



## Geology and mineralization of the Bayan Obo supergiant carbonatite-type REE-Nb-Fe deposit in Inner Mongolia, China: A review

Yi-ke Li<sup>a</sup>, Chang-hui Ke<sup>a</sup>, Hong-quan She<sup>a,\*</sup>, Deng-hong Wang<sup>a</sup>, Cheng Xu<sup>b</sup>, An-jian Wang<sup>a</sup>, Rui-ping Li<sup>a</sup>, Zi-dong Peng<sup>a</sup>, Ze-ying Zhu<sup>a</sup>, Kui-feng Yang<sup>c</sup>, Wei Chen<sup>d</sup>, Jian-wei Zi<sup>d,e</sup>, Wen-lei Song<sup>f</sup>, Yong-gang Zhao<sup>g</sup>, Li Zhang<sup>g</sup>, Hong Yu<sup>a</sup>, Bin Guo<sup>g</sup>, Sheng-quan Zhou<sup>a</sup>, Xing-yu Yuan<sup>g</sup>, Jing-yao Liu<sup>a</sup>

<sup>a</sup> MNR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China

<sup>b</sup> Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China

<sup>c</sup> Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

<sup>d</sup> State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China

<sup>e</sup> John de Laeter Centre, Curtin University, Bentley, WA 6102, Australia

<sup>f</sup> State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China

<sup>g</sup> Bayan Obo Iron Mine, Baotou Steel (Group) Co., Ltd., Inner Mongolia, Baotou 014080, China

### ARTICLE INFO

#### Article history:

Received 27 September 2023

Received in revised form 24 October 2023

Accepted 24 October 2023

Available online 25 October 2023

#### Keywords:

Rare earth elements

Niobium ore

Iron ore

Fluorite ore

Igneous carbonatite

Fenitization

Metasomatism

Anti-skarn

Bayan Obo

### ABSTRACT

The Bayan Obo supergiant carbonatite-related rare-earth-element-niobium-iron (REE-Nb-Fe) endogenetic deposit (hereafter as the Bayan Obo deposit), located at 150 km north of Baotou City in the Inner Mongolia Autonomous Region, is the largest rare-earth element (REE) resource in the world. Tectonically, this deposit is situated on the northern margin of the North China Craton and adjacent to the Xing'an-Mongolian orogenic belt to the south. The main strata within the mining area include the Neoproterozoic Se'ertengshan Group and the Mesoproterozoic Bayan Obo Group. Generally, the rare earth, niobium, and iron mineralization within the deposit are intrinsically related to the dolomite carbonatites and the extensive alteration of the country rocks caused by the carbonatite magma intrusion. The alteration of country rocks can be categorized into three types: contact metasomatism (anti-skarn and skarn alteration), fenitization, and hornfelsic alteration. As indicated by previous studies and summarized in this review, the multi-element mineralization at Bayan Obo is closely associated with the metasomatic replacement of siliceous country rocks by carbonatite magmatic-hydrothermal fluids. The metasomatic process is comparable to the conventional skarnification that formed due to the intrusion of intermediate-acid magmatic rocks into limestone strata. However, the migration pattern of SiO<sub>2</sub>, CaO, and MgO in this novel metasomatic process is opposite to the skarn alteration. Accordingly, this review delineates, for the first time, an anti-skarn metallogenic model for the Bayan Obo deposit, revealing the enigmatic relationship between the carbonatite magmatic-hydrothermal processes and the related iron and rare earth mineralization. Moreover, this study also contributes to a better understanding of the REE-Nd-Fe metallogenic processes and the related fluorite mineralization at the Bayan Obo deposit.

©2023 China Geology Editorial Office.

## 1. Introduction

The Bayan Obo deposit is the largest rare earth element (REE) accumulation in the world, despite that the precise data of REE oxide resources is disputed as published by different

sources [43.5 Mt, data from Baotou Steel (Group) Co., Ltd; 112 Mt, Xie YL et al., 2019; 92 Mt and 83 Mt of Bayan Obo mine and tailings dam respectively, Weng et al., 2015; Potential resources estimated up to 333 Mt, Fan HR et al., 2022]. Furthermore, this deposit also hosts a proved iron ore resource of 1.56 Gt, an estimated niobium resource of 6.6 Mt, a predicted fluorite resource of 132 Mt, and a thorium resource of 0.22 Mt, all of which are top ranked among China's ore deposits (Chao ECT et al., 1997; Xie YL et al., 2019). Significantly, the REE resource in this deposit accounts for more than two-thirds of the world's total proven

First author: E-mail address: [like430@cags.ac.cn](mailto:like430@cags.ac.cn) (Yi-ke Li).

\* Corresponding author: E-mail address: [974307769@qq.com](mailto:974307769@qq.com) (Hong-quan She).

Literary editor: Li-qiong Jia

doi:10.31035/cg2023082

2096-5192/© 2023 China Geology Editorial Office.

Copyright © 2023 Editorial Office of China Geology. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.

This is an open access article under the CC BY-NC-ND License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

reserves, thus holding great economic value and having attracted the interest of numerous geologists worldwide.

### 1.1. The discovery of the Bayan Obo deposit

In July 1927, Dao-heng Ding, an assistant professor of the Department of Geology, Peking University and member of the Sino-Swiss Expedition, discovered the Bayan Obo iron deposit (currently known as the Main Orebody of Bayan Obo) during his field trip. In December 1933, his report entitled *Report on Bayan Obo Iron Deposit in Suiyuan* was published in Issue 23 of *Geological Report*, a journal co-sponsored by the Institute of Geology of the Ministry of Industry and the Institute of Geology of the National Institute of Peiping. This report was the first to document the discovery process, location, traffic conditions, stratigraphic characteristics, topographic structure, and mineral resources of the Bayan Obo deposit, kicking off the research, exploration, and exploitation of the Bayan Obo deposit. In the summer of 1934, commissioned by Dao-heng Ding, Zuo-lin He, a researcher at the Institute of Geology, Academia Sinica, and a full-time lecturer in mineralogy at the Department of Geology, Peking University, conducted research on rock samples from the Bayan Obo deposit. In 1935, the *Note on Some Rare Earth Minerals from Beiyin Obo, Suiyuan* (in English), authored by Zuo-lin He, was published in Volume 14, Issue 2 of the *Bulletin of the Geological Society of China*. This publication was the first to announce the identification of two distinct REE minerals in the fluorite-type ores, which were temporarily named “Bliyinlte” and “Aborte” but subsequently proven to be bastnaesite and monazite, respectively. Therefrom, the Bayan Obo deposit, which is now recognized as the world’s largest REE deposit, was introduced to the world for the first time.

More precisely, the iron orebody discovered by Dao-heng Ding in 1927 is the current Main Orebody of the Bayan Obo deposit. During the Counter-Japanese War, the Japanese puppet regime conducted eight geological surveys on the Bayan Obo deposit. Among these surveys, the most comprehensive and detailed survey was conducted by the team led by Huang CJ from the Resources Survey Bureau of North China Development Co., Ltd. from June 11 to August 20, 1944. During this survey, the new eastern orebodies (i.e., the East Orebody) and a series of western orebodies (i.e., the West Orebody) were discovered. In August 1946, Chun-jiang Huang authored a survey report entitled *Iron Ores Nearby Bayan Obo, Bailing Temple, Suiyuan*. This report described the discovery processes of the West and East orebodies and was published in Issue 11 of *Geological Review*. In late May 1950, the No. 241 Geological Survey Team, led by Kun-yuan Yan, discovered a sedimentary metamorphic iron deposit, which is now known as the South Orebody, at about 20 km south of the Bayan Obo deposit. Subsequently, Professor Fu-li Yuan, then the head of the Department of Geology of Tsinghua University, discovered an orebody known as the North Orebody on the north of the deposit during the geological survey in Bayan Obo. In 1953, the Ministry of Geology conducted a magnetic survey on the Bayan Obo deposit and identified a significant magnetic anomaly at the

Dongjielegele area, 1.5 km south of the East Orebody. Subsequent exploration and verification confirmed the presence of the Dongjielegele orebody. From 2019 to 2020, Yi-ke Li et al. from the Bayan Obo Scientific Research Base of the Baogang Group, Institute of Mineral Resources, Chinese Academy of Geological Sciences conducted an integrated, high-resolution geological-gravitational-magnetic-electrical-seismic exploration. Their efforts predicted the existence of concealed orebodies in the deep part between the Main and East Orebody. The total 30000-meter drilling of 34 holes, drilled by the Institute of Surveying and Mapping of Baotou Steel Group Co. LTD confirmed the presence of deep, thick, and large concealed iron-REE orebodies (Li YK et al., 2022).

### 1.2. History of geological research on the Bayan Obo deposit

Over the past decades, significant progresses as to the origins, mineralization epochs, and REE mineralogy of the Bayan Obo deposit have been achieved (Lawrence et al., 1990; Zhang PS, 1996, 1998, 2001; Yang XM et al., 1999; Zhang et al., 2003), contributing substantially to the development of the theory on REE mineralization. Significantly, dozens of geological universities and research institutes throughout China have participated in research on the deposit, primarily including the No. 241 Geological Team, the Sino-Soviet Joint Geological Team formed by the Soviet Academy of Sciences and the Chinese Academy of Sciences, the No. 105 Geological Team, relevant institutes under the Chinese Academy of Sciences, the institutes of geology and mineral resources under the Chinese Academy of Geological Sciences, and various scientific research organizations having participated in mineral processing and metallurgy for the purpose of making breakthroughs in the exploration of the deposit in Baotou, as well as universities and colleges such as Peking University, China University of Geosciences, University of Science and Technology of China, and Lanzhou University.

Despite massive research data have been obtained from the Bayan Obo deposit, geologists hold different views on its mineralization processes, fluid evolution, mineralization epochs, and the origins of primary ore-bearing country rocks (dolomites). This is because both the secondary intricate deformations and hydrothermal alteration have largely complicated the geological and geochemical characteristics of this deposit. Opinions on the origin of the Bayan Obo deposit include sedimentary origin (Meng QR, 1982; Wei JY et al., 1983, 1994), sedimentary modification-metasomatism (Lai XD, et al., 2013; Institute of Geochemistry, Chinese Academy of Sciences, 1988; Zhang YX et al, 1998, 2008; Hou ZL, 1989; Qiao XF et al., 1997), submarine volcanic sedimentation (Yuan ZX et al., 1991, 1995; Bai G et al., 1985, 1996), volcanic apparatus or volcanic origin (Hao ZG et al., 2002; Xiao RG et al., 2006; 2012), subduction fluid metasomatism (Ling MX, et al., 2013; 2014), metasomatic replacement by high-temperature hydrothermal fluids and mantle fluids (Cao RL et al., 1994), carbonatite magma origin combined with prolonged metallogenic modification (Song WL, et al., 2018), carbonatite magmatic-hydrothermal fluids

(Zhou ZL et al., 1980; Liu TG; 1986, 1990; Wang XB et al., 2002; Hu L 2018, 2020), and carbonatite fenitization (Wang KY et al., 2010, 2018; Elliott H, et al., 2018; Liu, et al., 2018; Yang K, et al., 2019). The proposed mineralization epochs range from Mesoproterozoic to Late Proterozoic and Paleozoic (Institute of Geochemistry, Chinese Academy of Sciences; Zhang ZQ et al., 1997, 2004; Smith MP et al., 2015; Fei XJ et al., 2019). Benefited from numerous studies over the past two decades, some consensus have been reached, including that the ore-hosting dolomites in the Bayan Obo deposit are igneous in origin, and that the mineralization in this deposit is governed by the emplacement of igneous carbonatites, as primarily evidenced by the fact that both the fenitization and fenite-like ores intimately related to the emplacement of carbonatite are widespread in the main and eastern orebodies (Le Bas MJ, et al., 1992, 1997, 2007; Tao KJ et al., 1998; Yang XM et al., 1999; Wang KY et al., 2018; Yang KF et al., 2011, 2012, 2019; Fan HR et al., 2002a, 2002b; Liu YL et al., 2018).

## 2. Regional geological setting

The Bayan Obo deposit is located at the northern margin of the North China Craton and adjacent to the Xing'an-Mongolian orogenic belt to the south. Based on regional stratigraphic units, the deposit clearly comprises a platform system in the south and a fold system in the north (Bai G et al., 1996; Fig. 1). Conventionally, researchers defined the northern boundary of the North China Craton as the area from the north side of Bayan Obo to the Xar Moron River (Wang HZ, 2006), and determined the border between the North China Craton and the Hercynian fold belt in Inner Mongolia to be the Ulanpaulig fault about 30 km north of Bayan Obo (Zhang PY et al., 1993). Based on the ophiolites sporadically exposed along the Solon Obo-Ujuur Xubuut area on the Sino-Mongolian border, some scholars identified the area of the Bayan Obo deposit as the plate suture zone where the Paleo-Asian Ocean was subducted under the North China Craton (Li CY et al., 1984). The deposit has experienced complex tectonic evolution since the Proterozoic (Zhao et al., 1999, 2005; Zhai et al., 2015), including the Late Paleoproterozoic-Neoproterozoic multi-stage rifting events (Zhaertai-Bayan Obo-Huade Mesoproterozoic rift zone; Zhai et al., 2015), and the Paleozoic subduction-associated multi-stage magmatism (Zhang ZQ et al., 1994; Liu YL et al., 2004), metamorphism, and deformation (Zhang ZQ et al., 2003; Smith MP et al., 2015). The prolonged tectonic evolution gave rise to complex geological and geochemical characteristics of the deposit, and led to extensive disputes over its mineralization background, epochs, and process.

### 2.1. Strata in the southern platform

Exposed strata on the northern margin of the platform are characterized by Archean to Paleoproterozoic basements, extremely thick Mesoproterozoic rift deposits, small-scale, thin Neoproterozoic and Paleozoic cap rocks, and Meso-Cenozoic strata mostly distributed in some fault basins, while Silurian-Devonian strata are absent. The ancient basement

strata primarily comprise the Paleoproterozoic Xinghe Group, Mesoproterozoic Wulashan Group, Neoproterozoic Se'ertengshan Group, and Paleoproterozoic Baoyintu Group, which jointly constitute the basement structural layers on the northern margin of the North China Craton. The cover strata of the northern platform predominantly comprise the Mesoproterozoic Bayan Obo and Zhaertai groups and the Neoproterozoic Shinagan Group, with Paleozoic strata exposed locally. During the Meso-Neoproterozoic, the North China Craton was an unstable basement, and the cover strata consisted of the rift deposits on the margin of the North China Craton. Consequently, the Bayan Obo and Zhaertai groups were formed, with the former serving as the ore-bearing stratum of the Bayan Obo deposit. During the Meso-Cenozoic, the circum-Pacific continental margin where the southern platform lay was active, forming many faulted basins of variable sizes. The strata formed in this period were dominated by continental clastic coal-bearing suites and lacustrine gypseous carbonate formations, with the Cretaceous Bainvyangpan Formation developing locally. Under the influence of the activation of circum-Pacific structures, the regionally extensive Hannuoba basalt erupted during the Miocene.

### 2.2. Strata in the northern fold area

The Precambrian strata in the northern folded area sporadically occur in some ancient terrane fragments, with primary outcrops including the Baoyintu and Ailigemiao groups. This area contains complete Paleozoic strata, including marine clastic, carbonate, and volcanic suites. The pre-Carboniferous strata in this area are mostly deformed and metamorphosed, primarily consisting of basalts, dacitic lavas, tuffaceous sandstones, and pyroclastic rocks of the Baerhantu Group, Silurian-Devonian marine clastic and carbonate formations, and the Carboniferous-Permian volcanic-sedimentary suites. The Meso-Cenozoic strata in this area are sedimentary suites in graben basins, which merely include continental clastic and volcanic coal-bearing suites with thicknesses exceeding 5000 m. Cenozoic strata are extensively distributed in this area, primarily consisting of lacustrine mudstones and clastic rocks interbedded with carbonate sequences.

### 2.3. Geotectonic environmental evolution

The formation and evolution of the Bayan Obo deposit are closely associated with two major regional tectonic events: the breakup of the Columbia Supercontinent during the Mesoproterozoic and the closure of the Paleo-Asian Ocean during the Paleozoic.

#### 2.3.1. Mesoproterozoic rifting and emplacement of carbonatites

After colliding and converging with its peripheral blocks to form the preliminary North China Craton, it comes to extension and breakup stage of the Yinshan Block. Based on

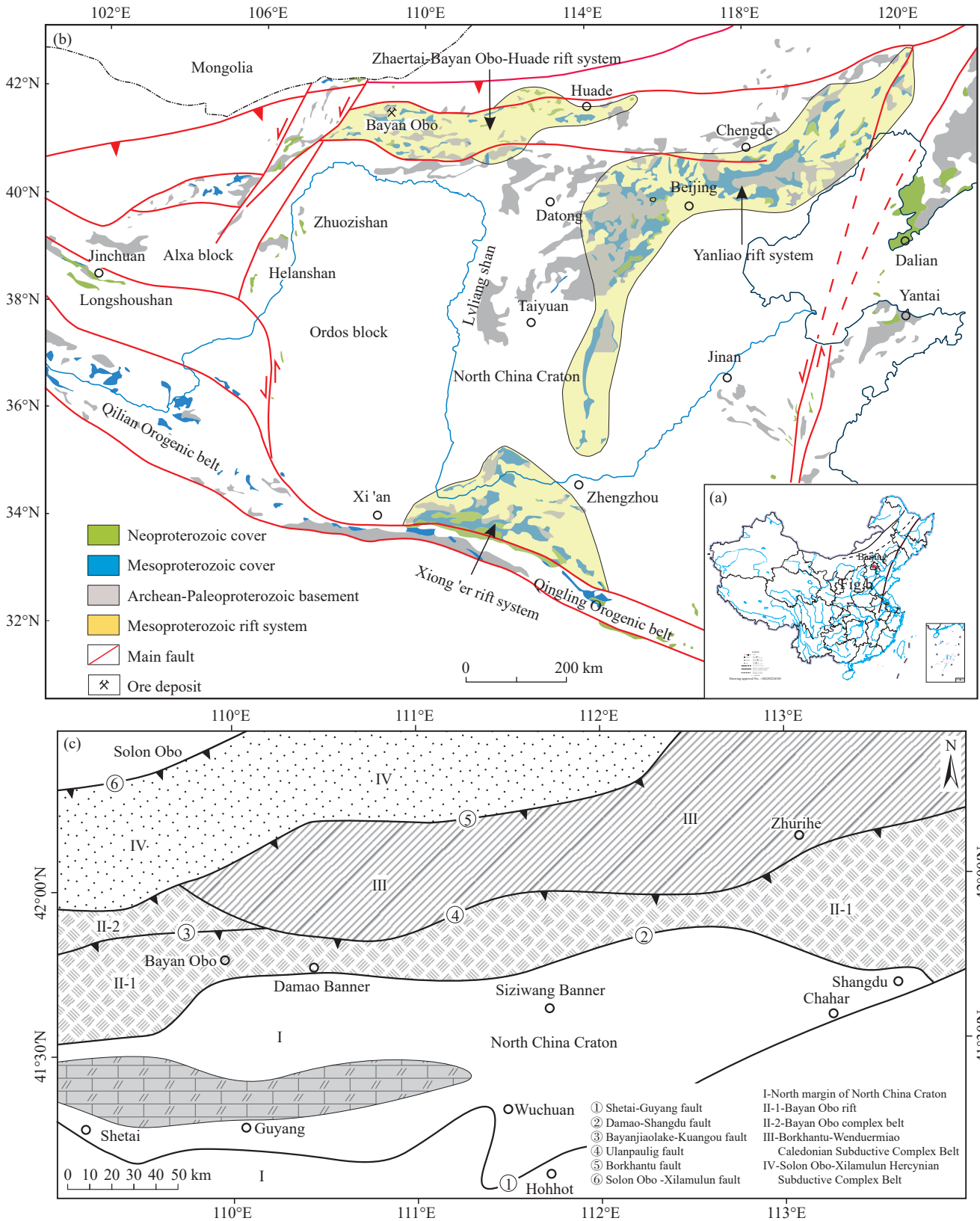


Fig. 1. Map showing the geotectonic setting in the Bayan Obo area.

the systematical investigation on the Bayan Obo-Langshan rift system, Wang J et al. (1992) proposed that the Bayan Obo REE deposit occurs in the Proterozoic rift and that its mineralization is associated with the activities of continental-margin rifts. Hou GT et al. (2005) suggested that the North

China Craton witnessed the intrusion of extensive mafic dyke swarms and the formation of aulacogens at 1830–1770 Ma, indicating the platform began to enter the breakup stage. Yan GH et al. (2007) posited that the alkaline and carbonatite magmatic activities occurred on the northern margin of the

North China Craton during the late Paleoproterozoic, which also indicates the breakup event of the platform during this period, and argued that the breakup event is a response to the breakup of the Columbia supercontinent (Zhang SH et al., 2022). At this stage, the Bayan Obo and Zhaertai rifts began to form at the northern margin of the western section of the North China Craton. In the Bayan Obo rift, the Dulahala and Jianshan formations were deposited sequentially. By comparison, the Shujigou and Zenglongchang formations were successively deposited in the Zhaertai rift. The Dulahala Formation consists primarily of gravel-bearing coarse-grained feldspathic quartz sandstones and quartz sandstones, while the Jianshan Formation predominantly comprises siltstones and silty mudstones, implying its rapid sedimentation in a rifting environment. The presence of mafic volcanic rocks in the Jianshan Formation suggests a rift environment, with the mafic volcanic rocks having a crystallization age of 1728 Ma (Liu CH and Liu FL, 2015). Wang HC et al. (2012) discovered a quartz syenite formed at around 1702 Ma in the Guyang area south of Bayan Obo. The quartz syenite possesses the characteristics of non-orogenic magmatic rocks, also indicating the existence of a rift environment. Although the Wenduermiao and Bainaimiao groups at the north of Bayan Obo were considered as Neoproterozoic strata, they both contain many Mesoproterozoic blocks (Xu B, 1998; Wu TR et al., 1998). Thus, the Bayan Obo rift is not an aulacogen that died out after only preliminary development, but a continental-margin rift characterized by the formation of oceanic crust during extension.

Statistics on the spatial distributions of most carbonatites (330 localities) around the world indicate that the spatial occurrence of most carbonatites are associated with penetrating tectonic faults (*Rare Element Deposits*, Issue 17, 1965; Woolley, 2008) and are primarily located at platform-margin fold belts and the depressions of continental rifts (such as carbonatites in the Great Rift Valley). It has been roughly determined that the igneous carbonatites associated with the Bayan Obo REE deposit were formed around 1.3–1.4 Ga (Zhang SH et al., 2017; Zi JW et al., 2023). Furthermore, the spatio-temporal distributions of the carbonatites are closely connected with the formation and evolution of the Bayan Obo rift system. Apparently, the deep-rooted transcrustal faults formed during the development of the Bayan Obo rift provided spaces and pathways for the emplacement of carbonatites.

### 2.3.2. Subduction and closure of the Paleo-Asian Ocean and the deformation and recrystallization of dolomites

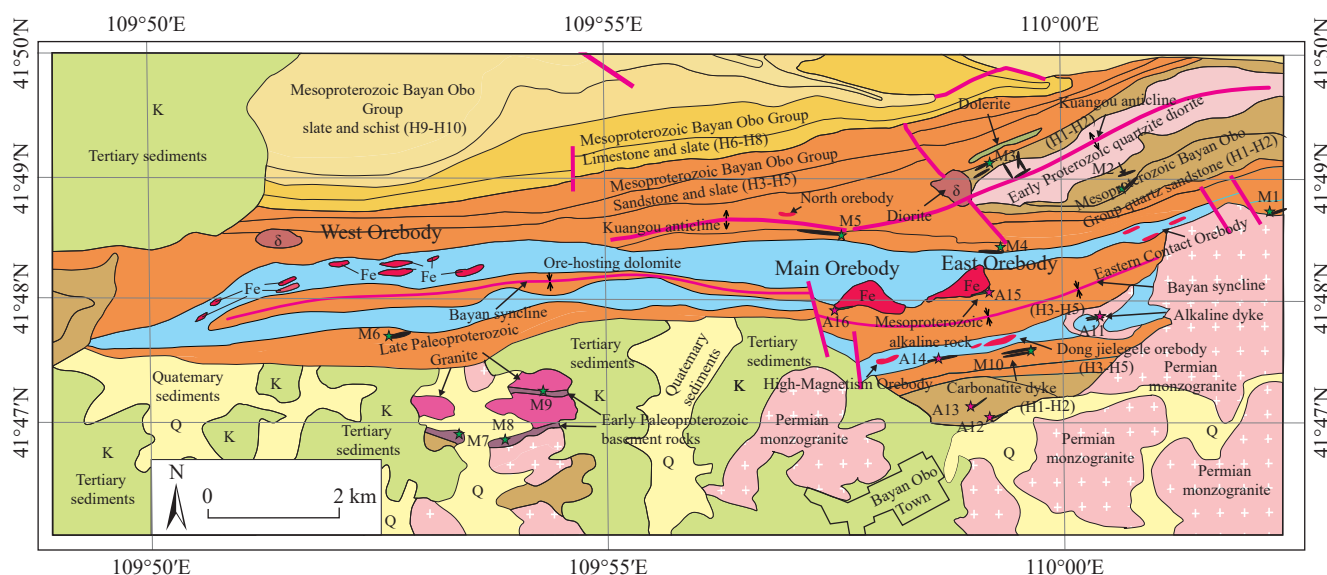
As research on the mineralization of the Bayan Obo deposit deepens, increasing attention has been attracted to the effects of the Paleo-Asian Ocean's closure on the mineralization of the deposit (Ling MX et al., 2013; Yang XY et al., 2015; Song WL et al., 2018). On both sides of the Ulanpaulig fault, complexes including the Wude complex, Bilute olivine, and Engeer gabbro-diorite are exposed as structure complex rocks. These complexes, occurring along island arcs or in an active epicontinental environment, are

associated with the subduction of an oceanic plate beneath the continent. As the plate continuously penetrated downward during subduction, the structural blocks scraped off were gradually spliced. Consequently, the plate subduction zone migrated away from the continent, leading to the formation of the Huheengeer-Bilute and Wude melanges. This may indicate that as the North China and Siberian plates converged during the Caledonian, the oceanic crust of the Paleo-Asian Ocean had been subducted beneath Bayan Obo, which was then incorporated into the fold deformation zone of the active continental margin. Consequently, the strata in the Bayan Obo area underwent structural deformations on various scales, as evidenced by the presence of large-scale tight folds, a series of thrust faults, and ductile shearing (Lawrence JD et al., 1990; Hao ZG et al., 2002; Le Bas MJ et al., 2007). As a result, many ductile-shear-zone-isoclinal-fold-imbricate-thrust fault structures were formed. However, due to their own density and hardness, early carbonatites were the most prone to undergo fold deformations and mylonitization, with coarse-grained dolomites forming fine-grained dolomites after recrystallization (Chao ECT et al., 1992). Strictly speaking, the Bayan Obo deposit occurred in Caledonian tectonic melange belts, with the early carbonatites occurring as thrust nappes or tectonic slices (Zhang YX et al., 2009; Wang KY et al., 2012). This finding is critical to understanding the mineralization process of the Bayan Obo deposit.

## 3. Geological setting of the Bayan Obo deposit

### 3.1. Strata of the mining area

Wang J et al. (1992) systematically investigated the Bayan Obo-Langshan rift system, proposing that the Bayan Obo REE deposit occurs in Proterozoic rifts and that its mineralization is associated with the activities of continental-margin rifts. Yuan ZX et al. (1995) and Zhang ZQ et al. (2003) considered that strata exposed in the deposit include the Neoproterozoic Se'ertengshan Group and the Mesoproterozoic Bayan Obo Group. The Se'ertengshan Group primarily comprises plagioclase-chlorite schists, quartz-biotite-chlorite schists, hornblende-plagioclase gneisses, and migmatites. This group is distributed in the southeastern portion of the East Orebody and on the south side of the West Orebody. The Bayan Obo Group can be divided into six rock formations and 18 lithologic members. The H1–H10 lithologic members of the lower Bayan Obo Group are exposed in the deposit (Fig. 2), and their lithologies are shown in Table 1. From bottom to top, the Bayan Obo Group consists of the Dulahala, Jianshan, Halahuogete, and Bilute formations, with lithologies including quartzites, quartz sandstones, slates, crystalline limestones, dolomites, biotite schists, and slates from the bottom upward and a total thickness of about 2500 m (Table 1). The main ore-hosting carbonate rocks in the Bayan Obo deposit are classified into the H8 member of the Halahuogete Formation (known as H8 dolomites). However, the origin of the H8 dolomites has long been controversial (sedimentary origin vs. magmatic origin). Despite various opinions on the origin of the petrological



**Fig. 2.** Geological map of the Bayan Obo iron-REE deposit (modified after the Inner Mongolia First Regional Geological Institute, 1996; Inner Mongolia Geological Survey Institute, 2002; and data for geological mapping in this study).

**Table 1.** Stratigraphic sequences of the Bayan Obo iron-REE deposit.

Epoch	Formation	Main lithology	Symbol	Former division	
Mesoproterozoic (Bayan Obo Group)	Jixianian	Bilute Formation	Carbon- and silt-bearing sericite slates	$Jxb^2$	H10
		Sericite slates, silt-bearing sericite slates	$Jxb^1$	H9	
		Halahuogete Formation	Halahuogete slump limestone breccias	$hw$	
		Silty micritic limestones and reef limestones	$Jxh^3$	H8	
		Interbeds consisting of calcareous medium-coarse-grained quartz sandstones and silt-bearing micritic limestones	$Jxh^2$	H7	
	Changchengian	Jianshan Formation	Light-gray calcareous medium-coarse-grained quartz sandstones	$Jxh^1$	H6
			Silt-bearing sericite slates and carbon-bearing sericite slates interbedded with sandstone (the main intrusive horizon and main country rocks of dolomite carbonatites in the Bayan Obo deposit)	$Chj3$	H5
			Dark-gray metamorphic coarse-grained quartz sandstones and coarse-grained feldspathic quartz sandstones	$Chj^2$	H4
			Silty slates, carbonaceous slates, and carbon- and silt-bearing sericite slates	$Chj^1$	H3
			Light-gray metamorphic medium-coarse-grained quartz sandstones	$Chd^2$	H2
Dark-gray metamorphic coarse-grained feldspathic quartz sandstones and sericite slates	$Chd^1$	H1			
Early Proterozoic	Se'ertengshan Group	Migmatites, biotite hornblende gneisses, and two-mica schists (intruded by alkaline granites and a small quantity of carbonatite dykes)	$Pt_1s$		

property of the H8 dolomites, increasing pieces of chronological and geochemical evidence support the magmatic carbonatite origin (Hao ZG et al., 2002; Yuan ZX et al., 2004; Yang XM et al., 2000; Fan HR et al., 2006a, 2014, 2016). The other rock units in the lower Bayan Obo Group are generally considered a set of metamorphic sedimentary rocks or metamorphic volcanic rocks (Yuan ZX et al., 1995; Zhang ZQ et al., 2003). Based on extensive geological mapping and massive petrographic observation, the authors of this study further confirm that this set of dolomitic rocks are of magmatic origin, supporting the view that the ore-hosting dolomites were formed during the emplacement of carbonatite magmas. Notably, the H8 lithologic member shown in Table 1 only refers to the representative lithologic strata (limestone strata) in the typical section of the Jianshan

Formation on the north side of Kuangou. To avoid ambiguity, we prefer to employ the term ore-hosting dolomite (Dolt for short) or dolomite carbonatite, rather than the H8 dolomites in previous literature, to represent the ore-bearing rocks.

### 3.2. Structures of the mining area

Deformation is widespread in the Bayan Obo deposit, with the Ulanpaulig fault and Baiyinjiaolake deep-seated faults (Fig. 1) roughly governing the structural framework, mineralization, and magmatic activity in the region (Hao ZG et al., 2002). Except for the above regional structures, the 1:50000-scale geological mapping further reveals complex structures in the deposit and its peripheries. The fold structures in the deposit exhibit multistages of folded

deformations of different properties and directions. Large and medium-sized fold structures manifest relatively gentle hinge plunges and a nearly EW axial trend, while small folds are mostly sporadically distributed within the large and medium-sized ones. The predominant fold structure in the deposit is the Kuangou anticline, which exhibits a nearly EW axial trend and an E-directed plunge. The core strata of the Kuangou anticline include the Neoproterozoic Se'ertengshan complexes and Paleoproterozoic granite gneisses, while both flanks of the Kuangou anticline comprise strata of the Bayan Obo Group. Among them, the southern flank in the east underwent the Hercynian granite intrusion, while the southern flank in the west of the anticline was previously considered a residence for a secondary syncline (i.e., the Bayan syncline). The Bayan Obo deposit is situated on the southern flank of the Kuangou anticline. Fault structures are highly extensive in the deposit, including nearly EW-, NWW-, NW-, NE-, and nearly SN-trending faults, leading to the discontinuity in the strikes of lithostratigraphic units (Zhang ZQ et al., 2003). Fault structures within the deposit are characterized by NS-trending thrust nappes occurring in the nearly EW direction, with densely distributed faults of varying sizes mostly cropping out in an imbricate form. The dominant direction of the fault structures in the deposit is EW-trending, including the Saiwusu ductile shear zone and the Kuangou fault in the north and the thrust faults and ductile shear zones in the south, followed by NE- and NW-trending faults (Zhang ZQ et al., 2003). As revealed by the deformation characteristics of the carbonatites and other rock units in the deposit, the Dolts, together with the Changchengian Dulahala and Jianshan formations and the Jixianian Bilute Formation, exhibit ductile shear deformations. Therefore, it seems that the Bayan Obo deposit is located in a giant ductile shear zone, which includes the Saiwusu ductile shear zone in the north and ductile shear zones in the south (Zhang ZQ et al., 2003). Further verification is required for this inference.

### 3.3. Magmatic rocks of mining area

The REE-Nb-Fe orebodies in the Bayan Obo deposit are closely associated with a set of dolomite carbonatites (i.e., Dolts), with the spatial distribution of mineralization strictly confining to the Dolts and/or the alteration zones between the Dolts and their country rocks. The Dolts are banded or lentoid in shape in the W-E direction, occurring in the Bayan Obo Group, with a W-E length of about 16 km and an N-S width of 1–3 km. Given that the carbonatites are critical to understanding the origin and mineralization of the Bayan Obo deposit, and that there are controversies with respect to their origin, this study highlights the genesis of this set of carbonatites based on systematical geological mapping of the Bayan Obo deposit in recent years.

The origin of Dolts in the Bayan Obo deposit has long been disputed, and it is considered that the Dolts were formed by sedimentary metamorphism - hydrothermal metasomatism (Chao ECT et al., 1992, 1997; Cao RL et al., 1995; Qin CJ et al., 2007; Wang J et al., 1994; Xu C et al., 2008; Yang XY et

al., 2009; Wang ZG et al., 1973; Zhou YS, 2006; Yuan ZX et al., 2004; Zhao JD et al., 1991; Zhang ZQ et al., 2004; Meng QR, 1982; Cao RL et al., 1996), igneous carbonatites (Le Bas MJ et al., 1992; Le Bas MJ et al., 1997; Ni P et al., 2003; Yuan ZX et al., 1992; Zhou ZL et al., 1980; Liu TG, 1986; Yang KF et al., 2011; Chen W et al., 2020), submarine volcanic sedimentation (Bai G et al., 1983; Yuan ZX et al., 1991; Ding TP, 2003), deep-sourced hot brines (Gao JY et al., 1999), micrite mounds (Zhang YX et al., 1998; Qiao XF et al., 1997), or meteorite impact (Yao D et al., 1998). Overall, these opinions can be classified into igneous or sedimentary origins. The igneous origin can be further divided into carbonatite magma intrusion and volcanic eruption sedimentation, while the sedimentary origin suggests that the Bayan Obo deposit was formed by normal sedimentation or was modified by hydrothermal superimposition after sedimentation. Besides, some researchers attributed the mineralization to deep-sourced hot brines or meteorite impact. Many papers issued in recent years suggest that the Dolts are igneous carbonatites and might be consanguineous with the carbonatite dykes exposed at the periphery of the Bayan Obo deposit (Le Bas MJ et al., 1997, 2007; Yang XM and LeBas MJ, 2004; Yang KF, 2019; Wang KY et al., 2018). Accordingly, the magmatic origin predominates gradually.

Based on our latest mapping, geological profile survey, and laboratory research, we argue that the Dolts in the Bayan Obo deposit are of magmatic origin. Our evidence is as follows:

(1) The Dolts are in intrusive contact with their country rocks. For instance, it is common to observe dolomite veinlets intruding into the country rocks and causing observable alteration (Ke CH et al., 2021). However, given that these dolomites normally intruded along the strata, they were traditionally accepted as interlayers of the sedimentary rocks. Moreover, the ore-hosting dolomites and the carbonatite dykes found at the periphery of Bayan Obo are identical in mineral composition, structure, ore-bearing property, and REE-trace element geochemistry, suggesting a consanguineous relationship between them. Furthermore, the ore-hosting dolomites exhibit almost the same occurrence as the strata, and the current occurrences of the Dolts were caused by secondary tectonic movements.

(2) Both the alkaline granite plutons and alkaline veins within the deposit were contemporaneous with the Dolts. Furthermore, the veins contain typical alkaline hornblendes, with formation epochs roughly consistent with those of the ore-hosting dolomites and carbonatite dykes (Ke CH et al., 2021). Dolomite carbonatite intrusion can be observed in the alkaline granites that intruded into the Wulashan Group in the southern Dongjielegele carbonatite pluton. The alkaline granites, combined with the ore-hosting dolomites and carbonatite dykes, form an alkaline assemblage. Like other alkaline granite-carbonate assemblages in the world, the alkaline assemblage in the Bayan Obo agrees with the rift-related geological tectonic setting (Xie YL et al., 2015, 2016; Woolley AR et al., 2008a). The A13 alkaline granite (Fig. 2)

in the deposit yielded zircon U-Pb ages of  $1311 \pm 21$  Ma (Ke CH et al., 2021; internal data), indicating that this granite formed contemporaneously with the ore-hosting dolomites and carbonatite dykes, and was associated with the activity of the Bayan Obo rift.

(3) The ore-hosting dolomites contain the xenoliths of lamprophyres, slates, sandstones, and mafic rocks (Ke CH et al., 2021). Some xenoliths possess chilled margins, indicating that they are country rocks trapped by carbonatite magma during the ascending emplacement.

(4) Microscopic observation shows that quartz in the ores are the metasomatic relicts of country rocks rather than of a hydrothermal origin. Sandy quartz (content: 5%–30%) is generally residual in the most common banded fluorite-REE and fluorite-magnetite ores. The sandy quartz primarily exhibits xenomorphic granular grains with sizes varying in a range of 0.005–0.1 mm. Some quartz grains are metasomatized by fluorites, riebeckites, and aegirines, becoming embayed in shape, with some retaining layered structures. Therefore, the quartz is not of hydrothermal origin, and instead it is residual quartz grains from the metasomatism between Dolts and country rocks during the intrusion of the Dolts. Its protoliths are siltstones or argillaceous siltstones of the Bayan Obo Group. Hydrothermal quartz should be subhedral-euhedral crystals and mostly occurs as veins and veinlets. Generally, hydrothermal quartz veins are rare in the Bayan Obo deposit since the Dolt are undersaturated with respect to  $\text{SiO}_2$ .

(5) Previous researchers have identified many types of carbonatite dykes in the study area (Fig. 2; Le Bas MJ et al., 1997; Yang K et al. (2019) and references therein). These carbonatites were classified into fine- and coarse-grained dolomite carbonatites and fine-grained calcite carbonatites. We argue that the ore-hosting dolomites and various carbonatite dykes in the study area are consanguineous and have generally consistent emplacement ages, merely differing in the placement times, which fell into different stages. The ore-hosting dolomites and various carbonatite dykes, together with the above-mentioned alkaline granite plutons and veins, form an alkaline rock-carbonatite assemblage. Fine-grained dolomite carbonatites serve as the ore-bearing main body. Their differences in grain size could be formed by different facies transition rather than varying types. For instance, the Dongjielegele carbonatite pluton is dominated by fine-grained dolomite carbonatites, with coarse-grained dolomite carbonatites only visible locally. However, there is no significant boundary between them. Specially, dolomite carbonatites, located 1 m away from the contact zone between Dongjielegele carbonatite pluton and its country rocks, exhibit porphyritic textures and host coarse- and fine-grained dolomite or carbonate minerals. Among them, the coarse-grained dolomites account for 70%–75% of the volume, with grain sizes ranging from 0.05–2 mm, while fine-grained dolomites account for 25%–30% of the volume, with grain sizes between 0.02–0.1 mm. This characteristic is the same as the porphyaceous textures of ordinary granite plutons near a

contact zone during their emplacement. For dolomites, some of their original rock textures and structural characteristics are easily neglected due to their simple mineral composition and the effects of late metamorphism and modification.

(6) Based on the results of this study, as well as previous results of the major elements, REEs, trace elements, and carbon, oxygen, and strontium isotopes of the dolomite carbonatites in the study area, we suggest that the carbonatites (both veined carbonatite dykes and ore-hosting dolomites) in the Bayan Obo deposit are of magmatic origin. The dolomites in the deposit exhibit  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of 0.70266–0.70293,  $\epsilon\text{Nd}$  values varying from  $-2.5$  to  $+1.0$  ( $t = 1.3$  Ga), and  $\delta^{18}\text{O}_{\text{VSMOW}}$  values of 5.0‰–6.2‰, all suggesting a mantle-derived magma distinct significantly from those of sedimentary carbonates (Le Bas, et al, 1992; Shu Y et al., 2001; Fang T et al., 1994; Tao KJ et al., 1998; Yang XM et al., 2000; Wang KY et al., 2002; Yang KF et al, 2011, 2019; Fan HR et al., 2002, 2006b).

Moreover, except for the Dolts that host the REE-Nb-Fe mineralization, there are also Proterozoic alkaline ultramafic-intermediate volcanic rocks and veins (such as carbonatites, syenites, fenites, alkaline gabbros, and alkaline olivine pyroxenites; Zhang ZQ et al., 2003; Ling MX et al., 2014) and Hercynian granites in the Bayan Obo deposit. These rocks are mainly exposed in the eastern and southern portions of the deposit, with ages ranging from 243.2 Ma to 293.8 Ma (Ling MX et al., 2014). Mafic veins in the deposit include gabbros, lamprophyres, and diabases (diabase-porphyrites), as well as albite and syenite veins. Nearly 100 igneous carbonatite dykes are distributed in the deposit, intruding into the Bayan Obo Group and leading to the fenitization of country rocks to varying degrees (Le Bas, et al, 1992; Tao KJ et al., 1998). The veins exposed on the surface are meters to hundreds of meters in length and one to tens of meters in width. Despite different strikes, these veins trend in the nearly EW direction overall. Based on the proportions of their minerals, the carbonatite dykes in the Bayan Obo deposit can be divided into dolomite carbonatite dykes, calcite - dolomite carbonatite dykes, and calcite carbonatite dykes (Wang KY et al., 2002; Wang XB et al., 2002). These carbonatite dykes are well-recognized igneous carbonatites in the deposit. Some of them exhibit REE mineralization, and their fabric characteristics and whole-rock chemical composition are comparable to those of Dolts. These findings suggest that carbonatite dykes and the Dolts share similar origins (Le Bas MJ et al., 1997, 2007; Yang XM et al., 2000). Researchers have conducted extensive studies on the igneous carbonatite dykes at the periphery of the deposit (Hao ZG et al., 2002; Fan HR et al., 2006a; Yang KF et al., 2011; Wang KY et al., 2018), especially the No.1 carbonatite dyke (also called the Wu dyke) in the northeastern part of the East Orebody. Zircon grains were selected from these vines (Fan HR et al., 2006a; Liu YL et al., 2005a; Lai XD, 2013; Liu et al., 2018). Most of these zircon grains yielded older ages and were further interpreted to be zircon from basement rocks that were trapped during the emplacement of carbonatite magmas. Only a few zircon and

monazite grains yielded ages of about 1.3 Ga or 1.4 Ga that are comparable to the whole-rock Sm-Nd isochron ages, representing the formation ages of the carbonatites (Zhang ZQ et al., 1994; Wang KY et al., 2018; Zi JW et al., 2023).

### 3.4. Alteration of country rocks

Various types of metasomatism and hydrothermal alteration occurred extensively within and outside of the Dolts. The latter is more prominent within the contact zones between the Dolts and their country rocks. According to the types of alteration minerals, the alteration can be classified into fluorite, aegirine, riebeckite, albite, potassium feldspar, skarn, calcite, pyrite, biotite, magnetite, and barite types. The alteration minerals are frequently paragenetic and superimposed in space. According to the differences in the types of both alteration and major altered mineral assemblages, this study divides the alteration into contact metasomatism, fenite alteration, and hornfelsic alteration. Contact metasomatism primarily occurs within and around carbonatite contact zones. This type of alteration refers to dimetasomatism between carbonatite magmas and country rocks that results in anti-skarn alteration. Fenite alteration primarily refers to the intense fenitization of rocks (carbonatites and partial country rocks) near contact zones and the country rocks of Dolts caused by the high- and medium-temperature fluids during the intrusion of Dolts. This type of alteration leads to the formation of numerous new minerals like riebeckite, albite, potassium feldspar, biotite, calcite, and apatite, which form broad fenitization zones. Fenite alteration is accompanied by weak magnetite alteration. Additionally, the barite and fluorite alteration occurring in the middle-late hydrothermal process are superimposed on the fenitization zones. In previous literature, the so-called metasomatism of potassium, sodium, and fluorine all belong to hornfelsic alteration or fenitization. Hornfelsic alteration refers to the biotite alteration of the siltstones, pelites, and argillaceous siltstones (having formed various slates after regional metamorphism) at the periphery of Dolts that forms biotite hornfels or the recrystallization of quartz sandstones that results in the formation of metamorphic quartz sandstones or quartzites. The metamorphic quartz sandstone or quartzite assemblage constitutes the hornfelsic alteration zones formed by thermal contact metamorphism outside Dolts.

#### 3.4.1. Contact metasomatism

The Bayan Obo deposit has experienced two types of contact metasomatism: (1) the metasomatism of silicic country rocks by carbonatite magmas that leads to anti-skarns during the intrusion of the former into the latter, and (2) the typical skarns and associated mineralization related to the intrusion of late Paleozoic granites into carbonatites along the eastern contact zone. However, the second type of contact metasomatism primarily modified previously formed Dolts and orebodies, thus leading to limited alteration and mineralization.

#### (1) Anti-skarn alteration

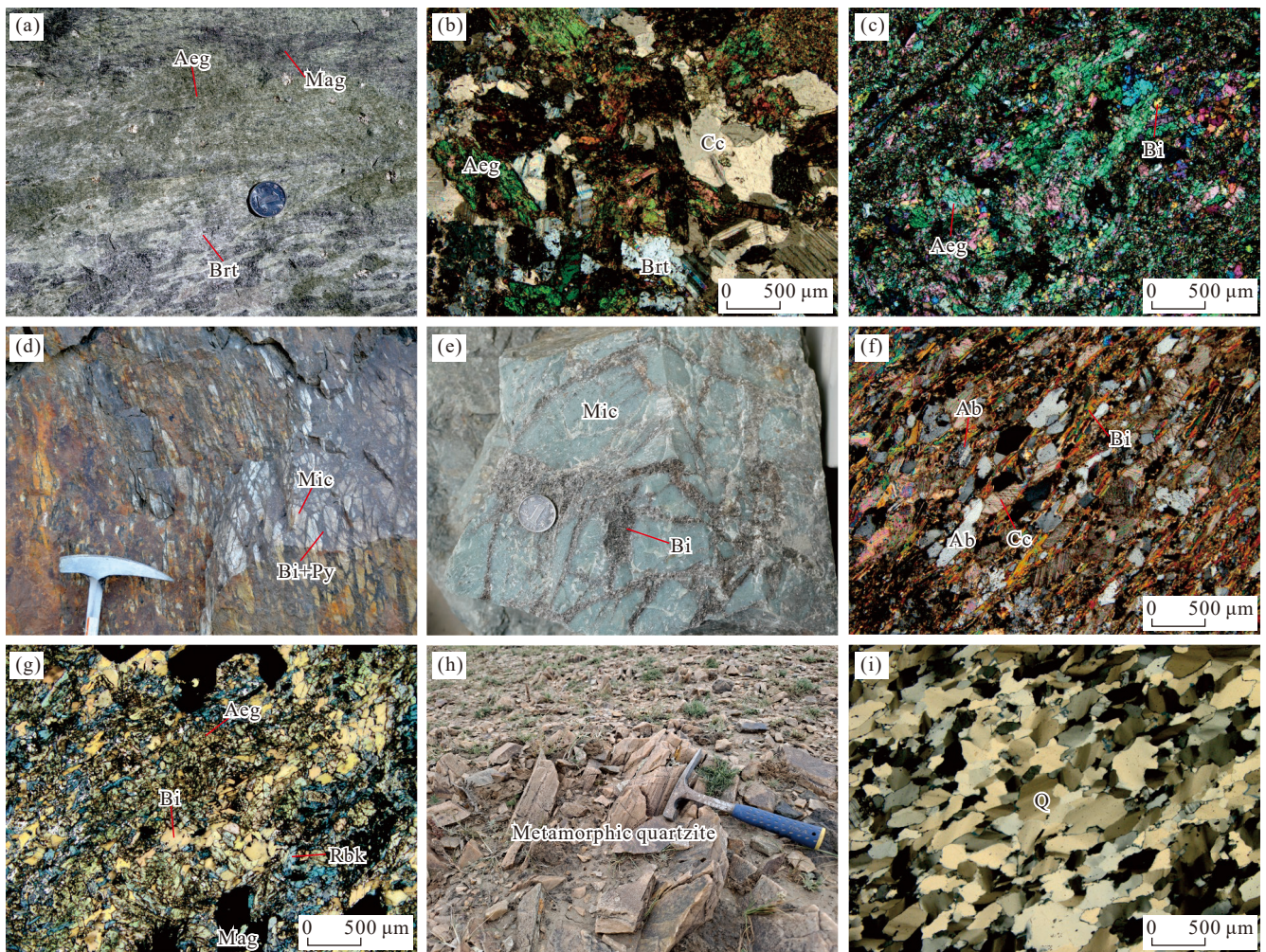
Anti-skarn refers to the metasomatic rocks formed by dimetasomatism between Dolts and country rocks near the contact zones during the intrusion of dolomite carbonatites (Figs. 3a–c). Anti-skarn consists primarily of aegirines and riebeckites. The siliceous constituents in the metasomatic minerals primarily originate from country rocks (the sandstones and siltstones of the Jianshan Formation), while the sodium, iron, calcium, and magnesium constituents are mainly from dolomite carbonatites. The formation of anti-skarn is similar to that of skarn (mainly comprising garnets and diopsides), which formed during the contact of granites and carbonate, except for the opposite material metasomatism and element migration directions. The anti-skarn in the Bayan Obo deposit is primarily found in the Main and East Orebody, specifically within and near the main orebodies. This type of alteration formed principally in the melt-fluid stage of carbonatite magma at a temperature inferred to be above 450°C. Comparable to the skarn-type deposit, the anti-skarn minerals formed early are also dominated by aegirines and riebeckites due to the superimposed modification in the late hydrothermal stage. Especially, since most of the aegirines have decomposed, the aegirines in the Bayan Obo deposit are distributed discontinuously in the form of relicts or lumps. The REE-rich orebodies in the deposit were primarily formed by the decomposition of anti-skarn minerals that was caused by the extensive activity of hydrothermal fluids rich in REEs and volatile matter.

#### (2) Skarn alteration

The eastern contact zone of the Bayan Obo deposit experienced typical skarn-type metasomatism characterized by dimetasomatism between granites and dolomites, forming a set of magnesium-rich skarn assemblages. The altered rocks include humite-phlogopite skarn, diopside-phlogopite skarn, and tremolite-phlogopite skarn. Except for diopside, phlogopite, and tremolite, alteration minerals generally include calcite, microcline, riebeckite, fluorite, apatite, and quartz, as well as minor amounts of metallic minerals such as magnetite, monazite, pyrochlore, allanite, niobite, and aeschynite. Altered rocks are distributed several to a dozen of meters away from the granites. The granites and skarns were formed primarily during the Permian according to the dating results of granites (Fan HR et al., 2009). These rocks, inferred to be formed by the modification of previous Dolts by intermediate-acid magmatism, and are not the major orebodies in the Bayan Obo deposit.

#### 3.4.2. Fenitization

The intrusion of ore-hosting dolomites led to fenitization, in addition to form anti-skarn near the contact zones. Especially, during the intrusion, copious alkaline substances such as potassium, sodium, calcium, and magnesium in magmas migrated extensively toward country rocks along with the hydrothermal fluids, leading to the intense hydrothermal metasomatic alteration of country rocks. This type of hydrothermal metasomatic alteration is named fenitization, primarily occurring in the high- and medium-



**Fig. 3.** Major alteration types in the Bayan Obo iron-REE deposit. a–Magnetite-bearing aegirine-type anti-skarns in the Main Orebody, with magnetite forming lenses in late deformation; b–aegirine-type anti-skarns, in the East Orebody, decomposed and metasomatized by late barites and calcites; c–banded aegirine-type anti-skarns, containing a minor amount of biotite; d–biotite-pyrite veinlet network in potassium-rich slates on the eastern wall of the East Orebody; e–biotite veinlets filling along the fractures of potassium-rich slates in the western pit in the West Orebody; f–fenites subjected to the albite and biotite alternation, with argillites serving as their protoliths; g–riebeckite-biotite fenites, containing a minor amount of magnetite, with argillites serving as their protoliths; h–metamorphic quartzites in the south of the Main Orebody, with quartz sandstones (with hornfelsic alternation) serving as their protoliths; i–medium-grained metamorphic quartzites, showing wavy extinction and directionality; Aeg–aegirine; Mag–magnetite; Brt–barite; Cc–calcite, Bi–biotite; Mic–microcline; Py–pyrite; Ab–albite; Rbk–riebeckite; Q–quartz.

temperature hydrothermal stage during the intrusion of ore-hosting dolomites.

Fenitization is widespread within the ore-hosting dolomites and in the peripheral Jianshan Formation, especially near contact zones. Alteration minerals include aegirine, alkaline hornblende, hornblende, actinolite, calcite, potassium feldspar, biotite, and albite. They are predominated by aegirine and alkaline hornblende, which primarily comprise alkaline pyroxene and riebeckite, respectively (Fig. 3g). In previous literature, the so-called aegirine, riebeckite, potassium feldspar, biotite, and calcite alteration were all related to fenitization. Various alteration mineral assemblages have been formed due to the differences in mineral composition and alteration intensity, and they are referred to as different types of alteration and rocks.

The most intense fenitization in the Bayan Obo deposit is principally found in the contact zone between Dolts and the

Jianshan Formation's country rocks, followed by xenoliths within the Dolts. The xenoliths are generally blocky or banded fenites due to metasomatism. The primary alteration minerals include aegirine, riebeckite, biotite, and a minor amount of calcite, and their protoliths are inferred to be the argillites or argillaceous siltstones (transitioning into silty slates or sericite slates post-metamorphism) in the first member of the Jianshan Formation (H3). A closer distance from Dolts to the contact zone is associated with higher riebeckite and biotite contents, succeeded by the albite and potassium feldspar contents. The fenites are generally green or dark grayish-green. The metasomatism weakens gradually from the contact zone toward the country rocks, with alteration minerals progressively dominated by albite, along with minor quantities of biotite, riebeckite, potassium feldspar, and calcite, which are grayish-green or green and gray. The distal areas of the contact zone primarily show

weak riebeckite alteration, with the presence of a small amount of albite. The riebeckite, roughly occurring as veins, is gray or grayish-green in color and retains relatively intact protolith structures. The zone with intense fenitization along the major contact zone of Dolts represents the current width of the orebodies in the Main Orebody, up to 300–400 m. The intense biotite-riebeckite alteration zone along the periphery of the contact zone is up to 10–20 m wide, with a small amount of riebeckite still visible 500 m away from the Dolts. Fenites are scarce around small-scale carbonatite dykes, with fenitization zone widths mostly less than 1 m.

Weak metasomatism is present within the ore-hosting dolomites, merely encompassing weak fenitization. Within the ore-hosting dolomites immediately close to the contact zone, minor amounts of humite, riebeckite, and biotite are generally visible, which is largely due to the weaker activity of  $\text{SiO}_2$  compared to Ca, Mg, K, and Na in the country rocks. Little  $\text{SiO}_2$  migrates into the ore-hosting dolomites, while the highly active Ca, Mg, K, and Na can migrate far away under the thermal drive of the ore-hosting dolomites. Therefore, the external zone of the ore-hosting dolomites is subjected to more significant alteration.

The intensity of fenitization is related to the carbonatite pluton size, contact-zone structure, and protolith composition. A larger carbonatite pluton and more fault structures in the contact zone correspond to more intense alteration and larger orebodies. The country rocks, which consist of silty rocks and argillaceous siltstones, contribute to intense fenitization. By comparison, the country rocks that mainly comprise quartz sandstones exhibit weak fenitization, with veined riebeckite alteration developing locally. The xenoliths within Dolts generally show intense fenitization. The alteration products are mostly intact fenites and are accompanied by mineralization.

In previous literature, albitites and potassium-rich slates were always treated as sodium- or potassium-rich rocks with unknown origins. Sometimes they were regarded as volcanic rocks or submarine hydrothermal sedimentary rocks. However, albitites and potassium-rich slates are both fenitization products formed by the alteration and metasomatism of the potassium and sodium in Dolts after the plutons entered country rocks during their intrusion. Albitites are the most widespread in the country rocks close to the deposit. They appear as layered or banded pure albitites or arfvedsonite-albite interbeds on the mining face to the south of the Main Orebody. Pure albitites, milky white, form black riebeckite albitite bands in the case of high arfvedsonite content. Therefore, the albitites mostly exhibit alternating black and white bands and are gradually integrated with potassium-rich slates and biotite schists. The albitites are enriched in sodium, with a  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  content of over 8% and a  $\text{Na}_2\text{O}$  content generally exceeding 6%. Such rocks primarily include albitites, albitite riebeckites, and biotite-riebeckite slates, which are the same type of altered rocks actually, with merely slightly varying mineral compositions in different locations.

Potassium-rich slates are the most extensive in places where carbonatite dykes or veins are presented, with an overall alteration range varying between 300 and 500 m. They can be divided into two types according to their colors: grayish-green to yellowish-green slates and black-green slates. These rocks, which show tight blocky or banded structures, are microcrystalline or cryptocrystalline, with grain sizes below 0.01 mm, and contain irregular acicular aggregates in a directional arrangement. For some potassium-rich slates containing microplagioclase (up to 0.1 mm), they are densely distributed as lenses or veinlets (Fig. 3e). A 200–300m thick, potassium-rich slate zone is found between the Main and East Orebody. With  $\text{K}_2\text{O}$  contents of up to 7%–16%, the potassium-rich slates in this zone meet the criteria for comprehensive utilization and can be used as raw materials of potassium fertilizer (Fei HC, 2005; Institute of Geochemistry, Chinese Academy of Sciences, 1988).

Additionally, in the late stage of hydrothermal activity, veinlets of various mineral assemblages were formed in the Bayan Obo deposit, penetrating or cutting into various mineral assemblages that formed in the stages of contact metasomatism and thermal metamorphism. Minerals that formed in the veined mineralization stage include calcite, fluorite, barite, pyrite, galena, pyrrotite, and sphalerite. These minerals generally show weak alteration or limited recrystallization at vein edges. Therefore, the vein-type mineralization is not a major alteration type.

#### 3.4.3. Hornfelsic alteration

Hornfelsic alteration refers to the thermal contact metamorphism of country rocks caused by the intrusion of carbonatite magma. Hornfelsic alteration in the Bayan Obo deposit can be divided into two types: (1) the contact metamorphism-induced recrystallization of argillites, argillaceous siltstones, and siltstones that leads to the formation of biotite, sericite, and further biotite hornfels, and (2) the heat-induced recrystallization of quartz sandstones that results in the formation of metamorphic quartz sandstones and quartzites. The biotite hornfels and biotite-albite hornfels near the fenites that are close to contact zones generally contain minor amounts of monazite. Additionally, some of them contain magnetite, forming hornfel-type magnetite ores.

## 4. Characteristics of Orebodies and the metallogenic belt

The Bayan Obo deposit is hosted in the dolomite carbonatites and the contact zone between these dolomite carbonatites and their country rocks—slates, along the southern flank of the Kuangou anticline, between both flanks of the Bayan syncline. This deposit forms a narrow E-W-directed metallogenic belt that stretches approximately 18 km in length and 2–3 km in width (Fig. 2). Based on the distribution of various deposits, as well as the exploration and exploitation conventions, the Bayan Obo deposit can be divided into four ore blocks from east to west: the Eastern Contact Orebody (including the Boluotou Orebody), the East Orebody (including Dongjielegele ore block), the Main

Orebody (including the High-magnetism Orebody), and the West Orebody (Fig. 2). In the chronological order of their discovery, these orebodies include the Main Orebody, the East Orebody, the West Orebody, and the Eastern Contact Orebody (including the Boluotou Orebody).

The Main Orebody, including the ore block exhibiting high-amplitude magnetic anomalies, is located in the NNW of the Bayan Obo area, with a linear distance of 2.5 km. The orebody lies on the northern flank of the Bayan syncline, with a W-E length of 1250 m and a N-S width of 415 m, making it the largest orebody in the Bayan Obo deposit. Several associated small orebodies are also distributed on the north and south sides of the Main Orebody. Additionally, the High-magnetism Orebody is situated on the southern flank of the Bayan syncline.

The East Orebody (i.e., the Ulan iron orebodies, including the Dongjielegele Orebody) is situated 200 m to the east of the Main Orebody. Its orebody extends 1200 m long in the W-E direction and up to 350 m wide in the N-S direction, serving as the second largest orebody in the Bayan Obo deposit. The Dongjielegele Orebody lies within the southeastern part of the East Orebody and on the southern flank of the Bayan syncline.

The orebody of the West Orebody extends from the No. 2 exploration line in the west to the No. 96 exploration line in the east, encompassing a total length of approximately 10 km and a N-S width of around 1 km. This orebody comprises northern and southern metallogenic belts, which are 200–500 m apart, with the distance gradually increasing towards the west. The orebody, mainly occurring in ore-hosting dolomites, comprises multiple small lentoid orebodies.

The Eastern Contact Orebody, including the Boluotou Orebody, is situated on the northern flank of the Bayan syncline to the east of the East Orebody, lying in the area where ore-hosting dolomites are in contact with Jurassic granites.

In the Bayan Obo deposit, iron, niobium, and REE orebodies are intimately associated with each other in paragenesis, occurring primarily within the Mesoproterozoic dolomite carbonatites (i.e., Dolts) and the contact alteration zone between these Dolts and their country rocks. The distribution and occurrence of these orebodies mirror that of the country rocks, displaying stratoid or lentoid shapes that vary in scale and morphology according to those of the dolomite carbonatites. Notably, dolomite carbonatites diminish towards the western portion of the deposit. However, they progressively widen and deepen towards the east along the No. 3 exploration line, resulting in correspondingly larger orebodies.

The entire dolomite carbonatite serves as the host for iron, REE, and niobium mineralization. The entire Dolt rock mass comprises REE orebodies, while varying sizes of iron orebodies have been delineated in Dolts and their contact alteration zone with country rocks based on an industrial grade of TFe > 20%. Due to large-scale REE mineralization, the spatial distribution of orebodies reveals an intermingling

and cross-cutting relationship between REE iron orebodies.

Iron, niobium, and REE orebodies exhibit paragenesis either within the same or different orebodies. Paragenesis within the same orebodies refers to the coexistence of REEs or niobium in iron orebodies, with both exhibiting an identical special relationship. In the Main and East Orebodies, iron orebodies exhibit a higher REE content compared to dolomite carbonatites as their country rocks. The reverse is true for the West Orebody. Paragenesis in different orebodies means that REE or niobium ores occur in the country rocks of iron ores and are separated from them. In this case, iron, niobium, and REE orebodies in the Main, East, and West Orebodies demonstrate distinct spatial relationships.

#### 4.1. Characteristics and sizes of orebodies

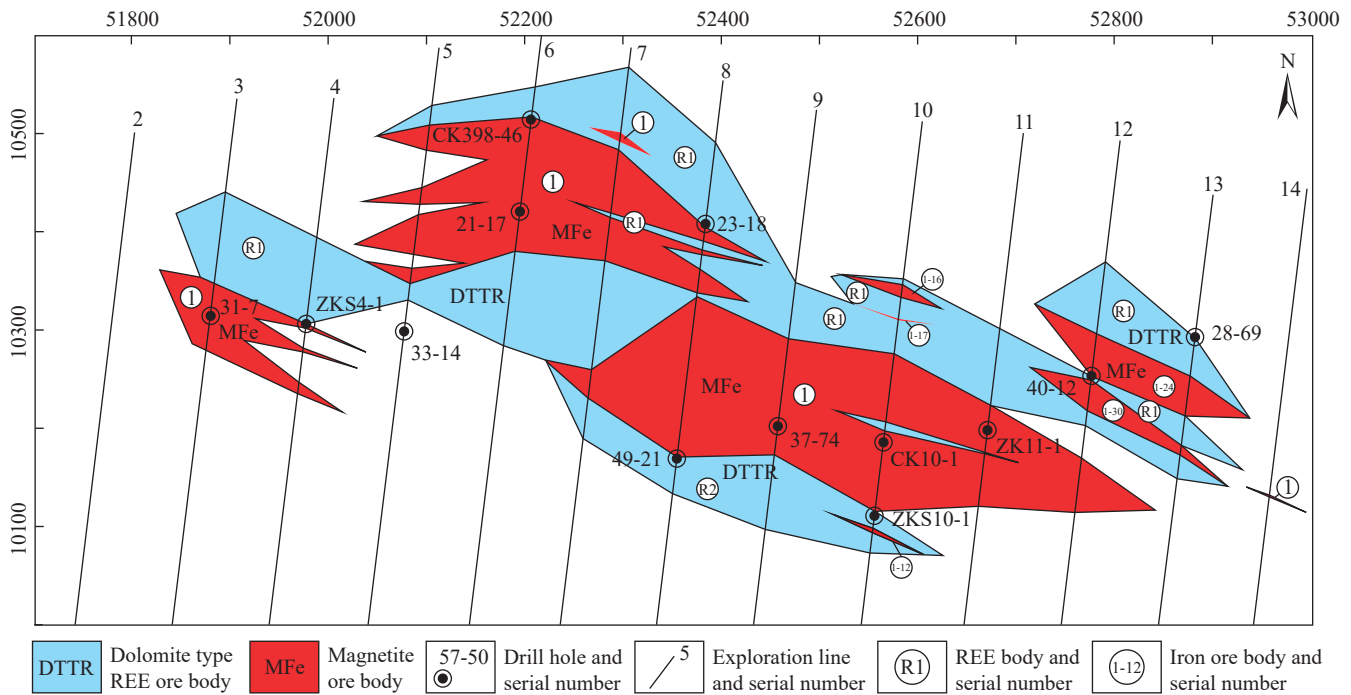
The iron and REE orebodies in the Bayan Obo deposit are exclusively found within Dolts and the contact alteration zones between these plutons and their country rocks—slates. Typically exhibiting a podiform shape, they extend in a W-E direction. These orebodies display extensive outcrops that gradually thin downward before diverging and eventually disappearing. In the West Orebody, the scattered outcrops and disconnected ore layers form concealed bodies.

##### 4.1.1. The Main Orebody

The Main Orebody consists of a podiform iron orebody, referred to as the No. 1 orebody, which includes 29 branch orebodies. These orebodies are wide in the central part, and narrow toward both ends, with a broad upper section that gradually tapers downwards. As interlayers are inserted vertically into the surface and underground east and west during pinch-out, vertical country rocks are wedged into the orebodies from bottom to top, causing them to split. The boundaries of these large-scale orebodies in the Main Orebody are deep and undelineated. For instance, the outcrops of the No. 1 orebody have a slightly podiform shape with a W-E length of 1250 m and a maximum N-S width of 415 m between the No. 7 and No. 8 exploration line profiles. Furthermore, this particular orebody reaches a maximum burial depth of 970 m along the No. 8 exploration line profile.

As shown in the 1260 m horizontal section map (Fig. 4), the orebodies in the Main Orebody spread from No. 2 to No. 14 exploration lines, with a NWW-SEE strike and an overall nearly E-W-trending distribution. On the north side of the mining area, thick REE orebodies are located on the foot wall, overlain by iron orebodies. Iron orebodies are distributed on the south side of the hanging wall of the REE orebodies. Small amounts of REE and niobium ores can be found on the hanging wall on the south side of the iron orebodies. Lenticular niobium ores are distributed between the No. 8 and No. 14 exploration lines, with slates widespread along their southern margin.

The profiles reveal that the iron, REE, and niobium orebodies are obliquely superimposed upon each other. For instance, along the No. 8 exploration line (Fig. 5), thin



**Fig. 4.** Horizontal section at a depth of 1260 m showing the iron, rare earth element, and niobium orebodies in the Main Orebody of the Bayan Obo deposit.

niobium orebodies, REE orebodies, and thick iron orebodies occur roughly from south to north with thick REE-bearing dolomites lying on the foot wall. The iron and REE orebodies are intercalated in veins, with the latter interspersed within the former. As depth increases, the iron orebodies gradually pinch out while conversely REE orebodies.

#### 4.1.2. The East Orebody

The orebodies in the eastern part of the ore block are narrow in the west and wide in the east. The main orebody, numbered No. 2 comprises 20 branch orebodies. The orebodies in the eastern portion diverge and pinch out to the east of the No. 24 exploration line, manifesting significant changes. A small separate orebody is formed by country rocks in the northeastern part of No. 2-1 orebody, extending over 800 m along the dip direction. The deep boundaries of the superlarge orebodies in the eastern portion are undelineated. The No. 2 orebody in the East Orebody has a NEE strike, with a W-E length of 1200 m. Its western and eastern portions show S-N widths between 50–115 m and approximately 350 m, respectively. The southward-inclined orebodies thin out downward, without defined deep boundaries. The maximum extension of these orebodies has not been determined yet. Currently, the deepest borehole (WK20-2) in the East Orebody has footage of 1775.4 m, and the elevation of the end location of the drilling hole is -100 m. However, it still fails to penetrate dolomites on foot wall. Drilling results confirm high REE mineralization within, dolomites reaching cut-off grade, indicating considerable resource potential for deeper parts of the Bayan Obo deposit. A majority of iron orebodies are paragenetic with REE orebodies, while niobium and REE orebodies can also be found in dolomites outside iron orebodies. Individual REE and niobium orebodies will not be

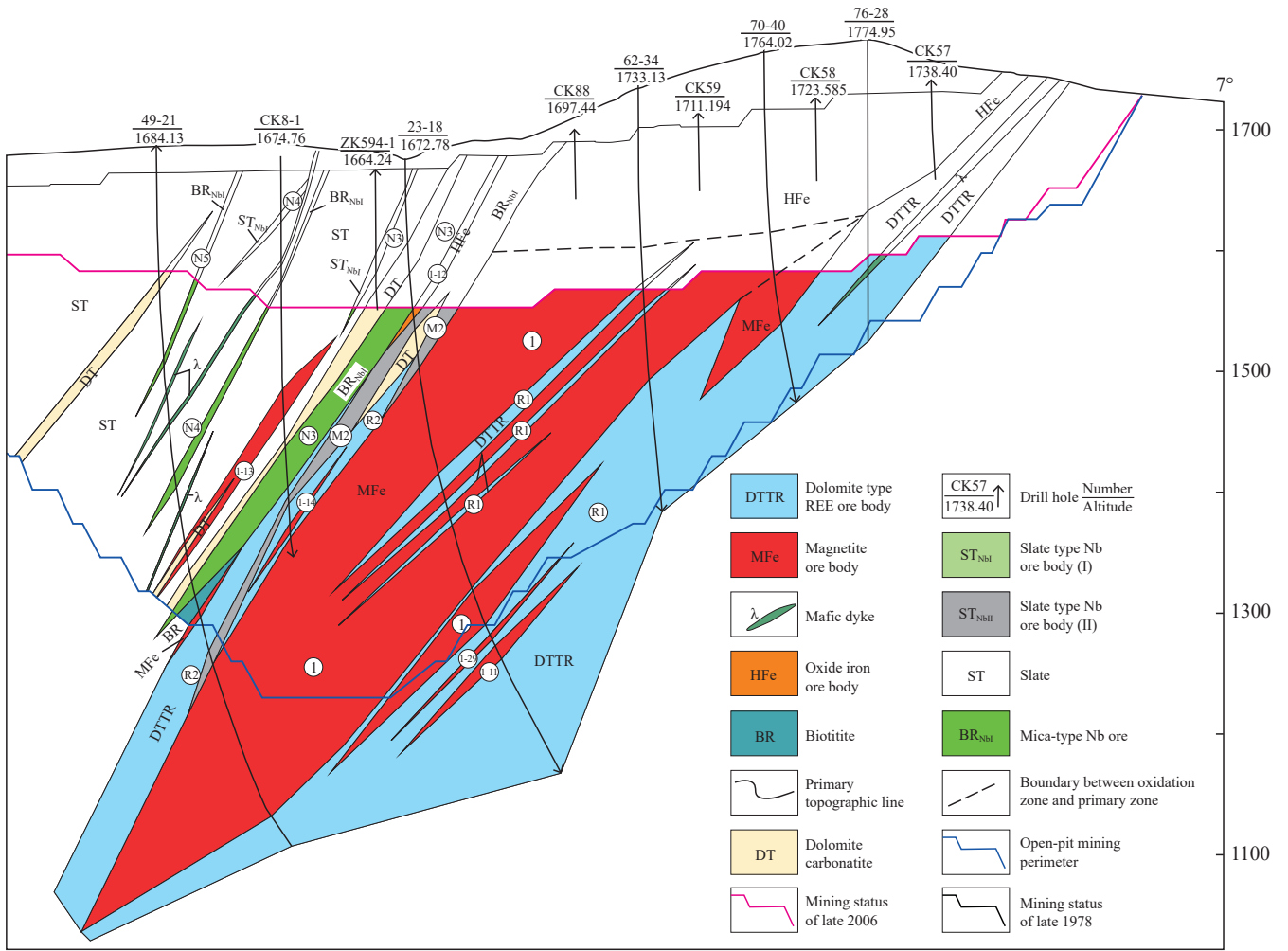
detailed in this study.

The horizontal section at a depth of 1430 m reveals NW-extending orebodies, including REE, iron, and REE orebodies sequentially from north to south. Besides, a few niobium orebodies are distributed between the Nos. 16 and 19 exploration lines on the southwest side. The orebodies are intermingled with mafic and mica dykes, surrounded by slates (Fig. 6). The niobium orebodies in the southern region exhibit small dimensions and thin layers. Thick layers of REE and iron orebodies are vertically stacked, forming a multi-layer structure with the foot wall (in the north) still hosting REE orebodies.

For instance, along the NNW-oriented No. 22 exploration line (Fig. 7), a few quartzite-slate interlayers are exposed on the south side of the mining pit. Within the pit, abundant slates can be found in the south, overlying dolomite-type REE ores with some local iron ore lens. Thick magnetite orebodies underlie the REE orebodies and exhibit a feather-like, parallel distribution pattern of elongated fluorite-type REE ores. These magnetite orebodies overlie aegirine and riebeckite rocks. Dolomite-type REE orebodies are distributed beneath thick iron orebodies, which are undetermined in thickness and also contain lentoid magnetite orebodies in the deep parts.

#### 4.1.3. The West Orebody

Based on the exploration campaign in 1987 and supplemented by recent data, the West Orebody is divided into 11 main iron orebodies: eight in Dolts and three in dolomites and surrounding alteration-derived mica slates. These iron orebodies are numbered I ( $I^1$ ,  $I^2$ ), II, III ( $III^1$ ,  $III^2$ ), IV, V ( $V^1$ ,  $V^2$ ), VI ( $VI^1$ ,  $VI^2$ ), VII VIII, IX, X, and XI. Among them, Nos. I, II, III, IV, V, and VI orebodies contribute to 95.6% of the total ore reserves. Moreover, the Nos. I, III, IV,



**Fig. 5.** The No. 8 exploration line profile showing the iron, rare earth element, and niobium orebodies in the Main Orebody of the Bayan Obo deposit.

and V orebodies are large-scale with reserves exceeding 100 Mt each. Together with 102 affiliated orebodies, the West Orebody possesses 113 iron orebodies in total (Fig. 8). The orebodies are concentrated in the central region between the Nos. 16 and 48 exploration lines, exhibiting large scales and a maximum depth of 855 m (along the No. 40 exploration line). The orebodies in the western region (west of the No. 16 exploration line) have shallow depths. On the other hand, the orebodies in the eastern region (east of the No. 48 exploration line) manifest small thicknesses, scales, and extension bodies. The Nos. V and III orebodies serve as the largest in this area, hosting 58.6% of the total iron ore reserves.

Niobium mineralization is widespread in the West Orebody, forming four niobium-bearing horizons with varying shapes: (1) niobium orebodies within dolomites and slates in the upper part of Dolts; (2) niobium orebodies in the lower part of Dolts; (3) niobium orebodies in the upper part of Dolts, and (4) niobium orebodies within dolomites and slates in the H9 stratum. They are mostly lentoid or stratoid in shape, with attitudes consistent with those of the iron orebodies and showing a parallel distribution. A total of 362 isolated niobium orebodies are concentrated between the Nos. 16 and 48 exploration lines mainly consisting of single-

drilling-controlled lens-like formations. The largest orebody within the West Orebody is No. 254 orebody extending over a distance exceeding 1 km, hosting 23.4% of all known niobium reserves.

The REE orebodies in the West Orebody are extensive, but they exhibit lower grades (mostly between 1%–2%) compared to those in the Main and East Orebodies. The REE mineralization presents large-scale and overall mineralization, being divided into multi-layer orebodies by iron orebodies. Consequently, the REE orebodies diverge at sites with strong iron mineralization and converge at sites with weak iron mineralization. There are a total of 62 REE orebodies in the West Orebody. Among them, Nos. R4, R7, R36, and R59 host 94.75% of the total reserves, with the largest REE orebodies—R4 and R7—accounting for 60.24% of the total reserves. The REE orebodies gradually expand from west to east, first diverging and then converging, and those in the south gradually diminish.

The orebodies in the West Orebody are controlled by a Bayan syncline (synform), with a core composed of thick dolomite-type REE orebodies and flanks consisting of alternating stratiform or lentoid iron, REE, and niobium orebodies. For example, along the No. 8 exploration line,



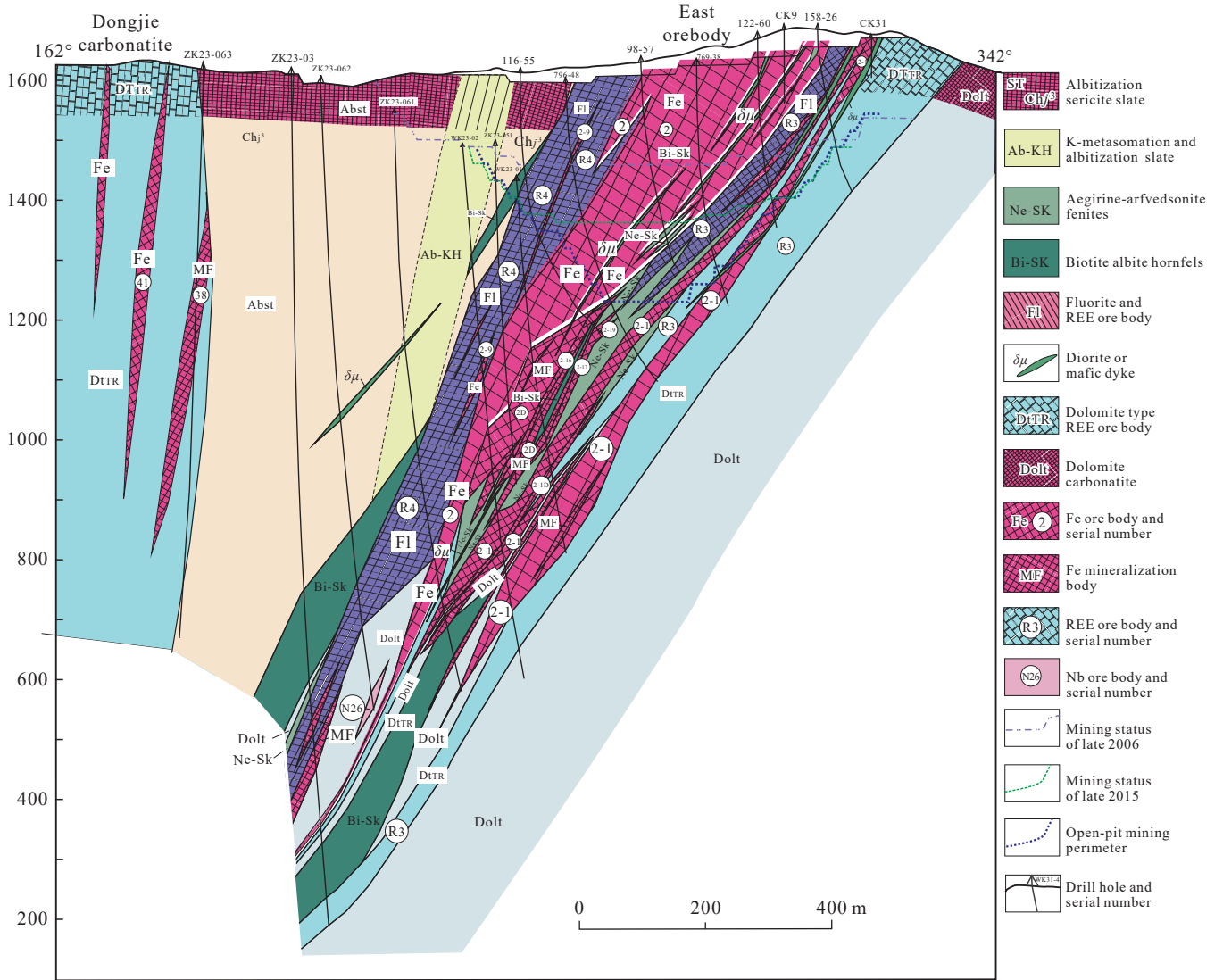


Fig. 7. The No. 23 exploration line profile showing the iron, rare earth element, and niobium orebodies in the East Orebody of the Bayan Obo deposit.

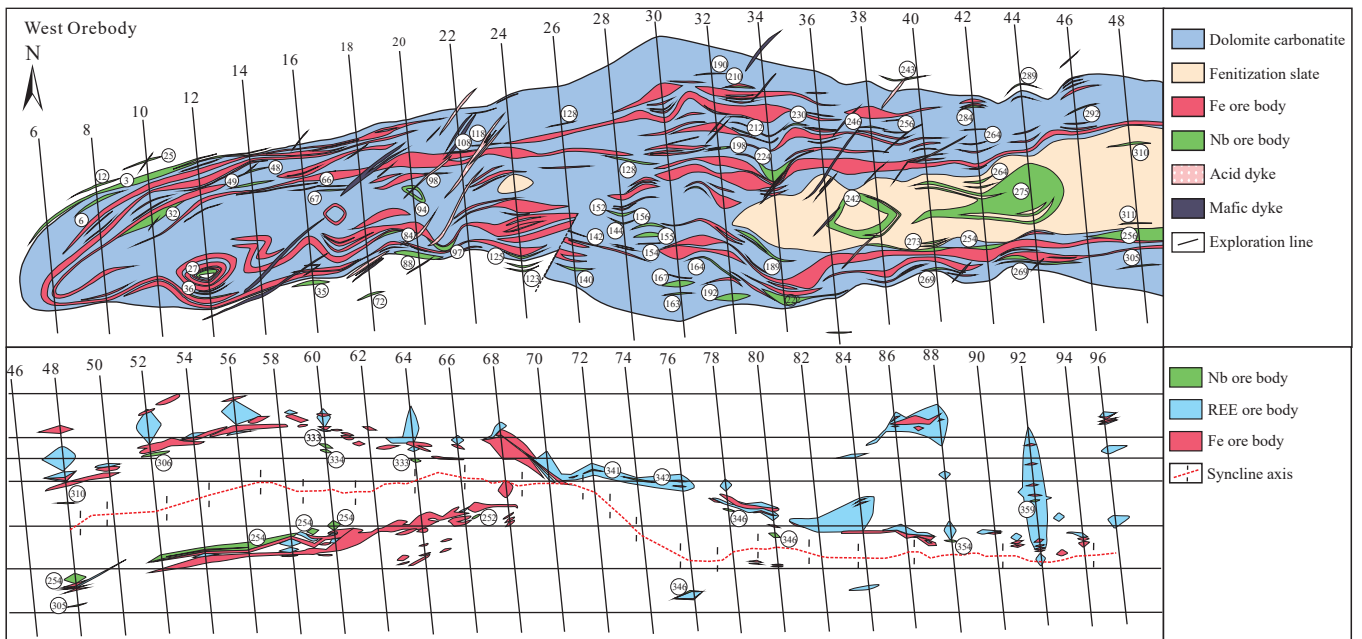
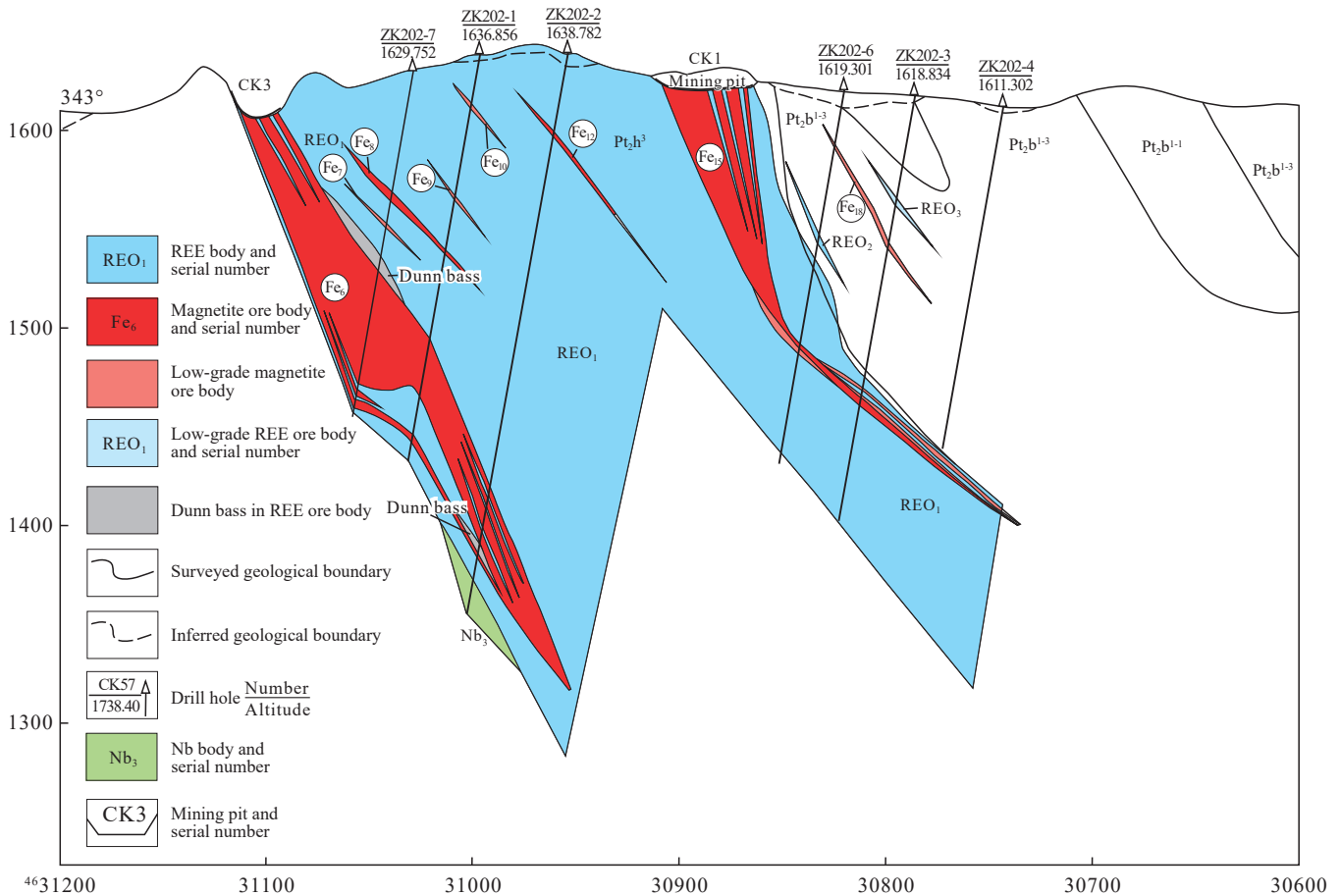


Fig. 8. Map showing the spatial distributions of iron, rare earth element, and niobium orebodies in the West Orebody of the Bayan Obo deposit.



**Fig. 9.** The No. 202 exploration line profile showing the iron and rare earth element orebodies in the Eastern Contact Orebody.

completely delineating REE ores.

## 4.2. Compositions of ores and minerals

### 4.2.1. Ore types

The two main orebodies in the main and eastern blocks, along with the iron-REE orebodies in other blocks, are closely associated with fenitization. This suggests that the Bayan Obo deposit was formed through the metasomatism between iron-REE-enriched carbonatite magmas and the country rocks. In this study, the ore types and mineralization zoning were updated based on the latest opinion on the origin of the deposit. As a result, it is considered that the mineralized zones are distributed around and on both sides of the contact zone. The details are as follows: (1) The center of the contact zone experienced significant fenitization, resulting in the formation of blocky iron-REE ores with almost complete decomposition of original minerals in finites; (2) Banded REE-Fe ores with slightly low grade of iron ores and some riebeckite and aegirine minerals can be found from the center to both sides of the contact zone. Meanwhile, fluorites have also developed, and the REE content increases; (3) On the side of the contact zone toward rock masses, REE-bearing carbonatite orebodies are found; (4) From both sides towards country rocks, finites transition into hornfel-type REE ores which gradually transform into hornfels and altered rocks without any ores outward.

The mineralization and alteration zones from the carbonatite center toward country rocks are as follows: REE-bearing carbonatite zone → carbonatite-type REE ore zone → banded (fluorite-aegirine-riebeckite) iron-REE mineralized zone → blocky iron-REE ore zone → banded fluorite-aegirine-riebeckite iron-REE mineralized zone → biotite-albitite-REE hornfel mineralization zone → albitite potassic alteration zone → weak riebeckite-sericite alteration zone. This zoning may be incomplete in some sections due to tectonic effects among others. Due to metasomatism, country rock xenoliths within the Dolts could also form similar but generally incomplete mineralization zoning, mostly developing into low- to middle-grade iron-REE ores with aegirine-riebeckite bands. These ores have slightly lower mineralization grade and quality compared to the ores in the contact zone.

Accordingly, the ore types in the Bayan Obo deposit can be simplified into four major types: dolomite-type REE ores, banded fenite-type REE-Nb-Fe ores, massive REE-Nb-Fe ores, and hornfel-type REE-Fe ores. Additionally, a small quantity of skarn-type REE-Fe ores are found in the eastern portion of the deposit.

### (1) Dolomite-type REE ores

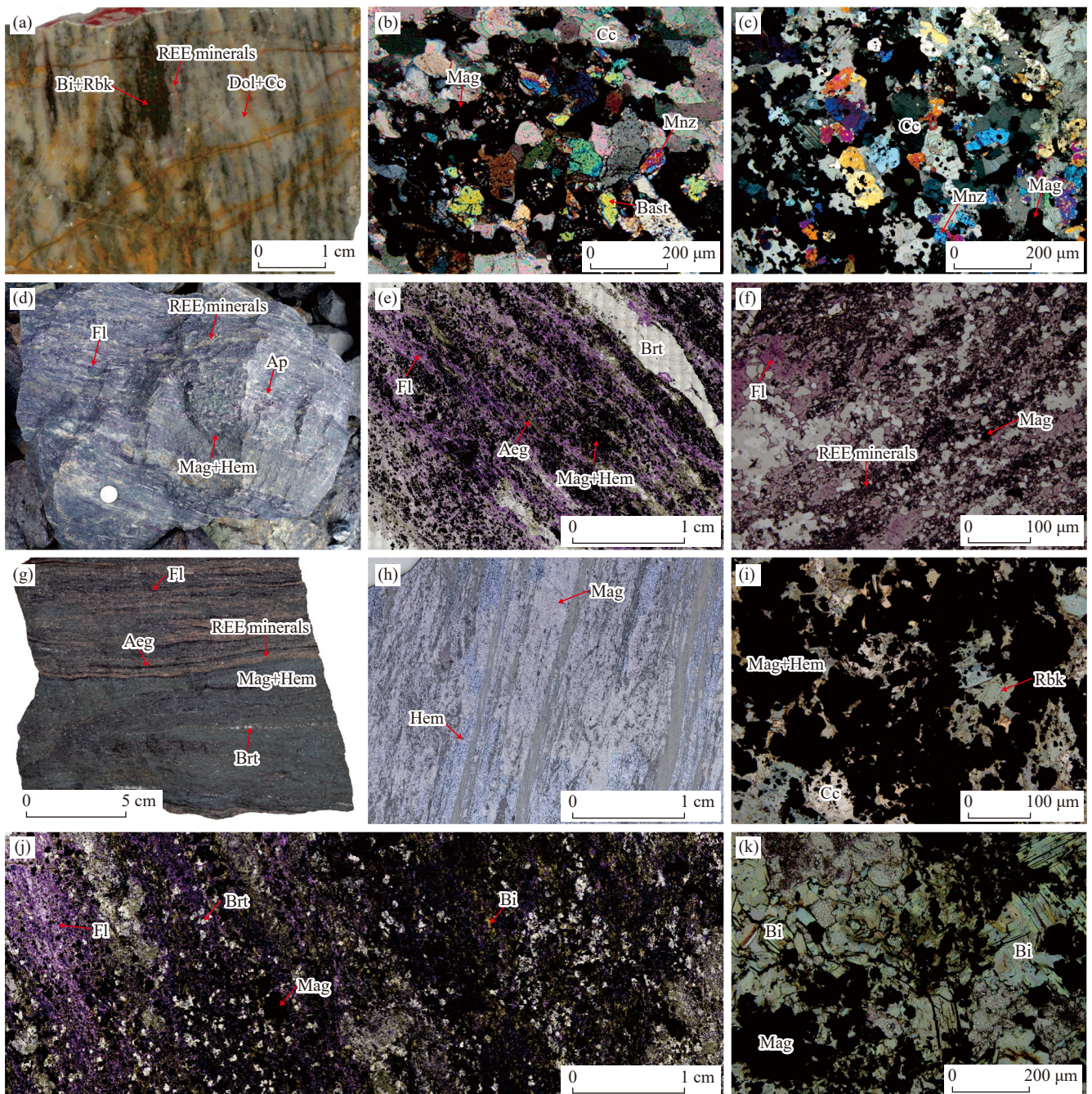
Dolomite-type REE ores are mainly found in the Bayan Obo deposit, which is extensively exposed in the Eastern Contact Orebody, as well as the East, Main, and West orebodies. These ores exhibit blocky, disseminated, or

veinlet-disseminated structures (Figs. 10a–c). Dolts in the deposit generally contain over 1% REEs ( $\text{RE}_2\text{O}_3$ ; Table 3), which provide the largest proportion of REE reserves. However, near the edge of Dolts or in proximity to the contact zone, the REE content is generally higher and meets the ore criteria. The mineral composition of these ores is dominated by dolomites (above 90%), with fine-grained textures and widespread fluorites, magnetite, monazites, and bastnaesites. Due to late regional metamorphism, directional structures can be observed in most carbonatites. Besides, some Dolts exhibit insignificant banded structures, containing primary banded minerals such as apatite, bastnaesite, riebeckite, fluorite, and

humite. There exist some small Dolts whose whole-rock grades meet the criteria for REE ores, such as the Dongjielegele carbonatite pluton.

## (2) Fenite-type REE-Nb-Fe Ores

Fenite-type REE-Nb-Fe Ores are primarily distributed near the foot wall in the Main and East orebodies (i.e., in the northern parts), occasionally found on the upper wall near the East Orebody but are rare in the West Orebody. Their upper parts are adjacent to blocky iron ores. Their primary minerals include aegirine, riebeckite, fluorite, magnetite, hematite, monazite, and various REE minerals such as bastnaesite. They generally contain a significant amount of residual silty quartz



**Fig. 10.** Typical ore types and structures of the Bayan Obo deposit. a–c–Dolomite-type REE ores; d–f–(Banded) fenite-type REE-Nb-Fe ores; g–i–Massive REE-Nb-Fe ores; j–k–Mica-type REE-Fe-fluorite ores; Aeg–aegirine; Brt–barite; Cc–calcite; Bi–biotite; Mic–microcline; Py–pyrite; Ab–albite; Rbk–riebeckite; Mag–magnetite; Hem–hematite; Fl–fluorite; Bast–bastnaesite; Mnz–monazite; Ap–apatite.

**Table 2. Chemical compositions of main ore types in the Bayan Obo deposit.**

Ore type	Location	Sample No.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	MnO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	TFe <sub>2</sub> O <sub>3</sub>	Loss on ignition	Nb ( $\times 10^{-6}$ )	REEs
Dolomite-type REE ore	Main Orebody	20BY06/01B	5.71	0.016	0.304	12.57	1.23	29.5	0.671	0.422	1.93	6.79	29.64	21.7	5.27
	Main Orebody	20BY06/02B	7.23	0.023	0.323	11.44	0.962	32.72	1.06	0.566	0.596	4.45	27.97	25	4.24
	Main Orebody	20BY06/06B	1.95	0.009	0.077	10.36	0.858	41.21	0.185	0.127	0.167	3.9	26.85	31.9	3.53
	West Orebody	17XK05/1B	0.46	0.01	0.01	15.8	2.24	23.7	0.1	0.03	0.58	12.75	41.69	76.2	1.12
Dolomite-type iron-REE ore	Main Orebody	20BY03/16B	<0.010	0.268	0.07	3.05	0.697	19.5	<0.010	0.061	3.36	50.68	10.6	1132	3.93
	Main Orebody	20BY03/22B	<0.010	0.137	0.078	5.66	1.06	32.64	<0.010	0.045	1.35	27.47	19.19	427	3.04
	Main Orebody	20BY03/25B	1.47	0.311	0.078	4.5	0.521	21.98	0.08	0.144	6.69	33.44	13.62	794	8.8
	West Orebody	17XK09/1B	4.27	0.14	0.01	10.6	2.55	15.98	0.63	0.18	0.13	32.9	28.14	500	0.78
Massive REE-Fe ore	Main Orebody	20BY01/03B	6.15	0.169	<0.010	0.181	0.456	4.05	1.22	0.012	0.622	79.95	0.1	233	2.56
	Main Orebody	20BY01/16B	3.68	0.4	0.107	1.46	0.951	22.17	0.312	0.331	1.32	54.1	2.45	491	2.13
	Main Orebody	20BY01/23B	0.049	0.027	<0.010	2.6	2.01	18.74	<0.010	0.064	0.053	57.87	10.74	109	0.14
	Main Orebody	20BY01/31B	2.5	0.119	0.065	3.36	2.47	13.38	0.154	0.266	0.608	61.92	11.76	158	0.86
Fenite-type REE-Nb-Fe ore	Main Orebody	20BY04/23B	11.78	0.157	0.16	3.63	6.33	19.97	1.42	0.426	0.788	34.09	5.98	355	2.9
	Main Orebody	20BY08/25B	22.53	0.057	0.343	0.33	0.047	7.16	4.48	0.022	3.45	46.7	3.06	120	7.04
	Main Orebody	20BY04/09B	7.39	0.1	0.287	2.6	4.36	26.57	0.657	0.538	2.177	25.5	6.65	63	4.54
	Main Orebody	20BY04/23B	11.78	0.157	0.16	3.63	6.33	19.97	1.42	0.426	0.788	34.09	5.98	355	2.9
Biotite hornfel-type ore	West Orebody	17XK16/1B	14.5	0.03	0.05	10.5	2.18	13.4	2.13	0.23	0.13	26	27.55	289	0.99
	Main Orebody	BY2106	27.29	1.94	18.04	11.05	0.12	0.34	0.63	4.36	0.16	30.03	3.16	340	0.23
	East Orebody	BY2123 0	36.49	5.72	14.91	5.28	0.76	1.13	1.18	7.75	0.05	22.71	1.15	2140	0.12
	East Orebody	BY2125 3	44.84	0.32	0.44	10.35	1.6	5.96	2.56	0.61	0.19	30.1	1.74	759	0.4
	West Orebody	XK33	14.32	3.47	3.85	12.55	1.75	10.25	0.1	3.47	1.12	29.08	12.68	1170	0.97

(5%–30%), followed by potassium feldspar, albite, barite, and calcite. Their mineral bands are typically composed of fluorite, REE minerals, calcite, aegirine, and riebeckite. Depending on the mineral compositions, fenite-type REE-Nb-Fe ores can be subdivided into several subtypes, such as fluorite, aegirine, riebeckite, or calcite subtypes. Fluorite-bearing REE-Nb-Fe ores, commonly found in this deposit, serve as the primary high-grade REE ores due to their high contents of various REE minerals. The aegirine REE-Nb-Fe ores generally contain 5% to 8% (occasionally up to 15%–20%) of REEs. These ores exhibit banded or veinlet-banded structures with band widths varying from 2 mm to 2–5 cm. Aegirine and riebeckite are the main minerals in green bands, while purple bands or veinlets are predominantly composed of fluorite (Figs. 10d–f). The presence of blocky aegirine ores interspersed with fluorite suggests that fluorite formed at a later stage than aegirine.

### (3) Massive REE-Nb-Fe Ores

Massive REE-Nb-Fe Ores are of the most significant type of iron ores in the deposit. They are primarily distributed in the central portions of the Main and East orebodies, transitioning to banded fenite-type REE-Nb-Fe Ores in the upper and lower portions of the orebodies. In the West Orebody, they appear as lenses within local dolomite-type iron ores. Their primary minerals include magnetite (above 65%) and hematite (Figs. 10g–i; Table 3), followed by fluorite and aegirine, with medium to high REE content. They also contain late-filled hydrothermal veins, such as aegirine-aeschynite, fluorite-bastnaesite, and fluorite-calcite-bastnaesite veins.

### (4) Hornfel-type REE-Fe ores

Hornfel-type REE-Fe ores, situated near the main orebody of the main contact zone, are prevalent in the West Orebody. They are composed of albite biotite hornfels and some biotite

Table 3. List of minerals identified in the Bayan Obo deposit.

Ore type	Iron ore	REE ore	Niobium ore	Thorium ore	Scandium ore	Fluorite ore	Potassium ore	Sulfide ore	Phosphate ore	Other	Total
Minerals	Magnetite, hematite, specularite (variant of hematite), siderite, limonite, ilmenite, goethite, lepidocrocite, martite, mushketovite, hercynite, picotite, jacobsite, etc.	Monazite, bastnaesite, parisite, cordylite, huanghoite*, cebait*, lanthanite, allanite, chevkinite*, britholite, cerianite, parisite-(Nd), rhabdophane, daqingshanite*, fergusonite-(Ce)*, clinofergusonite e-(Ce)*, aeschnynite-group minerals (aeschnynite-(Ce, Nb)*, aeschnynite-(Nd, Nb)*, aeschnynite-(Nd)*, aeschnynite-(Ce), titanium-rich aeschnynite, cerium-bearing aeschnynite, etc.), carbocernaite*, baiyuneboite*, unknown new mineral* ([Ca <sub>0.5</sub> □ <sub>0.5</sub> BaCe <sub>2</sub> (CO <sub>3</sub> ) <sub>4</sub> F]), etc.	Aeschnynite, pyrochlore, niobite, manganoniobite, ilmenorutile-rutile, fersmite*, broceenite, baotite*, niobium-titanium-neodymium, fluorine pyrochlore*, nioboixiolite*, etc.	Uranothorite, ferrothorite, monazite, thoriamite, aeschnynite-(Nd), etc.	Ilmenorutile, bastnaesite, magbasite, etc.	Fluorite	Microplagioclase	Pyrite, pyrrothite, galena, sphalerite, molybdenite, chalcopyrite, etc.	Monazite, apatite, rhabdophane, phosphorous-silica-calcium-cerium, etc.	Quartzite: quartz, silica, etc. Manganese: pyrolusite and psilomelane. Native gold, dolomite-related jade, aemite, baotite*, inkstone, etc.	185
Number of mineral types	20	30	10	6	3	1	1	6	4	103	
Exploitation and utilization	Utilized	Utilized	Pilot test: to be produced in 2013 as per planning	Formerly produced	Pilot test: to be produced in 2013 as per planning				Minerals such as silica and dolomite have been utilized		

Organized after Bayan Obo Iron Mine, Baotou Steel (Group) Co., Ltd. 2007. Annals of Bayan Obo iron deposit (1957–2006), 239–258. Note: \* denotes minerals discovered for the first time in China.

hornfels (Figs. 10j–k). Their primary minerals include albite, biotite, and magnetite, followed by aegirine, riebeckite, fluorite, magnetite, and minor amounts of sulfides like barite, pyrite, galena, and sphalerite. Besides, their REE minerals include bastnaesite, monazite, and aeschynite. The biotite appears dark green under a microscope. The schistose structure is evident in hornfel-type REE-Fe ores, with a directional arrangement of biotite

### (5) Skarn-type ores

Skarn-type ores are distributed merely in the outer contact zone between granites and dolomites in the eastern portion. They are associated with humite-phlogopite skarns and riebeckite-alkalic feldspar skarns, but they are not the main ore type.

#### 4.2.2. Mineral composition of ores

The Bayan Obo deposit contains ores of multiple types and complex compositions. According to statistics, 185 types of minerals have been identified in the deposit, as detailed in Table 2. The ores host 20 types of iron minerals, 30 types of REE minerals, and 10 types of niobium minerals. Magnetite and hematite are predominant iron minerals, with the others including siderite and specularite. The REE minerals encompass monazite, bastnaesite, parisite, cordylite, and Huanghoite, which are dominated by the former two types. The niobium minerals include aeschynite, pyrochlore, niobite, manganoniobite, and ilmenorutile-rutile, with the former three types prevailing. Additionally, the ores also contain abundant elements such as thorium, potassium, sulfur, and phosphorus. The primary gangue minerals include fluorite, aegirine-augite, riebeckite, and barite, and the primary sulfides include pyrite and galena.

#### 4.2.3. Chemical composition and grade of ores

A total of 71 elements have been identified in the Bayan Obo deposit, including iron, niobium, and REEs, as well as various dispersed and radioactive elements. Blocky iron ores have an average TFe content of 58.78%. REEs in ores consist predominantly of cerium-group elements, accounting for 97% of the total REE content ( $\Sigma$ REE). The  $\Sigma$ REE is the highest in fluorite-type ores with a  $\text{TR}_2\text{O}_3$  content ranging from 5.89% to 18.40%, and the lowest in blocky niobium-REE iron ores with  $\text{TR}_2\text{O}_3$  content ranging from 0.49% to 2.88%. The ores in the Bayan Obo deposit are rich in Nb and depleted in Ta. Sodium pyroxene- and fluorite-type ores exhibit the highest niobium content at an average of 0.16%. The radioactive elements in ores are dominated by Th, with  $\text{ThO}_2$  and uranium contents ranging from 0.029% to 0.051% and from 0.00n% to 0.000n%, respectively. Dispersed elements such as Ga, In, Sc, Rb, Cs, Zr, and Hf show relatively low contents in ores. Other elements like Na, F, P, K, S, and Ba show relatively high contents in ores, with P enriched in the dolomites and K enriched in potassium-rich slates country rocks of iron ores.

Nb and REEs are primarily enriched in orebodies in the Main and East orebodies. The country rocks of the hanging and foot walls predominantly exhibit Nb and REE mineralizations occurring in dolomite-type ores, which

process significant industrial importance due to their large scales and high grades. In the West Orebody, rocks related to niobium and REEs include dolomites, biotites, and slates. In the eastern contact zone, niobium and REE mineralizations are concentrated in altered dolomites and phlogopite diopsidites, with an intermittent distribution of orebodies in the form of lenses.

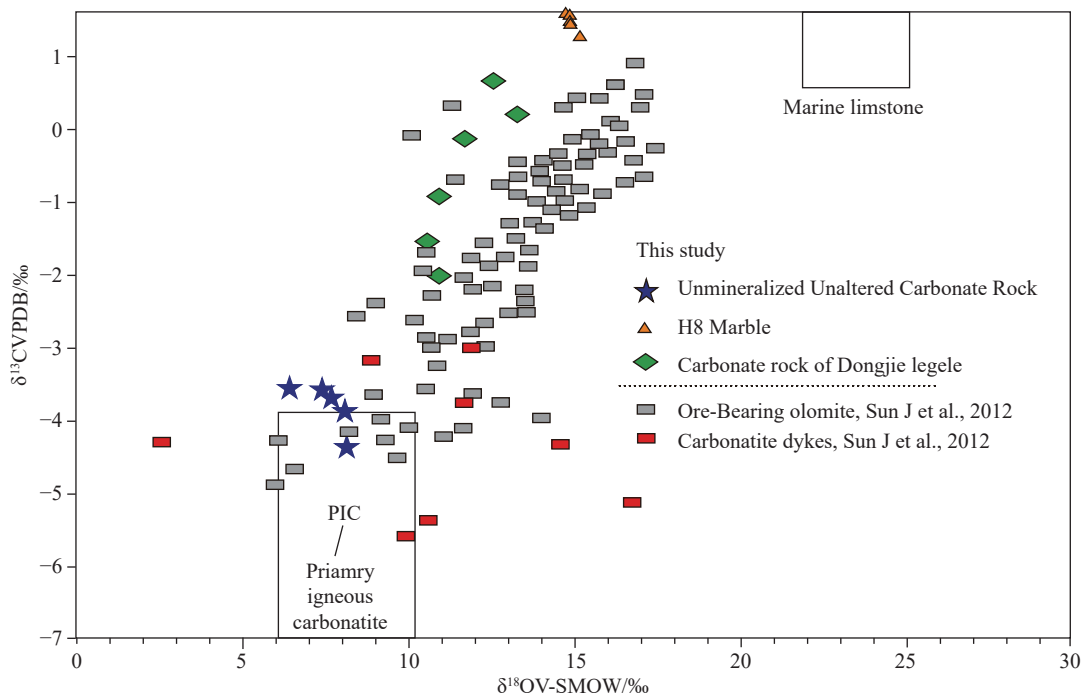
## 5. Geochemical characteristics of the Bayan Obo deposit

### 5.1. Carbon and oxygen isotope

Extensive studies have been conducted on the carbon and oxygen isotopes of various rocks, ores, and minerals in the Bayan Obo deposit. The carbon and oxygen isotopic compositions suggest three potential origins of the dolomites: (1) sedimentation in enclosed or partially enclosed basins; (2) mixing of deep-sourced thermal brines with seawater; and (3) formation from carbonatite magmas.

Different types of dolomites in the Bayan Obo deposit display a wide range of carbon and oxygen isotope values, which mainly align with the end members of typical igneous carbonatites and marine sedimentary carbonate rocks (Fig. 11). By comparison, the dolomites exhibit slightly variable carbon isotopic values, with  $\delta^{13}\text{C}_{\text{VPDB}}\text{‰}$  values ranging from  $-7.6\text{‰}$  to  $0.6\text{‰}$ , consistent with those of the normal mantle value ( $-5\text{‰} \pm 2.0\text{‰}$ ) (Hoefs J, 1987). However, they show significantly large range of oxygen isotope values, with  $\delta^{18}\text{O}_{\text{V-SMOW}}\text{‰}$  values vary between  $+6.7\text{‰}$  and  $+15.7\text{‰}$ , surpassing those of the mantle ( $5.7\text{‰} \pm 1.0\text{‰}$ ; Degens ET and Epstein S, 1964; Fritz P and Smith DGW, 1970; Sheppard SMF and Schwarz HP, 1970). The carbon and oxygen isotope values of dolomites in the Bayan Obo deposit are distinct from those of sedimentary limestones near the Main Orebody (average  $\delta^{13}\text{C}_{\text{VPDB}}$  value:  $1.2\text{‰}$ ; average  $\delta^{18}\text{O}_{\text{V-SMOW}}\text{‰}$  value:  $14.4\text{‰}$ ). Since sedimentary dolomites were formed under supergene conditions, they are relatively enriched in  $^{13}\text{C}$  and  $^{18}\text{O}$ , with  $\delta^{18}\text{O}$  values ranging from  $20\text{‰}$  to  $35\text{‰}$  and  $\delta^{13}\text{C}$  values approximately equal to zero due to insignificant variations over geological time (Hoefs J, 1987). However, Dolts in the Bayan Obo deposit show significantly lower  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values than sedimentary dolomites, suggesting that they do not originate from normally sedimentary carbonate rocks.

The ore-hosting carbonatites in the Bayan Obo deposit underwent intense fluid alteration and mineralization modification, which reset their carbon and oxygen isotope systems. Therefore, these carbonatites cannot reflect the geochemical characteristics of the primitive carbonatites. This study tested the unaltered pristine carbonatites located far away from the mineralization center in the West Orebody. The carbonatites yielded  $\delta^{13}\text{C}_{\text{VPDB}}$  values ranging from  $-3.7\text{‰}$  to  $-4.2\text{‰}$  and  $\delta^{18}\text{O}_{\text{V-SMOW}}$  values varying between  $6.7\text{‰}$  and  $7.7\text{‰}$ . These values are consistent with the isotopic compositions of typical igneous carbonatites, demonstrating an igneous origin for the ore-hosting carbonatites in the Bayan Obo deposit.



**Fig. 11.** Carbon and oxygen isotopic compositions of principal rock units in the Bayan Obo deposit.

### 5.2. Sulfur isotope

This study investigates the geochemical characteristics of sulfur isotope in the Bayan Obo deposit based on the  $\delta^{34}\text{S}$  values of 53 pyrite samples from the Main Orebody as summarized by the [Institute of Geochemistry, Chinese Academy of Sciences \(1988\)](#), seven pieces of sulfur isotope data obtained by [Ding TP et al. \(2003\)](#), and data derived by [Lai XD et al. \(2013\)](#); Table 4.

The sulfur isotope data reveal the following findings: (1) The whole-rock sulfur isotopic composition shows two distinct peaks instead of a tower-shaped pattern. One peak is about 0‰ (average: +0.02‰), suggesting a deep source, while the other is around +8‰ (average: +6.8‰), higher than that of the mantle-derived sulfur; (2) Compared to the whole rock data, barite shows significantly higher  $\delta^{34}\text{S}$  values, with an average value of +12.5‰, which is lower than the sulfur isotope value of sulfates in the Precambrian seawater (+25‰; [Zheng YF et al., 2000](#)) and falls into the previously determined  $\delta^{34}\text{S}$  distribution range for barite in the Bayan Obo deposit ([Zhang ZQ et al., 2003](#)).

The sulfur isotopes of the whole rock and barite in the Bayan Obo deposit indicate different evolutionary stages of the ore-forming fluids. The sulfur isotopic compositions of the whole rock and pyrite suggest a deep source origin, while high  $\delta^{34}\text{S}$  values may be attributed to exchange and mixing with sulfur from the crust or seawater. As a result, some pyrite exhibit  $\delta^{34}\text{S}$  values up to around +10‰. Previous studies ([Wu CD et al., 1999](#)) suggest that marine sulfur is the source of sulfur in barite, leading to significant fractionation and high  $\delta^{34}\text{S}$  values. However, the  $\delta^{34}\text{S}$  values of barite in the Bayan Obo deposit are significantly lower than those of contemporaneous seawater sulfates, indicating that the

seawater is not a major contributor of sulfur to sulfides in this deposit. Instead, they display distinct geochemical characteristics of deep-sourced sulfur. The authors of this study suggest that the two distinct sulfur isotope characteristics may reflect the results of sulfur isotopic fractionation of magmatic carbonatites and hydrothermal carbonate rocks. The reasons are as follows: Isotopic fractionation was controlled by temperature. As the temperature decreased,  $\text{SO}_2$  in ore-forming hydrothermal fluids underwent hydrolysis to form  $\text{H}_2\text{S}$ . In the late hydrothermal system, both  $\text{SO}_4^{2-}$  and  $^{34}\text{S}$  were present due to dynamic fractionation and isotopic exchange. In contrast,  $\text{H}_2\text{S}$  enriched in  $^{32}\text{S}$  first formed sulfide precipitates. These sulfides had low  $\delta^{34}\text{S}$  values, while the remaining sulfur became enriched in  $^{34}\text{S}$ . As  $\text{H}_2\text{S}$  decreased in the hydrothermal system, reverse isotopic exchange occurred and  $\text{H}_2\text{S}$  became more enriched in  $^{34}\text{S}$ . Consequently, residual hydrothermal fluids were enriched in  $^{34}\text{S}$ , leading to increasingly enriched sulfides with higher  $\delta^{34}\text{S}$  values from early magmatic carbonatites to late hydrothermal carbonatites. This trend resembles the variations observed in carbon and oxygen isotopes in typical skarn mineralization worldwide ([Smith MP et al., 2015](#)).

### 5.3. Strontium (Sr) isotope

The Sr isotopic composition of dolomites in the Bayan Obo deposit has been altered to varying degrees by late geological processes. However, dolomites contain low Rb content and high Sr content, resulting in low  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios. Furthermore, the radiogenic Sr generated by  $^{87}\text{Rb}$  decay is much less than the Sr formed during the rock formation, and the Sr content in the dolomites was slightly affected by late

**Table 4. Sulfur isotope data of main sulfides in the Bayan Obo deposit (‰).**

Test object	$^{34}\text{S}_{\text{CDT}} (\text{‰})$	Sampling location	Data source	Test object	$^{34}\text{S}_{\text{CDT}} (\text{‰})$	Sampling location	Data source
Barite	13.13	Barite vein in the eastern portion of the Main Orebody	Lai XD, et al., 2013	Pyrite	0.8	1606-m-deep dolomite-type iron ores along the No. 25 exploration line in the East Orebody	Institute of Geochemistry, Chinese Academy of Sciences, 1988
Whole rock	13.24	Barite vein in the eastern portion of the Main Orebody		Pyrite	1	1606-m-deep pyrite vein in iron ores along the No. 24 exploration line in the East Orebody	
Whole rock	-1.12	Sulfides in the eastern portion of the Main Orebody		Pyrite	0.3	1620-m-deep horizontal riebeckite-type iron ores in the East Orebody	
Whole rock	8.4	Sulfides in the eastern portion of the Main Orebody		Pyrite	0.4	1578-m-deep horizontal fluorite-type dolomites subjected to riebeckite alternation in the East Orebody	
Whole rock	0.14	Sulfides in the eastern portion of the Main Orebody		Pyrite	1	1606-m-deep iron-bearing aegirinites along the Nos. 25–26 exploration lines in the East Orebody	
Whole rock	-0.36	Sulfides in the eastern portion of the Main Orebody		Pyrite	1.1	1606-m-deep pyrite vein in iron ores along the Nos. 24–25 exploration lines in the East Orebody	
Whole rock	-4.63	Sulfides in the eastern portion of the Main Orebody		Pyrite	1.4	1620-m-deep horizontal aegirine-type iron ores in the East Orebody	
Whole rock	-1.08	Sulfides in the eastern portion of the Main Orebody		Pyrite	1.6	1594-m-deep horizontal carbonatite dik in the East Orebody	
Whole rock	-1.05	Sulfides in the eastern portion of the Main Orebody		Pyrite	1.6	1698-m-deep pyrite crystals in horizontal dolomites in the Main Orebody	
Whole rock	7.84	Sulfides in the eastern portion of the Main Orebody		Pyrite	1.7	1606-m-deep horizontal idiomorphic pyrite in the East Orebody	
Barite	10	Barite vein	Ding TP, et al., 2003	Pyrite	1.9	1662-m-deep veined pyrite in horizontal aegirinites in the East Orebody	
Barite	10.9	Barite vein		Pyrite	1.9	1686-m-deep horizontal aegirine vein in the Main Orebody	
Barite	14.6	Barite vein		Pyrite	2.1	1606-m-deep horizontal lumpy sulfides in the East Orebody	
Barite	13.1	Barite in ores		Pyrite	2.2	1606-m-deep fluorite-pyrite assemblages along the Nos. 3–4 exploration lines in the Main Orebody	
Whole rock	12.7	Whole rock		Pyrite	2.4	1674-m-deep horizontal fluorite-type iron ores in the Main Orebody	
Whole rock	11.2	Whole rock		Pyrite	3.1	1605-m-deep biotitite along the No. 25 exploration line in the East Orebody	
Whole rock	11.1	Whole rock		Pyrite	3.9	1698-m-deep pyrite vein in horizontal iron ores in the Main Orebody	
Pyrite	-3.9	1686-m-deep horizontal aegirine vein in the Main Orebody	Institute of Geochemistry, Chinese Academy of Sciences, 1988	Pyrite	4.9	1620-m-deep outer wall of the horizontal fluorite vein in the East Orebody	
Pyrite	-2.7	1686-m-deep iron ores along the No. 3 exploration line in the Main Orebody		Pyrite	4.9	1686-m-deep fluorite-type pyrite aggregates along the No. s exploration line in the Main Orebody	

**Table 4 (Continued)**

Test object	$^{34}\text{S}_{\text{CDT}}(\%)$	Sampling location	Data source	Test object	$^{34}\text{S}_{\text{CDT}}(\%)$	Sampling location	Data source
Pyrite	-1.9	1620-m horizontal vein pyrite in the East Orebody		Pyrite	5.2	1606-m-deep sericite schists in the East Orebody	
Pyrite	-1.8	1674-m-deep iron ores along the No. 4 exploration line in the Main Orebody		Pyrite	5.8	1662-m-deep horizontal biotite in the Main Orebody	
Pyrite	-0.9	1686-m-deep horizontal REE-Fe ores in the Main Orebody		Pyrite	6.2	1686-m-deep iron ores along the Nos. 3–4 exploration lines in the Main Orebody	
Pyrite	-0.9	1606-m-deep horizontal lumpy pyrite in the East Orebody		Pyrite	6.5	1686-m-deep quartzites along the Nos. 4–5 exploration lines in the Main Orebody	
Pyrite	-0.8	1674-m-deep horizontal fluorite-type iron ores in the Main Orebody		Pyrite	6.8	1606-m-deep glimmerites along the Nos. 25–26 exploration lines in the East Orebody	
Pyrite	-0.7	1686-m-deep horizontal tight blocky pyrite in the Main Orebody		Pyrite	6.8	1606-m-deep aegirinite fissures along the Nos. 25–26 exploration lines in the East Orebody	
Pyrite	-0.7	1606-m-deep dolomites subjected to riebeckite alteration along the No. 24 exploration line in the East Orebody		Pyrite	6.9	1686-m-deep quartzites along the Nos. 4–5 exploration lines in the Main Orebody	
Pyrite	-0.6	1686-m-deep iron ores along the No. 2 exploration line in the Main Orebody		Pyrite	7.1	1686-m-deep fluorite type iron ores along the No. 3 exploration line in the Main Orebody	
Pyrite	-0.6	1620-m-deep horizontal late hydrothermal vein in the East Orebody		Pyrite	7.2	1606-m-deep aegirinites along the Nos. 25–26 exploration lines in the East Orebody	
Pyrite	-0.5	1686-m-deep pyrite vein in the horizontal iron ores in the Main Orebody		Pyrite	7.2	1686-m-deep quartzites along the No. 5 exploration lines in the Main Orebody	
Pyrite	-0.1	1606-m-deep horizontal silicified slates in the East Orebody		Pyrite	7.2	1674-m-deep horizontal aegirine-type iron ores in the Main Orebody	
Pyrite	0	1698-m-deep horizontal lumpy pyrite in the Main Orebody		Pyrite	7.5	1606-m-deep pyrite zone of fluorite-type iron ores along the No. 24 exploration line in the East Orebody	
Pyrite	0	1698-m-deep horizontal lumpy pyrite in the Main Orebody		Pyrite	7.5	1606-m-deep mica-riebeckite-type iron ores along the No. 26 exploration line in the East Orebody	
Pyrite	0.1	1686-m-deep horizontal aegirine-type ores in the Main Orebody		Pyrite	7.8	168-m-deep iron ore fissures along the Nos. 4–5 exploration lines in the Main Orebody	
Pyrite	0.1	1696-m-deep horizontal iron ores in the Main Orebody		Pyrite	7.8	1722-m-deep dolomites in the Main Orebody	
Pyrite	0.1	1686-m-deep horizontal pyrite vein in the Main Orebody		Pyrite	11.1	1696-m-deep horizontal aegirine-type ores in the Main Orebody	

geological processes. Therefore, the Sr isotopic composition of dolomites closely resembles that of protoliths. The Dolts in the Bayan Obo deposit experienced significant fluid metasomatism. To accurately determine the Sr isotopic composition of dolomites and minimize late interference, this study delved into the unaltered and unmineralized pristine

carbonatites collected far from the mineralization center in the West Orebody. These carbonatites yielded  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranging from 0.702815 to 0.703021 (mostly less than 0.7030). Consistent with previous studies, Dolts in the Bayan Obo deposit generally exhibit stable Sr isotopes, with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios mostly less than 0.704. These values are significantly

distinct from those of normally deposited carbonate rocks (ca. 0.720) and the overlying and underlying slates of dolomites (0.7089–0.7253), but resembling the Sr isotopic composition of igneous carbonatite dykes. The Sr isotopic composition in the Bayan Obo deposit (Table 5) exhibits dual-source characteristics, with most data close to the mantle end member and a few data approaching seawater or sedimentary rock end members, suggesting that the Bayan Obo deposit predominantly originated from the mantle, with some possible from the crust. Therefore, the Dolts in the Bayan Obo deposit are of typical magmatic origin.

#### 5.4. Characteristics of ore-forming fluids

Opinions on the source of ore-forming fluids in the Bayan Obo deposit include sedimentary modification, metamorphism, magma, the capture of carbonatitic magma source, and mantle fluids. Given that the authors of this study hold the opinion that the Dolts in the Bayan Obo deposit are of magmatic origin and the formation of the deposit is primarily related to the contact metasomatism of carbonatites, it is noticeable that the source of the ore-forming fluids is sourced from carbonatites. It is suggested that carbonatites serve as ore-forming parent rocks and the source of ore-forming fluids to the deposit. The dolomite plutons rich in REEs and iron were differentiated in the later evolutionary stage, forming ore-bearing fluids. Then, the ore-bearing fluids filled and modified the fenites formed in the early stage. As a result, the deposit was formed. This process resembles the mineralization of skarn deposits formed by the intrusion of

typical intermediate-acid magmatic rocks.

As revealed by previous research on the fluid and melt inclusions (Ni P et al., 2003; Fan HR et al., 2002a, 2002b; Institute of Geochemistry, Chinese Academy of Sciences, 1988; Fan HR et al., 2003; Fan HR et al., 2006a; Qin ZJ et al., 2007; Hu L et al., 2018), carbonatite dykes from the Bayan Obo deposit contain various inclusions, including polycrystalline inclusions, two-phase aqueous inclusions, CO<sub>2</sub>-bearing three-phase inclusions, and mineral-bearing three-phase inclusions. These inclusions exhibit the same characteristics as those in typical carbonatites abroad, suggesting their magmatic origin (Ni P et al., 2003). The polycrystalline and melt inclusions have homogenization temperatures ranging from 680°C to 740°C, corresponding to the crystallization temperatures of rock masses during the emplacement of carbonatite magmas and the early formation stage of fenites.

The ore-forming fluids of the Bayan Obo deposit belong to the H<sub>2</sub>O-CO<sub>2</sub>-NaCl-(F-REE) system (Ni P et al., 2003; Fan HR et al., 2003, 2006a, 2006b; Wang KY et al., 2010; Smith MP et al., 2000; Institute of Geochemistry, Chinese Academy of Sciences, 1988). The homogenization temperatures of NaCl-H<sub>2</sub>O+ daughter mineral-bearing inclusions range from 420°C to 450°C, corresponding to the magnetite oxide stage. Therefore, it is reasonable to regard the Bayan Obo deposit as a special high-temperature hydrothermal deposit in the exploration stage (1954). The homogenization temperatures of NaCl-H<sub>2</sub>O and H<sub>2</sub>O-CO<sub>2</sub> inclusions range from 192°C to 336°C and from 240°C to 390°C, respectively.

**Table 5. Sr isotopic compositions of principal rock units in the Bayan Obo deposit.**

Sample No.	Sample description	<sup>87</sup> Sr/ <sup>86</sup> Sr ratio	Remarks
ZK106-3-03	Disseminated mineralized dolomite	0.702968	Data of unaltered carbonatites from the West Orebody measured in this study
ZK106-3-06	Disseminated mineralized dolomite	0.702886	
ZK106-3-08	Weakly mineralized banded dolomite	0.703021	
ZK106-3-09	Disseminated mineralized dolomite	0.703185	
ZK106-3-13	Weakly mineralized banded dolomite	0.702821	
ZK106-3-18	Sparsely disseminated mineralized dolomite	0.702815	
88/152	Coarse-grained dolomite	0.703163	Le Bas MJ, 1997
90/62	Coarse-grained dolomite	0.702951	
90/63	Fine-grained dolomite	0.703163	
88/157	Medium-grained dolomite	0.702989	
88/117	Fine-grained dolomite	0.703576	
88/142	Fine-grained calcite carbonatite	0.70686	
90/65	Dolomite marble (H8)	0.7262	
Y8/230	Sedimentary calcareous limestone in the northern portion of the Main Orebody (H8)	0.719919	
Statistical values	H3 slate in northern Kuangou	0.7229±0.0034	Institute of Geochemistry, Chinese Academy of Sciences, 1988
	H3 slate in the western segment of southern Kuangou	0.7253±0.0017	
	Limestone in the northern portion of the deposit	0.7214–0.7251	
	H3 slate in the eastern portion of southern Kuangou	0.7079±0.0016	
	H9 slate in the East Orebody	0.7089±0.0018	
	Biotite granites in ore bodies	0.7086±0.0004	
	Dolomites on the hanging and foot walls of Main Orebody	0.703–0.7065 (average: 0.704)	
	Carbonatite dikes on the eastern slope of the Jianshan Mountain	0.7041–0.7024 (average: 0.706)	

This temperature range of 200°C–390°C corresponds to the mineralization stage of fluorite-type REE ores. Fan HR et al. (2006a) found that brine and CO<sub>2</sub>-rich inclusions coexist and show similar homogenization temperatures, suggesting that immiscibility occurred in REE mineralization and the immiscibility of the original H<sub>2</sub>O-CO<sub>2</sub>-NaCl fluids might be attributable to carbonatite magmas. The total salinity of ore-forming fluids gradually reduced from 15%–5%NaCl<sub>equ.</sub> in the early stage to below 1%NaCl<sub>equ.</sub>, with mineralization pressures between 0.8–1.4 kbar, equivalent to mineralization depths ranging from 2.5–4.5 km (Smith MP et al., 2000).

### 5.5. Metallogenic age

Geochronological studies of the Bayan Obo deposit can be traced back to the 1950s to 1960s, obtaining nearly 1000 age analyses. However, different dating objects, methods, and accuracy yielded dispersed data, intensifying the disputes among scholars over the regional geological evolution and origin of the deposit. Regarding the debate concerning the superimposed or prolonged mineralization as indicated by these multi model age data, for instance, Song W et al. (2018) obtained ages ranging from 361–961 Ma through the in-situ dating of monazite, arguing that the mineralization lasted for one billion years. Since these age data have been summarized and analyzed thoroughly by many researchers (Fei XJ, 2019 and literature; Smith MP et al., 2015 and literature; Zhu XK et al., 2012), they will not be repeated in this study.

The mineralization of the Bayan Obo deposit is principally associated with the intrusion of carbonatite rock masses. Therefore, identifying the emplacement epoch of carbonatite rock masses becomes critical. Using various methods, previous research have dated the carbonatite dykes and Dolts in the Bayan Obo deposit, yielding relatively consistent age data: monazite-bastnaesite Sm-Nd isochron ages of 1312.5±41.2 Ma (Ren YC et al., 1994) and 1313±41 Ma (Zhang ZQ et al., 2001); the carbonatite whole-rock Sm-Na isochron age of 1223.65 Ma (Zhang ZQ et al., 1994), and the carbonatite dyke whole-rock Sm-Nd isochron age of 1354±57 Ma (Yang KF et al., 2011); dolomite whole-rock Sm-Nd isochron ages of 1273±100 Ma (Zhang ZQ et al., 2001); the Sm-Na isochron ages of apatite in coarse-grained carbonatite dykes of 1317±140 Ma, and the Th-Pb age of monazite in calcareous carbonatite dykes of 1321±14 Ma (Yang KF, et al, 2019). Zircon Th-Pb age of carbonatite sills 1301±12 Ma (Zhang SH et al., 2017; Li Q et al., 2018). The newly discovered alkaline granite in this study yielded a zircon Th-Pb age of 1311 Ma (Ke CH et al., published in another paper), similar to the ages of Dolt and carbonatite dykes. This study statistically analyzed some high-precision data selected from the dating results of the study area obtained by Smith MP et al (2015), Fei XJ et al. (2019), and Zhu XK et al. (2012). The peak value of 1320 Ma during the Mesoproterozoic, which coincides with the formation background of the ore-hosting Bayan Obo Group, can be used as the intrusion epoch of carbonatite rock masses, that is, the

primary formation epoch of the deposit. Additionally, the peak value of 1200–1400 Ma represents the response to the Mesoproterozoic Zhaertai-Bayan Obo rifting in the northern North China craton during the evolution of the Mesoproterozoic supercontinental rift (Wang J et al., 1989; Bai G et al., 1996; Shao JA et al., 2002; Zhao GC et al., 2003; Zhai MG et al., 2015; Yang XF et al., 2009).

Besides, other age peak values of the study area hold some geological significance, representing the intricate tectono-magmatic processes and their modification to the deposit. Based on the research results of tectono-magmatic processes in recent years, the authors of this study propose that age peaks at 1900–2050 Ma and 2550 Ma shown in Fig. 12 represent the formation and evolution timing of the Se'ertengshan Group, which is the basement of the study area (Fan HR et al., 2010). The ages ranging from 700–900 Ma indicate the Nanhuanian tectonic effects, which could be records of hydrothermal activity associated with the southward subduction and closure of the Paleo-Asian Ocean (Ling MX et al., 2013; 2014). The ages ranging from 400–500 Ma (Liu LS et al., 1996; Liu YL et al., 2001, 2005a, 2005b) represent the subduction-collision orogeny between the North China and Siberian plates during the early Paleozoic, witnessing the significant regional metamorphism and deformation of the deposit. The bedded ore bodies were supposed to be related to fold structures formed by orogenesis, and the banded structures in the ores could be further strengthened. This epoch was characterized by structural modification, exerting minor effects on mineralization and enrichment. The ages ranging from 260–280 Ma (Fan HR et al., 2009) represent the Neopaleozoic late Paleozoic magmatic intrusion, forming skarn-type ore bodies in the eastern segment of the deposit, which are the products of granitic magma contact metasomatism with Proterozoic ore-hosting carbonatites. This event mainly played a destructive role in the mineralization, ending the eastward extension of the metallogenic belt.

## 6. Genetic models of the Bayan Obo deposit

### 6.1. Mineralization stages

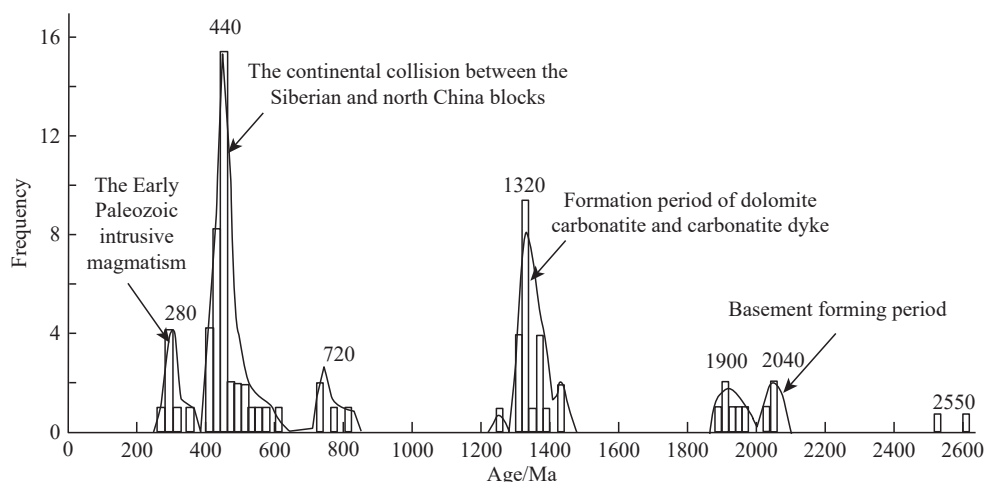
The mineralization stages of REE, niobium, and iron minerals in the Bayan Obo deposit are complex, resulting in various division schemes. This study proposes that the deposit was primarily formed by the contact metasomatism between carbonatites and country rocks, with three mineralization periods and five stages (Table 6).

#### 6.1.1. Carbonatite mineralization period

The carbonatite mineralization occurred during Mesoproterozoic rifting, resulting in the emplacement of carbonatites and the formation of the Bayan Obo iron-REE deposit. This period can be divided into five stages of mineralization.

##### (i) Igneous carbonatite stage

This stage is characterized by the emplacement of



**Fig. 12.** Histogram showing the dating data distributions of the Bayan Obo deposit (Fei XJ, 2019; Smith MP et al., 2015; Zhu XK et al., 2012).

carbonatite magmas, resulting in the formation of the main body of dolomite carbonatites. The minerals formed primarily consist of dolomites, with minor amount of apatites. Some apatites are intimately associated with monazites, forming disseminated monazites. It is inferred that magmas were emplaced parallel to bedding, and the mineralization during this stage was mainly associated with magma crystallization, suggesting magmatic ores.

#### (ii) Anti-skarn-fenite stage

At this stage, the semi-consolidated dolomite-carbonatite magmas underwent metasomatism by surrounding rocks, resulting in the formation of fenites within contact zones or country rock xenoliths. Moreover, the country rocks of the fenites underwent contact thermal metamorphism and hornfelsic alteration. The primary minerals formed include aegirine, riebeckite, biotite, calcite, albite, and potassium feldspar. Small amount of  $\text{SiO}_2$  migrated from contact zones to the carbonatites, leading to the formation of magnesium-rich minerals such as humite. Alteration minerals were predominantly formed during this stage. It is inferred that fenitization primarily occurred along the bedding of the early country rocks through metasomatism (pelites and argillaceous siltstones), laying a foundation for subsequent banded ores.

#### (iii) Magnetite oxide stage

This stage primarily witnessed the decomposition of fenite minerals within the contact zones. Early fenite minerals were altered by hydrothermal fluids rich in iron, niobium, and REEs during the late magmatic period, resulting in the formation of magnetite and hematite. Additionally, the liberation of iron from the decomposition of aegirine and riebeckite facilitated the formation of iron ores. Iron and niobium ores primarily emerged at this stage, corresponding to the oxide stage of skarn deposits.

#### (iv) Fluorite-REE mineralization stage

This stage predominantly witnessed the formation of abundant fluorite and REE minerals, which filled the cracks and gaps in magnetite and early fenitized minerals as veins and/or granules. In fissures of fluorite veins and the fluorite-rich banded ores, late REE mineralization primarily led the formation of fluorocarbonates. In aegirine-dominated rocks, these minerals can replace apatite or be filled in geodes. The

spatial distribution of the main fenites within contact zones is consistent between this stage and the magnetite oxide stage. Iron and REE minerals in the Bayan Obo deposit were primarily formed during this stage.

#### (v) Barite stage

The final stage of fluorocarbonate mineralization primarily involved the formation of barite in coarse crystal veins and geodes, and the formation of the barite is associated with the mineralization of parisite and huanghoite.

### 6.1.2. The early Paleozoic regional metamorphism and deformation period

The early Paleozoic regional metamorphism and deformation occurred during the Caledonian movement when the North China and Siberian plates collided. This process led to the structural deformation, regional metamorphism, and the formation of present-day anticlinal and synclinal structures, folding deformation, and mylonitization, as well as directional structures within the dolomites and ores. Regional metamorphism possibly intensified the banded structures. It primarily modified previous ore bodies, through recrystallization and regional metamorphism of some minerals. Accordingly, dolomite crystals and REE minerals may have grown or deformed, with minor effects on mineral enrichment or depletion.

### 6.1.3. Late Paleozoic-Mesozoic granite-related skarn mineralization period

Late Paleozoic-Mesozoic granite-related skarn mineralization occurred during the intrusion of Indosinian intermediate-acid granite, forming skarn-type ore bodies in the eastern part of the Bayan Obo deposit. During this period, the early iron-REE ore bodies were modified and destroyed, preventing the extension of metallogenic belts toward the east.

## 6.2. Mineralization process

Accepting the fact that the dolomite carbonatites in the Bayan Obo deposit have a magmatic origin, it is necessary to re-clarify the mineralization process of the deposit. Specifically, the carbonatite intrusion would have induced the

**Table 6. Mineralization stages and mineral formation sequence of the Bayan Obo deposit.**

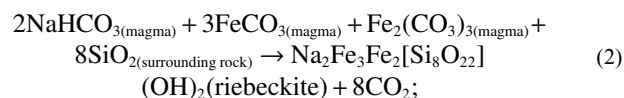
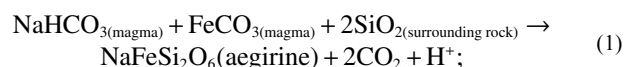
Primary minerals	I-Carbonatite mineralization period					II-Regional metamorphism and deformation period	III-Skarn mineralization period
	Dolomite stage	Fenitization stage	Magnetite oxide stage	Fluorite-REE mineralization stage	Barite stage		
Dolomite	█						
Calcite	█	█		---	---		---
Apatite	—						
Monazite	█			█			
Aegirine		█					
Riebeckite		█					█
Biotite		█					
Albite		█					
Potassium feldspar		█					
Magnetite			█	█			
Hematite			█				
Niobite			█				
Rutile			█				
Fluorite				█	---		---
Bastnaesite				█			
Other REE minerals				█			
Galena				---			
Pyrite				---		---	---
Barite				---	█		---
Structurally deformed minerals						█	

metasomatism and alteration (fenitization typically) of country rocks. Fenites are altered rocks primarily composed of aegirine and alkaline hornblende, formed from metasomatism between carbonatites or alkaline rock masses and country rocks. A typical case is the 700-m-wide fenitization zone at the periphery of the Fen carbonatite complex in Norway (Brögger WG, 1921; Elliott H, et al., 2018; Cooper et al., 2015; Mian I et al., 1986). The term fenite originates from this complex. The authors of this study contend that the metasomatism between carbonatite rock masses and surrounding rocks is comparable to the skarn alteration during the intrusion of intermediate-acid granitic magmas into the surrounding rocks of carbonatites, except for the inverse material exchange reaction direction of metasomatism.

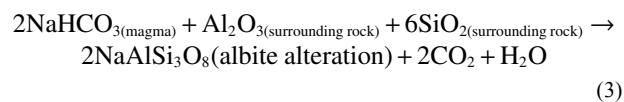
During the intrusion of intermediate-acid granitic magmas, the SiO<sub>2</sub> in the magma near the contact zone reacts with the CaO, FeO, and MgO in the surrounding rocks to form skarn minerals, such as diopside, garnet, or wollastonite. During the emplacement of carbonatite magma, the CaO, FeO, MgO, Na<sub>2</sub>O, and K<sub>2</sub>O in the magma react with SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in the surrounding rocks near the contact zone to form fenite minerals, such as aegirine, alkaline hornblende, humite, biotite, and calcite, with the heat energy required all from the magma. The carbonatite magma is extremely undersaturated as to SiO<sub>2</sub>, and the SiO<sub>2</sub> content in the Bayan Obo deposit's ore-hosting dolomites is mostly less than 1% and occasionally up to 10%. Therefore, the SiO<sub>2</sub> required to form fenite minerals could only come from the ore-hosting surrounding rocks. Typically, the emplacement of intermediate-acid magma forms skarn deposits in the contact zone, including

iron-copper-gold and lead-zinc polymetallic deposits. The contact metasomatism between alkaline rock-hydrochlorite magma and surrounding rocks during the emplacement forms REE, niobium, and iron ore deposits (Elliott et al., 2018). Actually, such fenite-type rare metal and REE deposits are special contact metasomatic deposits.

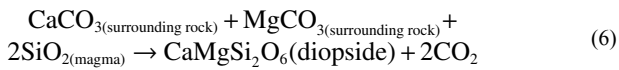
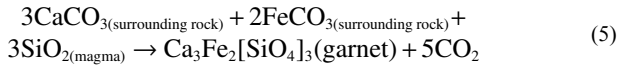
The contact metasomatism between carbonatite magma and SiO<sub>2</sub> in surrounding rocks to form aegirine and riebeckite can be expressed as follows:



The alkaline components in carbonatite magma react with aluminum and silicon in surrounding rocks to form albite and potassium feldspar, that is, the so-called sodium and alkali metasomatism, which should actually be hornfelsic alteration.



The contact metasomatism between typical intermediate-acid rock magma and the surrounding rocks of carbonatites to form skarn minerals can be expressed as follows:



The actual metasomatic process during the intrusion of carbonatite magma is much more complicated than that expressed by equations (1)–(4). Rather than directly reacting with quartz in the surrounding rocks, the alkaline components in the magma are preferentially metasomatic with the clay minerals in argillaceous sediments to form banded fenites. During the reaction, part of the remaining Ca forms calcite, and part of Ca and Fe flow into the hydrothermal fluids, providing materials to the formation of fluorite, iron, and parisite in the later stage.

### 6.3. Mineralization model: anti-skarn mineralization

According to the discussion above, the mineralization model of the Bayan Obo deposit was preliminarily established (Fig. 13). Due to the uplifting of the mantle lithosphere or the mantle plume during the Mesoproterozoic, the Langshan-Zhaertaishan-Bayan Obo rift system formed on the northern

margin of the North China craton, with an extremely thick Bayan Obo Group (volcanic-)sedimentary rock series thriving in this rift system (Zhou JB et al., 2002). During the evolution of rifts, the lithospheric thinning or decompression caused partial melting near the mantle asthenosphere or in deeper parts, forming carbonatite or alkaline rock magma chambers rich in REEs and large-ion lithophile elements (Wyllie et al., 1996, 1998). The initial carbonatite magma in the magma chamber, which rose to the lower crust or near the Moho discontinuity, differentiated and evolved, forming the parent magma of dolomite carbonatites in the Bayan Obo deposit, and further accelerating the enrichment of REEs and iron in the magma. Some differentiated dolomite-carbonatite magmas rose to the shallow crust along faults and intruded along the argillaceous rock or argillaceous siltstone layers in the Bayan Obo Group. Consequently, rocks in the contact zone experienced significant metasomatism and thermal contact metamorphism, forming hornfelsic alternation and fenitization zones at the periphery of rock masses. Meanwhile, the rise of minor amounts of alkaline granite and carbonatite magma formed carbonatite dykes and alkaline granite suites in the study area. The REE-enriched carbonatite magma gradually crystallized and cooled to form a low-grade carbonatite-type REE ore body. REEs at this stage were primarily enriched in apatite or monazite. The iron-, fluorine-, and REE-enriched fluids that formed during the crystallization of carbonatite magma caused the early fenite minerals to decompose and

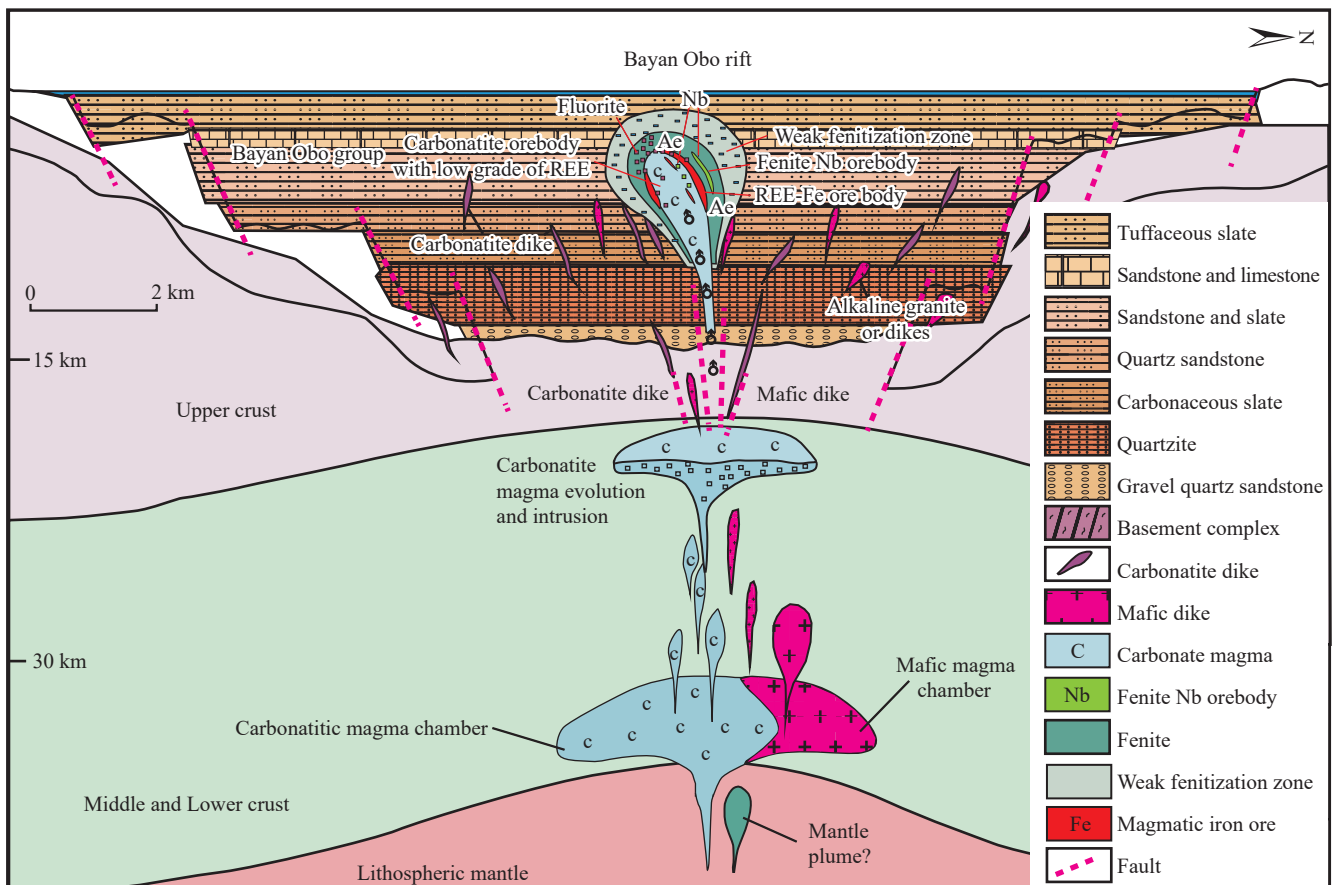


Fig. 13. The carbonatite intrusion and mineralization model for the Bayan Obo REE-Fe deposit .

form blocky iron ores via metasomatism near the contact zone or the fault zone. The aegirine in fenites comprise acmite and ferrosilite, and the iron decomposed from aegirine and riebeckite facilitated the formation of iron ores. With a decrease in temperature in the late stage of hydrothermal activity, fluorine and REEs in the fluids precipitated gradually to fill and metasomatize the early-stage minerals, forming the main iron and REE ore bodies in the Bayan Obo deposit. For sustained mineralization, the iron-, fluorine-, and REE-enriched fluids from deep magma chambers were presumably involved in the above processes.

Under the Nanhuanian tectonic effects during the 900–700 Ma after the deposit formed, the Paleo-Asian Ocean subducted to the south and closed, rifts ceased to expand, and the Bayan Obo Group and REE-Fe ore bodies underwent deep burial and low-grade metamorphism, exhibiting non-significant overall structural deformation. During the Caledonian, the collisional orogeny of the North China Craton and Siberian plates resulted in significant structural deformation and metamorphism of the Bayan Obo Group and REE-Fe ore bodies, and the Bayan synclinal structure formed, shaping the current structural styles and the deformation structures in ores.

#### 6.4. Contrasting with typical skarn deposits and this study's unsolved problems

As revealed by the above analysis, the formation of the Bayan Obo deposit is associated with the contact metasomatism between emplacing magmatic carbonatites and surrounding rocks. Moreover, the formation process of the Bayan Obo deposit is comparable to that of skarn deposits during the intrusion of intermediate-acid magmatic rocks, except for the inverse  $\text{SiO}_2$ , CaO, and MgO migration

direction of metasomatism. Comparing with skarn deposits can assist in further understanding the Bayan Obo deposit's formation process. The mineralization by contact metasomatism can be divided into two subtypes associated with intermediate-acid and carbonatite magmatism, i.e., skarn and anti-skarn deposits. Both skarns primarily composed of pyroxene, hornblende, and mica can be compared in many aspects. Table 7 shows a comparison of the main characteristics between the two types of deposits.

The authors argue that the main formation process, ore and alteration zoning, and later evolution process of the deposit can be better illustrated from the perspective of contact metasomatism between magmatic carbonatites and surrounding rocks, making alteration zoning and ore type classification more concise and explicit. However, with the limited research, there still exist many unsolved problems, which need to be tested, discussed, and explained in future work. We suggest the unsolved problems are as follows: the relationship between REEs, other ore-forming materials and dolomite-carbonatite magma evolution (originating from the Dolt rock masses or the continuous supply of fluids from the deep magma chamber), the detailed hydrothermal alteration zoning, the detailed alteration mineral distribution, and the accurate definition of the generation sequence of minerals and REE minerals. Solving these problems holds critical significance for building an effective deposit model and guiding prospecting.

## 7. Conclusions

(i) The dolomite carbonatites (i.e., the dolts or the former H8 dolomites) in the Bayan Obo deposit are of magmatic origin. Their emplacement occurred at about 1320 Ma, which

**Table 7. Comparison between carbonatite-associated anti-skarn deposits and typical skarn deposits.**

Main characteristic	Carbonatite-associated anti-skarn deposit	Intermediate-acid magmatic related typical skarn deposit
Main rock mass	Carbonatite-alkaline rock suite, with undersaturated $\text{SiO}_2$	Calc-alkaline intermediate-acid granite, with supersaturated $\text{SiO}_2$
Primary alteration	Fenite, biotite, sodium, potassic, and hornfelsic alternation	Skarn, marble, carbonatite, and chlorite alteration
Altered mineral assemblage	Aegirine, riebeckite, humite, biotite, calcite, albite, and potassium feldspar	Diopside, hornblende, phlogopite, actinolite, quartz, epidote, chlorite, and calcite
Mineralization and alteration zoning	Rock mass-fenite-hornfel, with the rock mass color gradually becoming lighter towards the periphery	Rock mass-skarn-marble (+hornfel), with the rock mass color gradually becoming lighter towards the periphery
Paragenetic/associated mineralization type	In addition to the deposit within the fenite rock mass, carbonatite-type low-grade REE ores also formed within the rock mass, associated with fluorites, potassium- and sodium-rich rocks at the periphery and rock mass, holding comprehensive utilization value	Porphyry deposits, self-altered rock mass mineralization, and greisen type mineralization can form within the rock mass, with hydrothermal vein mineralization at the periphery
Mineralization stage	Fenite, magnetite oxide, fluorite-REE, and barite mineralization stages	Skarn, oxide, quartz-sulfide, and carbonatite mineralization stages
Main deposit type	Rare metal and REE, and iron deposits	Iron, copper, gold, molybdenum, lead, zinc, and other non-ferrous metal deposits
Ore-forming fluid	$\text{NaCl-H}_2\text{O-CO}_2\text{+F+REE}$ fluid (highly oxidized)	$\text{NaCl-H}_2\text{O-CO}_2\text{+S+(CuPbZn)}$ fluid
Mineralization temperature	High-temperature hydrothermal type. 450°C–600°C: fenite formation; 400°C–450°C: magnetite formation; 200°C–350°C: REE mineralization	High-temperature hydrothermal type. 450°C–600°C: skarn formation; 400°C–450°C: magnetite formation; 200°C–350°C: copper, lead, and zinc ore enrichment
Geological setting	Predominantly extensional geological setting: mainly intracontinental rift zones, back-arc and post-collisional extension, continental margins, and rift zones	Local extension under compression background, subduction and collision zones
Representative deposit	Bayan Obo deposit, and Finland's Fen deposit	Daye Fe deposit, and Jiama porphyry-skarn deposit

is consistent with the formation time of the dolomites and carbonatite dykes in the deposit. Besides, alkaline granites of similar ages also occur in the deposit.

(ii) The formation of the Bayan Obo deposit is primarily related to carbonatite magmatism. During the magma emplacement, intense contact metasomatism occurred in contact zones, forming fenites and related mineralization, which serve as the primary factors in the formation of the deposit. The formation process of the Bayan Obo deposit is comparable to that of the typical skarn mineralization, but in an opposite material migration direction. The deposits formed by contact metasomatism can be divided into two subtypes: anti-skarn and skarn deposits, which are associated with carbonatite and intermediate-acid magmatism, respectively.

(iii) The ore-forming fluids of the Bayan Obo deposit were originated from magmatic carbonatites, which also served as the ore-forming parental rocks and fluid source. The differentiation of REE- and iron-rich dolomite carbonatites in the later magma evolution stage is critical to the formation of ore-forming fluids. The Bayan Obo deposit was principally formed by the filling, metasomatism, and modification processes of the early fenites by ore-bearing fluids. Hence, the Bayan Obo deposit was not formed by the superimposition of multi-stage geological processes.

(iv) The formation and evolution of the Bayan Obo deposit can be divided into three periods and five stages. However, the deposit was primarily formed by carbonatite activity during Mesoproterozoic rifting on the margin of the North China Craton. The REE mineralization occurred at about 1.3 Ga, which is consistent with the formation ages of the dolomites and carbonate dykes in the deposit, with the ore-forming materials being derived from the mantle. Later geological events, which merely caused REE redistribution and modification to some extent, did not result in significant REE mineralization or enrichment (Zhu XK et al., 2012). Collectively, these events did not substantially contributed to, but even destroyed the REE mineralization and enrichment.

(v) The genetic model of the Bayan Obo deposit is an anti-skarn model related to magmatic carbonatites. The high grade REE-Nb-Fe ores were formed during the carbonated magma-hydrothermal process. By comparison, the low-grade REE ores within carbonatite plutons are supposed to be associated with magmatic crystallization, suggesting a magmatic origin. The prospecting of this type of deposit should focus on areas subjected to alkaline magmatism in a rift setting. It is necessary to investigate the magmatic differentiation in the deposit and its relationships to mineralization and enrichment rather than study factors such as sedimentary and metamorphic modifications, fluid metasomatism, and mineralization superimposition.

## Acknowledgement

This study was jointly funded by the National Key Research and Development Program of China (2022YFC2905301), the National Natural Science Foundation

of China (42072114), geological survey projects (DD20230366, DD202211695), and the scientific research projects supported by the Baotou Steel (Group) Co., Ltd. (HE2224, HE2228, and HE2313). We would like to extend our gratitude to Profs. Zi-guo Hao for his kind invitations and very insightful comments on this manuscript. Profs. Yue-qing Yang, Shuan-hong Zhang, and Yong-gang Feng presented valuable comments and improved English composition. Special thanks go to the management and staff of the Baotou Iron and Steel Ltd. and the Bayan Obo Mine for their hospitality during fieldwork.

## CRedit authorship contribution statement

Yi-ke Li, Chang-hui Ke, Hong-quan She and conceived of the presented idea. Yi-ke Li, developed the theory and performed the computations. Yi-ke Li, Chang-hui Ke, and Hong-quan She, Li Zhang, Hong Yu, Bin Guo, Sheng-quan Zhou, Xing-yu Yuan carried out the field work. Rui-ping Li, Zi-dong Penga, Ze-ying Zhu carried out the experiment. Kui-feng Yang, Wei Chen, Jian-wei Zi, Wen-lei Song verified the analytical methods. Chang-hui Ke and Jing-yao Liu prepared all the figures of the manuscript. Deng-hong Wang, An-jiang Wang, Cheng Xu, Yong-gang Zhao encouraged Yi-ke Li, Chang-hui Ke to investigate a specific aspect and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

## Declaration of competing interest

The authors declare no conflicts of interest.

## References

- Bai G, Yuan ZX. 1985. Geology of carbonatite and related ore deposits. Bulletin of Institute of mineral deposit, CAGS, Beijing (in Chinese).
- Bai G, Wu CY, Yuan ZX, Zhang ZQ, Zheng L. 1996. Demonstration on the Geological features and genesis of the Bayan Obo ore deposit. Beijing: Geological Publishing House (in Chinese).
- Bai G, Yuan ZX, 1983. On genesis of Bayan Obo deposit. Bull. Inst. Mineral Deposits, Chinese Academy of Geological Sciences, (4), 1–15 (in Chinese).
- Brögger WG, 1921. Die eruptivegestein des kristianiagebietes, IV. Dasfengebiet in telemark. Norwegen, Naturv. Klasse 9, 150–167.
- Cao RL, Zhu SH, Wang JW. 1994. Material source and genesis of Bayan Obo Fe-REE deposit. *Chinese Science:Geoscience*, 24(12), 1298–1307 (in Chinese). doi: [10.1360/zb1994-24-12-1298](https://doi.org/10.1360/zb1994-24-12-1298).
- Cao RL. 1996. Frontiers of research on the mantle fluid. *Earth Science Frontiers*, 1996 (04), 2–12 (in Chinese with English abstract).
- Cao RL, Zhu SH. 1995. The mantle fluid and metallogeny. *Advance in Sciences*, 10(4), 324–329 (in Chinese with English abstract). doi: [10.11867/j.issn.1001-8166.1995.04.0323](https://doi.org/10.11867/j.issn.1001-8166.1995.04.0323).
- 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, PRC. *Applied Geochemistry*, 7(5), 443–458. doi: [10.1016/0883-2927\(92\)90005-N](https://doi.org/10.1016/0883-2927(92)90005-N).
- Chao ECT, Back JM, Minkin JA, Tatsumoto M, Wang J, Conrad JE, Makee, EH, Hou Z, Meng Q, Huang S. 1997. The sedimentary carbonate-hosted giant Bayan Obo REE-Fe-Nb ore deposit of Inner Mongolia, China: A cornerstone example for giant polymetallic ore deposits of hydrothermal origin. *U. S. Geological Survey Bulletin* 2143, 65. doi: [10.3133/b2143](https://doi.org/10.3133/b2143).

- Chen W, Liu HY, Lu J, Jiang SY, Zhang W. 2020. The formation of the ore-bearing dolomite marble from the giant bayan obo ree-nb-fe deposit, Inner Mongolia: insights from micron-scale geochemical data. *Mineralium Deposita*, 55(1), 1–16. doi: [10.1007/s00126-019-00886-4](https://doi.org/10.1007/s00126-019-00886-4).
- Cooper, A. F., Collins, A. K., Palin, J. M., Spratt, J. 2015. Mineralogical evolution and ree mobility during crystallisation of ancylite-bearing ferrocarnatite, haast river, new zealand. *Lithos*, 324–337. doi: <https://doi.org/10.1016/j.lithos.2015.01.005>.
- Degens ET, Epstein S. 1964. Oxygen and carbon isotope ratios in coexisting calcites and dolomites from recent and ancient sediments. *Geochimica et Cosmochimica Acta*, 28(1), 23–44. doi: [10.1016/0016-7037\(64\)90053-5](https://doi.org/10.1016/0016-7037(64)90053-5).
- Ding TP, Jiang SY, Tian SH, Wan DF, Bai RM, 2003. The Genesis of the Ore Hosting “Dolomitic Marble” in the Bayan Obo Deposit, Inner Mongolia, China: Constrained by Isotopic Results. *Acta Geoscientia Sinica*, 24 (6), 535–542 (in Chinese with English abstract). doi: [10.3321/j.issn:1006-3021.2003.06.010](https://doi.org/10.3321/j.issn:1006-3021.2003.06.010).
- Elliott H, Wall F, Chakmouradian AR, Siegfried PR, Dahlgren S, Weatherley S, Finch A, Marks M, Dowman E, Deady E. 2018. Fenites associated with carbonatite complexes, A review. *Ore Geology Reviews*, 93(2018), 38–59.
- Fan HR, Xie YH, Wang KY. 2002. Fluid Inclusions in Skarn in Eastern Contacting Zone of Bayan Obo REE-Nb-Fe Deposit. *Mineral Deposits*, 21(S1), 808–811 (in Chinese with English abstract)
- Fan HR, Chen FK, Wang KY, Xie YH, Ilde SW, Stair M. 2002a. Zircon U-Pb age of a carbonatite dyke from Bayan Obo REE-Fe-Nb deposit, Inner Mongolia and its geological significance. *Acta Petrologica Sinica*, 18(3), 363–368 (in Chinese with English abstract). doi: [10.3321/j.issn:1000-0569.2002.03.011](https://doi.org/10.3321/j.issn:1000-0569.2002.03.011).
- Fan HR, Tao KJ, Xie YH, Wang KY. 2003. Laser Raman spectroscopy of typical rare-earth fluoro-carbonate minerals in Bayan Obo REE-Fe-Nb deposit and identification of rare-earth daughter minerals hosted in fluid inclusions. *Acta Petrologica Sinica*, 19, 169–172. doi: [10.3321/j.issn:1000-0569.2003.01.019](https://doi.org/10.3321/j.issn:1000-0569.2003.01.019).
- Fan HR, Hu FF, Yang KF, Wang KY, Liu YS. 2009. Geochronology framework of late Paleozoic dioritic-granitic plutons in the Bayan Obo area, Inner Mongolia, and tectonic significance. *Acta Petrologica Sinica*, 2009.25(11), 2933–2938 (in Chinese with English abstract).
- Fan HR, Yang KF, Hu FF, Wang KY, Zhai MG. 2010. Zircon geochronology of basement rocks from the Bayan Obo area, Inner Mongolia, and tectonic implications. *Acta Petrologica Sinica*, 26(05), 1342–1350 (in Chinese with English abstract).
- Fan HR, Hu FF, Yang KF, Pirajno F, Liu X, Wang KY. 2014. Integrated U-Pb and Sm-Nd geochronology for a REE-rich carbonatite dyke at the giant Bayan Obo REE deposit, northern China. *Ore Geology Reviews*, 63(2), 510–519. doi: [10.1016/j.oregeorev.2014.03.005](https://doi.org/10.1016/j.oregeorev.2014.03.005).
- Fan HR, Yang KF, Hu FF. 2016. The giant Bayan Obo REE-Nb-Fe deposit, China: Controversy and ore genesis. *Geoscience Frontiers*, 7(3), 335–344. doi: [10.1016/j.gsf.2015.11.005](https://doi.org/10.1016/j.gsf.2015.11.005).
- Fan HR, Chen FK, Wang KY, Xie YH, Wilde S, Stair M. 2002b. Zircon U-Pb age of a carbonatite dyke from Bayan Obo REE-Fe-Nb deposit, Inner Mongolia and its geological, significance. *Acta Petrologica Sinica*, 18, 363–368 (in Chinese with English abstract).
- Fan HR, Hu FF, Chen FK, Yang KF, Wang KY. 2006. Intrusive age of no. 1 carbonatite dyke from Bayan Obo REE-Nb-Fe deposit, Inner Mongolia with answers to comment of Dr. Le Bas. *Acta Petrologica Sinica*, 22, 519–520. doi: [10.1016/S1872-2040\(06\)60043-1](https://doi.org/10.1016/S1872-2040(06)60043-1).
- Fan HR, Hu FF, Yang KF, Wang KY, 2006a. Fluid unmixing/immiscibility as an ore forming process in the giant REE-Nb-Fe deposit, Inner Mongolian, China: evidence from fluid inclusions. *J. Geochem. Explor.* 89, 104–107. doi: [10.1016/j.gexplo.2005.11.039](https://doi.org/10.1016/j.gexplo.2005.11.039).
- Fan HR, Xu Y, Yang KF, Zhang E, Li Xc, Zhang LL, She HD, Liu SL, Xu Xw, Huang S, Li O, Zhao L, Li XH, Wu FY, Zhai MG, Zhao YG, Wang OW, Yang ZF, Liu Y, Yan GY, Liu ZO, Cui F, Liu F. 2022. Intrusive style three-dimensional morphology of carbonatite and REE potential resources in the Bayan Obo giant deposit, Inner Mongolia. *Acta Petrologica Sinica*, 38(10), 2901–2919. doi: [10.18654/1000-0569/2022.10.01](https://doi.org/10.18654/1000-0569/2022.10.01).
- Fang T, Qiu, YZ, Qiu, XH. 1994. Characteristics and origin of C-O isotopes of REE-flourite carbonate in Bayan Obo ore deposit. *Chinese science Bulletin*, 21, 1982–1985 (in Chinese). doi: [10.1360/CSB1994-39-21-1982](https://doi.org/10.1360/CSB1994-39-21-1982).
- Fei HC, 2005. Dissertation on Ph. D. Genesis study of the Alkali rock series, rare earth element and magnetite deposit in Bayan Obo, Inner Mongolia. Chinese University of Geosciences (Beijing).
- Fei XJ, Zeng PS, Yan CJ, Wen LG. 2019. The regional geological evolution history of the Bayan Obo REE-Nb-Fe deposit derived from isotopic ages. *Geology and Exploration*, 55 (2); 0461–0471 (in Chinese with English abstract). doi: [10.12134/j.dzykt.2019.02.002](https://doi.org/10.12134/j.dzykt.2019.02.002).
- Fritz P, Smith DGW. 1970. The isotopic composition of secondary dolomites. *Geochimica Et Cosmochimica Acta*, 34(11), 1161–1173. doi: [10.1016/0016-7037\(70\)90056-6](https://doi.org/10.1016/0016-7037(70)90056-6).
- Gao JY, Wang YX, Qiu YZ, Zhang Q. 1999. Origin of the ore-bearing dolomite in Baiyun Obo ore deposit. *Acta Sedimentologica Sinica*, 1999(S1), 675–680 (in Chinese with English abstract).
- Hoefs J. 1987. Stable isotope geochemistry. 3rd edn. Springer, Berlin Heidelberg New York.
- Hao ZG, Wang XB, Li Z, Zhang TR. 2002. Bayan Obo Carbonatite REE-Nb-Fe Deposit: a rare example of neoproterozoic lithogeny and metallogeny of a damaged volcanic edifice. *Acta Geologica Sinica*, 76(4), 525–540 (in Chinese with English abstract). doi: [CNKI:SUN:DZXE.0.2002-04-017](https://doi.org/CNKI:SUN:DZXE.0.2002-04-017).
- Hou GT, Li JH, Liu YL, Qian XL. 2005. Late Paleoproterozoic extensional events in the North China Craton: Aulacogens and dykes. *Progress in Natural Science*, 2005(11), 1366–1373 (in Chinese with English abstract). doi: [10.1080/10020070612331343214](https://doi.org/10.1080/10020070612331343214).
- Hou ZL. 1989. The Bayan Obo Fe-Nb-REE-deposit: its basic geological features, metallogenesis and genetic model. *Geology and Prospecting*. 25, 1–5 (in Chinese with English abstract).
- Hu Le, Zhong-jian Wu, Yang Bai, An-jian Wang, (#)Yi-Ke Li(\*). Two metasomatic events recorded inapatite from the ore-hosting dolomite marble and implications for genesis of the giant Bayan Obo REE deposit, *Journal of Asian Earth Sciences*, 2018.8. 22, 172C: 56–65. doi: [10.1016/j.jseas.2018.08.022](https://doi.org/10.1016/j.jseas.2018.08.022).
- Hu Le, Yi-Ke Li(\*), Chuan MS, Li RP, Ke CH, Wu ZJ. 2020. Post-Magmatic Fluids Dominate the Mineralization of Dolomite Carbonatitic Dykes Next to the Giant Bayan Obo REE Deposit, Northern China. *Minerals*. doi: [10.3390/min10121117](https://doi.org/10.3390/min10121117).
- Institute of Geochemistry, Chinese Academy of Sciences. 1988. *Geochemistry of the Bayan Obo deposit*. Beijing, Science Press, 513.
- Ke C H, Sun S, Zhao Y G, Li Y K, Xu Z Y, Hao M Z, Li R P, Zhang L. 2021. Ore-controlling structure and deep prospecting of the Bayan Obo large-sized REE-Nb-Fe ore deposit, Inner Mongolia. *Geological Bulletin of China*, 40(1): 95–109. (in Chinese with English abstract).
- Lai XD, 2013. Dissertation on Ph. D. Study on the genesis of Bayan Obo REE-Fe ore deposit, Inner Mongolia. University of Science and Technology of China.
- Lawrence JD, Meng Q, Sun W. 1990. The Bayan Obo iron-rare-earthniobium deposits, Inner Mongolia, China. *Lithos*, 26(1–2), 43–65. doi: [10.1016/0024-4937\(90\)90040-8](https://doi.org/10.1016/0024-4937(90)90040-8).
- Le Bas MJ, Keller J, Tao KJ, Wall F, Williams CT and Zhang PS. 1992. Carbonatite dykes at Bayan Obo, Inner Mongolia, China. *Mineralogy and Petrology*, 36(3), 195–228. doi: [10.1007/BF01164647](https://doi.org/10.1007/BF01164647).
- Le Bas, MJ, Spiro B, Yang X, 1997. Oxygen, carbon and strontium isotope study of the carbonatitic dolomite host of the Bayan Obo Fe-Nb-REE deposit, Inner Mongolia, N. China. *Mineral. Mag.* 61, 531–541. doi: [10.1180/minmag.1997.061.407.05](https://doi.org/10.1180/minmag.1997.061.407.05).
- Le Bas, MJ, Yang XM, Taylor RN, Spiro B, Milton JA, Peishan, Z, 2007. New evidence from a calcite-dolomite carbonatite dyke for the magmatic origin of the massive Bayan Obo ore-bearing dolomite marble, Inner Mongolia, China. *Mineral. Petrol.* 91, 281–307. doi: [10.1007/s00710-006-0177-x](https://doi.org/10.1007/s00710-006-0177-x).

- Li CY, Wang Q, Liu XY, Tang YQ, 1984. Tectonic evolution of Asia. *Bulletin of the Chinese Academy of Geological sciences.*: 3–11 (in Chinese with English abstract). doi: [CNKI:SUN:DQXB.0.1984-03-001](https://doi.org/10.1039/c8ja00125a).
- Li Q, Liu Y, Tang GQ, Wang KY, Ling XX, Li J. 2018. Zircon Th–Pb dating by secondary ion mass spectrometry. *J. Anal. At. Spectrom.* 33, 1536–1544. doi: [10.1039/c8ja00125a](https://doi.org/10.1039/c8ja00125a).
- Li YK, Ke CH, Wang DH, Zhao YG, She HQ, Li RP, Hao MZ, Wang AJ, Deng Z, Gao YP, Zhang Q, Zhang L, LI JW, Hu GY, Liu Y, Guo B, Yuan XY, 2022. Important progress in prospecting and exploration of iron ore in deep border area of Bayan Obo deposit, Inner Mongolia, China, *Mineral Deposits*, 41 (1), 202–206 (in Chinese with English abstract).
- Liu CH, Liu FL. 2015. The Mesoproterozoic rifting in the North China Craton: A case study for magmatism and sedimentation of the Zhaertai-Bayan Obo-Huade rift zone. *Acta Petrologica Sinica*, 2009.31(10), 3107–3128 (in Chinese with English abstract).
- Liu LS, Gao L, Du AD, Su YL. 1996. The Re-Os isotopic age of molybdenite from Bayan Obo REE ore deposit. *Mineral Deposits*, 15(2), 188–191 (in Chinese with English abstract).
- Liu TG. 1986. A Discussion on the Genesis of Dolomite in Bayan Obo, Inner Mongolia—with Emphasis on the Composition of Oxygen and Carbon Isotopes. *Geological Review*, 32(2), 150–159 (in Chinese with English abstract).
- Liu TG. 1990. Discriminant analysis of genetic type of carbonate rock and discussion on genetic dolomitite in bai yinobo region. *Acta Sedimentologica Sinica*. 03, 93–102 (in Chinese with English abstract).
- Liu YL, Peng GY, Zhang X, Li HM, Chen JF. 2001. U-Pb and Pb-Pb Dating of the Host Rock-H8 Dolomite in Bayan Obo Ore Deposit. *Bulletin of Mineralogy Petrology and Geochemistry*. 2001, 04, 274–277 (in Chinese with English abstract). doi: [10.3969/j.issn.1007-2802.2001.04.020](https://doi.org/10.3969/j.issn.1007-2802.2001.04.020).
- Liu YL, Yang G, Chen JF, Du AD, Xie Z. 2004. Re-Os dating of pyrite from Giant Bayan Obo REE-Nb-Fe deposit. *Chinese Science Bulletin*, 49(024), 2627–2631. doi: [10.1360/04wd0185](https://doi.org/10.1360/04wd0185).
- Liu YL, Chen JF, Li HM, Qian H, Xiao GW, Zhang TR. 2005a. Single-grain U-Th-Pb-Sm-Nd dating of monazite from dolomite type ore of the Bayan Obo deposit. *Acta Petrologica Sinica* 21 (3), 881–888 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-0569.2005.03.027](https://doi.org/10.3969/j.issn.1000-0569.2005.03.027).
- Liu YL, Yang G, Chen JF, Du AD, Xie Z. 2005b. Re-Os dating of pyrite from Giant Bayan Obo REE-Nb-Fe deposit. *Chinese Science Bulletin*, 50(2), 172–175 (in Chinese). doi: [10.3321/j.issn:0023-074X.2005.02.012](https://doi.org/10.3321/j.issn:0023-074X.2005.02.012).
- Liu S, Fan HR, Yang KF, Hu FF, Rusk B, Liu X, Li XC, Yang ZF, Wang QW, Wang KY. 2018. Fenitization in the giant Bayan Obo REE-Nb-Fe deposit: Implication for REE mineralization. *Ore Geology Reviews*, 94, 290–309. doi: [10.1016/j.oregeorev.2018.02.006](https://doi.org/10.1016/j.oregeorev.2018.02.006).
- Ling MX, Liu YL, Williams IS, Teng FZ, Yang XY, Ding X, Wei GJ, Xie LH, Deng WF, Sun WD. 2013. Formation of the world's largest REE deposit through protracted fluxing of carbonatite by subduction-derived fluids. *Nature:Scientific Reports*, (3), 1776. doi: [10.1038/SREP01776](https://doi.org/10.1038/SREP01776).
- Ling MX, Zhang H, Li H, Liu YL, Liu J, Li LQ, Li CY, Yang XY, Sun W. 2014. The Permian-Triassic granitoids in Bayan Obo, North China Craton: A geochemical and geochronological study. *Lithos*, 190, 430–439. doi: [10.1016/j.lithos.2014.01.002](https://doi.org/10.1016/j.lithos.2014.01.002).
- Meng QR. 1982. The genesis of the host-rock-dolomite of the Bayan Obo iron ore deposits and the analysis of its sedimentary environment. *Geological Review*, 28(5), 481–489 (in Chinese with English abstract).
- Mian I, Le Bas M. 1986. Sodic hornblendes in fenites from the Loe Shilman carbonatite complex. *NW Pakistan:Mineralogical Magazine*, 50, 187–197. doi: [10.1180/minmag.1986.050.356.01](https://doi.org/10.1180/minmag.1986.050.356.01).
- 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).
- Qiao XF, Gao LZ, Peng Y, Zhang YX. 1997. Composite Stratigraphy of the Sailinhuodong Group and Ore-Bearing Micrite Mound in the Bayan Obo Deposit, Inner Mongolia, China. *GEOLOGICAL REVIEW*, 42(3), 147 (in Chinese with English abstract).
- Qin CJ, Qiu YZ, Zhou GF, Wang ZG, Zhang TR, 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 (in Chinese with English abstract). doi: [10.3321/j.issn:1000-0569.2007.01.020](https://doi.org/10.3321/j.issn:1000-0569.2007.01.020).
- Ren YS, Zhang YC, Zhang ZQ. 1994. Study on heat events of ore-forming bayan obo deposit. *Acta Geoscientica Sinica*. 15 (Z1), 95–101. (In Chinese with English abstract).
- Shao JA, Zhang LQ, Li DM. 2002. Three Proterozoic extensional events in North China Craton. *Acta Petrol. Sin.* 18, 152–160 (in Chinese with English abstract). doi: [10.3321/j.issn:1000-0569.2002.02.003](https://doi.org/10.3321/j.issn:1000-0569.2002.02.003).
- Shu Y, Zheng YF, Wei CS, Zhou JB, Yang XM, Yang XY. 2001. The isotopic geochemistry of the carbon and oxygen from the carbonatite in Bayan Obo, Inner Mongolia. *Geochemistry* 2001, 02, 169–176 (in Chinese with English abstract). doi: [10.3321/j.issn:0379-1726.2001.02.009](https://doi.org/10.3321/j.issn:0379-1726.2001.02.009).
- Sheppard SMF, Schwarz HP. 1970. Fractionation of carbon and oxygen isotopes and magnesium between coexisting metamorphic calcite and dolomite. *Contributions to Mineralogy and Petrology*, 26, 161–198. doi: [10.1007/BF00373200](https://doi.org/10.1007/BF00373200).
- Smith MP, Henderson P. 2000. Preliminary fluid inclusion constraints on fluid evolution in the Bayan Obo Fe-REE-Nb Deposit, Inner Mongolia, China. *Economic Geology*. 95, 1371–1388. doi: [10.2113/95.7.1371](https://doi.org/10.2113/95.7.1371).
- Smith MP, Campbell LS, Kynicky J. 2015. A review of the genesis of the world class Bayan Obo Fe-REE-Nb deposits, Inner Mongolia, China: Multistage processes and outstanding questions. *Ore Geology Reviews*, v.64, 459–476. doi: [10.1016/J.OREGEOREV.2014.03.007](https://doi.org/10.1016/J.OREGEOREV.2014.03.007).
- Song W, Xu C, Smith MP, Chakhmouradian AR, Brenna M, Kynický J, Chen W, Yang Y, Deng M, Tang H, 2018. Genesis of the world's largest rare earth element deposit, Bayan Obo, China. Protracted mineralization evolution over 1 by Geology, 46, 323–326. doi: [10.1130/G39801.1](https://doi.org/10.1130/G39801.1).
- Tao KJ, Yang ZM, Zhang PS, Wang WZ. 1998. Systematic geological investigation on carbonatite dykes in Bayan Obo, Inner Mongolia, China *Scientia Geologica Sinica*, 33 (1), 74–84 (in Chinese with English abstract). doi: [10.1088/0256-307X/16/9/027](https://doi.org/10.1088/0256-307X/16/9/027).
- Wang HC, Xiang ZQ, Zhao FQ, Li HM, Yuan GB, Chu H, 2012. The alkaline plutons in eastern part of Guyang County, Inner Mongolia: Geochronology, petrogenesis and tectonic implications. *Acta Petrologica Sinica*, 28 (09), 2843–2854 (in Chinese with English abstract).
- Wang J, Wang BL, Xu CH, 1989. The age and ore-bearing of the Langshan group and Bayan Obo group in Inner Mongolia. Hohhot: Peoples publishing House of Inner Mongolia (in Chinese).
- Wang J, Tatsumoto M, Li X, Premo WR, Chao EC T. 1994. A precise <sup>232</sup>Th-<sup>208</sup>Pb chronology of fine-grained monazite: Age of the Bayan Obo REE-Fe-Nb ore deposit: China. *Geochimica ET Cosmochimica Acta*, 58(15), 3155–3169. doi: [10.1016/0016-7037\(94\)90043-4](https://doi.org/10.1016/0016-7037(94)90043-4).
- Wang KY, Yang KF, Fan HR, Hu FF, HU FY, 2012. Addressing Some Problems on Research of the Bayan Obo Deposit. *Acta Geologica Sinica*, 86 (05), 687–699 (in Chinese with English abstract).
- Wang KY, Fan HR, Yang KF, Hu FF, Wu CM and Hu FY. 2010. Calcite-dolomite geothermometry of Bayan Obo carbonatites. *Acta Petrologica Sinica*. 26 (04), 1141–1149. (In Chinese with English abstract). doi: [10.1016/j.sedgeo.2010.03.004](https://doi.org/10.1016/j.sedgeo.2010.03.004).
- Wang KY, Zhang JE, Fang AM, Dong C, Hu FY. 2018. Genesis of the Bayan Obo deposit, Inner Mongolia: The fenitized mineralization in the ore bodies and its relation to the ore-bearing dolomite. *Acta Petrologica Sinica*. 34 (03), 785–798. (In Chinese with English abstract).

- abstract). doi: [10.1016/j.jseaes.2018.12.007](https://doi.org/10.1016/j.jseaes.2018.12.007).
- Wang XB, Hao ZG, Li Z, Xiao GW, Zhang TR. 2002. A Typical Alkaline Rock-Carbonatite Complex in Bayan Obo, Inner Mongolia. *Acta Geologica Sinica*. 2002 (04), 501–524. (In Chinese with English abstract)
- Wang HZ, He GQ, Zhang SH. 2006. The geology of China and Mongolia. *Earth Science Frontiers*, 2006(06), 1–13 (in Chinese with English abstract). doi: [10.3321/j.issn:1005-2321.2006.06.003](https://doi.org/10.3321/j.issn:1005-2321.2006.06.003).
- Wang, ZG, Li SB, Su. XZ. 1973. Genetic characteristics of sedimentary metamorphic hydrothermal metasomatic rare earth and iron ore deposits. *Geochimica*, 1973(01), 5–11 (in Chinese with English abstract).
- Wang, J, Li SQ. 1992. The Rifting System from Langshan to Bayan Obo. Beijing, Press of Peking University (in Chinese).
- Wei JY, Shangguan ZG, 1983. Oxygen isotope composition of magnetite and hematite in Baiyun Ebo iron deposit, Inner Mongolia. *Journal of Geology*, 3, 217–224 (in Chinese with English abstract).
- Wei JY, Jiang SY, Wan. DF. 1994. The silicon isotope composition of bayan obo rare-earth iron ore deposit, Inner Mongolia. *Acta Geoscientia Sinica*, 1994(Z1), 102–110 (in Chinese with English abstract).
- Weng ZH, Jowitt SM, Mudd GM, Haque N. 2015. A Detailed Assessment of Global Rare Earth Element Resources: Opportunities and Challenges. *Economic Geology*, 110, 1925–1952. doi: <https://doi.org/10.2113/econgeo.110.8.1925>.
- Woolley AR, Kjarsgaard BA. 2008a. Paragenetic types of carbonatite as indicated by the diversity and relative abundances of associated silicate rocks: Evidence from a global database. *Geochimica ET Cosmochimica Acta*, 72(46), 741–752. doi: [10.3749/canmin.46.4.741](https://doi.org/10.3749/canmin.46.4.741).
- Woolley, AR, Kjarsgaard BA. 2008. Carbonatite occurrences of the world. Map and database: Geological Survey of Canada, Open File Report 5796.
- Wu TR, Zhang C, Wan JH. 1998. Tectonic settings of ondor sum group and its tectonic interpretation in ondor sum region, Inner Mongolia. *Geological Journal of China Universities*, 1998(02), 49–57.
- Wu CD, Chen QY and Lei JJ. 1999. The genesis factors and organic petrology of black shale series from the upper Sinian to the lower Cambrian, southwest of China. *Acta Petrologica Sinica*, 15(3), 453–462 doi: [10.3969/j.issn.1000-0569.1999.03.014](https://doi.org/10.3969/j.issn.1000-0569.1999.03.014).
- Wyllie PJ, Jones AP, Deng J. 1996. Rare earth elements in carbonate-rich melts from mantle to crust. In: Jones, A. P., et al. (eds.), *Rare Earth Minerals: Chemistry, Origin and Ore Deposits*. London, Chapman & Hall, 77–104.
- Wyllie PJ, Lee WJ. 1998. Model system controls on conditions for formation of magnesiocarbonatite and calciocarbonatite magmas from the mantle. *Journal of Petrology*, 39, 1885–1893. doi: [10.1093/ptro/39.11-12.1885](https://doi.org/10.1093/ptro/39.11-12.1885).
- Xiao RG, Fei HC, Wang AJ, Yang Yan K. 2012. Formation and Geochemistry of the Ore-Bearing Alkaline Volcanic Rocks in the Bayan Obo REE-Nb-Fe Deposit, Inner Mongolia, China. *Acta Geologica Sinica*. 86 (05), 735–752 (in Chinese with English abstract). doi: <http://discovery.ucl.ac.uk/1370130/>.
- Xiao RG, Liu JD, Fei HC, Wang CZ, Huang XL. 2006. Types and Genesis of Na-Rich Rocks in the Bayan Obo REE-Nb-Fe Deposit, Inner Mongolia, China. *Geoscience*. 01, 151–164 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-8527.2006.01.018](https://doi.org/10.3969/j.issn.1000-8527.2006.01.018).
- Xie YL, Li YX, Hou ZQ, Cooke DR, Danyushevsky L, Dornery SC and Yin SP. 2015. A model for carbonatite hosted REE mineralization—the mianning–Dechang REE Belt, western Sichuan Province, China. *Ore Geology Reviews*, 70, 595–612. doi: [10.1016/j.oregeorev.2014.10.027](https://doi.org/10.1016/j.oregeorev.2014.10.027).
- Xie YL, Qu YW, Yang ZF, Liang P, Zhong RC, Wang QW, Xia JM, Li BC. 2019. Giant Bayan Obo Fe-Nb-REE deposit: Progresses, Controversaries and new understandings. *Mineral Deposit*. 38 (05), 983–1003 (in Chinese with English abstract).
- Xie Y, Hou Z, Goldfarb RJ, Guo X, Wang L. 2016. Rare earth element deposits in China. *Reviews in Economic Geology*, 18, 115–136.
- Xu B. 1998. Sedimentary environment and tectonic significance of the north belt of the ondor sum group in inner mongolia. *Scientia Geologica Sinica*, 1998(04), 25–30 (in Chinese with English abstract).
- Xu C, Campbell IH, Kynicky J, Allen CM, Chen YJ, Huang ZL, Qi L. 2008. Comparison of the Daluxiang and Maoniuping carbonatitic REE deposits with Bayan Obo REE deposit, China. *Lithos*, 106(1-2), 12–24. doi: [10.1016/j.lithos.2008.06.005](https://doi.org/10.1016/j.lithos.2008.06.005).
- Yan GH, Cai JH, Ren KX, He GQ, Mu BL, Xu BL, Li FT, Yang B. 2007. Intraplate Extensional Magmatism of North China Craton and Break-up of Three Supercontinents and Their Deep Dynamics. *Geological Journal of China Universities*, 2007(2), 161–174 (in Chinese with English abstract). doi: [10.1016/S1872-5791\(07\)60044-X](https://doi.org/10.1016/S1872-5791(07)60044-X).
- Yang KF, Fan HR, Hu FF, Wang KY. 2012. Sediment Source of Bayan Obo Marginal Rift and Genesis of Ore-Bearing Dolomite of the Giant REE Deposit. *Acta Geologica Sinica*. 86 (5), 775–784 (in Chinese with English abstract).
- Yang XM, Yang XY, Chen SX, Chen TH, Zhang PS, Tao KJ, Le Bas MJ, Wilson RN, Branson R, Campbell LS, Williams TC and Henderson P. 1999. New occurrence and mineralogy of Barium-Fluorocarbonate. *Chinese Science Bulletin*, 44(9), 984–989 (in Chinese). doi: [10.3321/j.issn:0023-074X.1999.09.021](https://doi.org/10.3321/j.issn:0023-074X.1999.09.021).
- Yang XM, Le Bas MJ. 2004. Chemical compositions of carbonate minerals from Bayan Obo, Inner Mongolia, China: implications for petrogenesis. *Lithos*, 72(1/2), 97–116. doi: [10.1016/j.lithos.2003.09.002](https://doi.org/10.1016/j.lithos.2003.09.002).
- Yang XY, Lai XD, Ren YS, Ling MX, Liu YL, Liu JY. 2015. Geological Characteristics and Their Scientific Problems of the Bayan Obo Fe-REE-Nb Deposit: Discussion on the Origin of Bayan Obo Super-large Deposit. *Acta Geologica Sinica*. vol. 89 (12), 2323–2350 (in Chinese with English abstract). doi: [10.3969/j.issn.0001-5717.2015.12.010](https://doi.org/10.3969/j.issn.0001-5717.2015.12.010).
- Yang XM, Yang XY, Chen H, Zhang PS, Tao KJ, Le Bas MJ, Henderson P. 1999. Geochemical Characteristics of a Carbonatite Dyke Rich in Rare Earths from Bayan Obo, China. *Journal of the Chinese Rare Earth Society*, 1999(04), 289–295 (in Chinese with English abstract).
- Yang XM, Yang XY, Zheng YF, Guo F, Zhang ZF, Zhang PS, Le Bas MJ. 2000. Carbon and Oxygen Isotope Characteristics of the REE-Rich Carbonatite Dyke from Bayan Obo, Inner Mongolia, North China. *Geological Journal of China Universities*, 2000(02), 205–209 (in Chinese with English abstract). doi: [10.3969/j.issn.1006-7493.2000.02.015](https://doi.org/10.3969/j.issn.1006-7493.2000.02.015).
- Yang K, Fan H, Pirajno F, Li X. 2019. The Bayan Obo (China) giant REE accumulation conundrum elucidated by intense magmatic differentiation of carbonatite. *Geology*, 47, 1198–1202.
- Yang KF, Fan HR, Santosh M, Hu FF, Wang, KY. 2011. Mesoproterozoic carbonatitic magmatism in the Bayan Obo deposit, Inner Mongolia, North China: Constraints for the mechanism of super accumulation of rare earth elements. *Ore Geology Reviews*, 40, 122–131. doi: [10.1016/j.oregeorev.2011.05.008](https://doi.org/10.1016/j.oregeorev.2011.05.008).
- Yang XY, Sun WD, Zhang YX, Zheng YF. 2009. Geochemical constraints on the genesis of the Bayan Obo Fe–Nb–REE deposit in Inner Mongolia, China. *Geochimica et Cosmochimica Acta*, 73(5), 1417–1435. doi: [10.1016/j.gca.2008.12.003](https://doi.org/10.1016/j.gca.2008.12.003).
- Yang XM, Yang XY, Chen SX, Chen TH, Zhang PS, Tao KJ, LeBas MJ, Wilson RN, Branson R, Campbell LS, Williams TC, Henderson P, 2009. Newly derived attitudes and mineralogical characteristics of REE-bearing fluorocarbonate minerals in the Bayan Obo deposit. *Science Bulletin*. 3–5 (in Chinese with English abstract).
- Yao D, Zhang LJ, Wiltshire J, Malahoff A, Ye YG. 1998. Geology and meteorite impact origin of bayan obo fe nb ree deposit, inner mongolia, china. *Marine Geology & Quaternary Geology*, 1998(04), 88–97 (in Chinese with English abstract). doi: [10.1088/0256-307X/15/12/024](https://doi.org/10.1088/0256-307X/15/12/024).
- Yuan ZX, Bai G, Wu CY, Zhang ZQ, Ye XJ. 1991. Metallogene epoch and genesis of the Bayan Obo Niobium-iron deposit, Inner Mongolia.

- Mineral Deposits, 10(1), 59–60 (in Chinese with English abstract).
- Yuan ZX, Bai G, Wu CY, Zhang ZQ, YE XJ. 1992. Geological features and genesis of the Bayan Obo REE ore deposit, Inner Mongolia, China. *Applied Geochemistry*, 7(5), 429–442. doi: [10.1016/0883-2927\(92\)90004-M](https://doi.org/10.1016/0883-2927(92)90004-M).
- Yuan ZX, Bai G, Wu CY, Ding XS, Zhang ZQ. 1995. Petrological features of volcanic rocks in H9 formation of the Bayan Obo ore district, Inner Mongolia, and their significance. *Mineral Deposits*, 14(3), 197–205 (in Chinese with English abstract).
- Yuan ZX, Bai G, Zhang ZQ. 2004. Autometamorphic phenomena of host rocks in the Bayan Obo ore deposit and their significance. *Acta Petrologica et Mineralogica*, 2004(01), 19–25 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-6524.2004.01.003](https://doi.org/10.3969/j.issn.1000-6524.2004.01.003).
- Zhai MG, Hu B, Zhao TP, Peng P, Meng QR. 2015. Late Paleoproterozoic-Neoproterozoic multi-rifting events in the North China Craton and their geological significance: A study advance and review. *Tectonophysics*, 662, 153–166. doi: [10.1016/j.tecto.2015.01.019](https://doi.org/10.1016/j.tecto.2015.01.019).
- Zhang PS, Tao KJ. 1996. Mineralogy of Bayan Obo. Beijing: Publishing House of geology. 1–182 (in Chinese).
- Zhang PS, Tao KJ, Yang ZM, Yang XM. 1998. Rare-earth Element Minerals in China. Beijing, Science Press, 1–234 (in Chinese).
- Zhang PS, Tao KJ, Yang ZM, Yang XM, Song RK. 2001. Genesis of Rare Earths, Niobium and Tantalum Minerals in Bayan Obo Ore Deposit of China. *Journal of the Chinese Rare Earth Society* Obo. 19, 97–102.
- Zhang PY, Li SQ, Wang CY, Niu SW, Sun SF, Guan AL, Liang W. 1993. The geologico-tectonical characteristics in Baiyun Obo region. *Bulletin Tianjin Institute Geol. Min. R.*, (28), 1–86 (in Chinese with English abstract)
- Zhang SH, Zhao Y, Liu YS. 2017. A precise zircon Th-Pb age of carbonatite sills from the world's largest Bayan Obo deposit: Implications for timing and genesis of REE-Nb Mineralization. *Precambrian Research*, 291, 202–219. doi: [10.1016/j.precamres.2017.01.024](https://doi.org/10.1016/j.precamres.2017.01.024).
- Zhang SH., Ernst R E., Yang Z., Zhou, Z., Pei, J., Zhao, Y. 2022. Spatial distribution of 1.4-1.3 ga lips and carbonatite-related ree deposits: evidence for large-scale continental rifting in the columbia (nuna) supercontinent. *Earth and Planetary Science Letters: A Letter Journal Devoted to the Development in Time of the Earth and Planetary System*. doi: <https://doi.org/10.1016/j.epsl.2022.117815>.
- Zhang YX, Jiang SQ, Zhang QL, Lai XD, Peng Y, Yang XY. 2008. A discussion on forming time of the Bayan Obo Group and ore-forming time of the Bayan Obo giant REE-Nb-Fe deposit, Inner Mongolia. *Geology in China*. 35 (6), 1129–1137 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-3657.2008.06.010](https://doi.org/10.3969/j.issn.1000-3657.2008.06.010).
- Zhang YX, Peng Y, Qian XF, Gao LZ, Yang XR. 1998. New knowledge of genesis of ore-bearing dolomite in Bayan Obo, Inner Mongolia. *Geological Review*, 44(1), 70–76 (in Chinese).
- Zhang YX, Yang ZF, Zhang QL. 2009. Geological and Geochemistry Research on Bayan Obo Ore Deposit and Micrite in Xishan Beijing. Beijing, Geological Publishing House, 1–112 (in Chinese with English abstract).
- Zhang ZQ, Tang SH, Wang JH Yuan ZX, Bai G. 1994. New datafor ore-forming age of the Bayan Obo REE deposit, Inner Mongolia. *Acta Geoscientia Sinica*, 29(1–2), 85–94 (in Chinese with English abstract).
- Zhang ZQ, Tang SH, Chen QT, Wang JH, Yuang ZX, Bai G. 1997. Sm-Nd Ages and Origins of Metamorphic Rocks for the H 9 Formation in the Bayan Obo Ore District and Relationship with the Ore Forming Event. *Acta Geoscientia Sinica*, 18(03), 44–51 (in Chinese with English abstract).
- Zhang ZQ, Tang SH, Yuan ZX, Bai G, Wang JH. 2001. The Sm-Nd and Rb-Sr isotopic systems of the dolomites in the Bayanobo ore Deposit, Inner Mongolia, China. *Acta petrologica Sinica*, 17(4), 637–642 (in Chinese with English abstract).
- Zhang ZQ, Tang SH, Wang JH, Yuan ZX and Bai G. 2003. Information about ore deposit formation in different epochs: Age of the west orebodies of the Bayan Obo deposit with a discussion. *Geology in China*, 30(2), 130–137 (in Chinese with English abstract).
- Zhang ZQ, Yuan ZX, Tang SH, Wang JH, Bai G. 2003. Information about ore deposit formation in different epochs: Age of the west orebodies of the Bayan Obo deposit with a discussion. *Geology in China*, 30 (2), 130–137 (in Chinese with English abstract).
- Zhang ZQ, Song B, Tang SH. 2004. Age and material composition of the Foping metamorphic crystalline complex in the Qinling Mountains: SHRIMP zircon U-Pb and whole-rock Sm-Nd geochronology. *Chinese Geology*, 31(02), 161–168 (in Chinese with English abstract). doi: [10.3969/j.issn.1000-3657.2004.02.007](https://doi.org/10.3969/j.issn.1000-3657.2004.02.007).
- Zheng YF. Stable Isotope Geochemistry. Science Press, 2000.
- Zhao GC, Wilde SA, Cawood PA, Li LZ. 1999. Tectonothermal history of the basement rocks in the western zone of the North China Craton and its tectonic implications. *Tectonophysics*, (310), 37–53. doi: [10.1016/S0040-1951\(99\)00152-3](https://doi.org/10.1016/S0040-1951(99)00152-3).
- Zhao GC, Sun M, Wilde, SA, Li SZ. 2003. Assembly, accretion and breakup of the paleo-mesoproterozoic Columbia supercontinent: Records in the North China Craton. *Gondwana Research*, 6, 417–434. doi: [10.1016/S1342-937X\(05\)70996-5](https://doi.org/10.1016/S1342-937X(05)70996-5).
- Zhao GC, Sun M, Wilde SA, Li SZ. 2005. Late Archean to Paleoproterozoic evolution of the North China Craton: Key issues revisited. *Precambrian Research*, (136), 177–202. doi: [10.1016/j.jseaes.2004.06.004](https://doi.org/10.1016/j.jseaes.2004.06.004).
- Zhao JD, Tatsumoto M, Minkin JA, Back JM, McKee EH, Ren YC, Li YM. 1991. Multiple lines of evidence for establishing the mineral paragenetic sequence of the bayan obo rare earth ore deposit of Inner Mongolia, China. *Contributions to Geology and Mineral Resources Research*, 1991(4), 1–17.
- Zhou JB, Zheng YF, Yang XY, Shu Y, Wei CS, Xie Z. 2002. Paleoplate Tectonics and Regional Geology at Bayan Obo in Northern Inner Mongolia. *Geological Journal of China Universities*, 8(1), 47–62. doi: [10.1007/s11769-002-0037-5](https://doi.org/10.1007/s11769-002-0037-5).
- Zhou ZL, Li GY, Song TY, Liu YG. 1980. On the geological characteristics and genesis of the dolomitic carbonatites at Bayan Obo, Nei Mongol (Inner Mongolia). *Geological Review*, 26(1), 35–42 (in Chinese with English abstract).
- Zhou ZL, Li GY, Song TY. 1980. On the geological characteristics and genesis of the dolomitic carbonatites at Bayan Obo, Nei Mongol (Inner Mongolia). *Geological Review*, 26(1), 0371–5736 (in Chinese with English abstract).
- Zhou YS. 2006. Discussion on the Sedimentary-Hydrothermal Metamorphic Genesis of Bayan Obo Iron Ore Deposit. *Inner Mongolia Science & Technology and Economy*, 2006(5), 58–59 (in Chinese). doi: [10.3969/j.issn.1007-6921.2006.05.030](https://doi.org/10.3969/j.issn.1007-6921.2006.05.030).
- Zhu XK, Sun J. 2012. Ore-forming epoch and episodes of REE mineralization in the Bayan Obo ore deposit, Inner Mongolia. *Acta Geoscientia Sinica*, 33(6), 845–856 (in Chinese with English abstract). doi: [10.3975/cagsb.2012.06.02](https://doi.org/10.3975/cagsb.2012.06.02).
- Zi JW, Li LX, Li YK, Rasmussen B, Ke CH. 2023. Magmatic-hydrothermal history of Bayan Obo REE-rich carbonatites revealed by monazite Th-Pb geochronology of the Wu dyke. *Earth Science* (in Chinese with English abstract). doi: [10.3799/dqkx.2023.027](https://doi.org/10.3799/dqkx.2023.027).