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A review of the genesis of the world class Bayan Obo Fe–REE–Nb deposits, Inner Mongolia, China: Multistage processes and outstanding questions

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ABSTRACT

The Bayan Obo Fe–REE–Nb deposit is the world's largest rare earth element (REE) resource and with the increasing focus on critical metal resources has become a focus of global interest. The deposit is hosted in the Palaeoproterozoic Bayan Obo Group, mainly concentrated in the H8 dolomite marble. The ores consist of light REE enriched monazite and bastnäsite, with a wide array of other REE minerals. Niobium mineralisation is hosted primarily in aeschynite and pyrochlore, although there are a wide range of other Nb-minerals. The origin of the host dolomite and ore bodies has been a subject of intense debate. The host dolomite has been proposed to be both of sedimentary origin and an igneous carbonatite. Carbonatite dykes do occur widely in the area, and consideration of the textural, geochemical and isotopic composition of the dolomite suggests an origin via intrusion of magmatic carbonatite into meta-sedimentary marble, accompanied by metasomatism. The origin of the ore bodies is complex, indicated most strongly by an ~1 Ga range in radiometric age determinations. Compilation of available data suggests that the ores were originally formed around 1.3 Ga (Sm–Nd isochron ages; Th–Pb ages of zircon), close in time to the intrusion of the carbonatite dykes. The ores were subsequently subjected to several stages of deformation and hydrothermal overprint, culminating in deformation, metamorphism and fluid flow related to the Caledonian subduction of the Mongolian Plate under the North China Craton from ~450 to 420 Ma (Th–Pb ages of monazite). This stage resulted in the formation of the strong foliation ('banding') of the ore. The presence of undeformed veins with alkali mineral fills, and the overprinting of the foliation by Nb minerals suggest that secondary fluid flow events may also have contributed to the metal endowment of the deposits, as well as remobilising the original Fe and REE mineralisation. The alteration mineralogy and geochemistry of the ores are comparable to those of many REE mineralised carbonatites. Initial Nd isotope ratios at 450 Ma, however, suggest crustal sources for the metals. These conflicting lines of evidence can be reconciled if a (at least) two stage isotopic evolution is accepted for the deposits, with an original mantle-sourced, carbonatite-related metal accumulation forming around 1.3 Ga with εNd close to 0. The ore was remobilised, with associated re-equilibration of Th–Pb isotope systematics during deformation at ~450 Ma. A further stage of alkaline hydrothermal fluid was responsible for Nb mineralisation at this stage. The complex geological history, with multiple stages of alkaline, high field strength element-rich, metasomatic fluid flow, is probably the main reason for the exceptional metal endowment of the Bayan Obo area.

1. Introduction

The Bayan Obo Fe–REE–Nb deposit is the world's largest REE resource (high grade reserves at 48 mT at 6 wt.% REE_2O_3; Drew et al., 1990). These are hosted in dolomite marble, or in complex 'banded ores'. Lower grade resources have been estimated at 750 mT at 4.1 wt.% REE_2O_3 hosted in massive magnetite and hematite (Fig. 1). The deposit is also a significant resource for Fe (1500 mT at 35 wt.% Fe; Chao et al., 1997) and Nb (2.2 Mt at 0.13 wt.% Nb_2O_3; Fan et al., 2003) (Fig. 1). The deposit was of critical importance, alongside HREE-enriched residual clay deposits, in leading to China's pre-eminence in the global REE market and hence the current situation of certain elements being classified as critical both because of their limitations in supply and potential impact on global markets. Such importance has naturally attracted intense scientific study, but despite this the origins of the deposit remain a subject of great debate. Genetic models have suffered from a lack of integration of available data and commonly have focussed on single geochemical indicators rather than taking account of all available evidence, up to and including the field and textural characteristics of the ore. This has led to a multitude of competing hypotheses for the origin of the ores, including metasomatism associated with granitic

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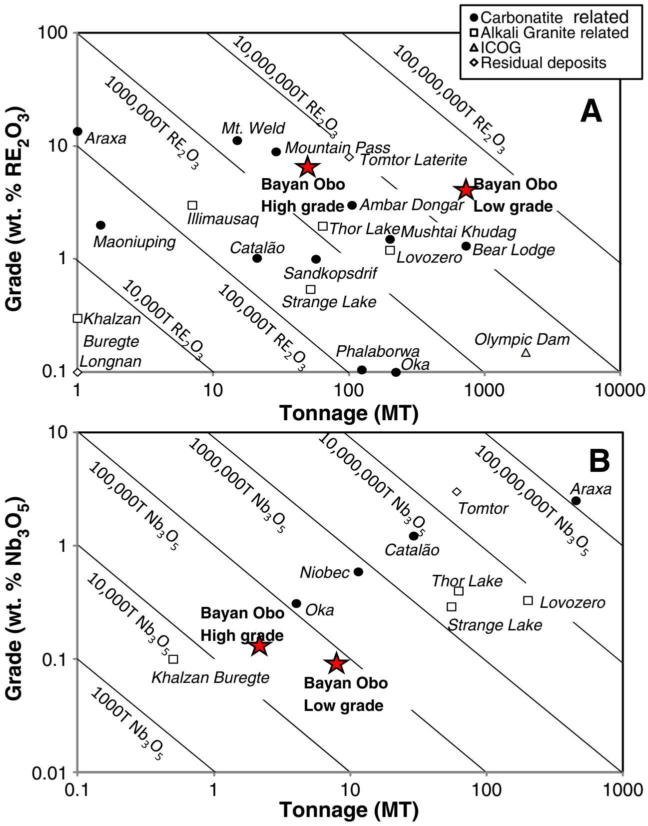

Fig. 1. Global comparison of reserve and resource estimates for major rare earth element (A) and Nb (B) deposits. Labelled lines show tonnes of contained metal. Grades and tonnages from Kogarko et al. (1995), Orris and Grauch (2002), Wu (2008), Humphries (2013), Long et al. (2010), Cordeiro et al. (2011), Szumigala and Werdon (2011) and references therein.

magmatism (Wang, 1973), sedimentary deposition (Meng, 1982), mineralisation from Caledonian 'subduction-related' fluids (Chao et al., 1997; Ling et al., 2013), continental rifting and magmatism (Yang et al., 2011a), sedimentary deposition with a metasomatic overprint (Chao et al., 1992; Qin et al., 2007), extrusive carbonatitic tuffs (Le Bas et al., 1992), and large-scale carbonatite magmatism (Yang and Le Bas, 2004). Following the detailed work of Chao et al. (1997), there is now a consensus that the ores are of hydrothermal metasomatic origin, although there is still debate as to the origin of the host dolomite with suggestions of a purely sedimentary origin (Chao et al., 1997; Hou, 1987; Meng, 1982), the result of carbonatite magmatism (Le Bas et al., 1992, 1997; Yang et al., 2011b; Yuan et al., 1992), or resulting from the metasomatic alteration of a sedimentary marble by magmatic fluids (Smith and Henderson, 1999; Yang et al., 2009). Many workers have now suggested that mineralizing fluids were multi-stage, essentially carbonatite-derived, yet diverse in composition (Campbell and Henderson, 1997; Fan et al., 2004, 2006a,b; Kynicky et al., 2012; Ni et al., 2004; Rankin et al., 2003; Smith, 2007; Smith et al., 2000; Wang et al., 2002, 2003; Yuan et al., 2000; Zhang et al., 2002). However, alternatives including mineralisation by fluids derived from the subducting Mongolian Plate in the Caledonian orogeny (Chao et al., 1997; Ling et al., 2013) have also been suggested.

A deeper understanding of the origin and evolution of the Bayan Obo deposits is of global importance. Such super accumulations of the REE are rare, with very few or no deposits of comparable size currently known (Fig. 1). Improved models for ore genesis at Bayan Obo may be a critically important guide in the location of future resources. The site is also an ideal natural laboratory for the study of the behaviour of the REE, including inter-element fractionations, potentially including those leading to HREE enrichment, their hydrothermal transport and deposition. Other high field strength elements (HFSE), also coming under the 'critical metal' classification, such as Nb have also been hydrothermally transported in the deposit (Smith and Spratt, 2012). In this paper we review the characteristics of the Bayan Obo ores, supplemented with new observations on the host marble and associated rocks, and then go on to present an integrated model which we believe accounts for all currently available data from the area, and assess the key remaining questions about the ores.

2. Regional geological setting

The Bayan Obo area is located on the northern margin of the North China Craton, bordered to the north by the Central Asian Orogenic Belt (Yang et al., 2011a; Fig. 2A). The North China Craton formed through the accretion of microcontinental blocks from 2.2 Ga to ~1.85 Ga (Zhao et al., 2011). The basement to the area consists of the Archaean Wutai Group gneisses and migmatites (Chao et al., 1997), which significantly pre-date the mineralisation and so are not discussed further here. The North China Craton underwent a period of rifting in the Mesoproterozoic during the breakup of the supercontinent Columbia, starting around 1.8 Ga, with the Zhaertai–Bayan Obo rift forming on the northern margins of the craton (Shao et al., 2002; Yang et al., 2009; Zhao et al., 2011). The rifting culminated around 1.27–1.30 Ga, and resulted in the formation of mafic dyke swarms that have been correlated over wide areas of the globe, and which may be represented in the Bayan Obo area by basaltic to basaltic-trachyandesite and carbonatite dykes (Yang et al., 2009). The Bayan Obo group sedimentary rocks, which host the ore bodies (Qiao et al., 1991), were deposited on the continental shelf to slope of the craton margin. Following this, the Bayan Obo area is interpreted to have been affected by three main periods of tectonic deformation. Subduction of the Mongolian oceanic plate under the North China Craton margin as part of the Caledonian orogenic system took place from early Cambrian times onward (Chao et al., 1997; Zhao and Li, 1987). A second phase of subduction has been interpreted to have taken place from Mid-Silurian times, resulting in the formation of ophiolite sequences ~270 km north of Bayan Obo (Wang et al., 1992). This extended period of Caledonian-age tectonism has significant implications for the origin and evolution of the ore bodies. The final phase of deformation occurred in the Permian as a result of Hercynian continent–continent collision with the Siberian plate. This period resulted in extensive granite magmatism across the area, but seems to have largely post-dated the formation of the ore bodies in the Bayan Obo area (Chao et al., 1997).

3. The Bayan Obo ore deposits

3.1. Host rocks

The host rock sequence in the Bayan Obo area is divided by the Kuanggou fault (Fig. 2), which has been interpreted as probably post-late Caledonian (younger than 400 Ma; Chao et al., 1992, 1997). The sedimentary rocks to the north of the Kuanggou fault are distinct from those to the south, which host the ore bodies, and are not considered further here. The main host rocks to the ore bodies are Proterozoic in age. Several stratigraphic schemes have been proposed for the Bayan Obo Group (e.g. Bai and Yuan, 1985; Drew et al., 1990; Meng, 1989; Yuan et al., 1992), but most studies follow the scheme developed by Chao et al. (1992), from the work of Meng (1982). The sequence is subdivided in to nine units (H1–9) composed of arkosic quartzites, carbonaceous slates, and purer quartzites (H1–6), grading into variably calcareous beds (from calcareous slate to dolomite marble — H7), and then the H8 dolomite marble. The H8 marble is overlain by a sequence of interbedded black shale, slate and biotite schist (Chao et al., 1992). The detailed stratigraphy of the area is summarised by Lai and Yang (2013) based on observations by Institute of Geochemistry, Academia Sinica (IGCAS) (1988). The H8 marble hosts the vast majority of