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Discussion on Le Bas *et al.* (1997) 'Oxygen, carbon and strontium isotope study of the carbonatitic dolomite host of the Bayan Obo Fe-Nb-*REE* deposit, Inner Mongolia, China', *Mineralogical Magazine*, **61**, 531–41

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ABSTRACT

Some important and interesting data on the O, C and Sr isotopic compositions of rocks associated with the Bayan Obo Fe-Nb-*REE* deposit have been reported by Le Bas *et al.* (1997). However, a number of points relating to the interpretation of these data, and also to the terminology adopted, are worthy of further discussion. The essence of this discussion is that some of the geochemical and isotopic signatures found at Bayan Obo are not exclusively consistent with an igneous origin. A replacement hypothesis involving deep-sourced fluids could also explain the pattern of data, if minor carbonatitic intrusions into a sedimentary sequence are considered.

KEYWORDS: carbonatites, stable isotopes, rare earth mineralization, replacement, fluorite, Bayan Obo.

Introduction

THE central debate as to the origin of the Bayan Obo Fe-Nb-*REE* deposit lies in the nature and origin of the host unit, referred to and mapped as the 'H8 dolomite' (Drew and Meng, 1990). Drew *et al.* (1990) described the geology of the area in detail, explaining that H8 was a carbonate bed within the Proterozoic Bayan Obo Group, and loosely dated between 1350 and 1650 Ma (Ren *et al.*, 1987). Drew *et al.* (1990) also described hydrothermal alteration effects, with a comment that crosscutting veins have a 'carbonatite-like mineralogy'. This, and subsequent studies by various authors have brought the question of a carbonatite presence to the forefront of discussion (Campbell and Henderson, 1997; Le Bas *et al.*, 1992, 1997; Liu, 1985; Tao *et al.*, 1998). Some suggest that the main outcrop of H8 is of igneous origin (Le Bas *et al.*, 1997; Liu, 1985). However, others sustain the view of Drew *et al.* (1990) that H8 is part of a stratigraphic sequence of sediments, or suggest a carbonatitic volcano-sedimentary setting (Yuan *et al.*, 1992). Some authors reject the notion of any carbonatite involvement in the genesis of the mineralization (Chao *et al.*, 1992; Wang *et al.*, 1994). More comprehensive reviews of the literature can be found in Wu *et al.* (1996), Wang *et al.* (1994), Le Bas *et al.* (1997) and Campbell and Henderson (1997).

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Terminology

The 'dolomite' label of Drew *et al.* (1990) for the H8 unit, whether of igneous or sedimentary origin, needs to be regarded only as a general indication as to the nature of the host rocks, and not as a rigid description of the actual lithologies found. When examined in the field, the occurrence of carbonates (calcite, dolomite and ankerite) is patchy. Large areas, particularly in the vicinity of the Main and East commercial pits, are practically devoid of carbonates, consisting instead of massive or banded magnetite-fluorite, or magnetite-fluorite-apatite assemblages, with or without alkali silicates, rare earth ore minerals and baryte (Campbell and Henderson, 1997; Drew *et al.*, 1990; Yuan *et al.*, 1992). Indeed, Meng (1989) compared the Bayan Obo rocks with another Proterozoic iron ore-carbonate formation on the margin of the North China Platform, namely, the Da Li Zi Formation. Occasional pockets of the dolomitic marble described by Le Bas *et al.* (1997) are found in the main pit areas of Bayan Obo, but in general the assemblages above predominate in the intensely mineralized areas near Bayan Obo town. Likely reasons for the rare and patchy occurrence of carbonate are outlined here and are of relevance to this discussion.

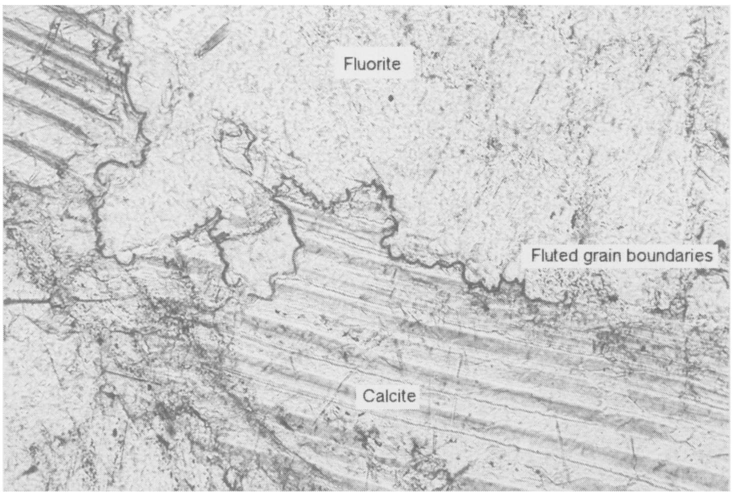
Le Bas *et al.* (1997) describe two facies, 'coarse-grained dolomite' and 'fine-grained dolomite', using a 1 mm grain size to distinguish them. While this is useful when dealing with genuine carbonate rocks of the region, the distinction is of little relevance in relation to the magnetite-fluorite-apatite rocks in the intensely mineralized areas that are also found far beyond the commercial pits. Specifically, the statement of Le Bas *et al.* (1997) that the 'ore bodies lie within the fine-grained marble' is rather misleading. This has important implications for the context of the isotope data reported, and a clearer projection of the overall picture.

Fine-grained dolomite

In the $\delta^{18}O$ *vs* $\delta^{13}C$ plot (Fig. 2 of Le Bas *et al.*, 1997), a trend is depicted that straddles the generally accepted fields, (Faure, 1986), of primary igneous carbonatite (PIC) and of limestone. Le Bas *et al.* (1997) state that the spread of points for their samples of fine-grained dolomite represents a magmatic fractionation trend of sovite to alvikite (lighter to heavier fractions). However, the alternative explanation, that original limestones underwent hydrothermal alteration by isotopically lighter, magmatically-derived fluids, must be fully considered in the light of crucial petrological evidence presented below, notably, replacement textures. Even though Le Bas *et al.* (1997) took care to sample away from the main mineralized areas, it is clear from their own samples (e.g. no. 7 (88/157) in their Table 1) and from the present author's own sampling, that fluorite is abundant in the far western reaches of the H8 outcrop, indicating widespread hydrothermal alteration (Campbell and Henderson, 1997).

Replacement textures

The abundance of replacement textures seen in the vicinity of the main ore bodies at Bayan Obo is striking, yet poorly acknowledged in the literature to date, apart from some detailed work by Chao *et al.* (1992, 1997). Campbell and



'IG. 1. Photomicrograph (PPL) of fluted grain boundaries (black line) between calcite, displaying truncated twin planes, and fluorite, representing replacement of the former by the latter. Field of view ≈550 × 800 μm.

Henderson (1997) comment on the deposition of fluorite, rare earth ores and apatite in relation to fluid-host interaction, but Campbell (1998) suggests specific reactions, e.g. the replacement of calcite by fluorite, a reaction that is well known in other contexts:

$$CaCO_3 + 2HF = CaF_2 + CO_2 + H_2O$$

Evidence for this reaction in the rocks of Bayan Obo is widespread. Figure 1 shows fluted contacts where calcite has been attacked by the F-bearing hydrothermal fluids, resulting in the precipitation of fluorite adjacent to the reaction front. In Fig. 16 of Chao *et al.* (1997), calcite-calcite grain boundaries are seen to be preferentially exploited. Additional evidence for this type of replacement reaction is found with the presence of probable reaction products H_2O and CO_2 as fluid inclusions trapped in secondary apatite and fluorite.

Coarse-grained dolomite

The isotope data for the coarse-grained dolomite lying within or close to the PIC field in Fig. 2 of Le Bas *et al.* (1997) are more convincing. These samples may well represent magmatic rocks, but probably only as minor intrusions cutting through the original Proterozoic sediment. This explanation is consistent with a number of other factors. (1) The swarm of carbonatitic dykes to the north of the main mineralized area provides undisputed evidence for the presence, at some time after the deposition of the Bayan Obo Group, of carbonatitic magmas intruding as minor igneous bodies (Le Bas *et al.*, 1992). (2) The fact that small (~1–3m thick) carbonatitic dykes intrude other metasediments of the Bayan Obo Group provides a possibility that the H8 unit could also have been a host, whatever its primary lithology. The location of 'coarse-grained dolomite' samples in Le Bas *et al.* (1997) is suggestive of sill-like bodies at the contacts between H7 and H8. (3) The reported fenite margins of Le Bas *et al.* (1997) can be accounted for by a consideration of small intrusions without a need to suggest that the ~16 × 2 km main outcrop is a giant intrusion (by carbonatite standards). However, unambiguous field evidence for igneous contacts is still lacking (see below). (4) Subsequent fluid-rock interaction and replacement would affect both the original host sediment and the minor intrusions, possibly obliterating good field evidence of contacts and possibly accounting for some of the protracted points of contention over the origin of the deposit. Dyke samples 13 and 14 (88/142 and 88/141) of Le Bas *et al.* (1997) and their isotope characteristics would appear to confirm this, but judgement as to the origin of the fluids needs further consideration. (5) Small numbers of hand specimens collected from the Main and East pits appear atypical of the main magnetite-fluorite-apatite-rare earth ore assemblages described earlier in this discussion, and more closely resemble the samples of Le Bas *et al.* (1997). One example displays an assemblage of calcite-apatite-pyrite-albite-rare earth minerals, including, notably, the presence of pyrochlore, a mineral strongly associated with carbonatites. It must be stressed that these few samples represent rare, localized anomalous rocks in the main mineralized area, and thus further support the small-intrusions hypothesis. (6) Deposition of much of the bastnäsite-type mineralization is well documented to have occurred at the time of extensive fluid interaction, which is also thought to have been the main mineralization event (Campbell and Henderson, 1997, Chao *et al.*, 1992, Drew *et al.*, 1990 and Wang *et al.*, 1994). However, there are many examples of pre-existing monazite grains displaying reaction textures. For example, monazite, enclosed by apatite and bastnäsite clearly represents an incomplete reaction with a fluid (E. Chao and P. Henderson 1995, pers. comm.)

$$3LnPO_4 + 4HF + 5CaCO_3 = 3Ln(CO_3)F + Ca_5(PO_4)_3F + 2H_2O + 2CO_2$$

It is stressed that the above reaction represents only one mechanism for bastnäsite deposition, and that the F-bearing fluids carried more rare earth species, contributing to the exceptional concentrations found in this world class deposit.

Strontium isotopes

A mantle signature from $^{87}Sr/^{86}Sr$ reported by Le Bas *et al.* (1997) for both the 'coarse-grained dolomite' and 'fine-grained dolomite' samples throughout the main outcrop of H8 provides reasonable evidence, not only for minor carbonatitic intrusions (coarse-grained dolomite), but also for a deep fluid source for the later mineralization. However, typical $^{87}Sr/^{86}Sr$ ratios of 0.705–0.706 (Faure, 1986) for mid-Proterozoic marine carbonates are not very much higher than the ratios of Le Bas *et al.* (1997). It is worthy of note that bulk analytical methods, despite the excellent separation procedures used today, always leave a little doubt in relation to contamination by inclusions of other phases, especially where the rock texture is very fine-grained. The significant levels of Sr in apatites associated with the mineralization at Bayan Obo (Campbell and Henderson, 1997), and the reporting of late-stage Sr-bearing carbonates as replacement phases (Chao *et al.*, 1997) should be noted in this context. Ideally, spot-isotopic analyses of carbonate from the main mineralized areas are needed.

Structural questions

One of the most fundamental questions yet to be resolved about Bayan Obo concerns the origin of the prominent banding that can be seen over vast areas in the vicinity of the two main commercial pits. Many authors, notably Chao *et al.* (1992, 1997), have put forward a tectonic argument attributing the intense, fine-scale, flat to wavy banding to compressional and shear stresses. Le Bas *et al.* (1997) agree, but with the additional argument that the deformation took place in an igneous environment, resulting in 'granular schlieren' of magnetite and apatite. While it is acknowledged that minor shear zones exist at Bayan Obo, and that Phanerozoic folding and thrusting has caused the present outcrop expression of beds of the Bayan Obo Group, convincing petrological evidence remains to be seen for a structural control for the widespread banding. True lineations are not easy to find in the field in the Main and East Pits. Occasionally, a lineation is expressed by alkali amphiboles, but these do not necessarily occur in the same plane as the banding, as shown by field measurements taken at one locality: 092/70 S (orientation of banding), and 38 to 146 (lineation). Furthermore, many localities display randomly oriented alkali silicates, superimposed on the banding that is ubiquitously depicted by discontinuous, sometimes wavy, 'layers' of magnetite and apatite and interstitial fluorite. Evidence of intense deformation is by no means obvious in aegirine, apatite, and equigranular magnetite and fluorite (Fig. 2*c,d,e,f* of Campbell and Henderson, 1997; Figs 4 and 5 of Chao *et al.*, 1992; Figs 10–16 of Drew *et al.*, 1990; Figs 4*b,d,e* of Le Bas *et al.*, 1992; Figs 3–5 of Yuan *et al.*, 1992), and in anhedral masses of apatite that sweep around trail-clusters of earlier apatite (Fig. 2*a* of Campbell and Henderson, 1997), and in the fluted grain boundaries of reaction fronts (Fig. 1, this paper).

Although Le Bas *et al.* (1992) have shown a good example of elongated apatite grains, this texture is not seen in any of the rocks typical of the main, banded, mineralized areas, despite a full and thorough investigation of the apatites (Campbell and Henderson, 1997). The elongated grains of Le Bas *et al.* (1992) can be explained easily by the small intrusions hypothesis (this discussion), with minor shear and/or flow structures having been concentrated at the margins of the body.

More significantly, the question of scale presents a dilemma. Such a widespread occurrence of the intense, mm-scale banding throughout the 1–2 km thickness of H8, would have to have been caused by a major, intense, tectonic shear event, such as would normally produce mylonites. In addition to the problems listed above, cataclastic textures normally associated with mylonites are far from evident. Chao *et al.* (1992) discuss this in relation to supposed mortar texture in their Fig. 6. However, even accepting that this might be a true mortar texture representing cataclastic processes, it is certainly not at all widespread like the intense banding described above. It would appear that field and petrological evidence for large scale tectonic shear, therefore, is just as difficult to prove as supposed sedimentary structures at Bayan Obo.

Conclusions

The purpose of this discussion has been to highlight the persisting areas of doubt surrounding the investigation of Bayan Obo geology, and their impact on the strength of interpretations put forward by all authors. It is in this spirit that attention to alternative explanations as summarized below, for the data of Le Bas *et al.* (1997), has been drawn.

The specific combination of low $\delta^{18}O$ *vs* $\delta^{13}C$, the trend between lighter and heavier oxygen and carbon isotopes in the 'fine-grained dolomite', and ^{87}Sr-^{86}Sr ratios of <0.705 (Le Bas *et al.*, 1997), is entirely consistent with the following scenario. In this simple outline, essentially dry, regional metamorphic events have been omitted deliberately for clarity of discussion about the isotopic effects. The absolute timing of the main events is to be discussed elsewhere.

(1) Deposition of the Bayan Obo Group, including H8, as a succession of sediments. Lithologically, these were a range of chemical sediments, some of which were carbonate

dominated, some phosphatic and iron-enriched ('heavy' $\delta^{18}O$ and $\delta^{13}C$ signatures initially, in 'fine-grained dolomite').

(2) Intrusion of small carbonatite bodies along the margins of H7 and H8, and in Archaean basement, H1–H7, H8 and H9 ('light' $\delta^{18}O$ and $\delta^{13}C$ signatures in 'coarse-grained dolomite' samples). Contact zones were fenitized.

(3) Large-scale, pervasive (but incomplete) alteration of H8 and small intrusives, by principally deep-sourced, F-enriched hydrothermal fluids, causing the trend towards lighter $\delta^{18}O$ and $\delta^{13}C$ signatures in 'fine-grained dolomite', and the extensive replacement textures along with significant rare earth mineralization.

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