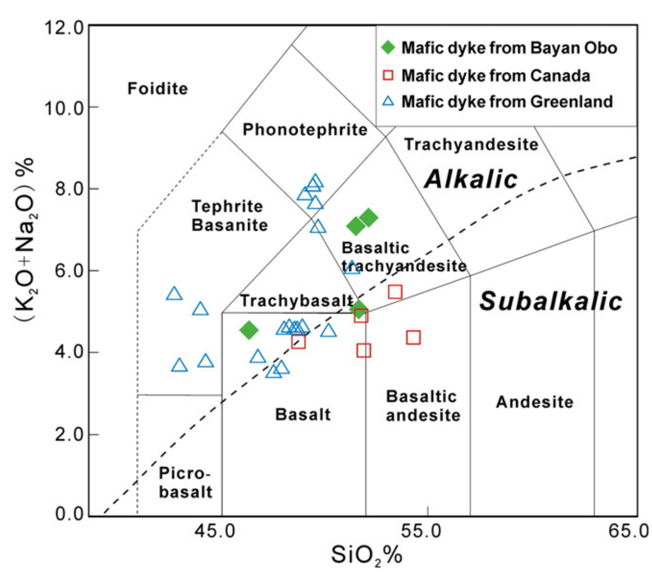

Fig. 4. Total alkalis versus SiO_2 diagram (Le Bas et al., 1986) for classification of mafic dykes from Bayan Obo region. The alkalic–subalkalic line is from Irvine and Baragar (1971). The mafic dyke data of Canada is from Schwab et al. (2004). The mafic dyke data of Greenland is from Goodenough et al. (2002). Errors bars are smaller than the symbol size.

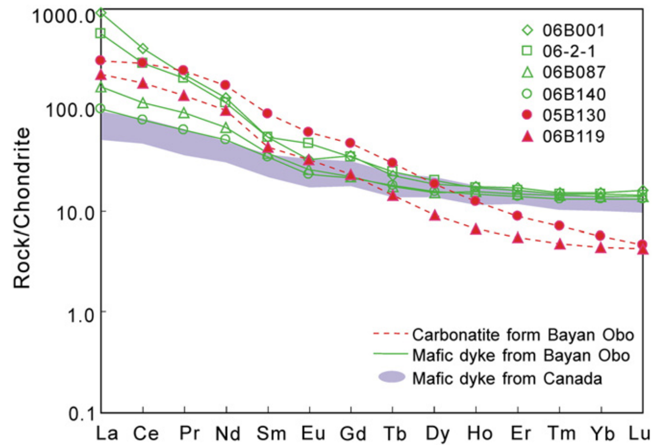

Fig. 5. Chondrite-normalized REE patterns for carbonatite and mafic dykes in the Bayan Obo region. The chondrite values are from Taylor and McLennan (1985). The mafic dyke data of Canada are from Schwab et al. (2004). Errors bars are smaller than the symbol size.

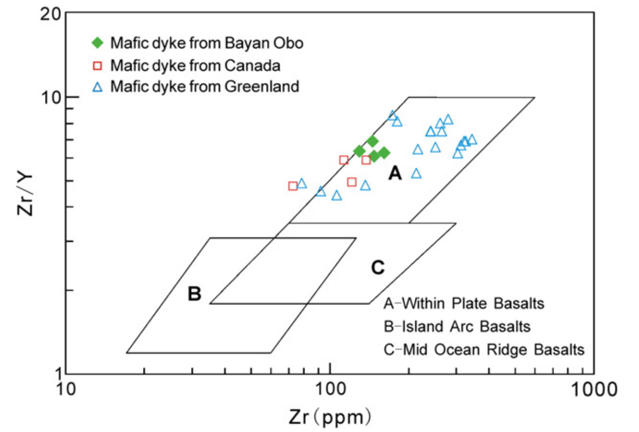

Fig. 7. (Zr/Y) versus Zr diagram (Pearce and Norry, 1979) of mafic dykes in the Bayan Obo region. The mafic dyke data of Canada are from Schwab et al. (2004). The mafic dyke data of Greenland are from Goodenough et al. (2002). Errors bars are smaller than the symbol size.

are similar to the mafic dykes from Canada and Greenland which formed during the same period (1.35–1.20 Ga), probably suggesting a common tectonic setting associated with the fragmentation of the Columbia supercontinent.

In spite of the positive Sr anomaly of the carbonatite, the trace element compositions of the carbonatite and mafic dykes are very similar, which suggests a common source region. Briqueu et al. (1984) suggested that Nb and Ta provide critical indications of the source properties of mantle magmas. The Nb/Ta ratio could remain stable even under different magmatic processes such as fractional crystallization and partial melting, and therefore provides an important indicator for characterizing the mantle sources (Kamber and Collerson, 2000). The Nb/Ta ratios of the mafic dykes in the Bayan Obo region define a tight cluster between 20.8 and 22.9, close to Nb/Ta values of the carbonatites from this region (17.9–20.7), further suggesting their common source characteristics.

6.3. Sr–Nd isotope and Sm–Nd isochron age

6.3.1. Sr–Nd isotope

The Sr and Nd isotope data for the carbonatite and mafic dykes from Bayan Obo are given in Table 2 and illustrated in Fig. 8. The carbonatite and mafic dykes show $\varepsilon_{Nd}(t) = -0.51$–$1.18$, but the initial Sr values of the carbonatite show a broader range between 0.702710 and 0.708871 than that of the mafic dykes. The isotopic composition of carbonatite from Bayan Obo, trending towards enriched mantle values, is apparently different from those of the carbonatites from east Africa (Bell and Blenkinsop, 1987, 1989), India (Simonetti et al., 1995; Veena et al., 1998) and Brazil (Roden et al., 1985). We interpret this variation to be a possible reflection of crustal contamination during the ascent and emplacement of mafic–carbonatitic magma within a continental margin rift (e.g., Schleicher et al., 1990).

Bell and Blenkinsop (1987) recognized that the genesis of carbonatite magmas mainly involved depleted mantle components since the Achaean to present day in North America and Africa. On the contrary, recent Sr–Nd isotopic studies of early Proterozoic carbonatite in Brazil show an enriched mantle source characteristic (Nelson et al., 1988; Antonini et al., 2003). Moreover most of the continental carbonatites, with representative values of initial Sr>0.703 and $\varepsilon_{Nd}(t) < +4$ interpreted as mixing between depleted and enriched mantle sources, are associated with crustal stretching and thinning (Schleicher et al., 1990; Smithies and Marsh, 1998; Tilton and Bellk, 1994). Our results from the Bayan Obo carbonatite also show characteristics suggestive of a multi-end-member mantle sources.

The isotope composition of the mafic dykes also suggests magma derivation from less enriched mantle sources, as against the features described from the mafic dykes of Greenland (Pearce and Leng, 1996; Goodenough et al., 2002). These results may suggest that the upper mantle beneath the NCC was enriched in the late Mesoproterozoic. In general, the Sr–Nd isotopic compositions of carbonatite and mafic dykes are very consistent, providing robust evidence for their close ties with regard to source material, and the possibility that the two rock suites represent end members differentiated from a parent alkalic–mafic magma.

6.3.2. Sm–Nd isochron age

The four mafic dyke samples dated in this study yield a whole rock Sm–Nd isochron age of 1227 ± 60 Ma, and the nine carbonatite dykes define an age of 1354 ± 59 Ma (Fig. 9). The slightly younger ages for the mafic dykes are consistent with the field relations of these two rock suites as described in a previous section. However the depleted mantle model ages (T_{DM}) for the mafic dykes (1895–1639 Ma) are quite similar to the results obtained from the carbonatites (1971–1689 Ma). These ages are also consistent with the time of initiation of the Zhaertai–Bayan Obo rift (1.75 Ga, Kusky and Li, 2003; Li et al., 2007), confirming their common tectonic affinity to the continental margin rift setting.

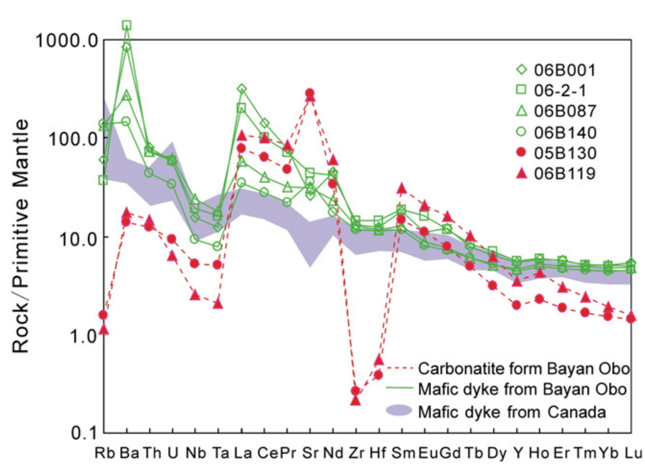

Fig. 6. Primitive mantle-normalized trace element abundance diagram for carbonatite and mafic dykes in the Bayan Obo region. Primitive mantle values are from Sun and McDonough (1989). The mafic dyke data of Canada are from Schwab et al. (2004). Errors bars are smaller than the symbol size.

Table 2
Sr and Nd isotope compositions of carbonatite and mafic dykes in the Bayan Obo region.

Rock type	Sample no.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$I_{Sr}(t)$	$\varepsilon_{Nd}(t)$	T_{DM}(Ga)
Mafic dyke	06B001	0.1722	0.705736	0.0679	0.511581	0.702710	−0.38	1.639
	06-2-1	0.0551	0.704858	0.0813	0.511682	0.703889	−0.51	1.689
	06B087	0.4494	0.711319	0.0985	0.511837	0.703421	−0.19	1.736
	06B140	0.3135	0.709802	0.1230	0.512021	0.704292	−0.45	1.895
Carbonatite stock	05B130	0.0001	0.702866	0.0965	0.511807	0.702866	1.18	1.745
	06B283	0.0001	0.702984	0.0841	0.511662	0.702983	0.50	1.748
Carbonatite dyke	06B119	0.0001	0.703168	0.0842	0.511630	0.703167	−0.15	1.788
	M-3-2	0.0005	0.708153	0.1266	0.512023	0.708143	0.16	1.971
	M-3-1	0.0001	0.706373	0.0591	0.511433	0.706371	0.38	1.690
	05B123	0.0563	0.708139	0.0695	0.511525	0.707047	0.35	1.717
	05B006	0.0005	0.708556	0.0444	0.511259	0.708546	−0.47	1.700
	M-12-1	0.0021	0.708911	0.0639	0.511488	0.708871	0.61	1.689
	M-12-2	0.0020	0.704784	0.1914	0.512624	0.704745	0.65	3.596
	05B157a	0.0019	0.705456	0.1870	0.512530	0.705419	−0.43	3.542

7. Discussion

The coexistence of carbonatite and alkalic mafic rocks, as observed in the Bayan Obo region of the present study, is usually related to continental rift environment (e.g. Hao et al., 2002). Under long-term slow stretching and thinning within a continental rift setting, the upper mantle maintains a low degree (5–7%) partial melting, leading to the generation of alkalic mafic magma. Our study suggests that the carbonatite and alkalic mafic dyke swarm in the Bayan Obo region are related to extensive distensional regime in the Bayan Obo rift during the middle Mesoproterozoic (1.4–1.2 Ga). A synchronous origin of carbonatite–silicate magma during the immiscible separation of an admixture in decreasing temperature and pressure has been theoretically (Wyllie, 1987; Lee and Wyllie, 1994) and experimentally (Veksler et al., 1998) confirmed.

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. Large areas in the Neoarchean Shanggan group granulite and amphibolite terrain were subjected to alkalic potassic alteration. The K-feldspar ^{40}Ar–^{39}Ar dating of rocks from the Xigeyu region of northern Hebei province, yields an age of 1262 Ma that correlates to the regional extensional event within the NCC (Shao et al., 2002). Additionally, ^{40}Ar–^{39}Ar data of porphyroblastic garnet in the high-pressure granulites from this region also indicate a 1250 Ma thermal imprint (Guo et al., 2001). In conjunction with the ages of the carbonatite (1354 Ma) and alkalic mafic dykes (1227 Ma) in the Bayan Obo region obtained in this study, we infer that the northern margin of the NCC experienced an extensive continental fragmentation event during the middle and late Mesoproterozoic (1.4–1.2 Ga).

The mid–late Neoproterozoic rifting within the NCC can be correlated to similar worldwide events associated with the breakup of the Columbia supercontinent (Rogers and Santosh, 2002, 2004, 2009; Kusky and Li, 2003; Kusky et al., 2007; Santosh et al., 2009). During its prolonged breakup history from ca. 1.8 Ga 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, 2004; Li et al., 2006; Li et al., 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

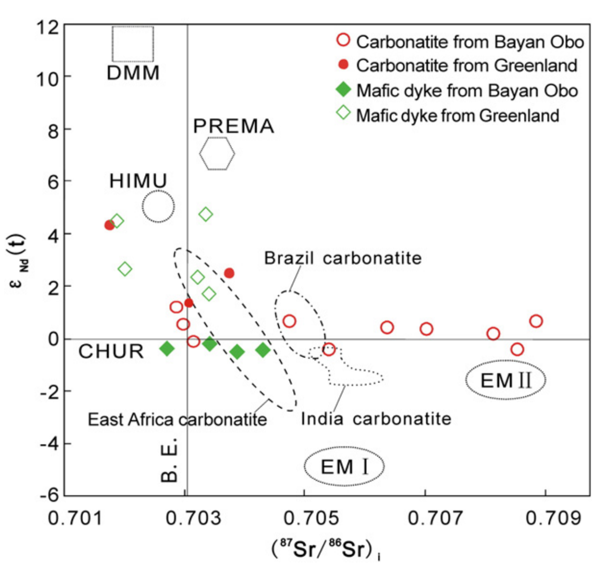

Fig. 8. $\varepsilon_{Nd}(t)$ versus initial Sr diagram for the carbonatite and mafic dykes in the Bayan Obo region, compared with the carbonatites from Africa (Bell and Blenkinsop, 1987, 1989), India (Simonetti et al., 1995; Veena et al., 1998), Brazil (Roden et al., 1985) and Greenland (Pearce and Leng, 1996), and the mafic dykes from Greenland (Pearce and Leng, 1996; Goodenough et al., 2002). DMM, EMI, EMII, PREMA and HIMU are the mantle end-member components (Zindler and Hart, 1986). Values for lines labeled B.E. (bulk Earth) and CHUR (chondritic uniform reservoir) are those for 1354 Ma, assuming present-day values of $^{87}Sr/^{86}Sr_{BE} = 0.7045$ and $^{87}Rb/^{86}Sr_{BE} = 0.083$, and $^{143}Nd/^{144}Nd_{CHUR} = 0.512638$ and $^{147}Sm/^{144}Nd_{CHUR} = 0.1967$. Errors bars are smaller than the symbol size.

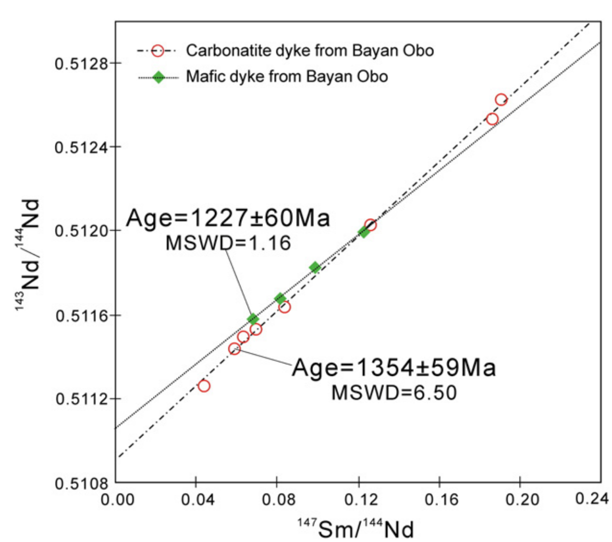

Fig. 9. Sm–Nd isochron diagram for the whole rock samples of carbonatite and mafic dykes in Bayan Obo region, conservatively using errors of 2% for $^{147}Sm/^{144}Nd$ ratio and 0.005% for $^{143}Nd/^{144}Nd$ ratio as an estimate for external precision. MSWD stands for mean square of weighted deviates. Errors bars are smaller than the symbol size.

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 includes 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 (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.

The similar whole rock Sm–Nd isochron ages of the mafic dyke (1227 ± 60 Ma) and carbonatite (1354 ± 59 Ma) from Bayan Obo, comparable Sr–Nd isotope characteristics and Nb/Ta ratios suggest their close petrogenetic relationship. The Zr/Y versus Zr composition also suggests their formation within a continental rift. Furthermore, the depleted mantle model age (T_{DM}) of the carbonatite and mafic dykes defines an age range of 1.97–1.64 Ga (Table 2), and is consistent with the timing of initiation of the Zhaertai–Bayan Obo rift (1.75 Ga, Li et al., 2007). 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 world-wide rifting events at this time that are associated with the final breakup of the Columbia supercontinent.

Hou et al. (2008a) proposed that the final fragmentation of the Columbia supercontinent (1.3–1.2 Ga) might have resulted from a giant mantle plume activity, and that the center of this plume was possibly located in the focal area of the giant radiating dyke swarm in between North America, west Australia and east Antarctica. Ernst et al. (2000) suggested that the Laurentia (Canadian Shield and Greenland Plate) and Siberian Plate were at low latitudes at 1267 Ma, and that the two plates were attached to each other during the late Mesoproterozoic. Wu et al. (2005) and Li et al. (2008) pointed out that the NCC, the Laurentia, the Baltica, and the Siberia shared a long-lived connection from ca. 1.80 Ga till 1.35 Ga or later based on their new paleomagnetic results. Hou et al. (2008a) also proposed that the final fragmentation of the Columbia might have occurred close to 1.20 Ga. Our studies confirmed extensive fragmentation within the Columbia supercontinent during the late Mesoproterozoic between 1.35 and 1.20 Ga (Fig. 10). Within the Columbia configuration, the southern margin of the NCC was connected to the eastern India, and the western margin was connected to the Canadian Shield during the Mesoproterozoic. Therefore, the NCC might have shared the same major mantle plume activity within the Columbia supercontinent, and

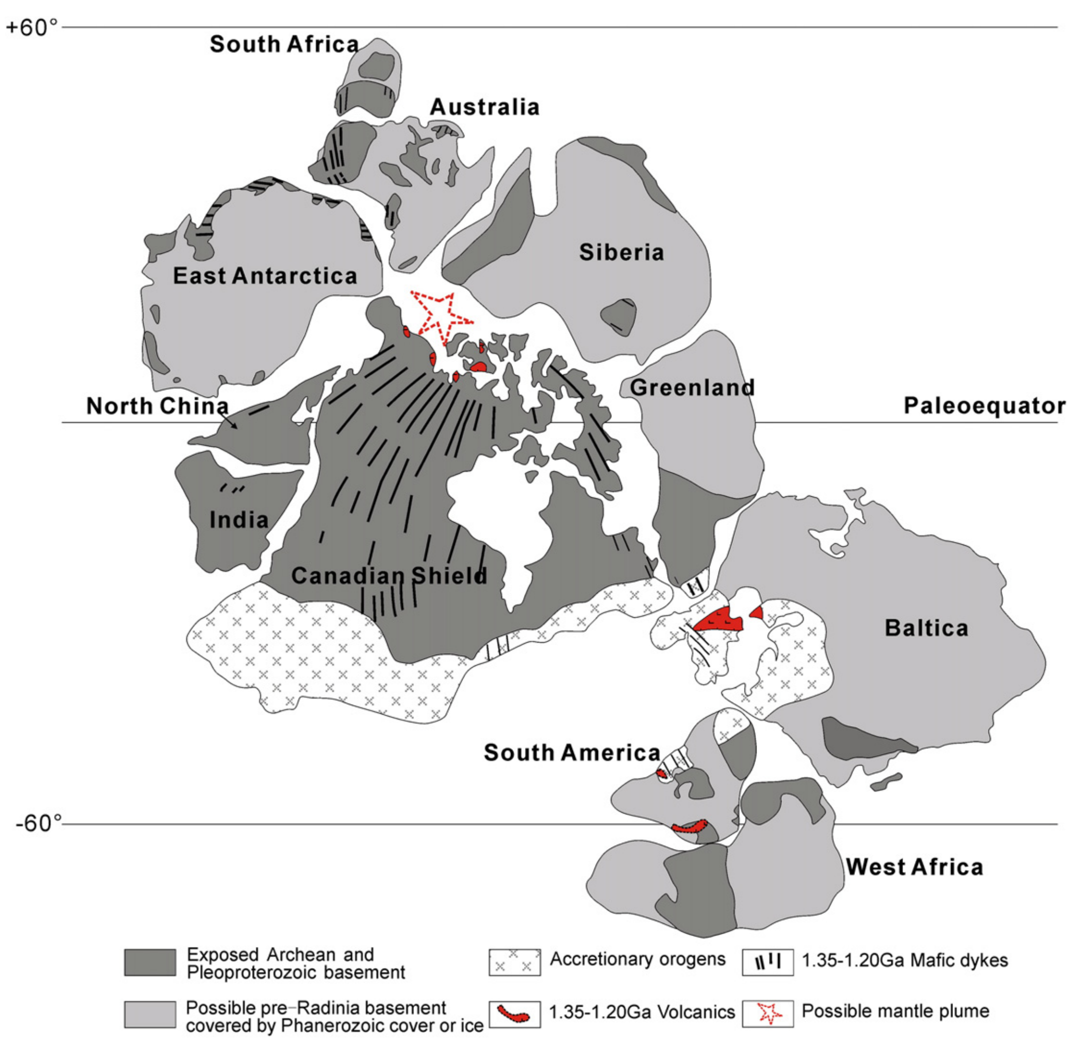

Fig. 10. The configuration of the supercontinent Columbia during 1.35–1.20 Ga as proposed in this study, modified after Hou et al. (2008a,b), Zhao et al. (2004) and Peng et al. (2005).

the carbonatitic–mafic dykes in the north margin of the NCC hence represent the true signature of the final fragmentation of Columbia supercontinent.

8. Conclusion

(1) This study reports the occurrence and characteristics of abundant carbonatite and mafic dykes from around the Bayan Obo giant rare earth element (REE) deposit in the northern margin of the North China Craton (NCC). The field relations show that the mafic dykes cut across the carbonatite dykes and the banded REE ore body.
(2) The whole-rock Sm–Nd isochron from four mafic dykes indicates an age of 1227 ± 60 Ma and those of nine carbonatite dykes yields a slightly older age of 1354 ± 59 Ma, consistent with the field relations.
(3) Similarities in trace elements and Sr–Nd isotopic compositions between the carbonatites and mafic dykes suggest common source characteristics.
(4) The geochemical and isotopic characteristics of the mafic dykes indicate their origin in a continental margin rift, the Bayan Obo rift. These rocks are recognized as the signature of mantle magmatism associated with the final fragmentation of the Columbia supercontinent at ca. 1.35–1.20 Ga.

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