



The occurrence and distribution of thorium in the giant Bayan Obo REE-Nb-Fe polymetallic deposit, China

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ABSTRACT

Thorium (Th) is increasingly regarded as a critical element for next-generation nuclear energy systems due to its status as the most abundant fissile material on Earth and its advantageous safety properties. The Bayan Obo deposit in Inner Mongolia (China), contains the largest known reserves of rare earth elements (REE) globally, along with significant amounts of niobium (Nb), iron (Fe), and Th. Despite the considerable Th resources within this deposit, the spatial distribution, occurrence state, and genetic relationship with the REE-Nb-Fe mineralized systems are still poorly understood.

In this study, Th distribution and the intrinsic relationship with REE-Nb-Fe mineralization were investigated by a systematic mineral-geochemical composition analysis (XRF, TIMA, and EPMA) of various rocks and ores in the Bayan Obo deposit. Spatially, Th concentrates along the contact zone (fluorite-rich banded/massive ores) between ore-hosting dolomite and K-rich slate, with four high-Th zones (>200 ppm) in the Main and East open pits. The abundance of Th in ores and rocks exhibits considerable variability, ranging from 1.1 to 587 ppm. This significant heterogeneity in the distribution of Th within the deposit is primarily attributed to Th migration induced by late thermal events, thereby creating scattered Th-Pb ages in the REE minerals. Chemical and mineralogical mapping indicates that Th in the Bayan Obo deposit is primarily hosted in REE minerals, Nb-bearing minerals and thorite. Although Nb-bearing minerals exhibit higher Th concentrations (e.g., aeschynite: 4.1 wt% ThO₂), REE minerals (e.g., monazite and fluorocarbonate) dominate Th resource volume due to their extensive distribution. Among these REE minerals, monazite in the disseminated, banded and vein ores of the West Open Pit displays the highest Th content (median >1 wt%). Additionally, the biotite-altered disseminated ore in the Main Open Pit contains elevated Th concentrations, present as thorite and Th-rich monazite. For efficient, resource-specific mining strategies, optimal ore types include: biotite-altered disseminated ores in the Main Open Pit and the disseminated and massive ores in the West Open Pit for Th-REE-Nb, and massive ores in the Main and East open pits for Th-Fe-REE.

Moreover, Th concentrations closely align with REE and Fe but diverge sharply from Nb. Thorium-REE-rich minerals mainly occur in fluorite-rich banded and massive ores, while Nb-bearing minerals concentrate in ores dominated by aegirine and riebeckite, linked to alkaline metasomatism. Geochemical analyses reveal a strong Th-F correlation but no association with K₂O or Na₂O, which highlighting distinct enrichment-precipitation pathways: the Th-REE-Fe systems rely on fluorination-driven, contrasting sharply with Nb's alkaline metasomatic origins. These insights guide targeted exploitation strategies and deepen understanding of the deposit's complex metallogenic history.

1. Introduction

Thorium (Th) is a crucial nuclear energy resource, characterized by

its exceptionally elevated melting point (1750 °C) and boiling point (4788 °C). These characteristics confer advantages such as excellent resistance to high temperatures, corrosion, and superior mechanical

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strength, leading to its extensive application in various fields, including catalysts, ceramics, refractory materials, nuclear medicine, and super-alloys (e.g., [Chroneos et al., 2023](#); [Man et al., 2023](#)). Compared with traditional nuclear fuel like uranium, Th is expected to serve as a new generation of “clean nuclear fuel” due to its abundant crustal content, enhanced safety feature, and reduced production of nuclear waste ([Schaffer, 2013](#); [Van Gosen and Tulsidas, 2016](#); [Chroneos et al., 2023](#); [Jyothi et al., 2023](#); [Ushakov et al., 2023](#)). For the past few years, several countries, including the United Kingdom, China, and India, have launched initiatives to develop novel thorium-based nuclear power projects (e.g., [Meng et al., 2013](#); [Van Gosen and Tulsidas, 2016](#); [Bedenko et al., 2019](#); [Chroneos et al., 2023](#)). For example, the commercialization of molten salt reactor (MSR) technology based on the thorium fuel cycle is rapidly progressing in China, as demonstrated by the successful testing of a 2 MW experimental reactor in 2021 ([Mallapaty, 2021](#)). This advancement is anticipated to substantially increase the global demand for Th resources ([Van Gosen and Tulsidas, 2016](#); [Jyothi et al., 2023](#)).

The global Th resource is estimated to total 6.35 million tons, with approximately 800 identified thorium deposits ([International Atomic Energy Agency, 2019](#); [Feng et al., 2024](#)). These resources, however, are unevenly distributed, predominantly located in countries such as India, Brazil, Australia, United States and China ([Ashley et al., 2012](#); [Chroneos et al., 2023](#)). Thorium deposits can be systematically categorized based on the types of host rocks into magmatic, metamorphic, and sedimentary placer types, and further subdivided into specific subtypes including carbonatite, alkaline rocks, placer, and hydrothermal vein types, and others ([Barthel et al., 1992](#); [Meng et al., 2013](#); [Van Gosen and Tulsidas, 2016](#); [International Atomic Energy Agency, 2019](#); [Chen et al., 2022](#); [Jyothi et al., 2023](#)). Notably, placer and carbonatite types account for 35 % and 30 % of global Th resources ([International Atomic Energy Agency, 2019](#); [Chen et al., 2022](#)), respectively. Although the extraction of monazite sand is relatively cost-effective, it poses significant environmental concerns. Conversely, Th deposits associated with carbonatite are expected to emerge as the predominant source of Th resources globally in the future.

Because of the extremely low partition coefficient between mantle minerals and melts (<0.1 ; [Ma and Shaw, 2021](#)), thorium becomes highly concentrated in carbonatitic magma generated by low-degree partial melting of the mantle (several hundred ppm; [Patel and Mangala, 1994](#); [Sedigh et al., 2024](#)). This thorium eventually accumulates in the residual melts or hydrothermal fluids during the later stages of magmatic evolution ([Huang et al., 2022](#)), and can theoretically form numerous Th-independent minerals such as thorite and thorianite, as well as Th-bearing minerals like monazite and aeschynite ([Meng et al., 2013](#); [Huang et al., 2022](#); [Sun et al., 2024](#)). Although carbonatite-type deposits host considerable Th resources, these are generally extracted as by-products from ores primarily enriched in rare earth elements (REEs) and niobium (Nb). Research specifically addressing the processes of thorium mineralization is relatively limited. Prominent examples of such deposits include the Bayan Obo REE-Nb-Fe(-Th) deposit and the Muluozhai REE(-Th) deposit in China ([She et al., 2023](#); [Chakhmouradian et al., 2025](#)), the Nolans Bore P-REE(-Th) deposit in Australia ([Anenburg et al., 2018](#)), the Fen REE(-Th) deposit in Norway ([Dietzel et al., 2019](#)), and the Araxá Nb(-Th) deposit in Brazil ([Barthel et al., 1992](#)). Consequently, the current understanding of thorium's occurrence and its enrichment mechanisms within these deposits remains insufficient, thereby limiting the effective exploitation of Th resources.

The Bayan Obo deposit in China is renowned for its vast reserves of REEs (57.4 Mt @ 6 wt%) and Nb (2.2 Mt @ 0.13 wt%) resources ([Drew et al., 1990](#); [Hao et al., 2002](#)), as well as significant quantities of Th, scandium, and fluorite resources. The Th reserves are estimated at approximately 221,000 tons with an average grade of 0.038 wt%, representing 77.3 % of the nation's confirmed resources ([Chen et al., 2022](#)). Currently, the deposit is extracting Fe, REE, and fluorite resources from the Main, East, and West open pits ([She et al., 2023](#)). Since its initial discovery as an iron deposit in 1927, extensive mineralogical and

geochemical research has been conducted to investigate the genesis of the ore-hosting dolomite ([Yang et al., 2019](#); [Chen et al., 2020](#); [She et al., 2023](#); [Ren et al., 2025](#)), the age of REE and Nb mineralization ([Campbell et al., 2014](#); [Li et al., 2021](#); [Yang et al., 2024a](#); [Zhu et al., 2024](#)), and the occurrence and enrichment processes of REE and Nb ([She et al., 2021](#); [Zhan et al., 2023](#); [Yang et al., 2024b](#); [Ren et al., 2025](#)). However, there has been limited research on the occurrence, distribution, and metallogenic processes of Th in the Bayan Obo deposit (e.g., [Chen et al., 2023](#); [Sun et al., 2024](#)). Consequently, the Th resources within this deposit remain entirely unutilized, and the abundant Th resources in the mined ore predominantly end up in tailings reservoirs, and waste slag produced by Fe and REE concentrate processing ([Su et al., 2005](#); [Zhu et al., 2015](#); [Chen et al., 2023](#)), leading to significant environmental concerns.

In this study, we systematically collected various types of rock and ore samples, including ore-hosting dolomite, and disseminated, banded, massive, and vein ores from three open pits at Bayan Obo. Based on detailed field investigations and petrographic observations, we conducted a comprehensive analysis of the mineralogical and *in-situ* geochemical compositions of various ores and Th-containing minerals using TIMA, μ -XRF, and electron microprobe techniques. This analysis aimed to elucidate the spatial distribution, occurrence state, and mineral associations of Th within the Bayan Obo deposit. Furthermore, we explored the intrinsic genetic relationship between Th and REE-Nb-Fe mineralization. This research enhances our understanding of the distribution characteristics and enrichment mechanisms of Th in the carbonatite magmatic-hydrothermal process, providing valuable insights for the efficient utilization of Th resources in the Bayan Obo deposit and contributing to the advancement of low-carbon energy development.

2. Geological background

2.1. Regional geology

2.1.1. Archean-Mesoproterozoic sequences

The Bayan Obo REE-Nb-Fe deposit is situated at the northern margin of the North China Craton, near the Central Asian Orogenic Belt ([Fig. 1](#)). The primary fault in the area, the Wulanbaolige deep fault, is located roughly 10 km north of the Bayan Obo deposit. A secondary fault, the Kuangou fault, trends east-west and is truncated by the Wulanbaolige fault. The basement complex contains Archean granite-gneiss in the southeastern of the mining area; the Early Proterozoic granodiorite, syenite, and biotite gneiss in the Kuangou anticline and south of the Main Open Pit; and the late Early Proterozoic garnet-bearing gneiss in the south of the East Open Pit ([Fig. 1](#); [Fan et al., 2010](#)). Overlying this basement unconformably is the Bayan Obo Group, a Paleoproterozoic to Mesoproterozoic rift-related sedimentary sequence nearly 10 km thick ([Fig. 1](#)), consisting of weakly metamorphosed clastic rocks, shale, and carbonates ([Zhong et al., 2015](#); [Zhou et al., 2018](#)). These strata, distributed mainly in the limbs of the Kuangou anticline, are subdivided into six formations and eighteen units, with sedimentation peaking around 1.6 Ga ([Yang et al., 2012](#); [Zhong et al., 2015](#); [Lai et al., 2016](#); [Zhou et al., 2018](#)).

More than 100 carbonatite dykes, dated between 1.4 and 1.2 Ga, are exposed around the three open pits in Bayan Obo and intruded into the basement complex and sedimentary formations ([Zhang et al., 2003](#); [Fan et al., 2006](#); [Yang et al., 2011](#); [Liu et al., 2018a](#)). These dykes, mostly 1 to 2 m wide and oriented NNE to NNW, are classified into dolomite, dolomite-calcite, and calcite types based on their mineralogy and sequence, with a progressive increase in REE content ([Yang et al., 2011](#)). At nearly the same time, ore-hosting dolomite intruded between the H₂ quartz sandstone and H₃ K-rich slate of the Bayan Obo Group in platy-like intrusions, extending 16 km in length and 1–2 km in width ([Fig. 1](#)). Based on mineral composition, grain size, and microscopic cutting relationships, previous studies divided the ore-hosting dolomite into coarse and fine dolomitic facies ([Yang et al., 2019](#); [She et al., 2021](#)). The coarse facies mainly occur along the northern margin of the

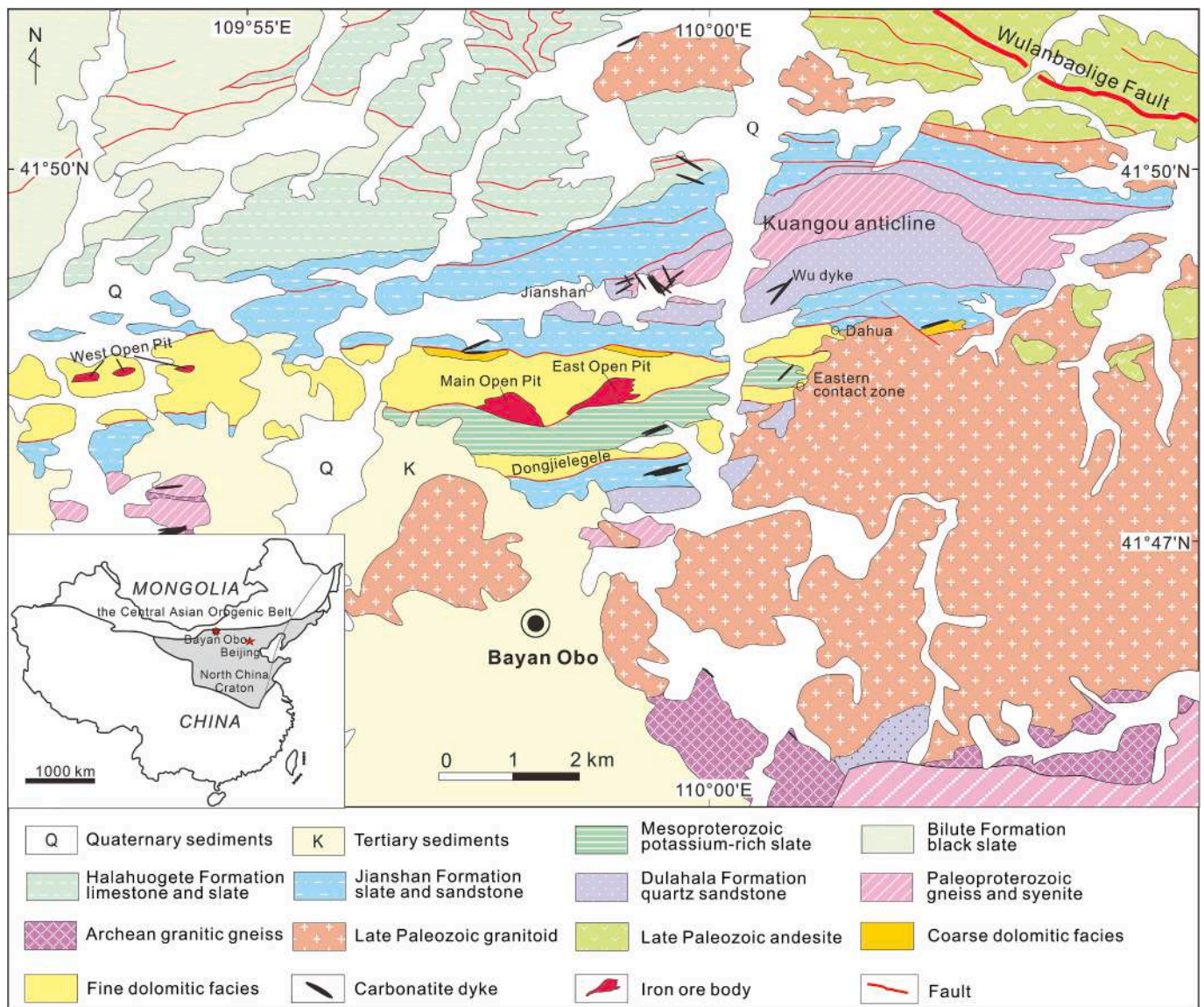


Fig. 1. Geographic location map and Geological sketch map of the Bayan Obo REE-Nb-Fe-Th-Sc deposit, revised from Yang et al. (2011).

carbonatite intrusion (Fig. 1), while the fine facies form the main rock-mass with an average REE_2O_3 grade of about 2 wt%.

2.1.2. Paleozoic sequences

Following the main Mesoproterozoic mineralization event, the Bayan Obo area underwent extensive reworking due to multiple thermal episodes, with the Caledonian vein mineralization (ca. 440 Ma) and Hercynian granite intrusion (ca. 270 Ma) being the most significant (Yang et al., 2007; Fan et al., 2009; Hu et al., 2009; Campbell et al., 2014; Ling et al., 2014). During the Caledonian period, dehydrated fluids derived from the subducting Paleo-Asian Ocean plate mobilized and concentrated REE from deep carbonatite sources (Xiao et al., 2003; Hu et al., 2009; Li et al., 2021; She et al., 2021), resulting in the formation of common vein REE ores predominantly in the shallow zones of the three open pits, with mineralization intensity diminishing with depth. These vein ores typically contain coarse-grained sulfides, baotite, aeschynite and other REE-Nb minerals (She et al., 2021).

In the Hercynian event, numerous granitoid stocks, including monzogranite, biotite granite, granodiorite, and gabbro diorite, were emplaced mainly in the southeast of the East Open Pit and south of the West Open Pit (Fig. 1), formed between 281 and 263 Ma, with peaking

around 270 Ma (Fan et al., 2009; Ling et al., 2014). This magmatism is linked to continent–continent collision during the late closure of the Paleo-Asian Ocean (Xiao et al., 2003). Contact zones between these granitic intrusions and the ore-hosting dolomite underwent skarn alteration, leading to localized Fe-Nb mineralization (Yang et al., 2007).

2.2. Ore deposit geology

The Bayan Obo deposit is currently being exploited for Fe, REE and fluorite from the East, Main and West ore bodies/open pits (Fig. 1). The ore bodies are lenticular, striking nearly E-W and dipping southward, hosted in dolomites trending EW. Intense alkaline hydrothermal alterations took place at the contact zone between the carbonatite pluton and the country rocks (metamorphic basement and sedimentary formations). This process resulted in a mineral assemblage characterized by aegirine, sodium amphibole, and biotite, and was accompanied by the formation of high-grade REE, Nb, and Fe ores. Corresponding ore types include dolomite-dominated REE-Nb-Fe ore, banded REE-Nb-Fe ore, massive fluorite-rich Fe ore, massive aegirine-rich REE-Nb-Fe ore, and massive Na-amphibole-rich REE-Nb-Fe ore (Fig. 2; Institute of Geochemistry, Chinese Academy of Sciences, 1988). Furthermore, a small amount of

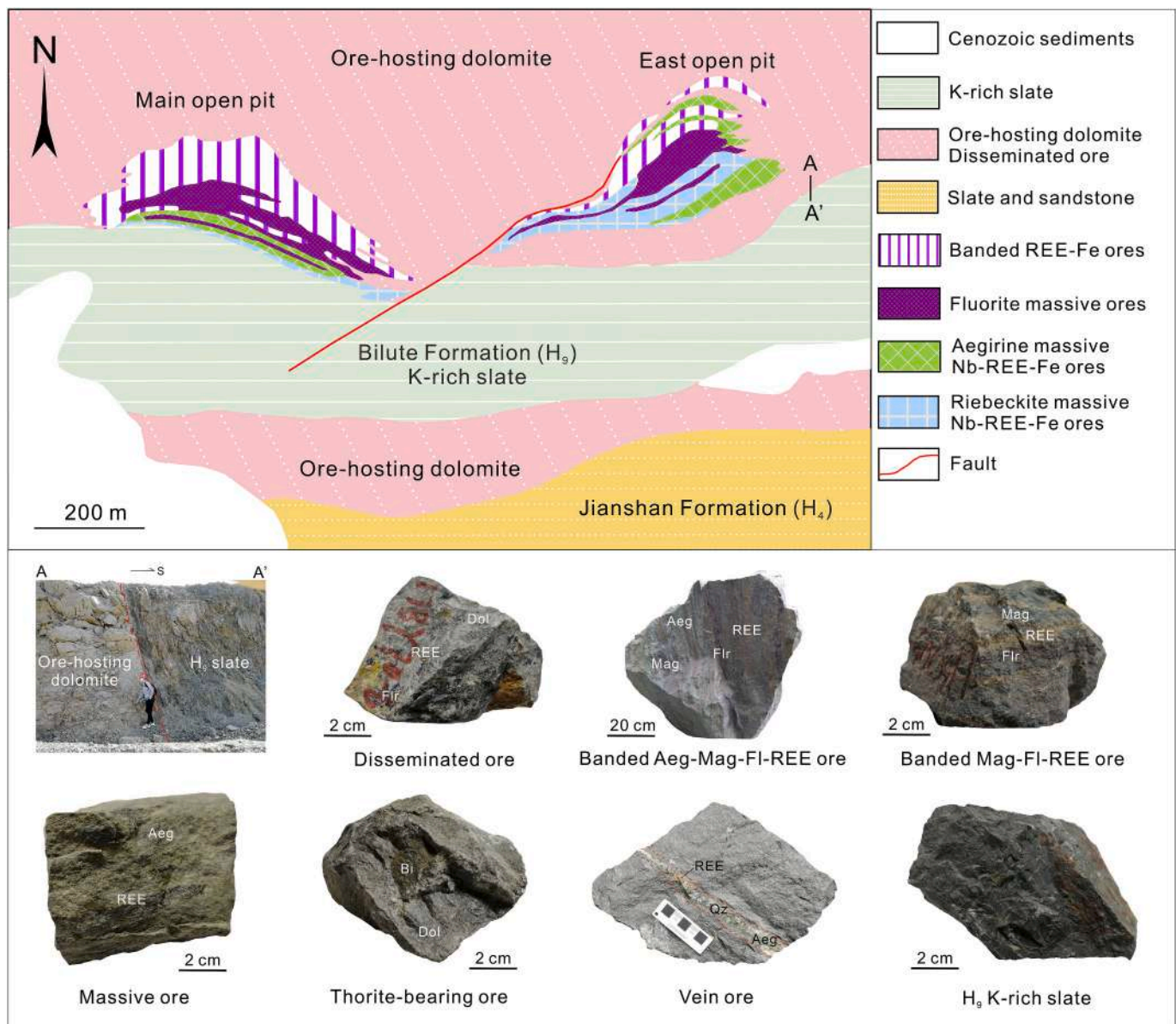


Fig. 2. Geological sketch and mineralization zoning map of the Main and East ore-bodies, along with representative ores from the Bayan Obo deposit. Modified after Institute of Geochemistry, Chinese Academy of Sciences (1988) and Liu et al. (2018). Aeg: aegirine; Bi: biotite; Dol: dolomite; Flr: fluorite; Mag: magnetite; Qz: quartz; REE: rare earth element mineral.

vein REE-Nb ore and beaded Fe-Nb ore are also distributed in the three open pits and the eastern contact zone, respectively. These ores are the products of the superimposed transformation of two Paleozoic thermal events (Yang et al., 2007; Hu et al., 2009). The primary REE minerals include monazite, bastnaesite, parisite, cebaite, and huanghoite; Nb-bearing minerals are predominantly represented by aegschynite, pyrochlore, columbite, fergusonite-(Y), and baotite; and the Fe minerals present are magnetite and hematite (She et al., 2021; Wang et al., 2024).

3. Samples and analytical methods

3.1. Sampling strategy

In this study, a total of 284 samples from the three open pits were analyzed to investigate the distribution characteristics of thorium in various rock and ore types and assess its enrichment degree. Among these, 48 samples were specifically selected to examine the occurrence and mineralogical composition of thorium. The samples primarily

consist of disseminated, banded, massive and vein ores, and K-rich slate (as shown in Figs. 2 and 3). Notably, disseminated ores form the predominant component of the ore-hosting dolomite, with major minerals including dolomite, calcite, magnetite, fluorite, apatite, monazite, and bastnaesite (Fig. 3a-b). Banded and massive ores represent the most significant ore types at Bayan Obo, hosting the majority of Fe, REE, Nb, Th, and fluorite resources. Banded ores are characterized by alternating bands of REE minerals, fluorite, and magnetite, whereas massive ores exhibit a dense aggregation of magnetite grains interspersed with REE-fluorocarbonate and gangue minerals (including aegirine, fluorite, biotite and riebeckite) (Fig. 3c-e). It is worth highlighting that the dolomitic carbonatite in the West Open Pit has undergone less hydrothermal alteration compared to those in the Main and East open pits. Consequently, the ore body predominantly comprises disseminated ores, with relatively limited occurrences of banded and massive ores. For a more detailed analysis of the mineral composition and associations of various ores, refer to She et al (2021).

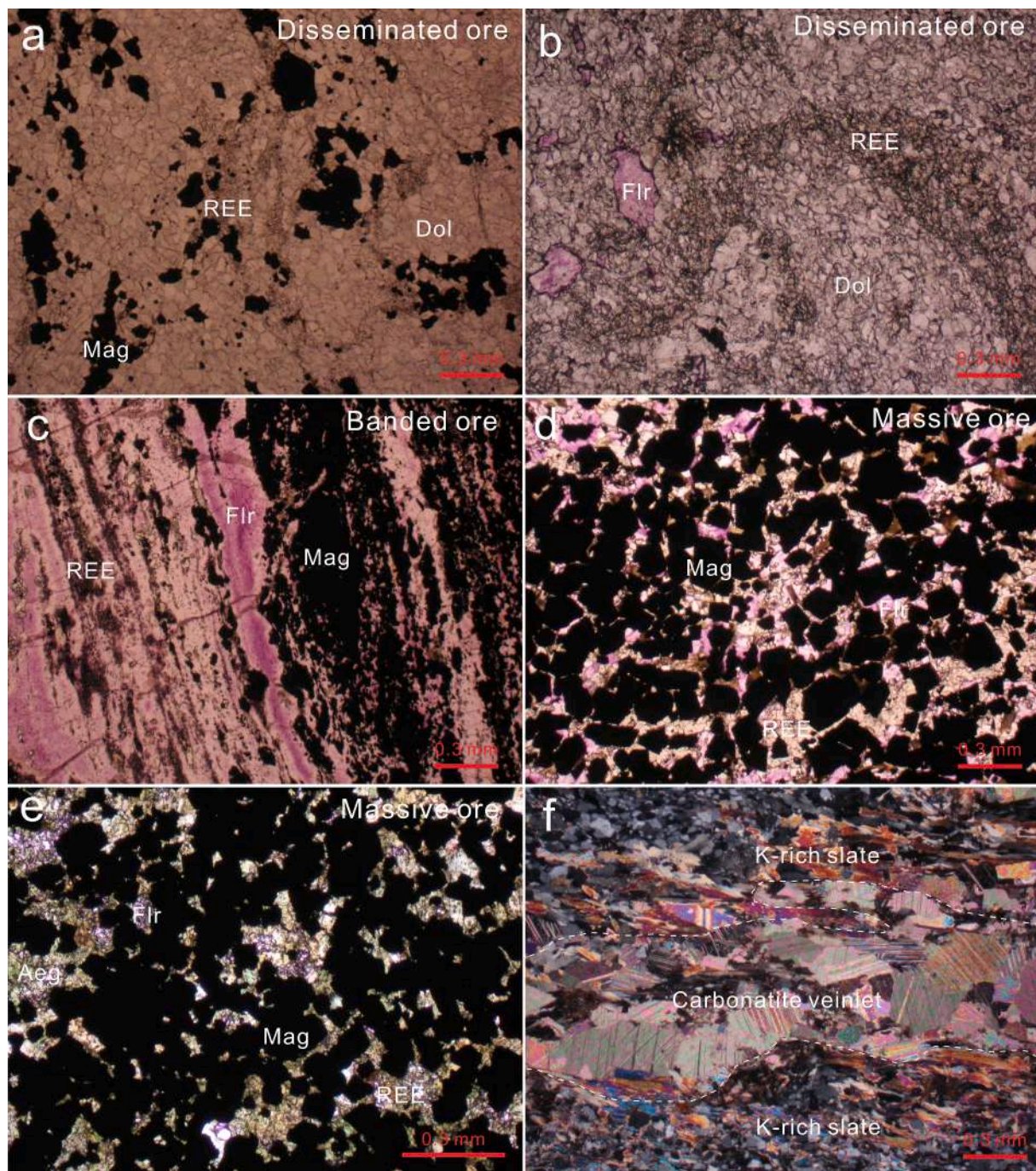


Fig. 3. Mineral associations in disseminated ore, banded ore and massive ore (a–e, under plane-polarized light), as well as the intrusive relationship between carbonatite veins and K-rich slate (f). The mineral abbreviations are presented in Fig. 2.

3.2. Micro X-ray fluorescence spectroscopy analysis (μ -XRF)

Micro XRF analysis was performed on a Bruker M4 TORNADO PLUS μ -XRF spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences. This instrument is equipped with two large-area silicon drift detectors featuring a super light window and a specifically optimized Rh X-ray tube. This configuration allows for the detection and analysis of a broad elemental range from carbon to americium, with an energy resolution of less than 145 eV at Mn-K α . A poly-capillary optic is incorporated to focus the beam spot to around 18 μ m, facilitating fast and non-destructive μ -XRF analysis of samples. This method offers semi-quantitative chemical data with a spatial resolution of approximately 20 μ m. In this study, all μ -XRF element mapping experiments were

performed with a voltage of 50 kV and a current of 600 μ A, using a step size of 20 μ m and a pixel acquisition time of 3 ms, under an air atmosphere at 3 mbar pressure. The raw data were processed and analyzed using M4 Tornado software, which helped to examine the spectral peaks and generate the elemental distribution maps of the surface.

3.3. Tescan integrated mineral analyzer (TIMA)

Mineral compositional mapping was performed on carbon-coated thin sections using a MIRA3 scanning electron microscope equipped with four EDS detectors at Guangzhou Tuoyan Analytical Technology Co., Ltd., China. In this study, dot mapping mode was employed to acquire backscattered electron (BSE) images and energy-dispersive X-ray

spectroscopy (EDS) data. Each measurement point was configured with an X-ray counting rate of 1000 kcps. The analysis was performed under an accelerating voltage of 25 kV and a beam current of 9 nA. The working distance was kept constant at 15 mm, with a pixel size of 3 μm and an energy spectrum step size of 9 μm . Current and BSE signal intensity were calibrated through an automated procedure involving a platinum Faraday cup. The performance of the EDS system was

validated using a manganese standard. Subsequently, the samples were analyzed using the TIMA liberation analysis software module, which automatically calculated the volumetric proportions of all mineral phases.

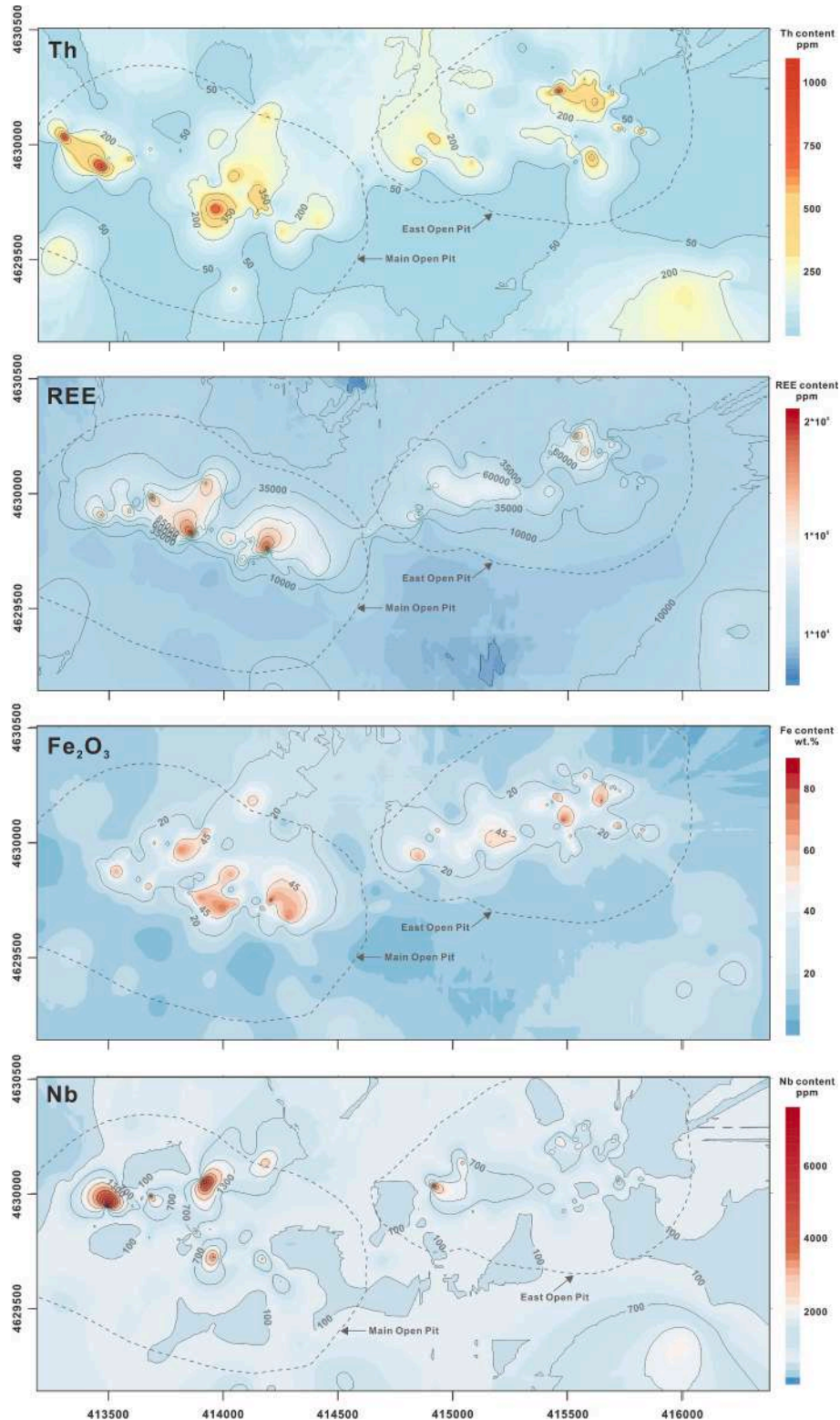


Fig. 4. The spatial distribution maps of Th, REE, Fe_2O_3 , and Nb content in the Main Open Pit and East Open Pit of the Bayan Obo deposit.

3.4. Whole-rock major and trace element geochemistry

A total of 284 ore and slate samples from the three open pits were analyzed for their major and trace element compositions at ALS

Laboratory Group (Guangzhou, China). All samples were freshly prepared. Surface impurities were removed prior to grinding, and tungsten steel grinding equipment was employed to grind the samples to a particle size of less than 200 mesh, ensuring no contamination during the

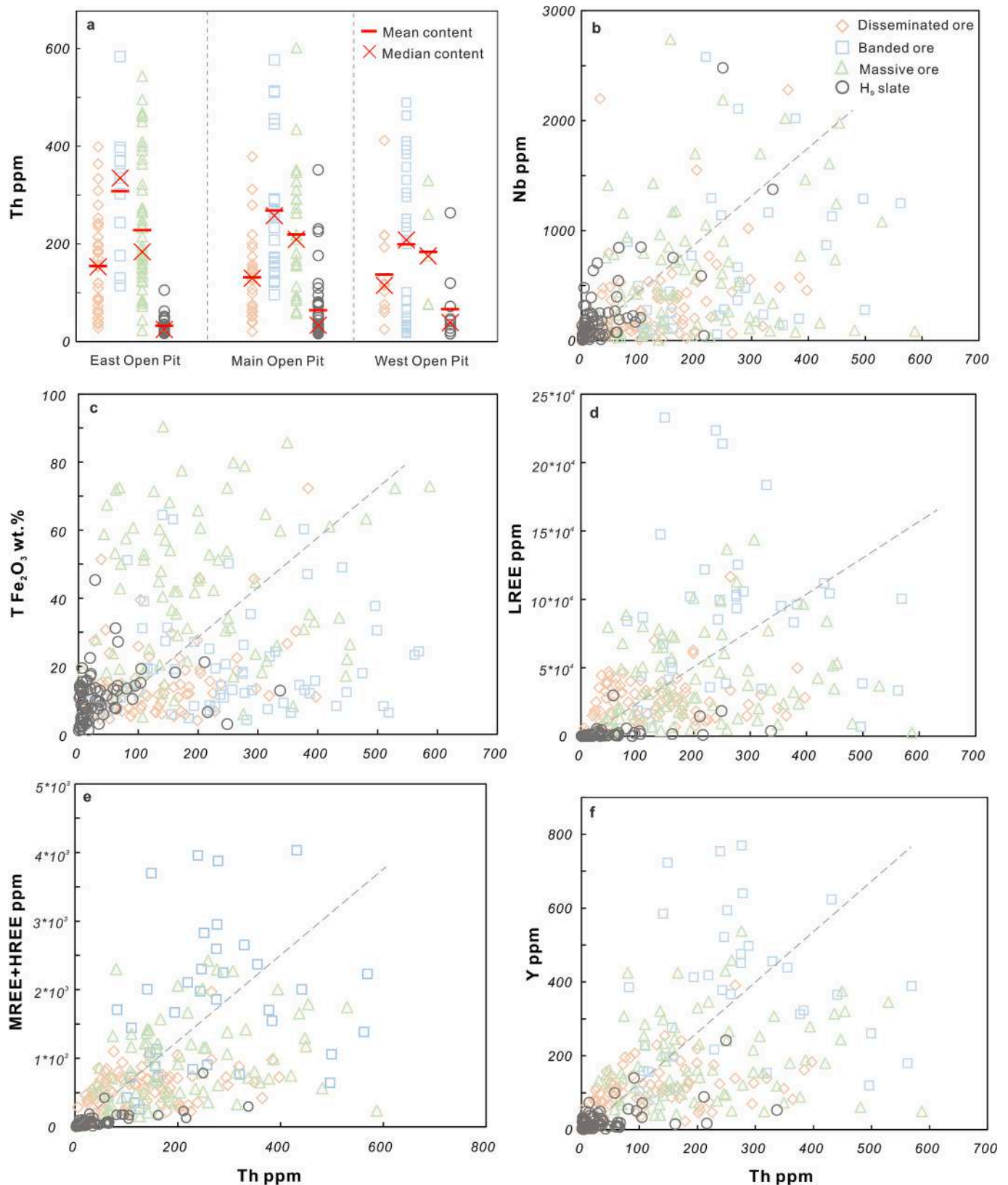


Fig. 5. Thorium content ranges (a) and elemental scatter diagrams (b-f) for various ores and K-rich slate from the three open pits at Bayan Obo.

process.

Whole-rock major element analysis was conducted by preparing mixtures of 0.5 g sample powder with 5 g of a $\text{Li}_2\text{B}_4\text{O}_7 + \text{LiBO}_2$ flux, which were then formed into wafers and analyzed using a PANalytical PW2424 X-Ray Fluorescence Spectrometer (XRF). The analytical uncertainty was generally within 0.1–1 % (RSD). Trace element concentrations in whole-rock samples were measured by Agilent 7900 Inductively Coupled Plasma Mass Spectrometry (ICP-MS). For this, precisely 40 mg of sample powder was digested using a mixture of HF , HNO_3 , and H_2SO_4 , followed by two evaporation steps at 150–200 °C. The residue was then dissolved in 49 ml of 1 % HNO_3 for analysis. External calibration was performed using synthetic pure standard solutions, and 1 ml of 500 ppb Indium was added to both samples and standards as an internal standard. Repeated analyses of standard reference materials confirmed that the precision for most elements was generally within 5 %. For a comprehensive description of the experimental procedures and analytical methods for major and trace elements, refer to Yang et al. (2023).

Coordinate processing of the chemical composition of ores and rocks, as well as the generation of contour maps, was performed using Surfer 11 software.

3.5. Major element analysis of REE and Nb minerals

The major element analyses of monazite and REE-fluorocarbonate were conducted using a JEOL JXA-8230 electron probe microanalyzer (EPMA) at Wuhan Sample Solution Analytical Technology Co., Ltd., Hubei, China. The analysis was performed under the following conditions: an accelerating voltage of 15 kV, a beam current of 10 nA, and a spot size of 3 μm . The peak counting time was set to 10 s, while 5 s for the low and high background, respectively. Calibration standards used were monazite for La, Ce, Sm, and Nd; pure metals for Th, U, Yb, Gd, Dy, Tb, and Y; pyrope for Al; quartz for Si; diopside for Ca; periclase for Mg; celestine for Sr; hematite for Fe; rutile for Ti; fluorapatite for P and F; tugtupite for Cl; synthetic PrF_3 for Pr; and barite for Ba and S. Data correction was carried out using ZAF calibration procedures.

4. Results

4.1. Whole-rock Th content

A total of 284 samples of disseminated, banded, and massive ores and K-rich slate from the three open pits were analyzed for major and trace elements, including ore-forming elements such as Th, REEs, Fe and Nb (Supplementary Table 1).

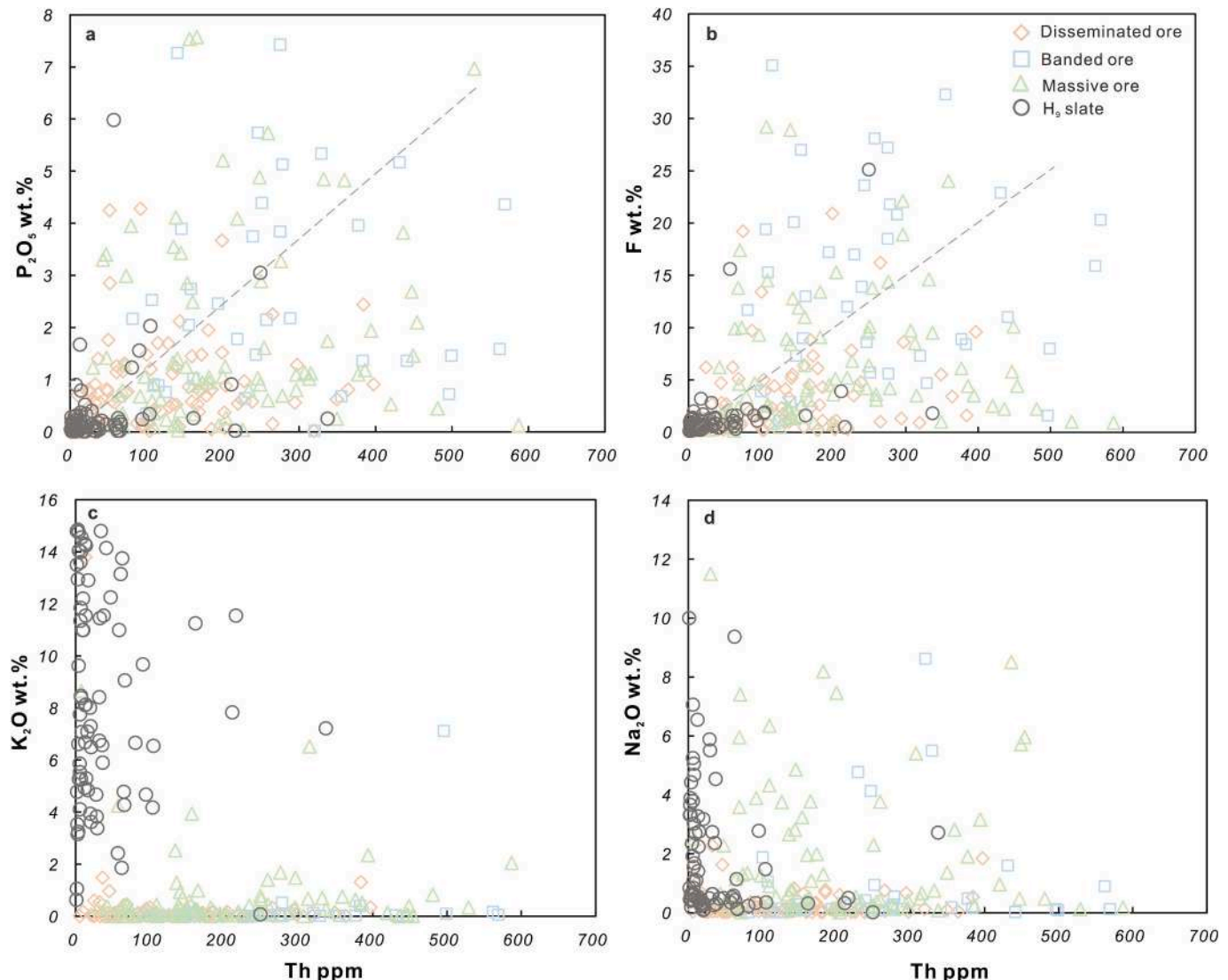


Fig. 6. Bi-modal diagrams of Th vs. P_2O_5 , F, K_2O and Na_2O for various ores and K-rich slate from the three open pits at Bayan Obo.

At the ore-body scale (Fig. 4), high Th contents (> 200 ppm) were observed in the central region of the East Open Pit and in both the central and western regions of the Main Open Pit. These locations correspond to the boundaries between ore-hosting dolomite and K-rich slate. Conversely, moderate to low Th content was predominantly distributed within the ore-hosting dolomite and K-rich slate themselves. Notably, the concentration centers of Th content align closely with those of REE and TFe_2O_3 (Fig. 4), yet exhibit a marked difference from the distribution pattern of Nb.

On the ore scale, in comparison to disseminated ores and K-rich slate, banded and massive ores from the three open pits exhibit significantly higher concentrations of Th, Nb, TFe_2O_3 , and REE (Fig. 5). Overall, the Th content demonstrates a positive correlation with the levels of TFe_2O_3 , REE, P_2O_5 , and F (Fig. 5b-f, 6a-b), while showing relatively weaker correlations with K_2O and Na_2O (Fig. 6c-d). Specifically, the Th content in banded ores from the East, Main, and West open pits ranges from 100 to 570 ppm (median: 320 ppm), 82 to 562 ppm (243 ppm), and 2.2 to 475 ppm (193 ppm), respectively. In massive ores, Th concentrations vary from 7.7 to 530 ppm (170 ppm), 42.9 to 587 ppm (195 ppm), and

61.5 to 315 ppm (161 ppm) for the East, Main, and West pits, respectively. For disseminated ores, the Th content ranges from 13 to 384 ppm (140 ppm), 5.6 to 364 ppm (115 ppm), and 10.3 to 397 ppm (101 ppm) across the same pits. Lastly, in K-rich slate, Th concentrations range from 1.96 to 90.6 ppm (10.1 ppm), 1.8 to 337 ppm (18.6 ppm), and 1.06 to 249 ppm (24.2 ppm) for the East, Main, and West open pits, respectively.

4.2. Element and mineral mapping on thin sections

Thorium distribution maps for two representative disseminated ore samples were determined using scanning $\mu\text{-XRF}$ spectrometers on thin sections (Fig. 7). Microscale analysis reveals that the Th distribution exhibits significant heterogeneity at the thin section scale, with concentration hotspots spatially correlated with REE enrichment zones, particularly Ce. Thorium predominantly occurs as isolated clusters within the gangue mineral matrix (primarily composed of dolomite), mirroring the dissemination pattern observed in the REE minerals of the disseminated ore. Notably, thorium enrichment displays extreme variability in individual concentration hotspots (Fig. 7b), highlighting

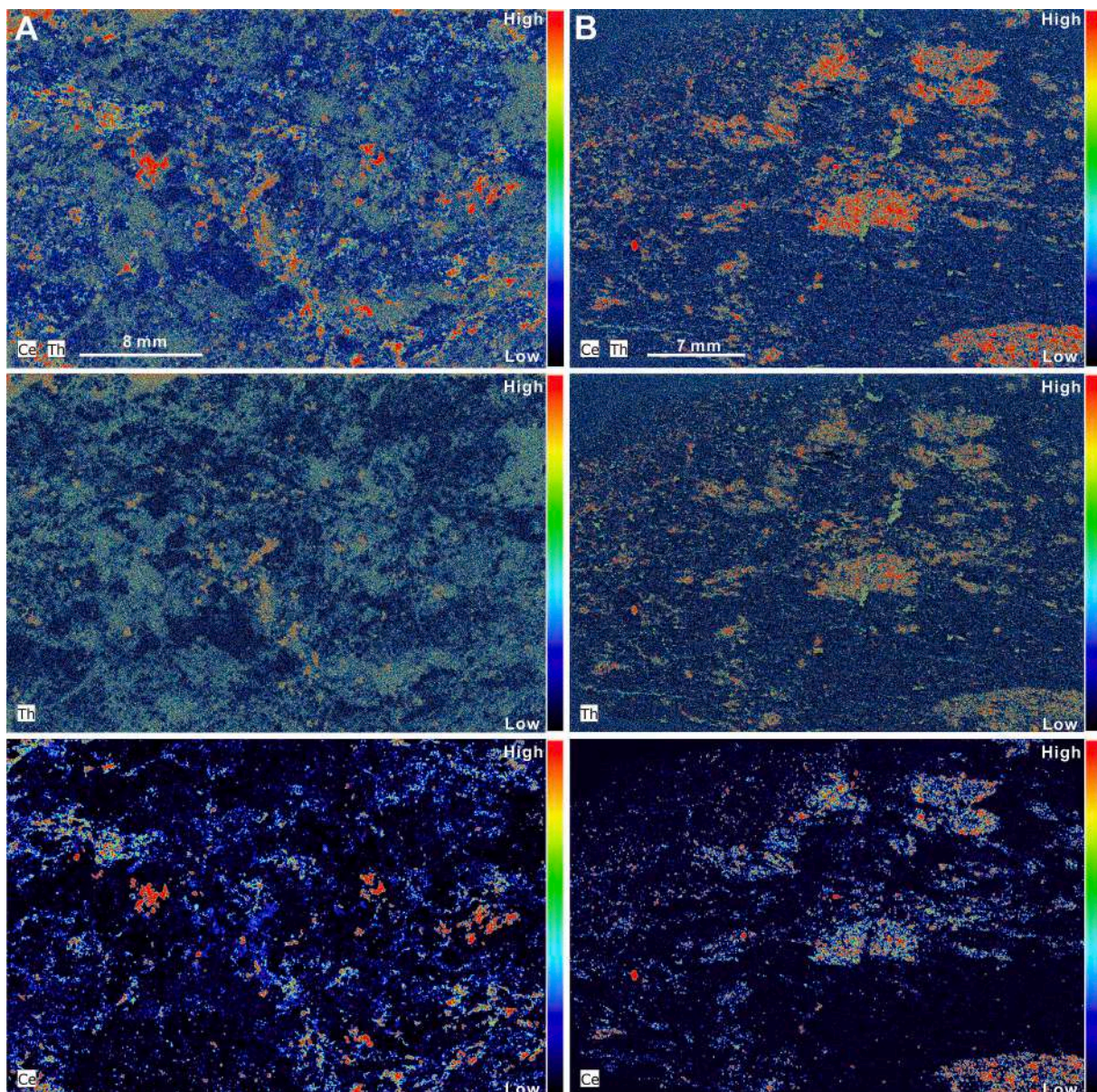


Fig. 7. $\mu\text{-XRF}$ element mapping of representative REE-Nb-Fe-Th ores from Bayan Obo, with a focus on Th and Ce.

significant geochemical partitioning at the mineral scale.

Mineralogical map of a disseminated ore from the Main Open Pit, characterized by biotitization and the presence of Th-bearing independent minerals, was generated using TIMA analysis. The primary Th-bearing mineral identified is thorite, which constitutes approximately 0.2 % of the total volume. Thorite is dispersed throughout a matrix dominated by calcite, biotite, and riebeckite, and is commonly associated with monazite, calcite, biotite, and magnetite (Fig. 8).

4.3. In situ Th content of Th-containing minerals

The major element compositions, including ThO₂, for a total of 125 grains of Nb-bearing minerals (including pyrochlore, aeschynite, baotite, and columbite), 657 grains of monazite and REE-fluorocarbonate minerals (such as bastnaesite, huanghoite, and cordylite), and 11 grains of thorite from disseminated, banded, massive and vein ores from three open pits were determined by EPMA (see Supplementary Tables 2, 3, 4). The thorium content ranges of Nb-bearing and REE minerals are illustrated in Figs. 9 and 10, respectively.

For Nb-bearing minerals (Fig. 9), pyrochlore, aeschynite, and fergusonite exhibit the highest ThO₂ content, with ranges of 0.02–1.28 wt% (median: 0.39 wt%), 0.02–24.94 wt% (4.09 wt%), and 0.01–3.66 wt% (0.81 wt%), respectively. In contrast, the ThO₂ contents of baotite, columbite, and fergusonite are generally lower than the average ThO₂ grade of ores in Bayan Obo. Ilmenorutile displays an extreme variability in ThO₂ content, ranging from 0.01 to 7.55 wt% (2.54 wt%).

For REE minerals, monazite typically has a higher ThO₂ content compared to REE-fluorocarbonate (Fig. 10), particularly the monazite in disseminated, massive and vein ores from the West Open Pit, which have the highest ThO₂ content, with the ranges of 0.11–2.69 wt% (0.83 wt%), 0.66–3.12 wt% (1.45 wt%) and 0.79–2.10 wt% (1.18 wt%). For REE-fluorocarbonate, those in the massive ores from the Main and East open pits, as well as the banded and vein ores from the West Open Pit, have relatively higher ThO₂ content (> 0.30 wt%), typically more than one order of magnitude higher than the average grade (0.03 wt%).

In the disseminated ore containing independent thorium minerals from the Main Open Pit, monazite has the highest ThO₂ content among all the REE minerals in Bayan Obo, with a range of 2.08–6.12 wt% (4.52

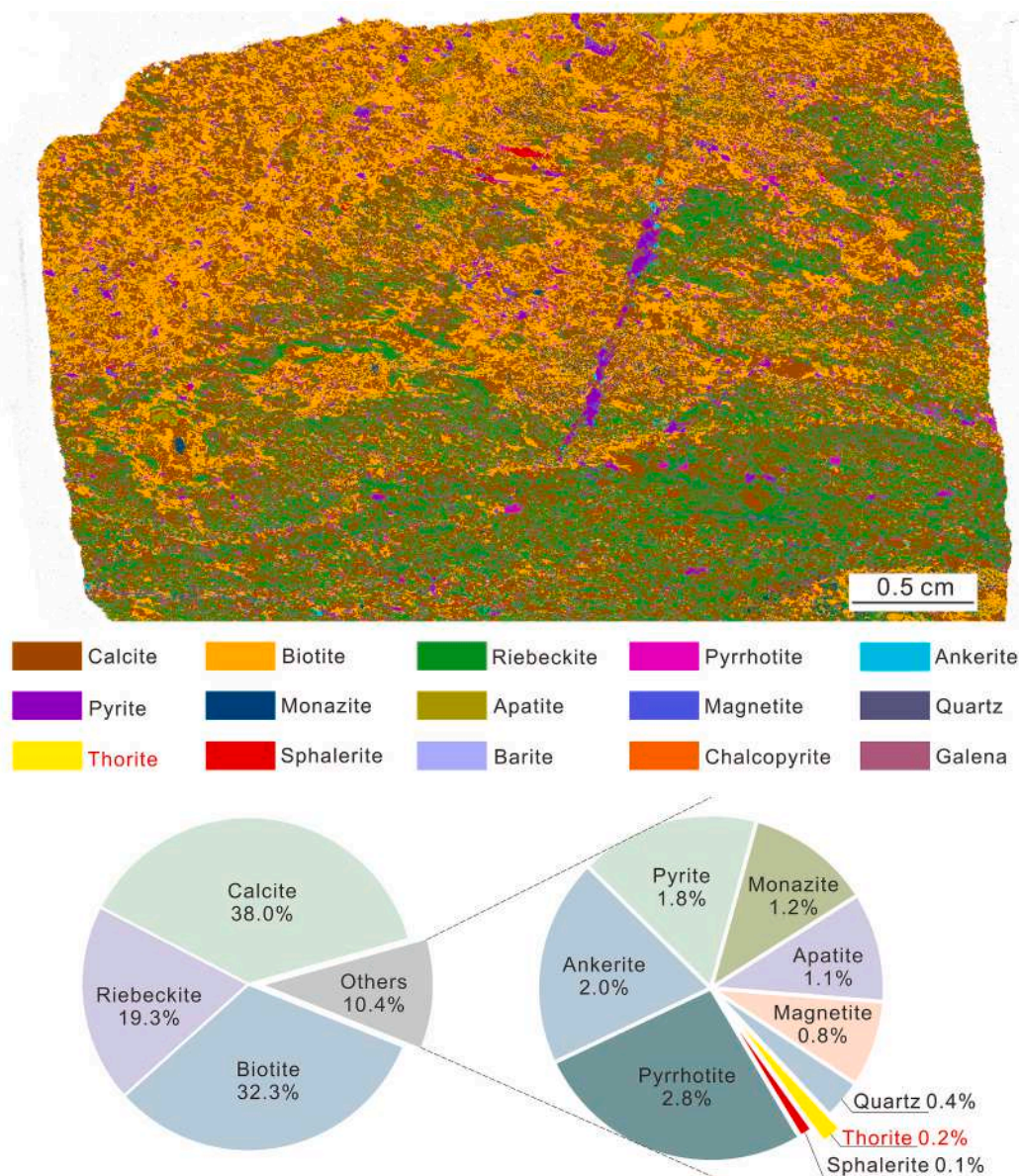


Fig. 8. The TIMA drawing and mineral proportion for the disseminated thorite-containing ores with biotitization in the Main Open Pit of Bayan Obo.

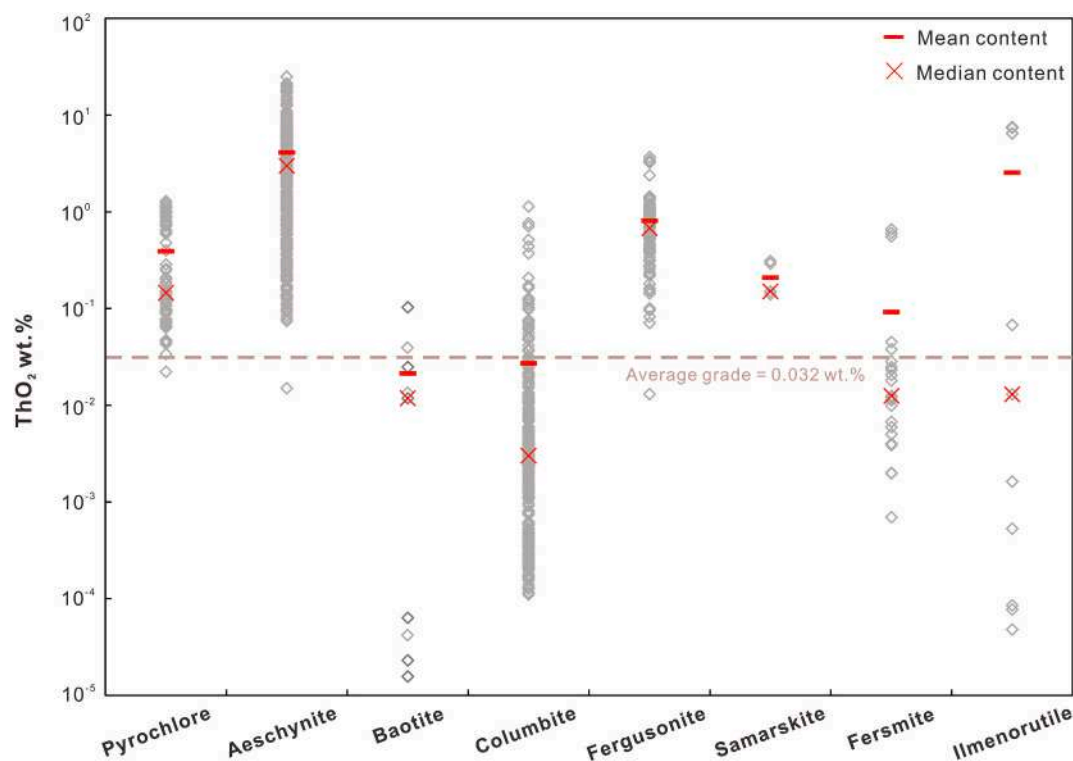


Fig. 9. Thorium content ranges for various niobium-bearing minerals from the three open pits at Bayan Obo. The thorium contents of these minerals are compiled from this study as well as previous studies by Liu et al. (2020), Zhan et al. (2023), Yang et al. (2024a, b), Yu et al. (2024) and Zhu et al. (2024).

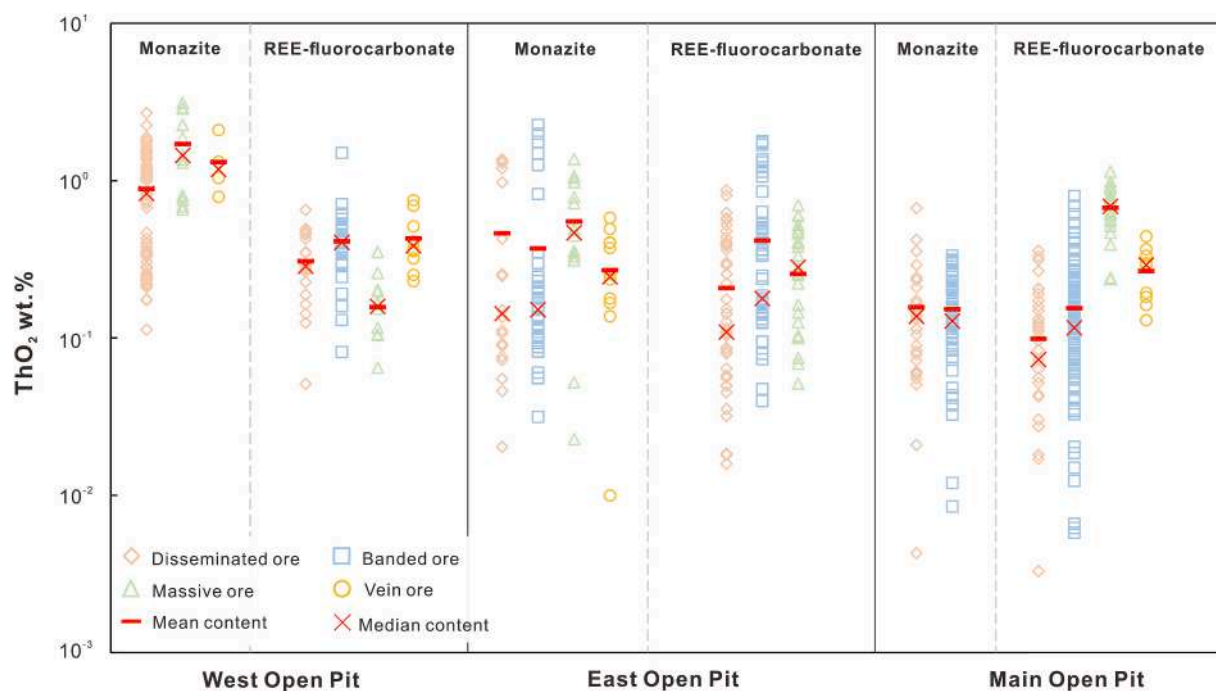


Fig. 10. Thorium content ranges for monazite and REE-fluorocarbonate minerals in representative ores from the three open pits at Bayan Obo.

wt%; Supplementary Table 4). Additionally, the ThO₂ content range for thorite in this ore is 56.5–61.1 wt% (57.3 wt%).

5. Discussion

5.1. The spatial distribution of thorium

Understanding the spatial distribution of Th in the Bayan Obo deposit is essential for determining its occurrence state and mineral phases, ultimately facilitating precise mining and efficient utilization of this

resource. The Bayan Obo deposit contains significant reserves of REEs, Nb, and Th; however, these resources are heterogeneously distributed throughout the deposit (She et al., 2021; Wang et al., 2024). Analysis of whole rock compositions (Fig. 5a; Supplementary Table 1) reveals that Th content in ores and host rocks ranges from 1.1 to 587 ppm, with a median of 113 ppm. This variability extends across specific lithologies: disseminated ores contain 5.6–397 ppm (median: 106 ppm), banded ores 2.2–569 ppm (237 ppm), massive ores 7.7–587 ppm (170 ppm), and K-rich slate 1.1–337 ppm (14.5 ppm). Such wide concentration ranges within individual ore types highlight the pronounced heterogeneity of Th distribution throughout the deposit.

At the ore-body scale, thorium distribution predominantly follows the contact zone between ore-hosting dolomite and K-rich slate, with dolomite exhibiting slightly higher Th concentrations than slate (Figs. 4, 5a). Four significant Th enrichment centers (Th > 200 ppm) occur in the central and western regions of the Main and East open pits, with the most pronounced concentration in the Main Open Pit's center (Fig. 4). Field geological surveys reveal that this distribution pattern correlates strongly with specific lithologies, particularly banded and massive fluorite-type ores (Fig. 2, 3c-d). The positive correlation between Th and F contents (Fig. 6b) suggests fluorination plays a crucial role in Th transportation and precipitation (Keppler and Wyllie, 1990). At the ore scale, comparative analysis demonstrates that banded and massive ores across all three open pits contain higher Th concentrations than disseminated ores and K-rich slate (Fig. 5a), indicating that intense hydrothermal alteration enhances Th enrichment. It is particularly important to emphasize that the disseminated ore with biotitization in the Main Open Pit exhibits exceptionally high Th content, attributable to the presence of abundant thorite and Th-rich monazite (Fig. 8).

5.2. Main Th-containing mineral

Clarifying the specific minerals in which Th occurs is essential for understanding the enrichment and mineralization processes of Th in the Bayan Obo deposit, as well as for the comprehensive utilization of its resources. To date, over 220 mineral types (including subtypes) have been identified in Bayan Obo (e.g., Shen and Zhao, 2023; She et al., 2025). Ore minerals are predominantly represented by monazite, REE-fluorocarbonate, columbite group, pyrochlore group, aeschynite group, and magnetite, while gangue minerals mainly include carbonates, fluorite, aegirine, riebeckite, biotite, apatite, and barite (She et al., 2021; Wang et al., 2024). Thorium in nature primarily occurs in two forms: (1) as independent mineral phases such as thorite and thorianite (Meng et al., 2013; Feng et al., 2024), and (2) as isomorphic substitutions in various REE-containing minerals, owing to the similar ionic radii of Th^{4+} (0.95 Å) and REE^{3+} (La-Lu: 1.15 ~ 0.93 Å; Rainsback, 2003; Jordens et al., 2013; Chen et al., 2022). Whole-rock chemical composition analyses and *in-situ* element mapping reveal that Th distribution in Bayan Obo is characterized by: (1) a strong positive correlation with REEs, P_2O_5 , and F (Figs. 5d-f, 6a-b), with thorium mainly concentrated in banded and massive ores (Fig. 5a); and (2) at the thin section scale, thorium-rich areas consistently coincide with REEs such as Ce (Fig. 7). These patterns indicate that Th in Bayan Obo is primarily hosted in rare earth minerals (notably monazite and fluorocarbonate) and niobium-bearing minerals (such as aeschynite and pyrochlore), while its content in dolomite, calcite, fluorite, magnetite, aegirine, and riebeckite is extremely low (Liu et al., 2018b; She et al., 2023; Liu et al., 2025).

The mineralization process of the Bayan Obo deposit is complex and multi-stage (She et al., 2021; Wang et al., 2024), encompassing Mesoproterozoic carbonatite magmatic-hydrothermal activity and two subsequent Paleozoic transformation events (vein mineralization and granitic intrusion). During the carbonatitic magma stage, niobium primarily occurs in pyrochlore, columbite, and minor amounts of fersmite and oboniobite. In the following hydrothermal stage, niobium is mainly hosted in aeschynite, pyrochlore, columbite, and ilmenorutile, with smaller quantities of fergusonite, samarskite, and baotite. The two

Paleozoic transformation events led to the formation of niobium mineral assemblages dominated by aeschynite and fersmite, respectively. Concurrently, rare earth minerals evolved from monazite in the magmatic stage to REE-fluorocarbonate in the early hydrothermal stage, and eventually to barium-bearing REE-fluorocarbonate in the late hydrothermal and transformation stages (She et al., 2021).

Extensive *in-situ* thorium data from this and previous studies (Liu et al., 2020; Zhan et al., 2023; Yang et al., 2024a, b; Yu et al., 2024; Zhu et al., 2024) indicate that aeschynite, fergusonite, and pyrochlore contain the highest Th concentrations among all Nb-bearing minerals (Fig. 9), attributable to their relatively high REE content in the crystal lattice (Liu et al., 2020; Zhan et al., 2023). Moreover, as the rare earth content in the three minerals decreases, the content of thorium also shows a decreasing trend (Fig. 9). Conversely, minerals such as baotite, columbite, samarskite, fersmite, and ilmenorutile generally exhibit low thorium content, reflecting their lower REE concentrations. Mineral mapping of the principal ore types reveals that aeschynite and pyrochlore are the most significant niobium mineral phases in Bayan Obo (She et al., 2021; Yang et al., 2024b), characterized by high abundance and widespread distribution, while other niobium minerals are comparatively scarce. Considering both the proportion of Nb-bearing minerals in the ores and their thorium content, aeschynite in hydrothermal ores and pyrochlore in ore-hosting dolomite can be regarded as the most important ore types for the comprehensive utilization of Nb-Th-REE resources in the Bayan Obo deposit.

Among all types of REE minerals in the Bayan Obo deposit, although their thorium content is significantly lower than that of aeschynite, pyrochlore, and fergusonite (Figs. 9, 10), these rare earth minerals constitute the main body of the ore and thus host the vast majority of the deposit's thorium resources. Notably, monazite found in the disseminated, banded, and vein ores of the West Open Pit contains the highest thorium content (median > 1 wt%; Fig. 10) among all REE minerals and is widely distributed. Especially, the disseminated ores contain a large amount of niobium minerals (pyrochlore and columbite; She et al., 2021), which can be regarded as an important ore type for the comprehensive utilization of REE-Th-Nb resources. Similarly, REE-fluorocarbonate minerals from the massive ores of the Main and East open pits, as well as the banded ores of the West Open Pit, also exhibit relatively high thorium content (median > 0.3 wt%; Fig. 10), and are considered significant for the integrated recovery of Fe-REE-Th resources. In addition, the disseminated ore with biotitization from the Main Open Pit is unique in Bayan Obo for containing independent thorium minerals; here, the ThO_2 content in thorite and monazite reaches 57.2 wt% and 4.52 wt% (Supplementary Table 4), respectively, making this ore type especially suitable for the comprehensive utilization of REE-Th resources.

These observations indicate that, while Bayan Obo is rich in thorium, its distribution is highly uneven across different minerals and ore types. Among them, the biotite-altered disseminated ores of the Main Open Pit, along with the disseminated and massive ores of the West Open Pit, represent the most favorable ore types for the comprehensive utilization of Th-REE-Nb resources. Meanwhile, the massive ores of the Main and East Open Pits are optimal for the integrated recovery of Th-Fe-REE resources.

5.3. Implications for the relationship between Th and REE-Nb-Fe mineralization

A clear intrinsic mineralization relationship between Th, REEs, Nb, and iron provides critical insights into both the source of ore-forming materials and enrichment processes. During low-degree partial melting of the mantle to form carbonatitic magmas, the incompatibility of Th and REEs in mantle minerals results in their elevated concentrations in the initial melts (e.g., Gurnis et al. 2013; Ma and Shaw 2021). Owing to their similar ionic radii and geochemical behaviors, Th and REEs are continuously co-enriched during subsequent magmatic and

hydrothermal evolution processes, eventually precipitating in REE minerals and, to a lesser extent, in Nb-bearing minerals. In the Bayan Obo deposit, thorium distribution exhibits significant heterogeneity across ore-body, ore, and mineral scales (Figs. 4, 5a, 7, 10), likely due to thorium migration caused by post-depositional thermal disturbances (Li et al., 2021). This remobilization explains the wide age range (1400–260 Ma) observed in Th-Pb dating of REE minerals, particularly monazite (Zhang et al., 2017; Li et al., 2021; She et al., 2023; Yang et al., 2024a).

At the ore-body scale, the distribution patterns of ore-forming elements show that thorium, REEs, and iron share similar concentration centers with significant overlap, whereas the concentration centers of niobium are notably distinct (Fig. 4). Mineralogical evidence reveals that REE-Th-rich minerals are mainly distributed in banded and massive ores rich in fluorite, while Nb minerals are primarily associated with aegirine- and riebeckite-rich ores formed through intense alkaline metasomatism (She et al., 2021). This spatial dichotomy aligns with geochemical correlations: Th shows strong positive associations with P_2O_5 and F but no linkage to K_2O or Na_2O (Fig. 6). Collectively, these mineralogical and geochemical relationships suggest that Th, REEs, and Fe share analogous precipitation mechanisms, distinct from Nb's enrichment pathways.

In summary, the ore-forming metals Th, REEs, Fe, and Nb all originate from carbonatitic magma produced by the low-degree partial melting of the mantle; however, their enrichment trajectories diverge. REE-Th-Fe mineralization is closely associated with the fluorination processes, as evidenced by the fluorite-rich assemblages; While Nb enrichment is governed by alkaline metasomatism, where alkali-rich fluids interact with silica-bearing country rocks to form the aegirine-riebeckite associations and precipitate Nb-bearing phases. This genetic framework highlights the critical role of fluid chemistry and host-rock interactions in decoupling the Th-REE-Fe and Nb mineralization systems.

6. Conclusions

Geochemical studies conducted at multiple scales indicate that thorium in the Bayan Obo deposit displays a significantly heterogeneous distribution across the orebody, ore, and mineral scales. At the ore body scale, Th primarily follows the contact zone between ore-hosting dolomite and K-rich slate. This spatial alignment correlates strongly with fluorite-rich banded and massive ores, where Th and F concentrations display a positive geochemical relationship. Such patterns suggest fluorination significantly controls Th migration and precipitation. At the ore scale, banded and massive ores contain higher Th content than disseminated ores and K-rich slate. Chemical analysis reveals thorium exists mainly in REE minerals (monazite and fluorocarbonate), Nb-containing minerals (aeschynite, pyrochlore) and independent Th minerals (thorite). *In-situ* analyses highlight aegirine, fergusonite, and pyrochlore as the most Th-enriched Nb-bearing minerals. Nevertheless, REE minerals, despite exhibiting lower Th content on an individual basis, constitute the predominant Th reserves owing to their extensive spatial distribution. Of particular significance, biotite-altered disseminated ores in the Main Open Pit contain exceptionally high Th levels, attributable to the presence of thorite and Th-rich monazite. For resource utilization, optimal ore types include: biotite-altered disseminated ores of the Main Open Pit and the disseminated and massive ores of the West Open Pit for Th-REE-Nb, and massive ores of the Main and East Open Pits for Th-Fe-REE.

Element distribution patterns show Th shares concentration centers with REE and Fe, but these differ from Nb concentrations. REE-Th-rich minerals predominantly occur in fluorite-rich banded and massive ores, while Nb minerals appear in aegirine and riebeckite-rich ores associated with alkaline metasomatism, which aligns with Th's positive correlation with F but not with K_2O and Na_2O . These mineral-geochemistry evidences suggest that Th, REE, and Fe likely share

similar precipitation processes, distinct from those of Nb.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.oregeorev.2025.106883>.

Data availability

Data will be made available on request.

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