Oxygen, carbon and strontium isotope study of the carbonatitic dolomite host of the Bayan Obo Fe-Nb-*REE* deposit, Inner Mongolia, N China

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Abstract

The large Fe-Nb-*REE* deposit at Bayan Obo is hosted by a dolomite marble within the thrust complex of marbles, quartzites and slates that belongs to the Bayan Obo Formation of mid-Proterozoic age. The dolomite is either a dolomitized sedimentary limestone subsequently mineralized and tectonically thrust and folded, or a dolomite (or dolomitized) carbonatite intrusion with late-stage recrystallization and mineralization that has been subsequently tectonically deformed.

O and C isotope data indicate that the sedimentary limestones and dolomites of the Bayan Obo Formation, which occur in the thrust stack together with quartzites and slates, have values of δO *c.* +20 per mil (SMOW) and δC *c.* zero. In contrast, the coarser grained facies of the large (0.5 × 10 km) dolomite marble which hosts the *REE* ore body has δO per mil values between +8 and +12 and δC values between −5 and −3, whereas the finer-grained recrystallized and *REE*-mineralized dolomite marble which occurs close to the ore bodies has δO between +12 to +16 and δC between −4 and zero. $^{87}Sr/^{86}Sr$ data confirm this distinction: >0.710 for the sedimentary rocks and <0.704 for the coarse- and fine-grained dolomite marbles.

These data are taken to indicate that the large and coarse-grained dolomite was an igneous carbonatite (as borne out by its fenitic contact rocks and trace element geochemistry), and that the finer grained dolomite recrystallized under the influence of mineralizing solutions which entrained groundwater. The stratiform features in the coarse-grained dolomite that are evident in the field are interpreted as tectonic layering.

KEYWORDS: carbonatite, dolomite, limestone, marble, Bayan Obo, oxygen isotopes, carbon isotopes, strontium isotopes.

The problem

THE world's largest Fe-Nb-*REE* deposit occurs at Bayan Obo in Inner Mongolia, China (110°E, 42°N), 150 km north of the Huango Ho (Yellow River) and the city of Baotou where the ore is processed. The deposit is hosted by a dolomite marble, the origin of which is controversial. Several authors, including Tu *et al.* (1985) and Chao *et al.* (1992, 1993), consider the marble to be sedimentary in origin and the ore deposit to be epigenetic. Others, including Liu

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Tiegeng (1986), Yuan Zhongxin *et al.* (1992) and Le Bas *et al.* (1992), consider the marble originally to have been igneous and carbonatitic, and that the ore deposit is likely to be related to the carbonatite. There is the further possibility that the marble was originally a sediment and later pervaded by carbonatitic fluids prior to the mineralization. The formation of carbonatite from a carbonate sediment in this manner is not a previously recognized process.

The issue is complicated by the fact that the marble has been recrystallized not once but twice, which process must have destroyed most of the original textural features. Furthermore, there is the possibility that the dolomite marble may be the product of dolomitization of a calcite rock, independent of whether it was igneous or sedimentary in origin. The controversy centres on the interpretation of the field relations and the geochemical evidence.

In order to avoid ambiguity, the following definitions are used here. Marble is any carbonate rock that has been recrystallized by metamorphism. Limestone and dolomite limestone are sedimentary rocks composed of calcite and dolomite respectively. Carbonatite is a general term for igneous carbonate rocks composed of >50% carbonate minerals, e.g. calcite carbonatite and dolomite carbonatite. All the Bayan Obo carbonate rocks can be described as marbles, only the grain size varies.

Field relations

All the marbles of the area are labelled H8 by the Chinese workers and that symbol is used here, although Drew and Meng (1990) relabelled them Y8 in accordance with recommended stratigraphic nomenclature and current practice of USGS mapmakers. The main outcrop of the dolomite marble occurs as a northward inclined sheet 12 km long and 1 km wide within a northward-dipping thrust pile of marbles, quartzites and slates of mid-Proterozoic age, and the whole area is intruded and underlain by a Permian granite which crops out mainly to the south of the ore deposit (Fig. 1). The dolomite marble occurs in two facies: coarse-grained (>1mm) and fine-grained (<1mm). The ore bodies lie within the fine-grained marble and the whole is capped by thick shales (Bai Ge and Yuan Zhongxin, 1985).

During a visit by Le Bas and colleagues in 1988 to examine carbonatite dykes reported to be cutting Archaean migmatites at Bayan Obo, the then prevailing view was accepted that the dolomite marble was a sediment (Tu *et al.*, 1985) and that the widespread layering visible in all outcrops was bedding. Subsequently, and after analysis of the dykes and the dolomite in the laboratory, it became evident that this dolomite had the geochemistry of a carbonatite, with the result that it was suggested that the dolomite marble, if bedded, must be a carbonatite tuff (Le Bas *et al.*, 1992). Later visits reveal that the calcite carbonatite dyke identified in 1988 is part of a swarm of carbonatite dykes, which cut and fenitize quartzites and shales of the Bayan Obo Formation.

The possibility of fossils and of sedimentary structures in the dolomite that hosts the ore bodies, requires comment. Chao *et al.* (1992) reported discontinuous lenses of massive and of thin bedded marbles and some cross-bedding. However the strong lineation shown by the marbles is the result of the numerous clusters of euhedral magnetite and apatite having been drawn out into granular schlieren. The lineation resulted from shearing, stretching and deformation interpreted to be related to the regional thrusting and folding (Chao *et al.*, 1993). This process, accompanied by recrystallization along the shear planes, provides an explanation for the lensoid and discontinuous elongate structures which have been interpreted as bedding. Intercalations of detrital apatite and quartz are also reported but without giving evidence for the detrital character claimed. Since both apatite and quartz segregations are common in carbonatites, their presence is not critical, but it may be observed that the main outcrop of H8 Bayan Obo dolomite marble contains abundant apatite (2–4%) which is rare in sedimentary dolomites but common in carbonatites. Furthermore, the apatite is blue in cathodoluminescence (Le Bas *et al.*, 1992) as in most carbonatites. Remains of algae and bacteria are reported near some of the ore bodies, but none have been verified or confirmed, and the preservation of any would seem unlikely when the history of several recrystallizations and mineralizations, recorded by Chao *et al.* (1992, 1993), is taken into account. Chao also showed that the fine-grained H8 dolomite marble formed by the recrystallization of the coarse-grained H8 dolomite marble (Chao *et al.*, 1993). That coarse-grained dolomitic rocks can recrystallise to a fine-grained form might be disputed as contrary to expectation, and this would have serious implications on the interpretations made here, but at Bayan Obo there is no doubt by those who have seen the rocks in the field and in thin section that the fine-grained dolomites are recrystallised coarse-grained dolomites.

The northern contact of the main dolomite marble is described by Drew *et al.* (1990) as one branch of the Kuanggou fault within the polyphase thrust system, but our field work north of the main ore body showed the contact to be intrusive with sodic amphibole developed in the fenitized quartzite next to the contact. The latter will be described in a later paper together with other fenitic aureoles marginal to that body of marble.

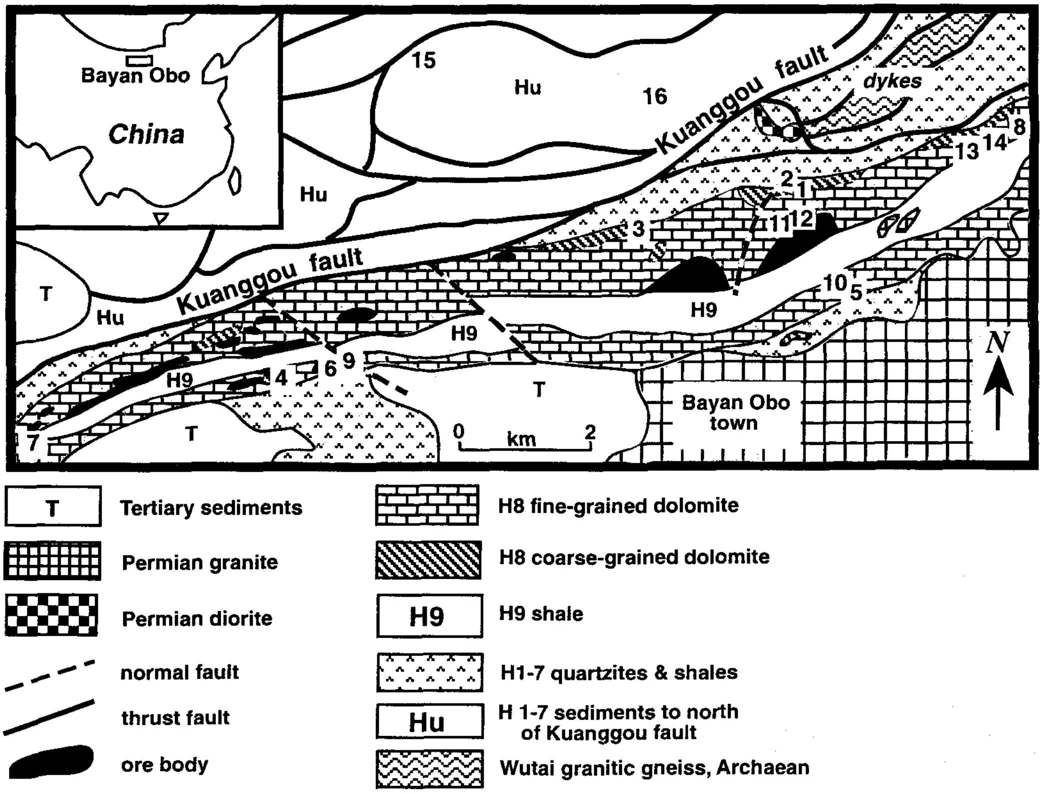

Fig. 1. Geological sketch map of the Bayan Obo region, N. China. The Main ore body is that above the 'B' of Bayan Obo town with the similarly large East ore body to its east. The western ore bodies comprise the numerous small ore bodies in the western half of the map. The numbers 1–16 show the localities of the samples listed in Tables 1 and 2. The area labelled 'dykes' marks the area of the carbonatite dyke swarm described by Le Bas *et al.* (1992). Only the major faults and thrusts are shown. Modified from Drew and Meng (1990).

Geochemistry

In this contribution, the dolomite marbles studied were collected across the whole outcrop (Fig. 1); many from as far away as possible from the Main and East ore bodies, unlike most previous studies. The aim was to obtain samples for analysis that might show the least possible metasomatic effects of mineralization on the dolomite marble and therefore identify the initial geochemical character of the marble. Detailed determinations of monazite Th-Pb isochrons indicate that the monazite mineralization began about 555 Ma ago but the banded ores which comprise the main deposits are related to subduction *c.* 474-400 Ma (Wang *et al.* 1994). Sm-Nd investigations by Yuan Zhongxin *et al.* (1992) suggest that the mineralization began earlier, about 1.5 Ga, and all authors agree that the mineralization was polyphase.

Preliminary analytical work (Le Bas *et al.*, 1992) suggested that the H8 dolomite marble which hosts the ore bodies has the trace element composition of a carbonatite, but further work remains to be done to be certain that these traces, even some kilometres away from the ore bodies, are not the result of regional mineralization. To address this problem, we turned to isotopes to provide the critical evidence.

The samples analysed

The samples analysed were selected to include ones with minimal tectonic deformation and least Fe-Nb-*REE* mineralization. They are listed in Table 1 and are considered to be the best representatives available of the coarse-grained and fine-grained H8 dolomites from the main outcrop. In addition, two samples (15 and 16) were taken from H8 dolomite and limestone

TABLE 1. Details of samples analysed. Localities are marked on Fig. 1.

1. Coarse-grained dolomite marble. Tabular and aligned crystals of twinned dolomite with sutured margins; scattered granules of magnetite, elongate clusters of granular apatite and ?fersmite after euhedral pyrochlore. 100 m from contact with quartzite, one km N of East Ore body (field number 88/150).
2. Coarse-grained dolomite marble. Mosaic-textured twinned dolomite with sutured margins and triple junctions; octahedral magnetite (4%), pyrochlore (<1%) and subprismatic apatite (4%). Two metres from contact with Na-amphibole-bearing quartzite and one km N of East Ore body (field number 88/152).
3. Coarse-grained dolomite marble. Dolomite has triple junctions; apatite is subprismatic; magnetite granules show alteration to hematite. Close to quartzite junction, 1.5 km NW of Main Ore body (field number B241).
4. Coarse-grained dolomite marble. Mosaic-textured dolomite with triple junctions, with apatite and magnetite. East side of minor ore body no. 10, and 6 km west of Main Ore body (field number 90/62).
5. Coarse-grained mineralized dolomite marble. Aligned crystals of dolomite penetrated by opaque minerals (?hematized magnetite) with parallel needles of colourless amphibole and scattered granules of monazite. Dong-ji-le-gele hills, 1 km SE of East Ore body, and south of H9 slate outcrop (field number B222).
6. Fine-grained dolomite marble, mosaic-textured dolomite with bands of Fe-oxides and RE minerals along foliation planes; folded. 100 m east of minor ore body no 10, and 5 km west of Main Ore body (90/63).
7. Medium-grained dolomite marble with Fe-oxides and fluorite. Near minor ore body no. 5 and 10 km west of Main Ore body (88/157).
8. Fine-grained dolomite marble with mosaic of triple-junctioned, mostly untwinned dolomite, a few scattered anhedral Fe-oxides and many subparallel trains of monazite granules. At eastern end of main H8 outcrop, 4 km ENE of East Ore body (90/58).
9. Fine-grained dolomite marble with mosaic of triple-junctioned dolomite; no opaque minerals but numerous short, randomly oriented trains of intergranular monazite. Two metres from locality 6 (90/64)
10. Fine-grained dolomite marble with thin lenses of Fe-oxides along foliation planes. Dong-ji-le-gele hills, 1 km SE of East Ore body, and south of H9 slate outcrop (88/117).
11. Fine-grained dolomite marble with abundant Fe-oxide grains, intergranular monazite and some barite. Hills forming the northern footwall of the East Ore body and about 100 m from exposed ore (88/148).
12. Very fine-grained dolomite marble with abundant Fe-oxides and monazite. Ten metres from 11 (88/147).
13. Fine-grained calcite marble from northern contact of 0.6 m wide carbonate dyke which cuts H9 slate, with 0.1 m wide albite-phlogopite-magnetite contact aureole. Marble comprises Mn-calcite, richterite, phlogopite and Ti-magnetite. In N–S trench south of Bolutou Mountain, 3.5 km ENE of East Ore body (88/142).
14. Fine-grained calcite marble from centre of carbonate dyke at locality 13 . Mineralogy similar to 88/142 but with more calcite. (88/141).
15. Dolomite marble, almost pure except for minor quartz veining. In massive, poorly bedded H8 dolomite of the Bayan Obo Formation, in thrust slice bounded to NW by a melange zone with sheared serpentines and metagabbros, and to the SE by quartzite. 5 km NW of Main Ore body (90/65).
16. Calcite marble from Bayan-Obo Formation quartzite-shale-limestone sequence in thrust slice 2.5 km NNW of Main Ore body. Sample kindly supplied by L.J. Drew (Y8/230).

units in the Bayan Obo Formation further north, to act as controls of samples of undoubted sedimentary origin. The major and trace element analyses were made on the Philips PW1400 and the ARL 9420+ XRFs in the University of Leicester using fused beads and pressed pellets, and run with international standards. The isotope analyses were carried out in the NERC Isotope Geosciences Laboratory. Samples for C and O isotope analysis were prepared according to the method of McCrea (1950). Isotope ratio measurements were carried out in a VG Optima mass spectrometer. Results are reported relative to the PDB and SMOW standards with an overall analytical precision of ± 0.05 per mil for δ^{13}C and δ^{18}O. The Sr isotope determinations were made on dolomite and calcite mineral separates. A within-run precision of better than 0.000007 was obtained and the NBS 987 standard gave 0.710201.

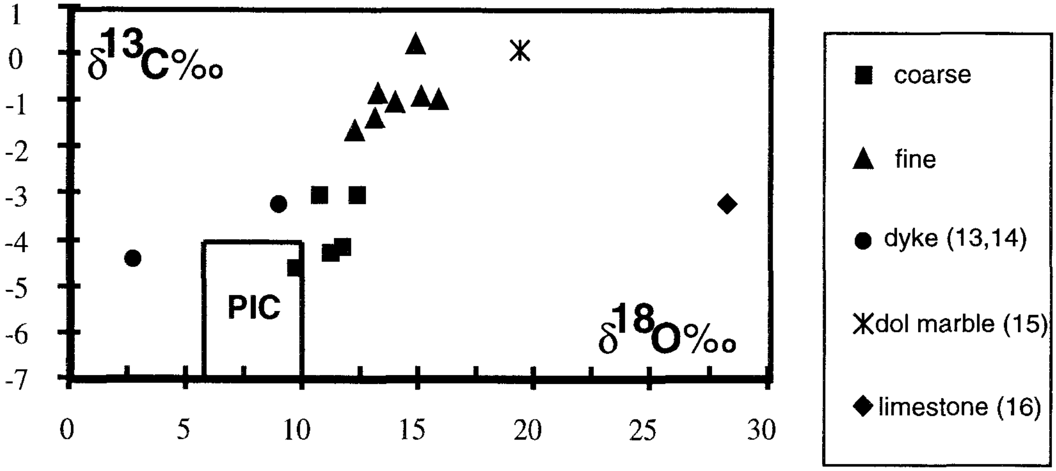

FIG. 2. Oxygen–carbon isotope plot of new data presented in this paper. PIC, Primary Igneous Carbonatite box. The plot shows the progressive increase in $\delta^{18}O$ and $\delta^{13}C$ as the dolomite recrystallizes from the coarse-grained to fine-grained.

O and C isotope geochemistry

Coarse and fine-grained dolomite marbles

On Figure 2 are plotted the O and C isotope data given in Table 2. The dolomite from the coarse H8 dolomite marble clusters in or near the Primary Igneous Carbonatite (PIC) box (as constructed by Reid and Cooper, 1992), whereas dolomite from the fine H8 dolomite marble lies in a trail between the coarse dolomite and the field for limestone (including dolomite limestone). Our data are limited but show the same distribution as data for dolomite published by Liu Tiegeng in 1986 (Fig. 3). The fine-grained dolomite marble was formed by the granulation and recrystallization of the coarse-grained dolomite marble, which process was associated with the early mineralization (Wang *et al.*, 1994), and the accompanying isotope change has evidently been one of progressively more ^{18}O and ^{13}C formation in the dolomite (similar to trend F in Fig. 4). This is the opposite of the direction of change of ^{18}O and ^{13}C during post-depositional alteration (trend A, Fig. 4) for dolomite in limestones (Hall and Veizer, 1996).

This distribution is, however, the same as that for carbonatites in general (Deines, 1989) and more particularly for sovitic coarse-grained carbonatites (in or near the PIC box) and for later, usually fine-grained carbonatites towards heavier O and C (Reid and Cooper, 1992). The same distribution is found for sovitic (coarse-grained) and alvikitic (fine-grained) carbonatites in South Africa (Clarke *et al.*, 1994) and in East Africa (Fig. 4). This distribution has been interpreted as the carbonatite fractionation sequence at mole ratios $H_2O/CO_2 < 1$ (Nielsen and Buchardt, 1985; Knudsen and Buchardt, 1991).

Calcite marble dyke rocks

The two dyke rocks (13, 14) analysed do not come from the dyke swarm indicated on Fig. 1 but from sheets which cut slate that forms the roof of the main H8 dolomite marble. The possibility was considered that they might originally have been limestones interbedded with shale, although the evident micaceous reaction rims at the contacts indicated that metasomatism (fenitization) had occurred. Had they been limestones, the O and C isotope compositions should have placed them at high $\delta^{18}O$ and high $\delta^{13}C$

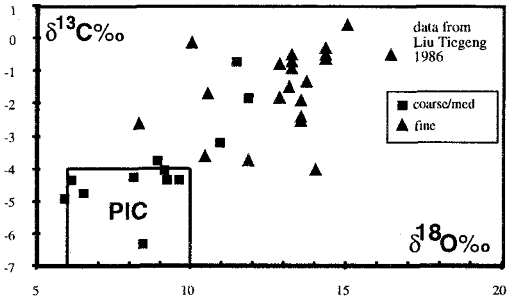

FIG. 3. Oxygen–carbon isotope plot of data reported by Liu Tiegeng (1986), confirming the progressive variation seen in Fig. 2.

TABLE 2. Bayan Obo dolomite and calcite marbles – selected major and trace element and isotope data

Sample/locality	1	2	3	4	5	6	7	8	9
field number	88/150	88/152	B 241	90/62	B 222	90/63	88/157	90/58	90/64
	c	c	c	c	c	f	f	f	f
SiO_2 %	1.17	2.06	2.72	2.04	24.26	0.37	4.16	0.38	0.44
$Fe_2O_3^t$ %	3.78	4.41	5.78	6.03	19.17	7.74	8.56	8.72	9.09
MnO %	0.56	0.78	0.78	0.82	1.12	1.22	0.93	1.35	1.30
MgO %	17.18	21.39	14.76	13.99	10.80	15.14	12.39	15.04	12.95
P_2O_5 %	3.25	2.88	2.38	4.20	0.12	0.24	0.18	0.07	0.52
Nb ppm	858	3824	473	73	333	40	579	68	611
Total *REE*	600 ppm	750 ppm	500 ppm	2250 ppm	3.5 wt %	2.5 wt %	7000 ppm	2.7 wt %	3.5 wt %
Sr ppm	4435	6242	3989	7771	1717	1992	3257	1681	1550
Ba ppm	438	98	117	961	10677	5498	532	385	204
$^{87}Sr/^{86}Sr$*	n.a.	0.703163	n.a.	0.702951	n.a.	0.703163	0.702989	n.a.	n.a.
$\delta^{18}O$ ‰$_{SMOW}$	11.03	9.60	11.57	10.54	12.20	15.71	14.72	13.09	14.97**
$\delta^{13}C$ ‰$_{PDB}$	−4.24	−4.56	−4.12	−2.99	−3.00	−0.92	0.28	−0.77	−0.87

Sample/locality	10	11	12	13	14	15	16	Veizer *et al.*
field number	88/117	88/148	88/147	88/142	88/141	90/65	Y8/230	1992
	f	f	f	edge dyke	mid-dyke	sed	sed	std dol
SiO_2 %	3.99	0.32	0.10	25.56	25.91	5.43	10.47	13.6
$Fe_2O_3^t$ %	14.58	19.86	19.74	5.60	8.53	0.18	0.41	1.6
MnO %	1.65	1.66	1.46	0.86	0.87	0.01	0.04	0.2
MgO %	12.39	12.45	11.64	10.87	8.29	19.60	1.40	15.8
P_2O_5 %	0.22	0.04	0.31	0.08	0.05	0.03	0.05	<0.1
Nb ppm	276	1452	3326	772	38	0.5	1	1
Total *REE*	4 wt.%	1.75 wt %	1.5 wt %	3.5 wt %	4.0 wt %	20 ppm	20 ppm	*c.* 25 ppm
Sr ppm	2685	1561	1617	894	2239	129	165	40
Ba ppm	674	6940	238	867	1262	34	117	128
$^{87}Sr/^{86}Sr$*	0.703576	n.a.	n.a.	0.706860	n.a.	0.726202	0.719919	>0.710
$\delta^{18}O$ ‰$_{SMOW}$	12.97	13.78	12.08	2.57	8.80	19.23	28.20	*c.* 25.0
$\delta^{13}C$ ‰$_{PDB}$	−1.34	−1.00	−1.59	−4.33	−3.20	0.17	−3.20	*c.* 0.0

c, coarse-grained; f, fine-grained; n.a., not analysed
* ± 0.000007; ** second sample of 9 gave $\delta^{18}O$ = 15.01, $\delta^{13}C$ = −0.87

values in Fig. 2. Although fine-grained, the sample from the middle of the dyke (14) plots near the coarse-grained dolomite, but the sample which comes from the edge of the dyke (13) has the unusually low $\delta^{18}O$ value of 2.6 per mil. It is possible that the low $\delta^{18}O$ arises from the convection, along the contact, of meteoric water in the adjacent slate driven by heat supplied from the dyke or from the Hercynian granite not far below.

Limestones

The two samples of undoubted Bayan Obo sediments (15 and 16 in Tables 1 and 2 and Fig. 1) plot separately from the others in Fig. 2 with higher $\delta^{18}O$ values. The dolomite in sample 15 lies in the field of limestones (Fig. 4) but with lower $\delta^{18}O$ values than for average dolomite limestone (* in Fig. 4) which suggests that the rock had undergone some post-depositional alteration that affected only the oxygen and not the carbon. Limestone sample 16 has the normal high $\delta^{18}O$ sedimentary value (+28.8) but a lower $\delta^{13}C$ per mil value of −3.2 (Fig. 2). This is most likely the result of local exchange with ground water of high organic content in an area marked by Drew and Meng (1990) with much minor thrusting.

Sr isotope geochemistry

All the coarse and fine-grained dolomite marbles of the main outcrop of H8 lie between the $^{87}Sr/^{86}Sr$ ratios of 0.702 and 0.705 as shown in Fig. 5*a* and *b*,

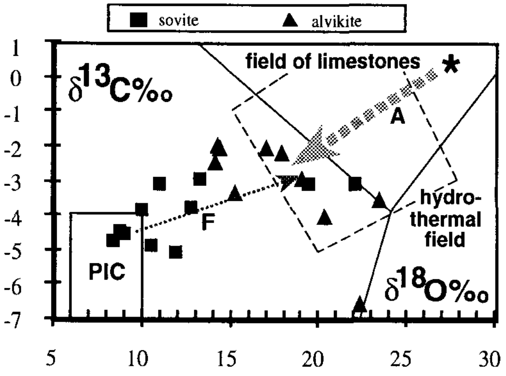

FIG. 4. Oxygen–carbon isotope plot of data from East and South African sovitic and alvikitic carbonatites (Clarke *et al.*, 1992; and unpublished Le Bas/Spiro database). F, fractionation trend of carbonatite magma from sovite to alvikite; some sovites are enriched in $\delta^{18}O$ as a result of hydrothermal alteration. A is trend of post-depositional alteration of dolomite, asterisk is average dolomite, and dashed box is field of dolomite formed by post-depositional alteration (Hall and Veizer, 1996).

including the strongly mineralized sample no. 10 (Table 2) and the six H8 samples taken near the ore bodies that are reported by Academia Sinica (1988, Table 7.35, p. 495). This leaves little doubt that the main outcrop of H8 dolomite marble has mantle Sr isotope values and that the mineralization process has not changed the ratio.

The calcite marble dyke (no. 13 , Table 2) has the slightly higher $^{87}Sr/^{86}Sr$ ratio of 0.706860 in keeping with the interpretation that this sample taken from the margin of the dyke interacted with fluids carrying the geochemical signature of the H9 shale.

The limestones taken from other outcrops originally mapped as H8 marble (Fig. 1) have much higher and typical sedimentary values $^{87}Sr/^{86}Sr$ ratios (15, 16 in Table 2 and Fig. 5*a*), which clearly distinguishes them from the main outcrop of H8 marble but makes them indistinguishable from other Proterozoic dolomite marbles, such as those described from Montana and Idaho by Hall and Veizer (1996).

Trace element geochemistry

Coarse and fine-grained dolomite marbles

The principal trace elements are given in Table 2 and representative samples with more complete data are plotted in Fig. 6*a*. The latter shows well the contrast between the dolomite/limestone group of carbonate rocks and the remainder. A full discussion on the trace element distribution of these rocks will not be entered into here, being reserved for another publication in which will be considered the much larger database of analyses of H8 marbles both in the main outcrop and in the many newly identified dykes. However a few relevant observations will be made which contribute to the aim of this paper.

The coarse-grained dolomite marbles have high P_2O_5 corresponding to the huge amounts of apatite visible in the hand specimen, while the fine-grained dolomite marbles have almost no apatite. The content of *REE*s is the reverse of that for P_2O_5, with some of the fine-grained dolomite marbles being so rich in *REE*s as to constitute economic deposits. The coarse-grained dolomite marbles have high Nb contents in keeping with the pyrochlore observed in many samples. The Nb content in the fine-grained dolomite marbles is more variable, sometimes as high but often less than in the coarse-grained dolomite marbles. Sr is high throughout while Ba is very variable.

The trace element content of the dolomite limestone and limestone contrasts strongly with that of the coarse and fine-grained H8 marbles (Fig. 6*a*), but is similar in most respects to Veizer's average dolomite limestone (Fig. 6*b*). The high Zr in the

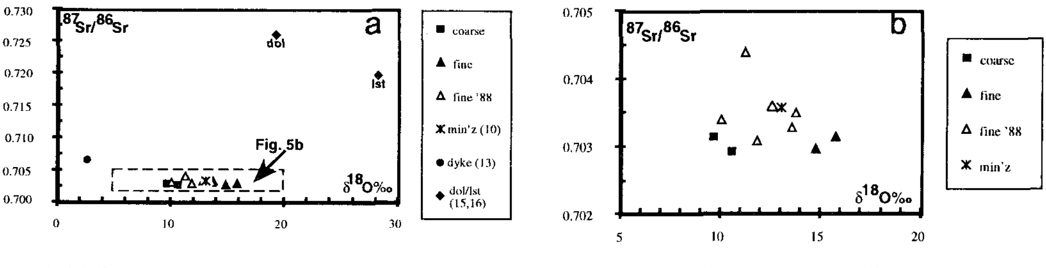

FIG. 5. (*a*) Oxygen–strontium isotope plot of new Bayan Obo data together with some reported by Academia Sinica (1988) – open triangles. Except for the dolomite limestone and limestone (dol/lst) and the dyke sample, all the dolomites plot in the range for mantle-sourced. (*b*) Enlargement of dashed box in (*a*) showing that both the coarse- and fine-grained and the mineralized dolomites have a similar range of $^{87}Sr/^{86}Sr$ ratios, indicating a common source.

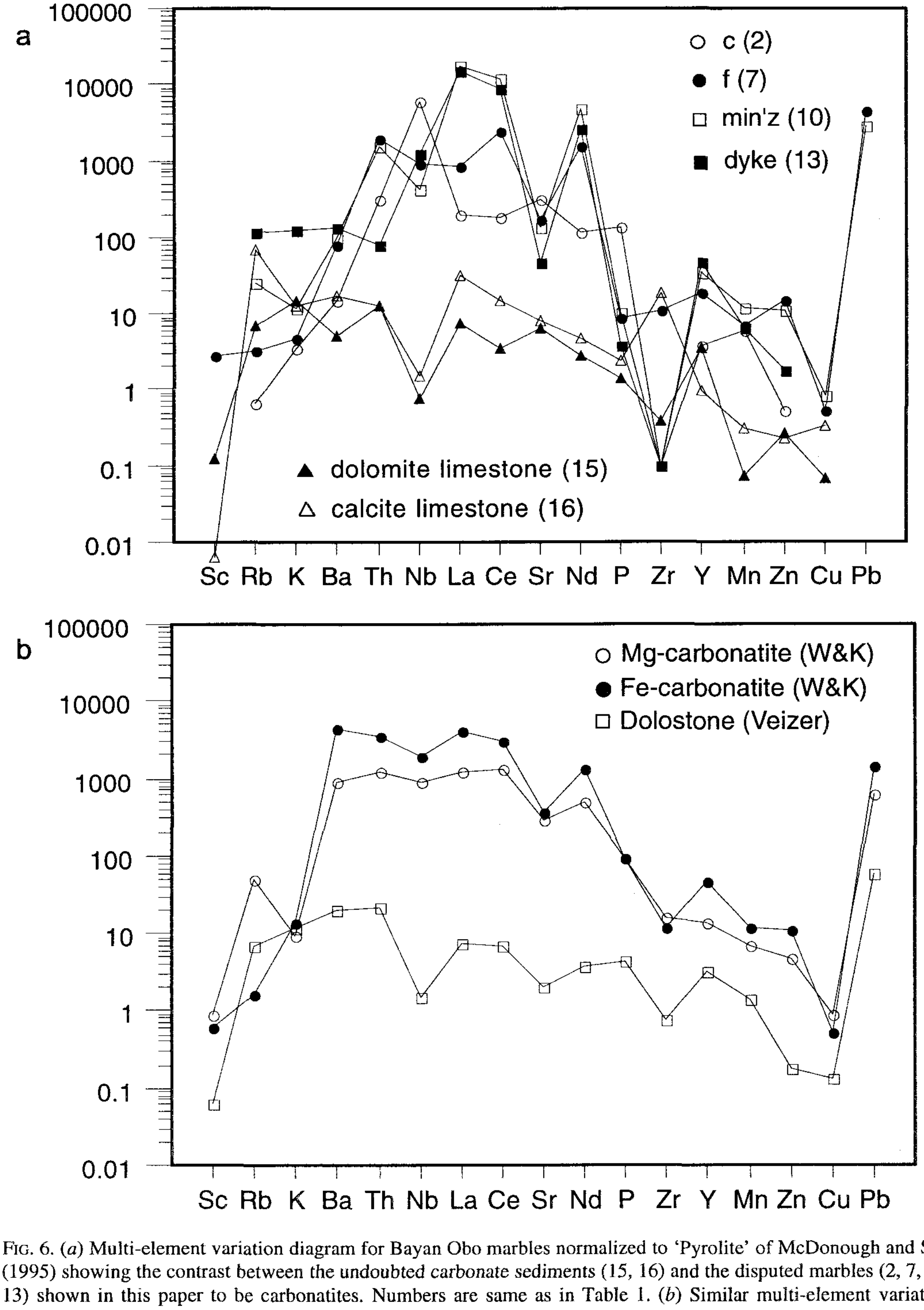

FIG. 6. (*a*) Multi-element variation diagram for Bayan Obo marbles normalized to 'Pyrolite' of McDonough and Sun (1995) showing the contrast between the undoubted carbonate sediments (15, 16) and the disputed marbles (2, 7, 10, 13) shown in this paper to be carbonatites. Numbers are same as in Table 1. (*b*) Similar multi-element variation diagram for average carbonatites (W&K, Woolley and Kempe, 1989) and average dolomite limestone (Veizer, 1990). Note the close similarity with (*a*) in the distribution patterns.

limestone may be taken to mean the presence of detrital zircon there.

The marble of the dyke rock and the mineralized H8 marble show considerable similarity although the former is a calcite marble and the latter a dolomite marble. The main difference is in the much higher content of Rb and K in the dyke rock, an effect of its marginal contamination by the adjacent slate. The similar and high *REE*, Th, and Y contents of both is interpreted to mean that the dyke has been affected by the same mineralization as that for the ore bodies, but comparing these data with those for the carbonatite dykes previously described (Le Bas *et al.*, 1992), it does not appear that the H8 coarse-grained dolomite marble described in this contribution can be considered as the dolomite limestone H8 rock type partially mineralized.

Discussion

Interpretation of the field relations of the dolomite marble at Bayan Obo presents problems. If fossil remains were present in the main outcrop of the H8 dolomite marble, then a sedimentary origin would be evident, but no substantiated evidence has been presented. Sedimentary structures could be variously interpreted because sedimentation processes within magmatic bodies are not uncommon.

The geochemical evidence is drawn from samples collected across the whole length and breadth of the main outcrop of H8 dolomite marble, that being the only marble of disputed origin. The sedimentary origin of the other outcrops of H8 marbles further north that occur as tectonic slices within the thrust pile, is undisputed. All the samples of the coarse H8 dolomite marble examined usually show contents of apatite and magnetite of several per cent. However this is much higher than that known for any marble of sedimentary origin. Apatite is reported in some marbles, e.g. in the Grenville marble (Robinson and Chamberlain, 1984), and a detrital origin is possible; more likely is derivation from interstitial phosphatic material of organic origin in the original sediment, but such occurrences are rare in limestones, particularly in the Proterozoic when organic activity was small. Since carbonatites are characterized by high contents of apatite and magnetite, their abundance supports the case that the coarse H8 dolomite marble is a carbonatite.

The chemical composition of the coarse and the fine-grained dolomite marbles is very different from the Bayan Obo dolomite limestones. This might however be ascribed to the marbles of the main outcrop being limestones metasomatically altered by the mineralizing solutions related to the ore-bearing fluids which formed the ore deposit. Mixing calculations of the several possible components have not been determined, but preliminary estimates suggest that the bulk major and trace element compositions of the coarse-grained dolomite marble could not be obtained in this way, although it could for the fine-grained dolomite marble (see Fig. 6*b*).

Of the numerous exposures examined within the main outcrop of the dolomite marble and the many analysed, not one resembled the dolomite limestone or limestone collected further north and, apart from the dykes, at none of the exposures examined north of the Kuanggou Fault were marbles seen resembling those of the main outcrop. Except for the dykes, the carbonate rocks north and south of the Kuanggou Fault are quite distinct, and the continuing use by authors of the symbol H8 for both causes confusion.

To the north of the coarse-grained dolomite marble is a sharp contact with quartzite, and in the quartzite next to the contact are randomly oriented needles of blue sodic amphibole. This is unusual for limestone-quartzite contacts but is common at the intrusive contacts of sovitic carbonatites (Woolley, 1969), and indeed occurs at the contacts of the carbonatites in the Bayan Obo dyke swarm indicated on Fig. 1. Such sodic metasomatism, or fenitization, is one of the characteristics of carbonatite intrusion.

At intervals along the whole length of the main outcrop of the dolomite marble is the formation of pure K-feldspar rock in the H9 slate which caps the marble. Like the sodic fenitization described above, such potassic metasomatism or fenitization is also well known around sovitic and dolomitic carbonatites, particularly in the roof zone. It has been variously described as feldspar-rock fenite (Baldock, 1973) or orthoclasite fenite (Sutherland, 1965) and is another characteristic feature of carbonatite intrusion.

The O, C and Sr isotope analyses provide better evidence for distinguishing a sedimentary from an igneous origin for the marbles at Bayan Obo. The marbles north of the Kuanggou Fault have isotopic compositions typical of sedimentary rocks, and they seem to persist with dolomitization; the isotopic composition of the coarse and fine-grained dolomite marbles are quite different. The earliest carbonate phase here is the coarse-grained dolomite marble (Chao *et al.*, 1992), and this has an isotopic composition indistinguishable from that for common carbonatite. To create such an isotopic composition by reaction with mineralizing fluids would require the fluid to be mantle-derived and not epigenetic as proposed by Chao *et al.* (1993). It might also be noted that the isotope changes from coarse to fine-grained are the same as those observed with fractionation of carbonatites (Clarke *et al.*, 1994).

The suggestion that the monazite mineralization could have caused the changes observed in the isotopes (Figs 2–4) is not supported by the sequence of changes described above. Had the dolomite marble began as sedimentary limestone, the first change would have had to be one of no mineralization (except possibly dolomitization) but a major reduction of $\delta^{18}O$, $\delta^{13}C$ and the $^{87}Sr/^{86}Sr$ ratio to mantle values. The next stage would have been the formation of the fine-grained dolomite marble with its *REE* mineralization, achieved with slight increase in $\delta^{18}O$ and $\delta^{13}C$ but none in the Sr ratio, the result being comparable to that known for later stage carbonatites elsewhere (e.g. Reid and Cooper, 1992). This would have been followed by the main ore mineralization (hosted by the fine-grained dolomite marble) with no further marked isotope changes. However had this happened, the major isotope changes would not correspond to the main mineralization events, as would be expected.

Thus there appears to be compelling evidence that the main outcrop of dolomite marble *began* as a rock of mantle origin and not that the mantle features were superimposed. What were superimposed were fluids which recrystallized the coarse-grained dolomite marble to the finer grained marble and that this was followed by a mainly monazite mineralization along the subparallel fractures through the fine-grained marble.

It remains unclear whether the similarities between the fine-grained dolomite marble and alvikitic carbonatite (cf. Figs 2 and 3 with Fig. 4) point to genetic similarities or not.

It is concluded that the coarse-grained dolomite marble of the main outcrop at Bayan Obo is a carbonatite intrusion subsequently recrystallized, and that the Fe-Nb-*REE* massive mineralization is not epigenetic but related to the carbonatite. The question of whether the dolomite in the coarse-grained and fine-grained dolomite marbles is primary or secondary remains unanswered. Trace elements give no useful evidence on this, here or in other carbonatites. But it may be observed that the Bayan Obo dykes are calcite carbonatites and they show few signs of dolomitization, yet some of them occur close to the H8 dolomite marble. The inference must be that there has been no dolomitization and that the dolomite is primary.

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