

Fluid inclusion study of carbonatite dykes/veins and ore-hosted dolostone at the Bayan Obo ore deposit

QIN ChaoJian¹, QIU YuZhuo^{1,2*}, ZHOU GuoFu¹, WANG ZhongGang¹, ZHANG TaiRong³ and XIAO GuoWang³

1. State Key Lab of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002

2. Key Lab of Dynamics of Mineralization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640

3. Bayan Obo Iron Mine, Baotou Steel-Iron Group, Baotou 014080

Received: 2006-07-2 Accepted: 2006-11-6

Qin CJ, Qiu YZ, Zhou GF, Wang ZG, Zhang TR and Xiao GW. 2007. Fluid inclusion study of carbonatite dykes/veins and ore-hosted dolostone at the Bayan Obo ore deposit. *Acta Petrologica Sinica*, 23(1):161–168

Abstract Fluid inclusion study has been carried out for the carbonatite dykes/veins and the ore-hosted dolostone of the Bayan Obo superlarge REE-Fe-Nb deposit in order to provide the evidence and constraint for their origin. Based on the detailed geological observation and mineralogical investigation, the heating and cooling stage and laser Raman spectroscopy were mainly used for the laboratory work of this study. Following results have been obtained: (1) The discovery of melt and melt-fluid inclusions from carbonatite dykes/veins in the Dulahara and Jianshan Mountains, combined with the fine-grained (aplitic) texture of rocks, as well as the types and features of fluid inclusions such as CO₂ enrichment, higher homogenization temperature, provides a direct evidence for the magmatic origin of these dykes/veins. (2) The carbonatite dykes/veins distributed in two regions, nearby the axis of the Kuangou anticline and in the east to Bayan Obo town, mainly show coarse-grained texture. No melt inclusion was found, and the fluid inclusions possess features of less CO₂, lower homogenization temperature and higher salinity. They are tentatively identified as veins formed by some carbonate-rich hydrothermal solution. (3) Bedding carbonate layers/lens within the hanging wall and foot wall of ore-hosted dolostone, previously recognized as of magmatic origin, mainly composed by dolomite. The existence of single phase pure aqueous inclusions with very low homogenization temperature indicates their sedimentary origin. (4) The ore-hosted dolostone possesses apparent bedding and laminated structures. No melt inclusion was found, but, both single phase pure aqueous inclusions and CO₂ bearing multi-phase fluid inclusions coexisted in dolostones. In the direction towards ore-bodies, the homogenization temperature and CO₂ contents of fluid inclusion show an increasing tendency. It indicates the sedimentary origin of dolostone superimposed by late fluid metasomatism.

Key words Fluid inclusion, Carbonatite dyke, Ore-hosted dolostone, Origin, Bayan Obo deposit

1 Introduction

The Bayan Obo Fe-Nb-REE deposit is the largest known REE deposit in the world, and abundant explorations and studies have been carried out on it (Institute of Geochemistry, 1988; Bai *et al.*, 1996; Zhang *et al.*, 2003). However, its origin is still in argument within investigators. There have been three major categories of hypotheses: (1) Sedex syngenetic mineralization (Yang and Drew, 1994; Tu, 1998); (2) hydrothermal metasomatic epigenetic mineralization (Wang *et al.*, 1973; Chao *et al.*, 1992); and (3) magmatic carbonatitic mineralization (Li, 1971; Bai *et al.*, 1996; Le Bas *et al.*, 1992, 1997). The focus of argument is the origin of ore-hosted dolostone (H8, or H6-8).

About two-score dykes/veins and layers/lens of carbonate composition were found in the ore district, previously all recognized as magmatic carbonatite (Tao *et al.*, 1998). And the existence of carbonatite dykes was taken by some researchers as a direct evidence for the magmatic origin of ore-hosted dolostone (Le Bas *et al.*, 1992, 1997). Moreover, some of them were described as branches of the huge carbonatite intrusive body, i.e. the ore-hosted dolostone (Li, 1971).

Many typical carbonatites around the world have been studied. Many kinds of fluid inclusions as well as some melt inclusions, fluid-melt inclusions were found in those carbonatites, and the typical inclusions were taken as the evidence of the origin, formation and evolution of carbonatite magmas (Nesbitt and Kelly, 1977; Samson *et al.*, 1995). As

* Corresponding author: E-Mail: qiuyuzhuo@gig.ac.cn

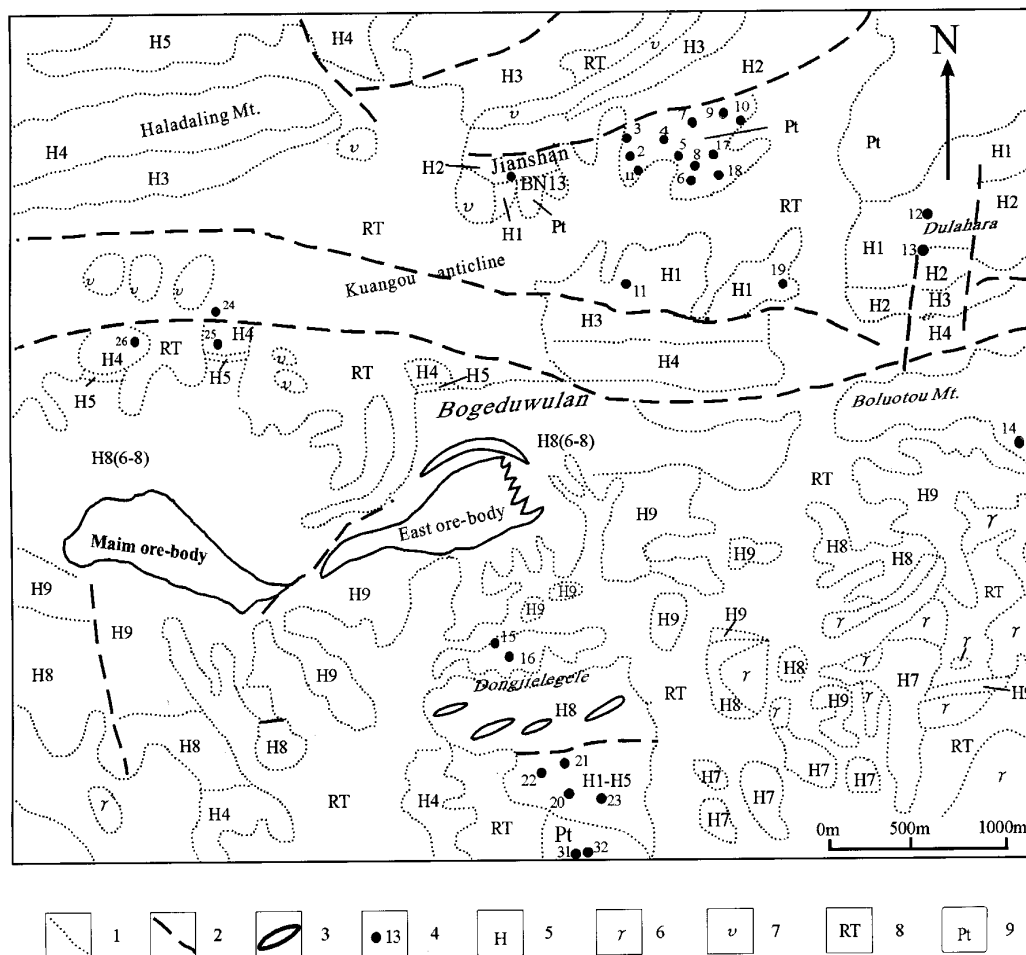


Fig. 1 Geological map of the main part of the Bayan Obo deposit and sampling place (modified from Tao *et al.*, 1998)
1-stratum borderline; 2-fault; 3-iron ore body; 4-carbonatite vein/dyke; 5-stratum of Bayan Obo Group; 6-granite; 7-gabbro and gabbro - diorite; 8-alluvium; 9-Sertengshan Group

for the Bayan Obo Ore deposit, many fluid inclusion studies have been done on the iron ores, ore-hosted dolostone and carbonatite dyke/veins (Institute of Geochemistry, 1988; Xie *et al.*, 1995; Smith *et al.*, 2000; Qin *et al.*, 2001, 2002; Fan *et al.*, 2002, 2003; Ni *et al.*, 2002; 2003). In this paper, we present mainly the results of fluid inclusion studies on both carbonate dykes/veins and ore-hosted dolostone. It provides the constraint to their origin, as well as for the understanding of mineralization in the deposit.

2 Geological outline

Tectonically, the Bayan Obo ore deposit is located at the middle section of northern margin of North China Craton. During middle Proterozoic, there was a marginal rift basin nearly E-W striking. A set of clastic and carbonate rock series of sedimentary or Sedex origin were deposited in the basin, i. e. the Bayan Obo Group. The basement of the basin consists of mainly the gneisses of Paleoproterozoic Sertengshan Group (previously called the

Wutai Group). The rocks of Bayan Obo Group have only undergone low degree metamorphism. From bottom to upper part in ore district, i. e. from H1 to H9, the lithology is conglomerate, quartzite, slate, quartzite, slate, carbonate rock and slate. The H8 (or H6-8) mainly composed by carbonate rocks is the host rock layer of Fe-Nb-REE ore-bodies as well as the REE ores (Institute of Geochemistry, 1988).

In the ore district, the Kuangou anticline in the north and the southern syncline are major structural units with a Kuangou deep fault along the axis of the anticline. They all are E-W striking with a length about 18km. Fig. 1 shows the geology of the eastern part of deposit. The main ore-body and east ore-body are located in the northern limb of the syncline, while the Dongjielegele small bodies in the southern one. Sixteen ore-bodies occur in the western section of the deposit hosted in both limbs of the syncline. A huge late Pleozoic granite botholith intruded in the eastern and southern parts of ore district, had been recognized as the source of late stage superimposed hydrothermal metasomatism (Institute of Geochemistry, 1988). In the eastern contact zone between granite and H8 carbonate

rocks, there are magnesium skarns with weak mineralization. Besides granite, about 40 gabbro and gabbro-diorite rock bodies in small size intruded in different part of the ore district. They are dated as co-magmatic products with granite and intruded by the latter.

Carbonatite dykes/veins were discovered in 1960s mainly in the eastern section of the ore district (see Fig. 1). Their sizes are rather small compared with huge ore-bodies of the deposit. Most of them cut the schistosity of gneisses swarmed in the axis of Kuangou anticline and two veins in the east of town, or cut the bedding of quartzite and conglomerate in the Dulahara and Jianshan mountains. In addition, there are several bedding layers/lens with carbonate composition distributed in both hanging wall and foot wall of the ore-hosted dolostone. They are also recognized as the carbonatite dykes/veins by Tao *et al.* (1998), but, they may be the intercalated beds of carbonate composition in quartzite and slate strata as shown in Institute of Geochemistry (1988) and identified by this work.

3 Sampling and analytical techniques

Samples examined in this study were taken from orebodies, ore-hosted dolostone and some of the carbonatites as well as layers/lens of carbonate composition at the Bayan Obo ore area. Doubly polished sections (about 200- to 300-um-thick) were prepared for fluid inclusion optical examination and microthermometric analysis. Heating and cooling experiments were carried out using a Linkam THMS/THMSG 600 heating/

cooling stage at the Department of Earth Science, Nanjing University and the Institute of Geochemistry, Chinese Academy of Sciences. The stage was calibrated with pure CO₂ and pure H₂ O (0 and 374.1℃) synthetic fluid inclusion standards supplied by FLUID INC. Laser Raman spectroscopy was used to check reference REE minerals and identify daughter minerals in fluid inclusions. Data were obtained using a Renishaw Raman MKI-1000 system equipped with a CCD detector and an Ar ion laser at the Institute of Geochemistry, Chinese Academy of Sciences. The laser beam with a wavelength of 514.5 nm was focused on reference REE minerals and daughter mineral crystals in fluid inclusions.

4 Characteristics of fluid inclusions in the carbonatite dykes/veins and the layers/lens of carbonate composition

According to geological occurrence, the carbonate rock bodies in ore area can be classified into two types; the stratum-cutting dykes/veins and the bedding layers/lens. Based on their spatial distribution, they can be grouped as following four districts, three dykes/veins groups; (1) around Dulahara and Jianshan mountains; (2) nearby the axis of the Kuangou anticline; (3) east to the Bayan Obo town; and (4) one layers/lens group intercalated within the hanging and the foot wall rocks of ore-hosted dolostone. The fluid inclusion characteristics and microthermometry of carbonatite dykes/veins and carbonate layers/lens are summarized in Table 1.

Table 1 Fluid inclusion characteristics and microthermometry of carbonatite dyke/veins and carbonate layers/lens

Carbonatites dykes/veins and carbonate layers/lens	Sample No.	Type of inclusions	Size (μm)	V/V + L (%)	Tm-CO ₂ (℃)	Tm-ice (℃)	Tm-clath (℃)	Th-CO ₂ (℃)	Th-total (℃)	Salinity (wt% NaCl)
carbonatite dykes in Dulahara and Jianshan mountains	13, BN13,	V + L aqueous inclusion	3 ~ 10	20 ~ 60		-5.2 ~ -18.1			290 ~ 450	8.0 ~ 21.0
		CO ₂ -rich inclusion	4 ~ 12	40 ~ 80	-56.8 ~ -57.2		2.9 ~ 8.4	22.1 ~ 27.2	265 ~ 420	3.2 ~ 12.0
carbonatite veins nearby the axis of the Kuangou anticline	8, 10, 17, 18	V + L aqueous inclusion	2 ~ 10	5 ~ 20		-8.7 ~ -10.6			125 ~ 290	13.5 ~ 14.6
		CO ₂ -bearing inclusion	2 ~ 10	10 ~ 20	-56.4 ~ -57.0		8.0 ~ 9.8	26.0 ~ 29.8	260 ~ 310	0.4 ~ 3.8
carbonatite veins in the east to Bayan Obo town	31, 32	V + L aqueous inclusion	3 ~ 8	5 ~ 40		-1.8 ~ -14.3			170 ~ 300	3.0 ~ 18.0
		CO ₂ -bearing inclusion	4 ~ 10	20 ~ 40	-57.2 ~ -57.8		8.8 ~ 9.7	26.8 ~ 30.1	265 ~ 296	0.6 ~ 2.4
layers/lens within the hanging and foot walls of iron ore-bodies	20, 23, 26	aqueous inclusion	1 ~ 4	<2					<80	

Tm-CO₂ : melting temperature of CO₂ ; Tm-ice : melting temperature of ice ; Tm-clath : melting temperature of gas-hydrate ; Th-CO₂ : homogenization temperature of CO₂ ; Th-total : Total homogenization temperature.

(1) Dykes/veins around Dulahara and Jianshan Mountains
Wall rocks include mainly the H1 quartz conglomerate and H2 quartzite of Bayan Obo Group, as well as the gneiss of the Sertengshan Group. Wall rock alterations including fenitization, aegirization, riebeckitization and albitization were strongly developed. There are strong aegirization in the xenoliths within dykes/veins. In the main part of the dykes/veins, calcite is the most abundant mineral in fine-grained with minor riebeckite, barite and bastnaesite. Many types of inclusions were found, i. e. solid, melt, melt-fluid, gaseous, V + L aqueous and CO₂ rich high salinity fluid inclusions (Fig. 2). The further identification and heating experiment for the melt and melt-fluid inclusions have not been conducted due to the difficulty and the limitation in the laboratory equipment. The gaseous inclusions, V + L

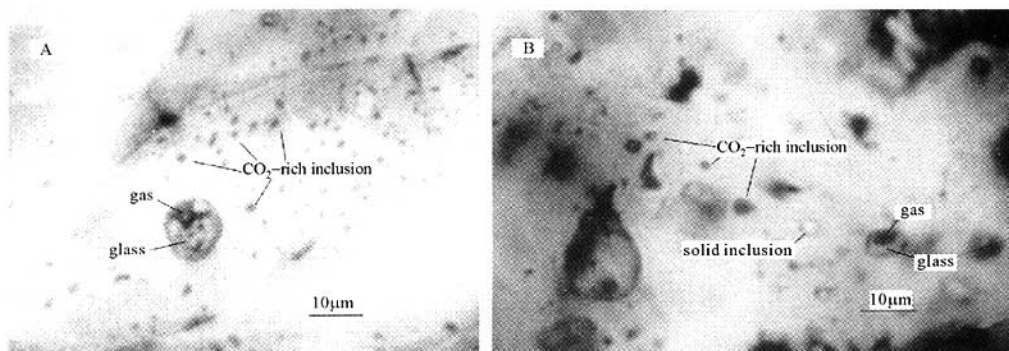


Fig. 2 Melt-fluid inclusions in carbonatite dykes at Dulahara and Jianshan mountains

A-coexistence of a melt inclusion and CO₂-rich inclusions; B-coexistence of a melt inclusion, CO₂-rich inclusions and solid inclusions

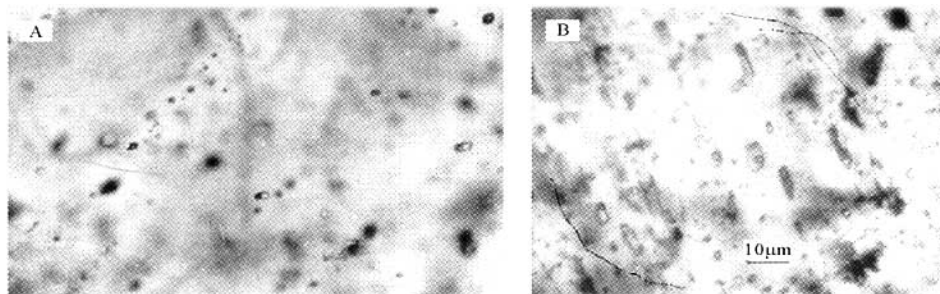


Fig. 3 Fluid inclusions in carbonatite veins at Kuangou anticline

A-fluid inclusions in carbonate mineral; B-fluid inclusions in barite mineral

aqueous inclusions and CO₂ rich high salinity fluid inclusions usually show regular shapes as rhombohedral and rectangle negative crystal forms in isolated distribution. For the V + L aqueous inclusions, the V/V + L ratio ranges from 20 to 60%, the homogenisation temperature (Th) 290 ~ 450°C, Tm-ice -5.2 ~ -18.1°C, salinity 8 ~ 21 wt% NaCl, and density 0.63 ~ 0.93 g/cm³. For the CO₂ - rich high salinity fluid inclusions, the content of CO₂ ranges 40 ~ 80 vol%, with Tm-CO₂ -56.8 ~ -57.2°C, Tm-clathrate +2.9 ~ +8.4°C and Th-CO₂ 22.1 ~ 27.2°C. Homogenisation temperature of CO₂ - rich inclusions ranges from 265 to 420°C. In the marginal part, the CO₂-bearing and V + L inclusions are predominate, with Th 330 ~ 220°C, salinity 4 ~ 12 wt% NaCl, and density 0.8 ~ 0.95 g/cm³. In the alteration zones, mainly V + L inclusions, 90 ~ 230°C with low salinity (< 6 wt% NaCl). The inclusions with higher salinity are mainly irregular shaped, distributed along fracture with the features of late stage alteration. The assemblage of multi-types of fluid inclusions, especially the existence of melt inclusions and melt-fluid inclusions provide the direct evidence for their magmatic origin, and also indicate the immiscibility between melt and fluid phases. It is exceptional and puzzled that we have found no melt inclusion in several samples of typical carbonatites from Mountain Pass, Lueshe and Araxa.

(2) Dykes/veins nearby the axis of the Kuangou anticline

The wall rocks are the gneisses of Sertengshan Group, developed the riebeckitization, fenitization and phlogopitization. Major minerals include calcite and dolomite, with minor bastnaesite, barite, magnetite, quartz and phlogopite. As shown in Fig. 3, fluid inclusions are abundant, and mainly are V + L

aqueous inclusions with rather regular shapes as rhombohedral, prismatic and tabular, developed in swarm. Most of them are very small, 2 ~ 8 µm with V/V + L ratio 10 ~ 20%, and melting temperature of ice -8.7 ~ -10.6°C, Th 125 ~ 290°C, mainly 160 ~ 200°C, salinity 13.5 ~ 14.6 wt% NaCl, and density 0.98 ~ 1.0 g/cm³. There are a few liquid CO₂-bearing aqueous inclusions with Tm-CO₂ -56.4 ~ -57.0°C, Tm-clathrate +8.0 ~ +9.8°C, Th-CO₂ +26.0 ~ +29.8°C, and total homogenisation temperature 260 ~ 310°C. Ni *et al.* (2002) found some daughter crystal-rich inclusions recognized as the salt-melt inclusions. The features of low Th, high salinity and density, as well as the shapes and distribution, indicate that they might be the products of crystallization of carbonate-rich solutions in fractures.

(3) Dykes/veins in the east to Bayan Obo town

Phlogopitization is common in the marginal zones of veins and in wall rocks, the gneisses of Sertengshan Group. Calcite is the major mineral, and there are minor apatite, bastnaesite, magnetite and phlogopite. Fluid inclusions are developed in uneven distribution. They are mainly V + L aqueous inclusions with V/V + L ratio 5 ~ 10%, a few up to 20 ~ 40%; and the size 3 ~ 8 µm (Fig. 4). The Th of V + L aqueous inclusions determined show three ranges: 300 ~ 260°C, 240 ~ 210°C and 210 ~ 170°C with salinities 10 ~ 18, 5 ~ 15 and 3 ~ 9 wt% NaCl, respectively. Some CO₂-bearing aqueous inclusions were found in samples. These inclusions are marked with Tm-CO₂ -57.2 ~ -57.8°C, Tm-clathrate +8.8 ~ +9.7°C, Th-CO₂ +26.8 ~ +30.1°C, and total homogenisation temperature 265 ~ 296°C. The shapes of fluid inclusions change from the negative crystal

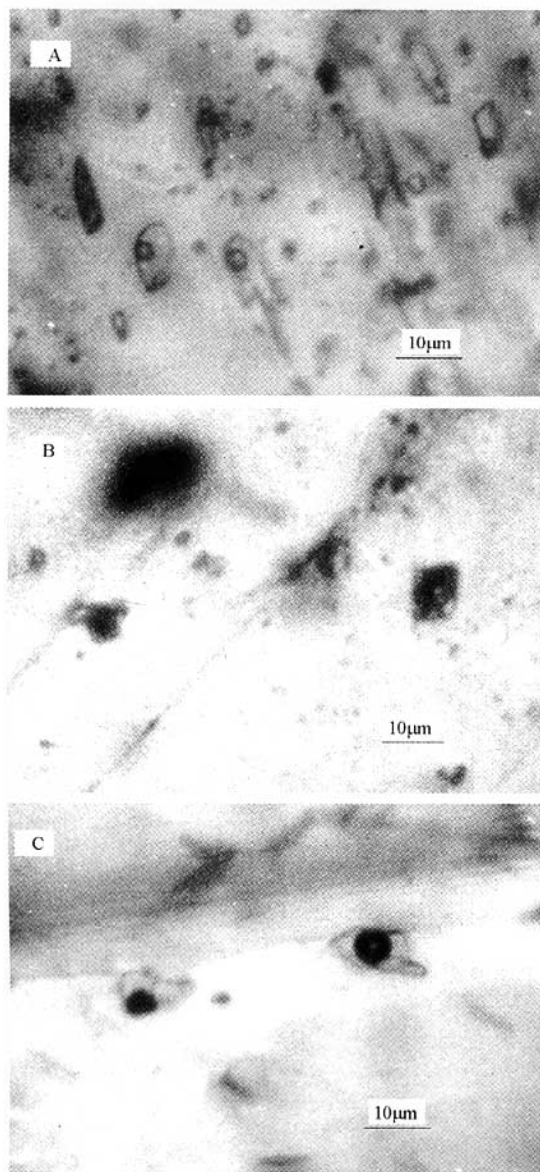


Fig.4 Fluid inclusions in carbonate veins in the east to Bayan Obo town

A-fluid inclusions; B-multi-daughter CO₂ inclusions; C-organic inclusions

forms of daughter crystal-bearing ones to the irregular ones of late stage. F/Cl ratio in fluid is 0.67 and lower than those of group (1) and (2). The low Th and salinity of fluid inclusions indicate the origin of metasomatism and alteration of late stage hydrothermal solutions with carbonate-rich and CO₂-poor features.

(4) layers/lens within the hanging and the foot wall rocks of ore-hosted dolostone.

There are many carbonate layers and lens in the ore district, recognized by some investigators as of magmatic origin, even described as the branches of huge so-called carbonatite intrusive

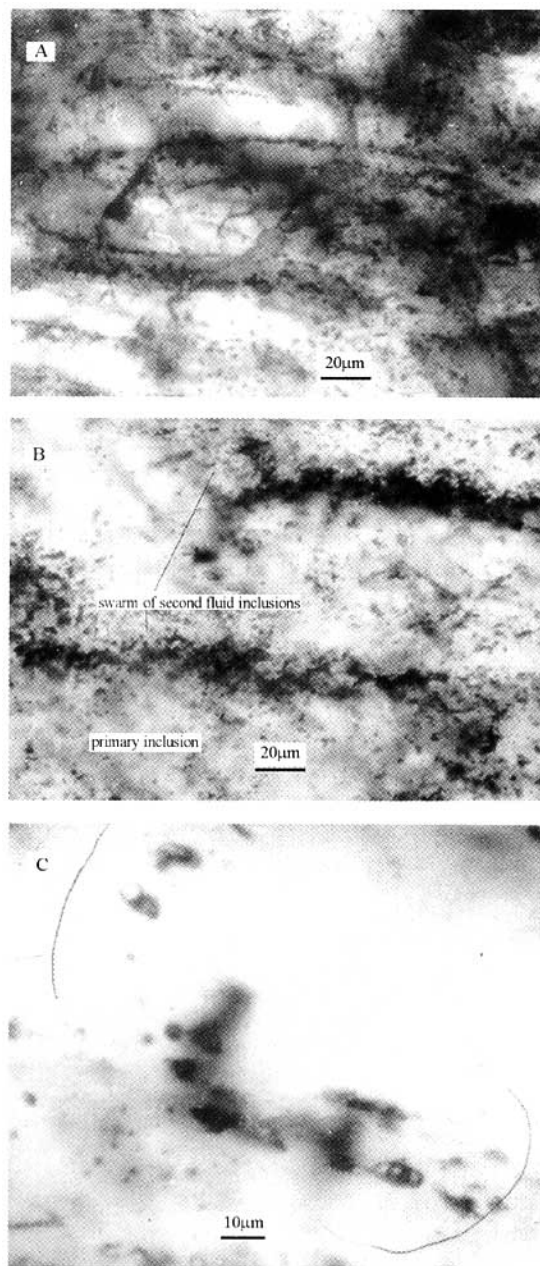


Fig.5 Fluid inclusions in H8 dolostone distant from the ore-bodies

A-fine secondary fluid inclusions in dolomite; B-primary and hydrothermal metasomatic origin inclusions in dolomite; C-CO₂-rich inclusions in apatite

(i. e. the ore-hosted dolostone). They mainly consist of dolomite, in a few cases, of calcite, with minor magnetite, apatite etc. Fluid inclusions are not developed, mainly the single phase pure aqueous inclusions with minor V + L inclusions, V/V + L ratio lower than 2%, Th of these inclusions mostly lower

Table 2 Fluid inclusion characteristics and microthermometry of ore-hosted dolostone

Domain of dolostone	Host-minerals	Type of inclusions	Size (μm)	V/V + L (%)	Tm- CO_2 ($^{\circ}\text{C}$)	Tm-ice ($^{\circ}\text{C}$)	Tm-clath ($^{\circ}\text{C}$)	Th- CO_2 ($^{\circ}\text{C}$)	Th-total ($^{\circ}\text{C}$)	Salinity (wt% NaCl)
distant from iron ore-bodies	dolomite	aqueous inclusion	< 5	< 5		-8.5 ~ -12.5			80 ~ 130	12.3 ~ 16.4
nearly the iron ore-bodies	dolomite	V + L aqueous inclusion	5 ~ 10	20 ~ 30		-3.8 ~ -13.4			240 ~ 290	6.1 ~ 17.3
		CO_2 -bearing inclusion	5 ~ 13	25 ~ 45	-57.2 ~ -58.8		5.0 ~ 9.0	16.0 ~ 25.8	300 ~ 350	2.0 ~ 9.1
	disseminated flourite	V + L aqueous inclusion	5 ~ 25	5 ~ 10		-13.3 ~ -15.4			130 ~ 245	17.2 ~ 19.0
within the iron ore-bodies	grained flourite	$\text{CO}_2 \pm \text{H}_2\text{O} \pm \text{carbonate}$ inclusion	5 ~ 20	70 ~ 100	-56.8 ~ -57.0			15.2 ~ 27.4	324 ~ 350	
	clean dolomite	aqueous inclusion	1 ~ 5	< 5		-11.4			85 ~ 155	15.4
	unclean dolomite	$\text{CO}_2 \pm \text{H}_2\text{O}$ inclusion	1 ~ 8	40 ~ 100	-57.8 ~ -59.2		5.6 ~ 7.6	12.0 ~ 22.6	310 ~ 325	4.6 ~ 8.0
		V + L aqueous inclusion		5 ~ 30		-1.6 ~ -13.2			160 ~ 420	2.8 ~ 17.1

Notes same as Table 1.

than 80 $^{\circ}\text{C}$. According to Raman probe examination, no CO_2 was found, but some dark substance, possibly being organic matter from sedimentary processes. They should be of sedimentary origin based on their geological occurrence, type and assemblage of fluid inclusions as well as low Th.

5 Characteristics of fluid inclusions in the ore-hosted dolostone

The ore-hosted dolostone can be spacially divided into three domains: (1) distant from iron ore-bodies, (2) nearby the iron ore-bodies, and (3) within the iron ore-bodies. The fluid inclusion characteristics and microthermometry of ore-hosted dolostone are summarized in Table 2.

(1) Distant dolostone. Fluid inclusions are commonly found and they mainly belong to the aqueous inclusion with minor V + L aqueous inclusions (Fig. 5). The size of them is small, less than 5 μm , with V/V + L ratio less than 5%. Most of them are hard to be identified for their phases. They are rounded or elliptic, clustering along planes and lines. The homogenisation temperature of V + L inclusions ranges from 80 to 130 $^{\circ}\text{C}$ and melting temperature of ice -8.5 ~ -12.5 $^{\circ}\text{C}$. In apatite there are many CO_2 -bearing multi-phase fluid inclusions, with V/V + L ratio from 10 ~ 20% to 30 ~ 50%. In the direction towards iron ore bodies, we found that the Th and CO_2 contents of fluid inclusions show an increasing tendency. The shapes of fluid inclusions are irregular with neck down feature. Fine fluid inclusions distributed along fractures showing banding and schistose structures of dolostone. It indicates the sedimentary origin of dolostone superimposed by late fluid metasomatism and alteration.

(2) Nearby dolostone. Fluid inclusions are abundant, and the V + L aqueous inclusions and CO_2 bearing inclusions are predominated (Fig. 6).

The V + L aqueous inclusions are distributed densely, 5 ~ 10 μm in size, and the V/V + L ratio is about 20 ~ 30%. The Tm-ice ranges from -3.8 to -13.4 $^{\circ}\text{C}$ and the Th 240 ~ 290 $^{\circ}\text{C}$. The CO_2 -bearing aqueous inclusions inclusions show rather regular

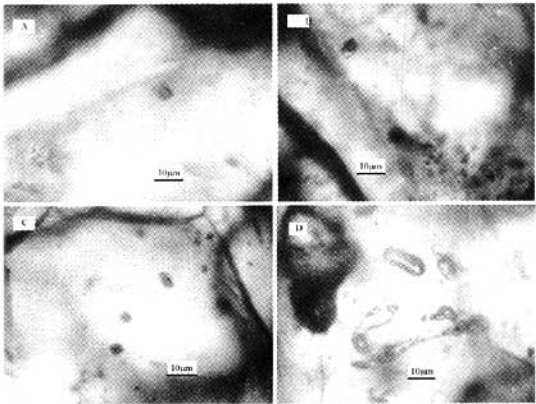


Fig. 6 Fluid inclusions in H8 dolostone nearby the ore-bodies

A-isolated CO_2 -rich inclusion in dolomite; B- CO_2 -rich inclusion with daughter in dolomite; C-coexistence of CO_2 -rich inclusion and vapor inclusion in dolomite; D-organic inclusions in flourite

shapes as rhombohedral, tabular, and elliptic. The contents of CO_2 are about 25 ~ 45vol%. The Tm-clathrate is in the range of +8.8 ~ +9.7 $^{\circ}\text{C}$, the salinity 2 ~ 9 wt% NaCl and Th- CO_2 + 26.8 ~ +30.1 $^{\circ}\text{C}$. The melting temperature of CO_2 ranges from -57.2 to -58.8 $^{\circ}\text{C}$, lower than the triple point of pure CO_2 . The Raman probe reveals CO_2 as the major composition with minor N_2 . Many CO_2 -bearing inclusions come to critical or sub-critical homogeneous in the range of 300 ~ 350 $^{\circ}\text{C}$.

(3) Within iron ore-bodies dolostone. Flourite commonly occurred in dolostone shown as two forms: the fine disseminated grains and the rather coarse-grains and veins. In the former, there are a few V + L inclusions with V/V + L ratios 5 ~ 10%, Th 130 ~ 245 $^{\circ}\text{C}$, salinity 17.2 ~ 19.0 wt% NaCl and density 1.03 ~ 1.07 g/cm³. In the latter, there are pure CO_2 inclusions, CO_2 -bearing three-phase inclusions, and daughter crystal-bearing CO_2 -rich inclusions with Tm- CO_2 -56.8 ~ -57.0 $^{\circ}\text{C}$, Th- CO_2 + 15.2 ~ +27.4 $^{\circ}\text{C}$. The total homogenisation temperature of CO_2 -

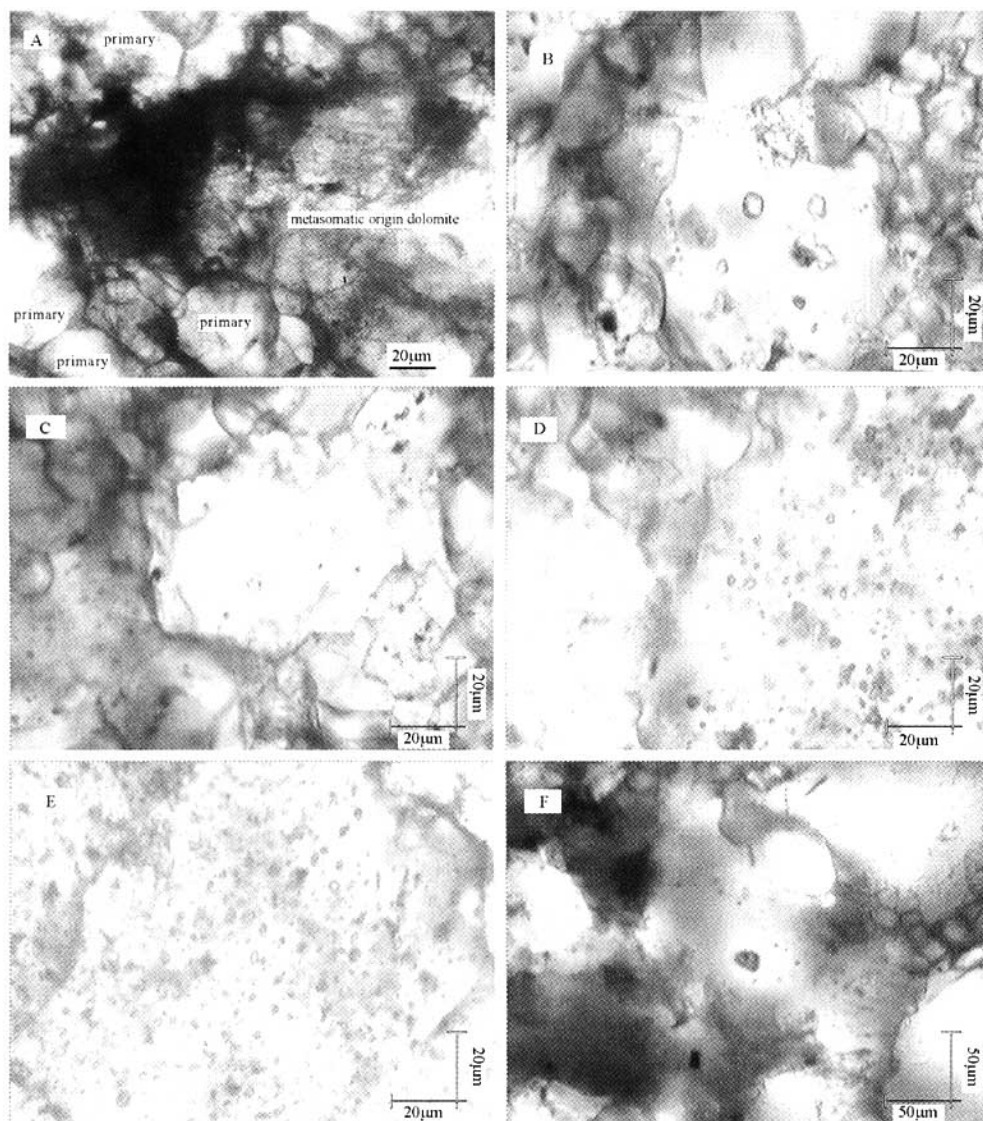


Fig. 7 Fluid inclusions in ore – bodies dolostone

A-hydrothermal metasomatism in dolomite; B-pure liquid inclusions in (comparatively) sedimentary-metamorphic dolomite; C-V-L inclusions in primary dolomite; D-swarm of CO_2 -rich inclusions in hydrothermal metasomatic origin dolomite; E-pure CO_2 inclusions in hydrothermal metasomatic origin dolomite; F-niobite identified by Laser Raman spectroscopy in hydrothermal metasomatic origin dolomite

bearing is about $324 \sim 350^\circ\text{C}$. Raman probe examination revealed H_2O and CO_2 , and no other gas was found in these fluid inclusions. The daughter mineral may be REE carbonate according to its Raman spectrum, crystal form and optical features. There are disseminated magnetite and niobite in fluorite (Fig. 7-F).

Two types of dolomite have been identified. First type is rather clean with less inclusions, a few aqueous inclusions are found in this type of dolomite. The aqueous inclusions have the characteristics of size in $1 \sim 3\mu\text{m}$, a few in $4 \sim 5\mu\text{m}$, V/V + L ratio less than 5%, Tm-ice -11.4°C and Th $85 \sim 155^\circ\text{C}$. In

most of aqueous inclusions no CO_2 and other gases was found as confirmed by Raman probe. This type of dolomite may probably be the dolomite of sedimentary origin (Fig. 7-A, B, C).

Another type is of less transparency due to the existence of much more fluid inclusions. Most of inclusions are in size of $1 \sim 5\mu\text{m}$ with only single phase of pure CO_2 as Raman probe determined. There are minor inclusions with sizes of $6 \sim 8\mu\text{m}$, being CO_2 -bearing three-phase inclusions, partially with daughter crystals. CO_2 40 ~ 90vol%, Tm- CO_2 $-57.8 \sim -59.2^\circ\text{C}$, Tm-clathrate $+5.6 \sim +7.6^\circ\text{C}$, Th- CO_2 $+12.0 \sim +22.6^\circ\text{C}$, critical homogenization temperature $310 \sim 325^\circ\text{C}$,

salinity 6 wt% NaCl or so, and density 0.66 ~ 0.95 g/cm³. Additional are V + L inclusions with V/V + L ratios 5 ~ 30%, Th 160 ~ 420°C, and salinity 2.8 ~ 17.1 wt% NaCl. This type of dolomite is of hydrothermal metasomatic origin (Fig. 7-D, E). Therefore, it is certain that previous results of O, C, Sr and Nd isotopic analyses for bulk dolostone should contain contributions from both sedimentary and hydrothermal processes in various ratios.

6 Conclusions

On the basis of fluid inclusion study, combined with geological observation, it is confirmed that carbonatite dykes were developed in the Bayan Obo ore district. The typical are those distributed around Dulahara and Jianshan Mountains. They cut the bedding or schistosity of wall rocks and contain melt and melt-fluid inclusions. The carbonatite dykes/veins distributed nearby the axis of Kuangou Anticline and in the east to Bayan Obo town, are tentatively identified as hydrothermal veins, because there is no evidence for salt melt, and melt inclusion found. Based on geological occurrence, and the characteristics and changing regularity of fluid inclusions, the bedding carbonate layers and lens, as well as the ore-hosted dolostone, are all of sedimentary origin, superimposed by late stage hydrothermal metasomatism in various degrees.

Acknowledgments This study is supported by China NSF 40473026. The early stage laboratory work of this study was carried out and supervised by professors LI Yin-Qing (Institute of Mineral Resources, Chinese Academy of Geological Sciences) and NI Pei (State Key Lab for Mineral Deposit Research, Nanjing University). The manuscript was considerably improved as a result of reviews by two anonymous reviewers.

References

- Bai G, Yuan ZX, Wu CY, Zhang ZQ, Zeng LX. 1996. Demonstration on the Geological Features and Genesis of the Bayan Obo Ore Deposit. Beijing: Geological Publishing House, 107p (in Chinese with English abstract)
- Chao ECT, Back JM, Minkin JA, Ren YC. 1992. Host-rock controlled epigenetic, hydrothermal metasomatic origin of the Bayan Obo REE-Fe-Nb ore deposit, Inner Mongolia, P. R. C. Applied Geochemistry, 7: 443 - 458
- Fan HR, Xie YH, Wang KY. 2002. Fluid inclusion study on the skarn section in the eastern contact zone of the Bayan Obo REE-Nb-Fe deposit. Mineral Deposits, 21(supp): 808 - 811 (in Chinese with English abstract)
- Fan HR, Tao KJ, Xie YH *et al.* 2003. Characteristics of laser Raman spectra of typical REE fluorocarbonate minerals and the identification of REE daughter minerals in fluid inclusions at the Bayan Obo REE-Fe-Nb deposit. Acta Petrologica Sinica, 19(1): 169 - 172 (in Chinese with English abstract)
- Institute of Geochemistry, Chinese Academy of Sciences. 1988. Geochemistry of the Bayan Obo Ore Deposit. Beijing: Science Press, 554p (in Chinese)
- Le Bas MJ, Keller J, Tao KJ, Wall F, Williams CT, Zhang PS. 1992. Study on Bayan Obo igneous carbonatite dykes. Scientia Geologica Sinica, (supp.): 130 - 137 (in Chinese)
- Le Bas MJ, Spiro B, Yang XM. 1997. Oxygen, carbon and strontium isotope study of the carbonatitic complex at Bayan Obo Fe-Nb-REE deposit, Inner Mongolia, N China. Mineral Magazine, 61: 531 - 541
- Li SQ. 1971. Report on the regional geological survey of the Bayan Obo plate (1:200000). Geological Bureau of Inner Mongolia, 79p (in Chinese)
- Nesbitt BE and Kelly WC. 1977. Magmatic and hydrothermal inclusions in carbonatite of the Magnet Cove complex, Arkansas. Contrib. Mineral. Petrol., 63: 271 - 294
- Ni P and Rankin AH. 2002. A possible magmatic origin of Bayan Obo Fe-Nb-REE deposit, China. Geochim. Cosmochim. Acta, 66 (supp): A552
- Ni P, Rankin AH, Zhou J. 2003. Fluid inclusion studies on carbonatite dyke and associated quartzite in Bayan Obo, Inner Mongolia, China. Acta Petrologica Sinica, 19(2): 297 - 306 (in Chinese with English abstract)
- Qin CJ and Qiu YZ. 2001. Recent progress in carbonatite research. Advance in Earth Sciences. 16:500 - 507 (in Chinese with English abstract)
- Qin CJ, Li YQ, Qiu YZ. 2002. Preliminary study on fluid inclusions of Bayan Obo carbonate vein-like bodies. Mineral Deposits, 21(supp.): 1013 - 1016 (in Chinese with English abstract)
- Samson IM, Liu WN, Williams-Jones AE. 1995. The nature of orthonagmatic hydrothermal fluids in the Oka carbonatite, Quebec, Canada: Evidence from fluid inclusions. Geochim. Cosmochim. Acta, 59(10):1963 - 1977
- Smith MP and Henderson P. 2000. Preliminary fluid inclusion constraints on fluid evolution in the Bayan Obo Fe-REE Nb deposit, Inner Mongolia, China. Econ. Geol., 95: 1371 - 1388
- Tao KJ, Yang ZM, Zhang PS, Wang WZ. 1998. Geological features of igneous carbonatite dykes at the Bayan Obo ore district. Scientia Geologica Sinica, 33: 73 - 83 (in Chinese)
- Tu GZ. 1998. On unique features of composition, geological setting and forming mechanism of non-conventional superlarge ore deposits-first discussion on non-conventional superlarge ore deposits. Science in China (series D), 28(supp.): 1 - 6 (in Chinese)
- Wang ZG, Li SB, Su XZ. 1973. Characteristics of the origin of sedimentary metamorphic and hydrothermal metasomatic REE-Fe ore deposit. Geochimica, 1: 5 - 11 (in Chinese with English abstract)
- Xie YH, Wang YL, Zhang RF. 1995. Discovery of REE minerals in fluid inclusions at the Bayan Obo ore deposit. Chinese Science Bull., 40 (20): 1870 - 1872 (in Chinese)
- Yang ZY and Drew LJ. 1994. On the Sedex origin of ore-hosted rock-dolostone at the Bayan Obo ore deposit. Review on Geology and Prospecting, 9(1): 39 - 47 (in Chinese)
- Zhang ZQ, Yuan ZX, Tang SH, Bai G, Wang JH *et al.* 2003. Age and geochemistry of the Bayan Obo Ore Deposit. Beijing: Geological Publishing House, 225p (in Chinese with English abstract)