

## THE GEOLOGY AND GENESIS OF THE BAYAN OBO Fe-REE-Nb DEPOSIT: A REVIEW.

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**Abstract** - The Bayan Obo Fe-REE-Nb deposit is currently the world's largest REE resource. It has estimated reserves of up to 1500 Mt of iron oxides (35 wt.% Fe), 48 to 100 Mt REE (6 wt.% REE<sub>2</sub>O<sub>3</sub>) and 1 Mt Nb (0.13 wt.% Nb). The deposits are hosted in the Proterozoic Bayan Obo group sediments, mostly in dolomite marble, although the deposits themselves are principally Caledonian in age (555 to 420 Ma). Iron occurs as magnetite and hematite, whilst the REE is principally present as monazite and bastnäsite, although over 16 individual REE-minerals and 17 REE-bearing niobium minerals are also present. The deposits are accompanied by an alteration assemblage of apatite, aegirine, aegirine-augite, fluorite, alkali amphibole, phlogopite and barite. Albite and K-feldspar occur in the overlying slates and schists.

The deposits were formed by multistage hydrothermal replacement of marble during Caledonian subduction. The source of metals and fluids is uncertain, although carbonatites, alkaline igneous rocks, A-type granites and subduction-derived fluids have all been suggested as possibilities. Late stage, low salinity fluids were responsible for extensive modification of the deposit, and an overprint of sulphide and barite alteration. The deposits show many similarities in processes to others of the Fe-oxide class, but there are important differences including the absence of significant base metal sulphide mineralisation, no enrichment in uranium, and the absence of evidence for the involvement of hypersaline brines in ore genesis.

### Introduction

The Bayan Obo Fe-REE-Nb deposits are located at 109°57'13"E, 41°46'22"N, 150km north of Baotou City, Inner Mongolia, China (Fig. 1). They have estimated reserves of 1500 Mt of iron oxides with an average grade of 35 wt.% Fe, 48 to 100 Mt of REE ore at an average grade of 6 wt.% REE<sub>2</sub>O<sub>3</sub> and 1 Mt with an average grade of 0.13 wt.% Nb (Drew *et al.*, 1990; Yuan *et al.*, 1992). They are currently the world's largest REE resource and the largest Nb deposit in China (Chao *et al.*, 1997). The deposits were discovered from large surface outcrops of iron oxides by Prof. Ding Daoheng in 1927, and the concentration of rare earth elements was recognised in 1936 by Prof. Ho Tsolin (Zhang *et al.*, 1995). Exploration and mining started in 1951, with the first iron ore being shipped in 1957. The deposits consist of two main ore bodies (Eastern and Main; Figs. 1 and 2) and a group of smaller bodies to the west (Western group).

Several possible modes of formation have been proposed for the deposits including syngenetic deposition (Meng, 1982; Hou, 1989) and syngenetic deposition from exhalative hydrothermal fluids (e.g., Tu, 1998). The work of Chao *et al.* (1997) has, however, demonstrated an epigenetic origin via multistage hydrothermal metasomatism. The high Fe and REE content of the ores and the alkaline nature of metasomatism associated with the deposits

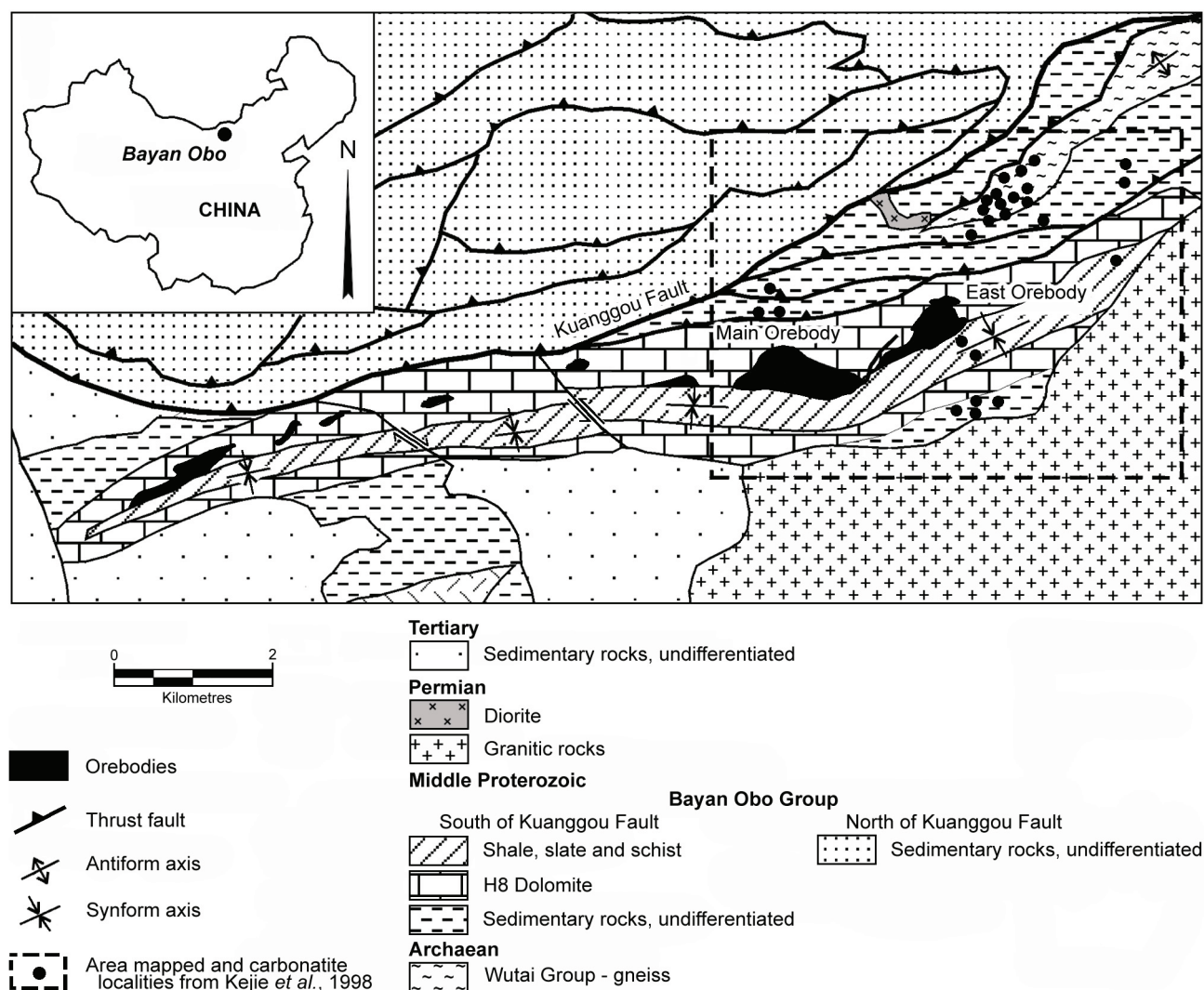
have lead to comparisons with the Fe-oxide-Cu-(Au-U-REE) deposit class (Hitzman *et al.*, 1992). Here we review the current knowledge of the geology and genesis of the Bayan Obo deposits and compare them with the Fe-oxide class.

### Geological Setting

#### *Regional Geology and Tectonic Setting*

The Bayan Obo Fe-REE-Nb deposit is located on the northern margin of the Sino-Korean craton and in the transitional zone between the craton margin and the Inner Mongolian Hercynian foldbelt. A deep-seated fracture zone (about 10km to the north of Bayan Obo) separates the two tectonic units (Yuan *et al.*, 1992; Bai *et al.*, 1996). This zone is strongly indicated by gravity and air-borne magnetic data, and represents a multi-stage ancient subduction and collision zone between the Sino-Korean craton and the Inner Mongolian fold belt (BGMR of Inner Mongolia, 1991; Wang and Zhang, 1992).

In the craton region, east-west-trending early Proterozoic migmatite, granulite, gneisses and schists of the Wu Tai group, approximately 2350 Ma in age, constitute the basement. Unconformably overlying the basement is the



**Figure 1:** Geological sketch map of the Bayan Obo area showing the localities of the main ore bodies. Adapted from Chao *et al.* (1992).

mid-Proterozoic Bayan Obo group, which is composed of coarse- to medium-grained clastic and carbonate rocks. Cambrian-Ordovician sediments are locally distributed in the areas south and east to the Bayan Obo area. Carboniferous and Permian continental coal-bearing clastic sedimentary sequences are variable in thickness and distributed further to the south.

In the foldbelt region to the north, several Precambrian terrains (mainly composed of quartzite, amphibolite, gneisses and marbles) are surrounded by thick Paleozoic marine volcanic-sedimentary packages, which are dominated by basaltic and dacitic lavas, tuffs, pyroclastics and sediments.

### Host Rocks

The Bayan Obo ore bodies occur within the Proterozoic Bayan Obo group of sediments which is divided into 18 horizons with the lower 9 horizons present in the Bayan Obo area (Drew *et al.*, 1990; Bai *et al.*, 1996). The Bayan Obo Group sequence begins with the H1 basal conglomerate, and is followed by a sequence of quartzites, carbonaceous slates, sandstones, limestones and siltstones (H2-H7). The

ore bodies are hosted in the H8 dolomite marble, and to a much lesser extent in the H9 slates and biotites schists. The Bayan Obo group is considered to be stratigraphically equivalent to the Chartai group, both of which were deposited on North China platform during Proterozoic rifting (1350 to 1650 Ma; Ren *et al.*, 1987; Qiao *et al.*, 1991). The Chartai group represents deposition on the continental shelf, whilst the Bayan Obo group represents deposition on the continental slope.

The H8 dolomitic marble occurs as a spindle-shaped concordant stratiform body and extends 18 km from east to west, with a width of tens to a 1000 metres. In the orefield the H8 marble has a fine- to medium-grained crystalline texture, massive and banded structure, and consists mainly of dolomite and calcite, together with abundant feldspar, quartz, Na-tremolite, magnesio-arfvedsonite, phlogopite, apatite, fluorite and baryte. It hosts the Main, East and West orebodies, and is pervasively REE- and Nb-mineralised itself. Away from the Bayan Obo orefield, the H8 carbonate rocks appear to be normal limestone. The H9 unit is dominated by feldspar rock that has light-coloured and dark-coloured varieties, and forms the hanging wall of the iron orebodies.

## Structure and Metamorphism

The sedimentary sequence in the region of the deposits is separated from a thrust and normal faulted sedimentary pile to north of deposits by the Kuanggou fault (Fig. 1). The sequence to the north of the fault is distinct from that in the mine area, and has undergone a lower degree of metamorphism (Chao *et al.*, 1997), suggesting the Kuanggou fault is post late Caledonian.

The area was subjected to two main periods of tectonic activity following deposition. The mine area is 100 km south of a suture marking subduction of the Mongolian oceanic plate under the northern edge of the North China platform during Caledonian times (555 to 396 Ma). Two stages of subduction are recognised, the first producing continental granite intrusions, and a second phase of Middle Silurian high-angle rapid subduction leading to island arc formation (Chao *et al.*, 1997).

During the Permian continent-continent collision deformed the northern edge of the Sino-Korean craton, and resulted in much of the complex structural geology of the mine area (Wang, 1985; Drew *et al.*, 1990). Tectonic transport during this period was from northwest-southeast, leading to large scale thrusting of the entire of the Bayan Obo area. Upright and overturned folding, numerous thrust faults and duplex structures are all common. Serpentinities are preserved in fault melange along thrust zones north of the Kuanggou Fault. South of the Kuanggou Fault the Bayan Obo group occurs in a broad syncline, the north limb of which dips 50 to 70°S, and the south limb 70 to 80°N. The deformation is associated with small chevron folds, meter wide shear zones and thrust faults all of which trend east-west, and some of which cut the ore deposits.

## Magmatism

The earliest magmatic activity in the immediate region of Bayan Obo was the intrusion of a group of carbonatite dykes described by Le Bas *et al.* (1992), Zhang *et al.* (1994) and Tao *et al.* (1998). At least 28 carbonatite dykes have now been recognised, ranging from 0.8 to 2.6m wide. The majority cut the Archaen Wu Tai gneiss to the north of the ore bodies, but others have been reported from within the Bayan Obo group sediments (Fig. 1). They have all been affected by subsequent deformation and in some cases the dyke margins are intricately folded (Le Bas *et al.*, 1992). The majority of the dykes are composed of calcite carbonatite (Le Bas *et al.*, 1992; Zhang *et al.*, 1994) although dolomite and calcite-dolomite carbonatites have also been recognised (Tao *et al.*, 1998). Other mineral constituents typically include apatite, magnetite, quartz, amphibole, K feldspar and biotite. Secondary monazite mineralisation occurs in some dykes (Le Bas *et al.*, 1992). The dykes are surrounded by fenite haloes, composed of aegirine, sodic amphibole, albite and K feldspar.

Several gabbros and alkalic gabbros outcrop both to north and to south of the ore bodies in the Bayan Obo area. They occur as stocks and dykes with dimensions ranging from

tens of square meters to 2000 m long by 50 to 60 m wide. These basic bodies intrude into the Bayan Obo group and are intruded by, or occur as xenoliths enclosed by, Permian granite. One of these gabbroic intrusion has been dated at 316 Ma using Rb-Sr isochron techniques (Hu *et al.*, 1988; Bai *et al.*, 1996).

A large volume of granitoid rocks of Permian age outcrops in the Bayan Obo area, mainly to the south of the ore bodies. The rocks include diorite, granodiorite, biotite granite, and leucogranite (Drew *et al.*, 1990). These rocks post-date the main mineralisation. Caledonian granite magmatism is not exposed in the vicinity of the ore bodies, but Chao *et al.* (1997) drew attention to the Hejao plutonic rocks which are exposed ~50 km south of Bayan Obo, and which may be related to the same large-scale tectonic events. These rocks consist of granodiorite, monzonite, and quartz-biotite diorite. They were dated to 455±3.4 Ma, and were inferred to be either A-type or S-type granitoids.

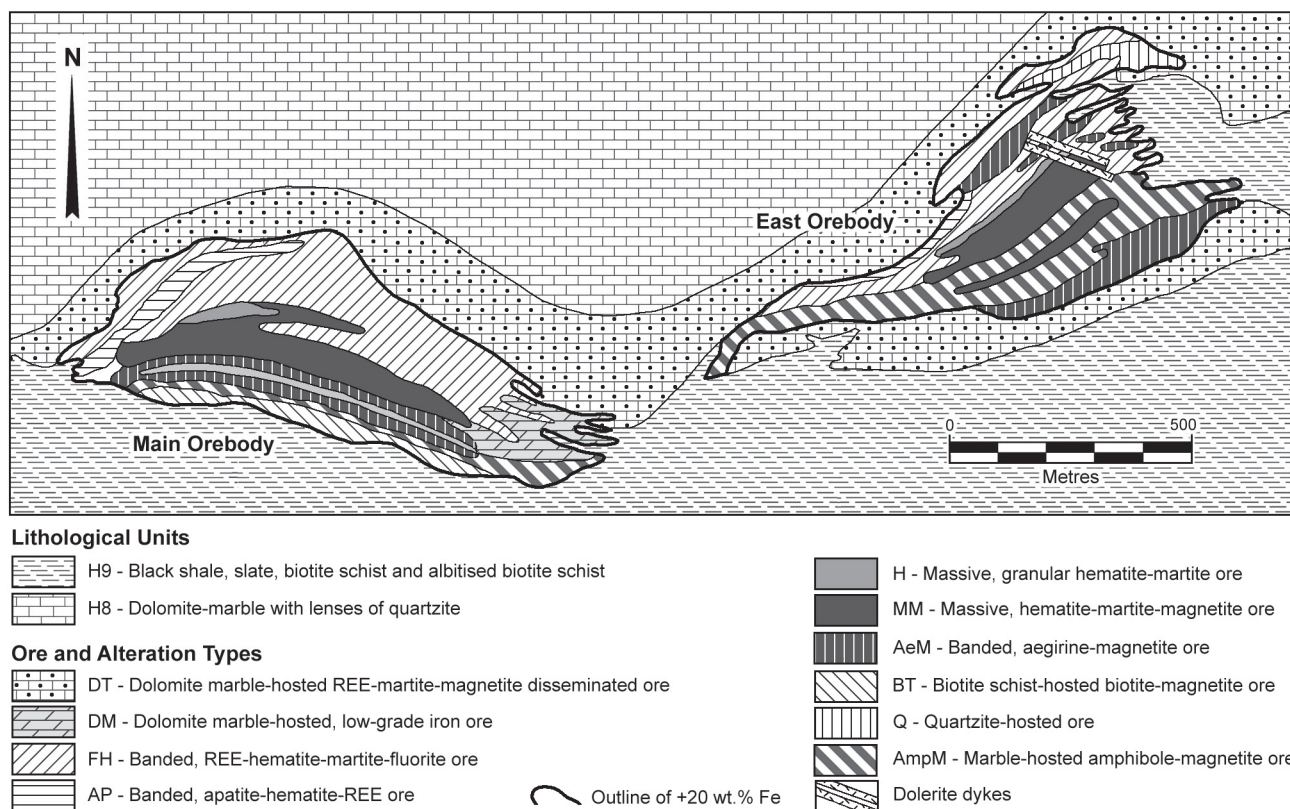
## Alteration and Mineralisation

### *Alteration and Mineralisation in the Main Ore Bodies.*

The paragenesis of the deposit is extremely complex with at least eleven stages developed throughout an extended geological history (Chao *et al.*, 1992, 1993; Wang *et al.*, 1994) and multiple generations of many minerals (Campbell and Henderson, 1997). Mineralogical studies have recognised over 170 mineral species, 18 of which were first described from Bayan Obo (Zhang, 1991; Zhang and Tao, 1986; Zhang *et al.*, 1995).

The earliest stages of REE mineralisation at Bayan Obo are stringers of monazite, which are associated with ferroan dolomite, ankerite and magnetite and occur in fractures and along grain boundaries in relatively unaltered dolomite marble. In the two main ore bodies the disseminated mineralisation has been overprinted by later stages forming the main banded ores. The banding is probably a metasomatic effect that has been enhanced by deformation during the Permian tectonism (Drew *et al.*, 1990). Massive, unbanded pods are preserved in places. In the banded ores monazite, bastnäsite and apatite occur associated with the development of several stages of magnetite and hematite. Major monazite mineralisation preceded bastnäsite mineralisation, although there are several generations of both. This mineralisation was followed by the widespread replacement of the host dolomite by aegirine and aegirine-augite, followed by fluoritisation (and further REE and Fe mineralisation) of much of the remaining carbonate. Fluoritisation is accompanied by the development of phlogopite and alkali-amphibole in the banded ores and further magnetite and hematite mineralisation. Variations in the degree of overprinting of the different alteration assemblages produced banded ores of varying mineralogy, which define a broad scale zonation to the two deposits (Fig. 2). The banded ores are cut by veins containing assemblages of aegirine-apatite, aegirine-calcite, aegirine-barite and fluorite-apatite-alkali amphibole





**Figure 2:** Sketch map of the Main and East Ore bodies showing the principle ore and alteration types. Modified from Chao *et al.* (1997).

all with associated REE-fluorocarbonate mineralisation. Ca-REE fluorocarbonates including parisite and unnamed polysomatic minerals of varying Ca:REE ratio occur associated with fluorite alteration. The final stage of REE mineralisation involves barite in veins and vugs, which is associated with parisite, huanghoite ( $\text{BaREE}(\text{CO}_3)_2\text{F}$ ) and other Ba-REE fluorocarbonates.

The sequence of Fe-oxide mineralisation is also complex. According to Chao *et al.* (1997) the earliest phase was the deposition of euhedral magnetite in partly altered marble, which was then replaced by hematite to form martite. This was followed by the deposition of granular hematite, banded magnetite and finally massive magnetite. Further development of hematite may be related to the late stage alteration of the ores.

Nb mineralisation is concentrated in the west ore bodies, where it occurs as disseminated minerals within the H8 dolomite marble (Chao *et al.*, 1997). Nb-rutile is associated with granular hematite, columbite is associated with magnetite in disseminated ores, and aegirine and pyrochlore occur as coarse grains in veins associated with huanghoite and alkali-amphibole which cut the main and east ore bodies. Pyrochlore also occurs in skarns associated with the Permian granites. Other Nb minerals occur throughout the dolomite marble including fergusonite and fersmite.

Sulphide mineralisation is a minor feature of the ore deposits and is dominated by pyrite with subsidiary pyrrhotite, sphalerite, galena and chalcopyrite. It is mostly associated with barite veins or alteration, and hence

represents a manifestation of the late stage modification of the deposit. Gold has been reported at Bayan Obo, but only in quartz veins hosted in shear fractures cutting the quartzo-feldspathic metasediments of the Bayan Obo group which are probably unrelated to the main Fe-oxide deposits (Chen *et al.*, 1990).

### *Alteration in the H9 Siliciclastic Sediments*

The H9 unit, consisting of black shale, slate and biotite schist occurs in the core of Bayan Obo synform, forming the hanging wall to the ore bodies. It is thought to have contributed to the formation of the ore bodies by reacting with hydrothermal fluids to form an impermeable cap-rock, which focussed fluid flow into the H8 dolomite below (Drew *et al.*, 1990). Albite is present throughout the shale unit as bodies of albite schist and albitite, which represent relicts of an earlier phase of alteration (Drew *et al.*, 1990). Albite was initially replaced by hyalophane (Ba-feldspar), and subsequently by K-feldspar. The shale shows alteration to microcline throughout most of its length. K-feldspar is commonly associated with biotite. Apatite and monazite mineralisation is also common in the unit. Brecciation and vein stockworks occur in the base of H9 shale, particularly in the hanging wall of the East ore body. Clasts are composed of fine-grained K-feldspar-altered slate and schist. The veinfill and matrix minerals include K-feldspar, hyalophane, albite, biotite, fluorite, barite, monazite, magnetite, pyrite and quartz (Drew *et al.*, 1990). Na-K-Fe metasomatism (aegirine-sodic amphibole-albite-K-feldspar) also affected the H5-H7 siliciclastic rocks below the stratigraphic level of the ore deposits.

## Geochemistry

The major and trace element chemistry of the Bayan Obo ore bodies have been the subject of several studies. Chao *et al.* (1997) presented bulk rock chemistry of samples subdivided on the basis of ore type. The major element chemistry reflects the dominant mineral assemblage of particular alteration type, with major variations in the concentrations of most elements. Most notably the total REE content (as  $\text{REE}_2\text{O}_3$ ) varies from 2.01 to >48 wt.%, the Fe content (as  $\text{Fe}_2\text{O}_3$ ) from 2.14 wt. % to 45.75 wt.% and the F content from 0.02 to 28.0 wt. %. It is also notable that there are no enrichments in U, S, Ta, Al and base metals. Le Bas *et al.* (1992; 1997) examined a range of trace elements in both the carbonatite dykes and the H8 dolomite marble, and concluded that the marble was closer in composition to typical carbonatite than to typical sedimentary carbonates. This may be an indicator of carbonatite provenance of the marble, or alternatively of pervasive metasomatism during the formation of the ore bodies.

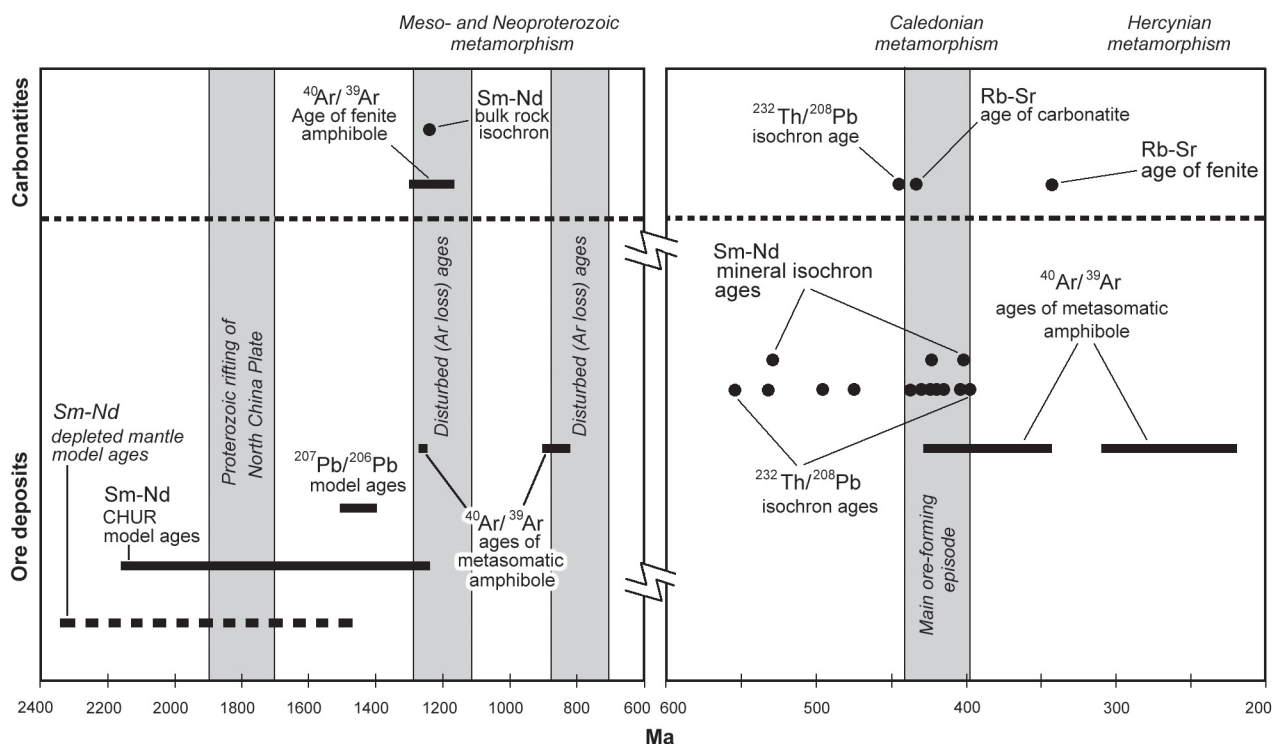
The bulk REE patterns of the ores have been studied by Wang (1981) and Yuan *et al.* (1992), whilst the REE patterns in individual minerals have been studied by Chao *et al.* (1997), Campbell and Henderson (1997) and Smith *et al.* (2000). The bulk rock patterns and the chemistry of individual minerals are dominated by Ce. Both Wang (1981) and Yuan *et al.* (1992) noted major changes in the ratio of La to Pr and Nd despite the overall extreme light REE enrichment of the ores, and the lack of Eu anomaly. Chao *et al.* (1997) showed that these changes reflected changes in the composition of monazite and bastnäsite with paragenesis. Smith *et al.* (2000) demonstrated that these changes could be interpreted on the basis of changes in the fluid chemistry and an overall decrease in the temperature of mineralisation with time.

## Age of Mineralisation

The geochronology of Bayan Obo is summarised in Fig 3. The Bayan Obo group sediments are interpreted as Middle Proterozoic in age on the basis of the presence of microfossils (Meng, 1982) and their relationship to the surrounding sedimentary sequence (Qiao *et al.*, 1991). Following deposition the Bayan Obo group underwent three major metamorphic episodes, distinguished using  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of amphibole (Conrad and McKee, 1992; Chao *et al.*, 1997). These are - Late Proterozoic ( $\approx 900$  Ma), probably also indicated by Rb-Sr cooling ages of black slates derived by Ren *et al.* (1994) (749 to 685 Ma); Caledonian (425 to 343 Ma) and Hercynian (310 to 220 Ma).

A number of studies have suggested Proterozoic ages for mineralisation at Bayan Obo (Nakai *et al.*, 1989; Philpotts *et al.*, 1991; Yuan *et al.*, 1992; Zhang *et al.*, 1994; Ren *et al.*, 1994), but these are mainly based on Sm-Nd or  $^{208}\text{Pb}/^{204}\text{Pb}$  model ages, and are not relevant to the age of ore formation. The same studies derived bulk rock Sm-Nd isochron ages ranging from 1.42 to  $\sim 1$  Ga. However, bulk rock sampling at Bayan Obo may include several generations of minerals in a single sample, and the isochrons frequently have large errors. Philpotts *et al.* (1991) pointed out that the bulk rock analyses in their study did not define a true isochron. Nakai *et al.* (1989) used La-Ba dating to derive Proterozoic ages for monazite, but this was based upon an isochron derived from a single data point and an assumed initial  $^{138}\text{Ba}/^{137}\text{Ba}$  ratio. Wang *et al.* (1994) and Chao *et al.* (1997) used  $^{232}\text{Th}/^{208}\text{Pb}$  geochronology to study the main ore forming episodes. They recognised two early, disseminated monazite and bastnäsite mineralisation episodes from 555 to 553 Ma and from 496 to 474 Ma, and the main stage of banded and vein-hosted REE mineralisation from 430 to 420 Ma,

**Figure 3:** Summary of the geochronology of the Bayan Obo ore deposits and carbonatites. See text for references.



coinciding with the formation of Caledonian metasomatic and metamorphic amphibole. Mineral isochron Sm-Nd ages also bracket the main stage of REE mineralisation to within this period (529±156 Ma, Philpotts *et al.*, 1991; 422±18 Ma, Zhang *et al.*, 1994; 402±18 Ma, 424±91 Ma, Ren *et al.*, 1994), as does a single Re-Os date derived from molybdenite from a sulphide vein cutting the banded ore of the East Mine (439±8 Ma; Liu *et al.*, 1996). Rb-Sr geochronology on samples from both the banded ores and from the K-silicate metasomatism of the overlying slates have produced ages in the range 429 to 305 Ma (Bai and Yuan, 1985; Philpotts *et al.*, 1991), which represent resetting of Caledonian mineral isotope systematics during Hercynian low grade metamorphism and granite intrusion.

The carbonatite dykes have been dated to 1233±65 Ma (Zhang *et al.*, 1994) and 1208±12 Ma (Ren *et al.*, 1994) using whole rock Sm-Nd and  $^{40}\text{Ar}/^{39}\text{Ar}$  techniques respectively. However, Rb/Sr analyses from a single carbonatite dyke gave an age of 433 Ma (Bai Yuan, 1985), whilst those from a separate fenite sample gave ages of 343±7 Ma (Zhang *et al.*, 1994). Ren *et al.* also obtained a  $^{232}\text{Th}/^{208}\text{Pb}$  age from carbonatite monazite of 445±11 Ma. These dates may relate to secondary mineralisation of dykes at the same time as the REE mineralisation in the ore deposits, whilst an earlier period of carbonatite magmatism is indicated by Sm-Nd whole rock and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages.

## Fluid Chemistry

Fluid inclusion studies of the Bayan Obo ore deposits have been carried out by Yishan *et al.* (1986), Xie *et al.* (1996) and Smith and Henderson (2000). Yishan *et al.* (1986) carried out vacuum decrepitation and leachate analyses of fluid inclusions in fluorite, magnetite and hematite, and concluded that the fluids were dominated by Na-Ca-K-Fe-Mg-Ba brines. Xie *et al.* (1996) reported the presence of REE-bearing daughter minerals in dolomite, confirming the capabilities of the fluid to transport significant amounts of the REE. Smith and Henderson (2000) presented microthermometric data on inclusions hosted in disseminated monazite, banded apatite and bastnäsite, banded and vein-hosted aegirine, vein-hosted apatite, bastnäsite and fluorite, and late stage banded fluorite and barite in eight samples from the Main and East ore bodies (Table 1).

At the disseminated monazite stage the fluids had compositions best represented by the system  $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}$ , with salinities ranging from 1 to 5 wt.%  $\text{NaCl}_{\text{equiv.}}$  and  $X(\text{CO}_2)$  from 0.3 to 0.45. Homogenisation temperatures indicate that this stage took place at temperatures of >280 to 330°C and pressures of >0.7 to 1.3 kbar. Fluids in the banded ores were initially aqueous, with salinities ranging from 6 to 10 wt.%  $\text{NaCl}_{\text{equiv.}}$ , but developed significant  $\text{CO}_2$

**Table 1:** Summary of calculated fluid inclusion compositions and  $T_h$  for fluid inclusions from the Main and East Orebodies at Bayan Obo. Data from Smith and Henderson (in press).

Stage & Mineral	Inclusion Type*	N	X(CO <sub>2</sub> ) (wt.%)		Salinity (wt.% NaCl <sub>equiv.</sub> )		Mode	T <sub>h</sub> (°C)	Phase
			Mean	Range	Mean	Range		Range	
Stage 1 - Disseminated Monazite									
Monazite	Lw+Lc+V	20	55	47 - 66	3.3	1.3 - 5.0	305	246 - 362	Lc
Stage 2 - Banded Ores									
Apatite	Lw+V	22	-	-	7.9	7.0 - 10.1	269	239 - 279	Lw
Bastnäsite	Lw+V	18	-	-	8.7	6.8 - 10.6	273	269 - 340	Lw
Bastnäsite	Lw+Lc+V	23	31	18 - 49	4.0	1.6 - 5.8	289	227 - 337	Lw
Stage 3 - Aegirine Alteration									
Aegirine	Lw+V	103	-	-	10.6	5.2 - 16.0	306	266 - 370	Lw
Stage 3 - Post - Aegirine vein fill									
Apatite	Lw+Lc+V	67	56	34 - 73	2.35	0.1 - 6.0	279	254 - 370	Lc
Bastnäsite	Lw+Lc+V	21	59	44 - 87	2.8	1.6 - 6.7	285	235 - 296	Lc
Stage 4 - Fluorite (Primary)									
Fluorite	Lw+Lc+V	21	75	38 - 92	3.9	1.0 - 10.9	257	253 - 279	Lc
	Lw+Lc+V(SN)	23	62	45 - 74	7.4	2.9 - 12.7	-	228 - >450	Lc
	Lw+Lc+V(SN)	8	49	30 - 66	17.7	14.1 - 20.2	-	274 - >480	Lc
	Lw+Sh+V(SN)	19	-	-	35.8	26.9 - 60.0	-	221 - >500	Lw
Stage 4 - Fluorite (Secondary)									
Fluorite	Lw+V	61	-	-	10.9	5.4 - 18.9	171	134 - 270	Lw
	Lw+Sh+V	8	-	-	28.3	26.5 - 32.3	180	159 - 198	Lw
Stage 5 - Barite stage									
Barite	Lw+V (1ary)	17	-	-	1.0	0.2 - 6.4	136	129 - 188	Lw
	Lw+V (2ndry)		-	-	1.2	0.0 - 6.4	166	135 - 216	Lw

\*Lw – aqueous liquid; Lc – carbonic liquid; V – vapour; Sh – halite; SN – nucleated on solid



contents ( $X_{\text{CO}_2} = 0.1$  to  $0.3$ ), due to carbonate dissolution during water-rock interaction at temperatures  $>400$  to  $\sim 300^\circ\text{C}$  and pressures  $>0.9$  to  $1.4$  kbar. Evidence for phase separation from co-existing brine and  $\text{CO}_2$ -rich fluid inclusions in vein fluorite indicates pressures of  $0.8$  to  $1.0$  kbar during vein formation, and hence temperatures of  $430$  to  $460^\circ\text{C}$  for aegirine alteration, and  $340$  to  $240^\circ\text{C}$  for apatite, bastnäsité and fluorite vein fill. Fluids responsible for aegirine alteration were dominantly aqueous, with salinities from  $5$  to  $15$  wt.%  $\text{NaCl}_{\text{equiv.}}$ , whilst those responsible for apatite and bastnäsité mineralisation had salinities of  $1$  to  $6$  wt.%  $\text{NaCl}_{\text{equiv.}}$ , and  $X_{\text{CO}_2}$  from  $0.25$  to  $0.75$ . Late-stage fluorite and barite mineralisation took place from  $240$  to  $130^\circ\text{C}$ . The general trend of salinities in inclusions in fluorite suggests dilution from around  $10$  to  $15$ , down to  $5$  wt.%  $\text{NaCl}_{\text{equiv.}}$  during cooling. Halite bearing inclusions in these populations may indicate episodes of boiling, under pressures dropping to as low as a few tens of bars. Aqueous inclusions in barite have very low salinities ( $<1$  wt.%  $\text{NaCl}_{\text{equiv.}}$ ), possibly representing the modification of the deposits due to the ingress of meteoric waters.

## Metal Transport and Precipitation

In the majority of high temperature hydrothermal fluids Fe is typically transported as Fe-Cl complexes and solubility is mainly controlled by oxygen fugacity and pH (Chou and Eugster, 1977). All the Bayan Obo fluids are interpreted to be Cl-bearing, and the  $f\text{O}_2$  must have risen at least as high as the hematite-magnetite buffer. Under these conditions, at  $400^\circ\text{C}$ , Fe solubility is likely to have been in excess of  $1$  wt.%, especially in the saline brines present during banded ore formation, aegirine alteration, and primary and secondary fluoritisation at Bayan Obo. Low pH and the ligand chemistry of the fluid are also important in maintaining high REE solubilities (Wood, 1990; Haas *et al.*, 1995). The REE form strongly associated complexes with chloride, carbonate, phosphate and especially fluoride. The occurrence of apatite, REE-fluorocarbonates and fluorite all point to high initial concentrations of F in the mineralising fluids at Bayan Obo. The increase in pH caused by the interaction of the acid fluids necessary for REE transport with carbonate host rocks was important in the precipitation of the both REE minerals and Fe-oxides. Other possible deposition mechanisms include complex destabilisation caused by the reduction in the fluid F-content by the formation of F-bearing minerals, the addition of  $\text{CO}_2$  to the fluid on carbonate dissolution, and aqueous-carbonic fluid immiscibility.

The association of Ca-REE fluorocarbonates with late-stage fluorite and huanghoite with barite points to extensive remobilisation of the REE during late stage fluid influx, and their redeposition as a low temperature mineral assemblage (cf. Williams-Jones and Wood, 1992). This is again almost certainly a result of high F contents in the hydrothermal fluids indicated by the continued fluoritisation, and the predominance of REE-fluorocarbonate minerals.

## Origin of the Host Dolomite

The origin of the host dolomite at Bayan Obo has important bearing on the genesis of the ore deposits. Meng (1982) reported the presence of several types of sedimentary structure within the dolomite, along with microfossil algae and thalophytes. However, Le Bas *et al.* (1997) described all the lamination in the dolomite, which had previously been described as sedimentary, as resulting from tectonic processes relating to the thrusting and deformation of the sequence. They went on to show that the trace element and O and C isotope composition of the dolomite are comparable to average carbonatite values, and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is comparable to mantle values ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.702951$  to  $0.703576$ ). This is in contrast to dolomite and calcite marbles from other thrust slices containing the Bayan Obo group, which clearly showed a sedimentary signature ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.719919$  to  $0.726202$ ). These data were interpreted, in conjunction with fenite-like alteration along the margins of the dolomite unit, to indicate an igneous carbonatite origin for the deposit.

However, the data of Le Bas *et al.* (1997) and other data from Liu (1986) and Meng and Drew (1992) are also consistent with a model of recrystallisation of carbonates in the presence of a magmatic fluid of non-specific origin that evolved in composition via water-rock interaction with an originally sedimentary dolomite marble (Smith and Henderson, 2000). The composition of the dolomite has also been interpreted as resulting from the intrusion of carbonatite dykes into a pre-existing sedimentary marble (Campbell, 1999). The reported presence of microfossils and the sedimentary-like O and C isotope compositions of some of the samples analysed by Meng and Drew (1992) indicate that the modification of a sedimentary marble by metasomatic processes is probably the most likely model.

## Genetic Models and Fluid Source

Several possible modes of formation have been proposed for the deposits (reviewed by Wu *et al.*, 1996), including syngenetic sedimentary deposition (Meng, 1982; Hou, 1989), metasomatism associated with granitic magmatism (Wang, 1973), and deposition from exhalative, possibly carbonatite related, hydrothermal fluids (Yuan *et al.*, 1992). The work of Chao *et al.* (1992, 1993, 1997) has clearly demonstrated an epigenetic origin for the deposit, involving several stages of metasomatic replacement of the host dolomite marble. Caledonian continent-continent collision provided the tectonic setting for this mineralisation, and provided structural pathways and driving mechanisms for hydrothermal, and possibly magmatic, fluid flow. The sources of fluids and ore metals remain the major disputed aspects in genetic models for the Bayan Obo deposits. Models involving fluids derived from either subduction (Chao *et al.*, 1992, 1997; Wang *et al.*, 1994), anorogenic (A-type) granite magmatism (Chao *et al.*, 1997; Wang *et al.*, 1994), or carbonatite, or alkaline, magmatism (Yuan *et al.*, 1992; Drew *et al.*, 1990; Campbell and Henderson, 1997) have been proposed. The link to carbonatites has been

proposed on the basis of the extreme LREE enrichment of the deposits, the similarity between the alteration types present and those seen in fenites and associated with late stage alteration in carbonatites, and the presence of carbonatite dykes cutting the surrounding metasediments.

Wang *et al.* (1994) and Chao *et al.* (1997) rejected the carbonatite-related model for the genesis of the Bayan Obo deposit on the basis of isotopic data. They showed that at the formation age of the deposit (taken as 425 Ma) the majority of  $\epsilon_{\text{Nd}}$  values for mineral separates from Bayan Obo were in the range -15.6 to -16.6 and initial  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios of monazite were highly radiogenic. Philpotts *et al.* (1991) measured the  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios of a range of mineralised specimens ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.706104$  to  $0.707030$ ). Wang *et al.* (1994) and Chao *et al.* (1997) interpreted these data as indicating a lower crustal source in which previous U extraction to the upper crust had taken place. According to this model the REE were then leached by hydrothermal solutions generated during Caledonian subduction, or mobilised by granite magmatism. The Sm-Nd and Pb isotope data cannot, however, be uniquely interpreted as indicating a crustal source. An enriched upper mantle source with similar isotopic characteristics has been invoked for some carbonatites and associated alkaline igneous rocks (e.g., Lehmann *et al.*, 1994; Castorina *et al.*, 1997). Equally possible, is that the ore bodies represent the remobilisation of a Proterozoic alkaline-igneous concentration of the REE during the Caledonian. Such a model could account for the wide disparity between isotopic model ages and mineral isochron ages, the Proterozoic bulk rock isochron ages, and for the extended time period over which mineralisation took place.

Although many oxygen isotope studies of the dolomite host to the Bayan Obo ore bodies have been carried out, only limited data are available from the ore bodies. Yuan *et al.*, (1992) presented data on a range of magnetite samples from the ore bodies, ranging from -2.99 to +4.2‰. Simple calculations of the composition of fluids in equilibrium with magnetite and the host dolomite indicate that the a fluid in equilibrium with magnetite between  $\approx 200$  to  $400^\circ\text{C}$  could have acquired its isotope signature via oxygen exchange with the host dolomite in the same temperature interval.

On the basis of current data we suggest a model for the formation of the Bayan Obo ore bodies initially via the interaction of a magmatic-hydrothermal fluid, derived from carbonatite, alkali, or A-type granite magmatism, with a sedimentary marble. These fluids were Cl- and F-rich allowing them to carry both the REE and large quantities of Fe. The ore bodies were subsequently modified during Caledonian deformation by multiple stages of hydrothermal circulation, leading to further stages of Fe-oxide and REE mineralisation. This process culminated in the mixing of early fluids with low salinity meteoric fluids, contributing to fluoritisation of the ore bodies and ultimately barite and sulphide alteration. The low temperature modification of the deposit is at least partly responsible for much of the variety of REE minerals present in the area.

## Discussion: Bayan Obo as an Fe-Oxide-Type Deposit

The Bayan Obo deposits show many features in common with hydrothermal Fe-oxide-type deposits. Specifically these include the association of apatite with Fe-oxides, the development of albite and K-feldspar in siliciclastic rocks and the paragenetic sequence of high temperature Na-Fe-(Ca) alteration being replaced by lower temperature K-rich alteration, and finally late-stage barite mineralisation (Pollard and Williams, 1999). The sequence of alteration types associated with Fe-oxide deposits has been interpreted as a result of a combination of cooling of the hydrothermal fluids, and changes in the fluid chemistry on unmixing between aqueous and carbonic fluids (Pollard and Williams, 1999), both of which are clearly viable at Bayan Obo on the basis of fluid inclusion evidence. In terms of its REE enrichment Bayan Obo is most comparable to the Olympic Dam deposit, where REE mineralisation occurs within the hematite breccias (Lottermoser, 1995). However, it is notable that significant U enrichments do not occur at Bayan Obo, suggesting a distinct metal source to that at Olympic Dam.

At Bayan Obo it is difficult to establish a direct genetic link between the ore deposits and any local heat or fluid source. Local granites are younger than the age of mineralisation, whilst the carbonatite dykes are not volumetrically extensive, and may pre-date the ore deposits. Isotopic data indicate a source enriched relative to depleted mantle, which has been interpreted as indicating a lower crustal source for the metals. Fe-oxide deposits for which Sm-Nd isotope data are available typically indicate a source for the REE in local igneous or volcanic rocks, with no consistent source signature between different deposits (e.g. Cliff and Rickard, 1992; Johnson and McCulloch, 1995; Gleason *et al.*, 2000). The REE enrichment of these deposits is a function of effective mobilisation of the REE from a range of source rocks, rather than a relationship to a specific source.

Primary fluid inclusions from the limited number of igneous related Fe-oxide-(Cu-Au-U-REE) deposits in which they have been studied show extremely high salinities (up to 60 wt.%  $\text{NaCl}_{\text{equiv.}}$ ) at high temperatures ( $400$  to  $600^\circ\text{C}$ ), co-existing with  $\text{CO}_2$ -rich inclusions (e.g., Borrok *et al.*, 1998; Pollard and Williams, 1999; Ullrich and Clark, 1999; Ettner *et al.*, 1994; Lindblom *et al.*, 1996), whilst mineralisation in the Olympic Dam Fe-oxide-Cu-Au-U deposit was interpreted as occurring on the mixing of moderate salinity magmatic fluids with high salinity fluids, possibly derived from basinal brines (Oreskes and Einaudi, 1992). Deposition mechanisms for Fe, Cu and Au have been inferred to include decreasing P-T, redox reactions, increase in pH from unmixing and water-rock interaction and fluid mixing. Some similarities exist between Bayan Obo fluids and fluids from igneous-related Fe-oxide deposits, particularly the occurrence of Fe (and Mn) chlorides, the evolution of fluid composition via aqueous-carbonic fluid immiscibility, and the associated alteration characteristics. However, the very high salinities and high temperatures in early fluids and the presence of high-salinity basinal



brines at Olympic Dam are in contrast to the fluids that have so far been identified at Bayan Obo. Finally, the inferred presence of evaporites in the fluid source regions for many Fe-oxide deposits (Barton and Johnson, 1996; Ullrich and Clark, 1999), or the mixing between magmatic and external sources of S (Pollard and Williams, 1999) is also in contrast to Bayan Obo. Late sulphides at Bayan Obo (pyrite and galena) show  $\delta^{34}\text{S}$  values from -4 to +4‰ (Yuan *et al.*, 1992) suggesting a magmatic source for sulphur, and incompatible with the expected heavy sulphur isotope signature derived from an evaporitic input.

## Conclusions

The Bayan Obo Fe-REE-Nb deposits are a unique occurrence, largely due to their exceptional concentrations of the REE. They show many similarities to both the hydrothermal Fe-oxide deposit class, and carbonatite-related mineral deposits. The textural characteristics of the ore bodies, geochronological constraints and the wide range of fluid types indicated by fluid inclusions all support a multistage genetic model for the ore deposits. Current data supports a model whereby ore deposits were initially formed by the interaction of magmatic fluids with dolomite marble. These deposits were then extensively modified by multistage fluid flow during Caledonian subduction. The ultimate source of fluids and metals remains a subject of debate, although cases can be made for crustal sourced magmas, or for carbonatite-related fluids. Despite the undoubted Proterozoic age of the host sediments, the Bayan Obo deposits are not Proterozoic in age as has been suggested by a number of authors. The mineralisation occurred in several stages from ~555 to 400 Ma with the main ore forming period occurring between 430 to 420 Ma.

The Bayan Obo deposits have many similarities with Fe-oxide type deposits, particularly the development of mineralised magnetite-hematite bodies, the high REE-content of the ores, the presence of apatite as a gangue phase and the sequence of alteration types (i.e., Na-Ca-Fe alteration followed by K-Fe alteration). However, significant differences do occur. The alteration mineralogy is distinct at Bayan Obo, particularly the absence of major scapolite. This can be directly related to differences in fluid chemistry between Bayan Obo and the majority of Fe-oxide type deposits, with primary, hyper-saline brines being absent at Bayan Obo. The metal association at Bayan Obo is also distinct, with extreme REE and particularly LREE enrichment, only minor late stage base metal mineralisation and little or no Au and U.

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