Characterizing a new type of nelsonite recognized in the Damiao anorthosite complex, North China Craton, with implications for the genesis of giant magmatic Fe-Ti oxide deposits

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ABSTRACT

Nelsonite (Fe–Ti oxide–apatite rock) devoid of silicates offers a rare opportunity to investigate the magma processes for the formation of magmatic Fe–Ti oxide deposits. Both fractional crystallization and liquid immiscibility have been put forward, but the lack of robust evidences has hindered unambiguously distinguishing the role of these two processes in Fe–Ti mineralization. The nelsonite and associated Fe–Ti–P-rich rocks hosted in the Proterozoic Damiao anorthosite complex represent a typical example for studying Fe–Ti ore-forming processes. We recognized a new type of nelsonite (type-I) in
the Damiao complex, which is distinct from the two known types of nelsonite (type-II and III) from the same complex. The type-I nelsonite is characterized by its coexistence with oxide–apatite gabbronorite and granite in the same dike, and all these rocks have identical emplacement ages (1740 ± 7 Ma), subparallel REE patterns and major-element compositions lacking intermediate contents, suggesting derivation from conjugate Fe- and Si-rich melts generated by liquid immiscibility. The large type-II nelsonite bodies form irregular dikes along fractures in anorthosite and constitute the major ore type. The type-III nelsonite occurs as conformable layers or pods within oxide–apatite gabbronorite and pyroxenite, and occupies the end part of the type-II dike. The latter two types of nelsonites formed by extensive fractional crystallization of residual magma with crystal accumulation and subsequent hydrothermal replacement. During residual magma evolution, liquid immiscibility was crucial for Fe–Ti–P enrichment, fractional crystallization was responsible for enhancing oxide-apatite concentrations, and hydrothermal replacement was effective for mobilizing oxide-apatite concentrations. Our newly recognized nelsonite provides an unambiguous, outcrop-scale, field evidence for the operation of liquid immiscibility process. We show that giant magmatic Fe–Ti oxide orebodies can form by a combination of processes involving liquid immiscibility, fractional crystallization and hydrothermal mobilization.

**Keyword** Fe–Ti oxide deposits Nelsonite Liquid immiscibility Fractional crystallization Anorthosite

**INTRODUCTION**
Magmatic Fe–Ti oxide deposits associated with mafic layered intrusions and Proterozoic anorthosite complexes are important sources of iron, titanium and vanadium. Large Fe–Ti oxide orebodies represent extreme differentiation products of tholeiitic basalt magma, but the magmatic processes responsible for producing these oxide concentrations have been an enduring problem in economic geology and igneous petrology (Bowen 1928; Ashwal 1993; Duchesne 1999; Veksler 2009; Namur et al. 2012; Charlier et al. 2015; Bai et al. 2021). Nelsonite (Fe–Ti oxide–apatite rock) (Watson and Taber 1910) devoid of silicates constitutes an important ore type of the Fe–Ti oxide deposits, and has been widely regarded as a unique rock type critical for understanding the magma processes leading to Fe–Ti mineralization (Philpotts 1967; Kolker 1982; Tollari et al. 2008; Duchesne and Liégeois 2015).

Most nelsonite occurs in close association with Proterozoic anorthosite complexes, and generally form veins or dikes cross-cutting surrounding anorthosite, but sometimes also occurs as conformable layers within Fe–Ti oxide-rich silicate rocks (Ashwal 1993; Duchesne 1999; Zhang 2018). The origin of nelsonite remains enigmatic. The cross-cutting relationship and experimental results have led many researchers to consider an origin from crystallization of Fe–Ti–P-rich melt segregated from its Si-rich immiscible conjugate (Philpotts 1967; Kolker 1982; VanTongeren and Mathez 2012; Zhou et al. 2013; Wang et al. 2018; Coint et al. 2020), whereas others attribute the formation of such ore bodies to extensive fractional crystallization associated with crystal sorting and accumulation from a homogenous melt on the basis of their conformable occurrences (Dymek and Owens 2001; Pang et al. 2008; Song et al. 2013; Lindsley and Epler 2017). This discrepancy is largely due to the difficulty in distinguishing the role of fractional
crystallization and liquid immiscibility in Fe–Ti mineralization (Veksler et al. 2006; VanTongeren and Mathez 2012; Charlier et al. 2013; Kamenetsky et al. 2013; Honour et al., 2019a, b).

The ~ 1735 Ma Damiao anorthosite complex in the North China Craton offers an excellent opportunity to explore the origin of nelsonite, as it hosts abundant late-stage Fe–Ti–P-rich dikes/veins cross-cutting early-stage anorthosite, in association with transitional rock types including nelsonite, oxide–apatite gabbronorite and oxide–apatite pyroxenite (Zhao et al. 2009; Li et al. 2015a, 2019a; Zhang 2018). Both liquid immiscibility and fractional crystallization have been called upon to explain the origin of the nelsonite (Chen et al. 2013; Li et al. 2015a; He et al. 2016; Wang et al. 2017), but the lack of reliable evidences has hindered the testing of competing models. The liquid immiscibility model is supported by the vein/lense-like occurrence, net-texture and simple mineral assemblage of the nelsonite (Chen et al. 2013; He et al. 2016), but subsequent melting experiments have questioned the existence of silica-free immiscible Ca–Fe–Ti–P nelsonitic melt (Wang et al. 2017). Fractional crystallization is generally accepted to have contributed to the formation of large-scale nelsonite bodies, but this process cannot adequately explain the observation that apatite is separated from clinopyroxene that has similar density, but coexists with Fe-Ti oxides that have distinctly different densities (Zhang et al. 2021). The role of fractional crystallization and liquid immiscibility in Fe–Ti mineralization remains unclear.

In this study, we recognized a new type of nelsonite in a recently exposed mining occurrence of the Damiao anorthosite complex. We compare it with two known types of nelsonite from the Damiao complex, and present field and geochemical evidences for
critical evaluation of the relative role of liquid immiscibility and fractional crystallization
in the formation of large Fe–Ti oxide orebodies. The results and findings of this study
offer important insights into the genesis of magmatic Fe–Ti oxide deposits.

**GEOLOGICAL BACKGROUND**

The Damiao anorthosite complex is located in the Chengde area of the northern North China Craton (Fig. 1A), where Archean to Paleoproterozoic crystalline basement is overlain by Mesoproterozoic to Cenozoic cover. The Damiao complex is emplaced into Neoarchean (~2.5 Ga) high-grade metamorphic rocks, and is unconformably covered by Jurassic volcano–sedimentary rocks (Fig. 1B). The complex is divided into three separate bodies on the basis of field occurrences, namely the Eastern, Central and Western Bodies, with outcrop areas of ~30 km², <10 km² and ~80 km², respectively (Fig. 1B). Several small late Paleozoic to Mesozoic intrusions occur to the southeast, southwest and west of the complex (Fig. 1C). Baddeleyite Pb–Pb geochronology of gabbronorite and nelsonite from this complex yielded crystallization ages of 1736 ± 3 Ma and 1734 ± 7 Ma, respectively (Li et al. 2019a).

The Damiao anorthosite complex is characterized by two stages of emplacement: early-stage anorthosite (85 %) and minor norite (10 %), and late-stage intrusions of mangerite (4 %) and dike/vein-like Fe–Ti–P-rich rocks (1 %) into consolidated anorthosite massif (Fig. 1C, 2, 3). Most of the Fe–Ti–P-rich rocks are distributed in the triangle-shaped Western Body. Mangerite is restricted to the northwestern part of the Western Body, and is not found in direct contact with the Fe–Ti–P-rich dikes/veins. All the rock types are comagmatic and represent products of differentiation from high-Al basaltic parental magma (Zhao et al. 2009; Li et al. 2015a, 2019a).
The majority of the early-stage anorthosite and norite have been hydrothermally altered, resulting in bleached and highly friable rocks. Dark-colored, fresh to weakly altered anorthosite is less common and generally forms irregular blocks within the altered anorthosite. The dark-colored anorthosite consists of 85–95% plagioclase (An$_{40-55}$, Li et al. 2015a) and 5–10% pyroxene (hypersthene and diopside) with subordinate amounts of Fe–Ti oxides. The change in color of the anorthosite from dark to light during alteration is attributable to the expelling of minute Fe–Ti oxide inclusions from plagioclase (Li et al. 2014). Plagioclase has been replaced by a mixture of albite and clinozoisite in the light-colored anorthosite.

The late-stage Fe–Ti–P-rich dikes crosscut the early-stage anorthosite and norite with irregular but sharp boundaries (Fig. 1D, 2, 3), and have been mined for Fe and Ti for > 70 years. Most of these dikes are distributed in the Heishan–Dongdawa mining district of the Western Body, with a total proven ore reserve of 317 million tonnes (33.5% Fe and 8.6% TiO$_2$) (Li et al. 2015b). The Fe–Ti–P-rich rocks comprise oxide–apatite gabbrororite, oxide–apatite pyroxenite, nelsonite and massive Fe–Ti oxide ore. The oxide–apatite gabbrororite consists of plagioclase (10–30%), clinopyroxene (20–50%), Fe–Ti oxides (15–50%), inverted pigeonite (5–20%) and apatite (5–15%). The oxide–apatite pyroxenite consists of clinopyroxene (20–50%), inverted pigeonite (10–20%), Fe–Ti oxides (15–35%) and apatite (10–15%). The nelsonite and massive Fe–Ti oxide ore are composed of Fe–Ti oxides and apatite in variable modal proportions. The transition between rock types is gradual.

**GEOLOGY OF THE NELSONITE**

The newly identified type-I nelsonite in the Xiaogou mining district, ~5 km north to...
the Heishan–Dongdawa mining district represents a unique type characterized by its coexistence with granite and oxide–apatite gabbronorite (Fig. 2A–D, 4A–G). These rocks are developed in several elongate and irregular dike-like bodies restricted in early-stage coarse-grained norite. These dike-like bodies locally contain irregular fragments of norite. Boundaries between the dikes and enclosing norite are sharp but smoothly curved, and no alteration zone is observed (Fig. 2A–D). The largest dike extends >1 km, with thickness varying from 0.5-5 m. The granite occurs as irregular and discontinuous veins that dispersedly distributed in one or both sides of the dikes, and displays sharp contacts with nelsonite in the inner zone and norite in the outer zone (Fig. 2A). Most of the oxide–apatite gabbronorite blocks are enclosed by nelsonite with gradual or sharp contacts (Fig. 2B), and nelsonite locally forms stockworks filling fractures in the early-stage norite (Fig. 2C–D, 4B). The oxide–apatite gabbronorite consists of fine-grained plagioclase (30–40%), antiperthite (20–30%), orthopyroxene (10–20%), clinopyroxene (10–20%), Fe–Ti oxides (8–15%) and apatite (3–8%) (Fig. 4F). The granite displays coarse-grained equigranular texture and is composed of quartz (30–50%), K-feldspar (40–60%) and plagioclase (10–20%) (Fig. 4G). The type-I nelsonite is composed of generally constant modal proportions of Ti–magnetite (45–55%), ilmenite (20–30%), apatite (25–35%) and subordinate amounts of pyrite, pyrrhotite, sphalerite and zircon (Fig. 3A–E). The Ti–magnetite is characterized by trellis oxy-exsolutions of ilmenite lamellae. Apatite crystals occur as 0.5-10 mm equant, subhedral grains (Fig. 4A), or as elongate, euhedral grains varying in length from 0.1 mm to 10 mm with aspect ratio up to 10:1 (Fig. 4E). Elongate apatite crystals in the contact zone between the type-I nelsonite and norite fragments are commonly orientated parallel to the boundaries of the coarse-grained plagioclase and
orthopyroxene (Fig. 4B–D).

Most of the type-II nelsonite occur in the Heishan–Dongdawa mining district, and constitute a major ore type in the district, making up ~ 30% of the total ore reserves. They generally form orebodies as irregular dikes or veins along NE- and NW-striking fractures in the early-stage anorthosite and norite, with various shapes and sizes (Fig. 1D, 3A–C). The largest orebody has length, width and thickness up to 250 m, 50 m and 200 m, respectively. Mineralization layering is common in individual orebodies, with apatite-rich rocks (apatite up to 70%) concentrated in the upper part and near the margins, and oxide-rich rocks (<5 vol.% or no apatite) in the central and lower parts (Fig. 3B–C).

Chlorite-dominated alteration is commonly developed on both sides of the contact zone between orebody and anorthosite (Fig. 3B–C). The alteration zone is characterized by a decreasing proportion of chlorite from the margin of the orebody outward into the anorthosite. The width of alteration zone is generally positively correlated with the size of the associated orebody. The type-II nelsonite is composed of variable modal proportions of Fe–Ti oxides (Ti–magnetite and minor ilmenite) and apatite, with subordinate amounts of chlorite, pyrite, aluminous spinel and zircon (Fig. 4H). Ti–magnetite is trellis-textured with ilmenite lamellae in (111) planes due to subsolidus readjustment (Fig. 4I). Apatite is euhedral and equigranular with crystal size ranging from 0.2 to 5 mm. Fluid inclusions are widely developed in apatite, and yielded homogenization temperatures of 180–420°C and salinities of 6.2–38.9 wt% NaCl equivalent (Li et al. 2010).

The type-III nelsonite adjacent to Fe–Ti–P-rich rocks either occurs as conformable layers within layered oxide–apatite pyroxenite (Fig. 3D–E), or concentrates near the end of the Fe–Ti–P-rich dikes showing gradual contacts with oxide–apatite pyroxenite (Fig. 4E).
The oxide–apatite pyroxenite shows transitional contact with the oxide–apatite gabbronorite (Fig. 3D, 4J–K). It has been suggested that the oxide–apatite gabbronorite formed by rapid crystallization from the residual magma after anorthosite separation, and the oxide–apatite pyroxenite by slow and extensive fractional crystallization of the residual magma, whereas the nelsonite represents the most evolved cumulates directly crystallized and segregated from the magma of oxide–apatite pyroxenite (Li et al. 2015a).

These rock types are gradually changed. The type-III nelsonite comprises Ti–magnetite (40–60%), ilmenite (10–30%), apatite (10–40%), pyroxene (clinopyroxene and inverted pigeonite) (< 10%) and subordinate amounts of chlorite, pyrite, aluminous spinel and zircon. The textures of Fe–Ti oxides and apatite are similar to those of the type-II nelsonite.

Crystallized melt inclusions in plagioclase are observed in plagioclase-rich rocks of the complex, including early-stage anorthosite, type-I and III oxide–apatite gabbronorite and late-stage anorthosite (Fig. 4L–O). The melt inclusions are 50–300 μm across and show smooth boundaries with hosting plagioclase, suggesting a primary origin. They commonly have similar mineral assemblages comprising euhedral to subhedral clinopyroxene, apatite, ilmenite, magnetite, baddeleyite and chlorite (Fig. 4L–O).

**SAMPLES AND ANALYTICAL METHODS**

Samples of the type-I nelsonite (XGL-15, 5 kg) and oxide–apatite gabbronorite (XG11-21, 10 kg), and granite (XG19-1, 2 kg) were collected from the largest dike in the Xiaogou mining district (E117°52′11″, N41°09′46″) for geochronology. Zircon separation was carried out using conventional heavy liquid and magnetic separation techniques, followed by hand picking under a binocular microscope. Zircon grains
(including reference standards) were cast in 25-mm epoxy mounts and then polished until the inner section of the grains was exposed. Individual zircon crystals were imaged by scanning electron microscope (SEM) under back-scattered electron (BSE) and cathodoluminescence (CL) modes to reveal their morphology and internal textures. Zircon U–Pb dating of sample XGL-15 was performed using a SHRIMP II ion microprobe at the Beijing SHRIMP Center, Chinese Academy of Geological Sciences. The U concentrations and Pb/U ratios were calibrated using zircon standards M257 (U = 840 ppm; Nasdala et al. 2008) and TEMORA (206Pb/238U age = 417 Ma; Black et al. 2003), respectively. Zircon U–Pb dating of sample XG11-21 was conducted using a multi-collector CAMECA IMS 1280 ion microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing. The U concentrations were calibrated by zircon standard 91500 (U = 81 ppm, Wiedenbeck et al. 1995) and the Pb/U ratios by zircon standard Plešovice (337 Ma, Sláma et al. 2008), and the Qinghu zircon (159.5 ± 0.2 Ma, Li et al. 2013) was used as a monitor standard. Zircon U–Pb dating of sample XG19-1 was carried out using a Finnigan Neptune inductively coupled plasma–mass spectrometry (ICP–MS) equipped with a New Wave UP 213 laser ablation system at the Institute of Mineral Resources, Chinese Academy of Geological Sciences in Beijing. The zircon standards used for calibration and monitoring were 91500, Plešovice, and GJ1 (610 ± 2 Ma, Elhlou et al. 2006). The beam spot was 20–30 μm in diameter. Concordia diagrams and weighted mean ages were produced using the program Isoplot-3 (Ludwig 2012).

Thirteen samples were collected from the Xiaogou mining district for whole-rock geochemistry, including five from the type-I nelsonite, six from the associated oxide–
apatite gabbronorite, and two from the associated granite. Eight samples of the type-II and type-III nelsonites (four of each) were selected for apatite analysis of trace-element geochemistry. Whole-rock and apatite analyses were performed at the Analytical Laboratory of China National Nuclear Corporation in Beijing. Fresh samples were crushed to ~200 mesh powders prior to analysis. Major elements were analyzed by a scanning wavelength dispersion X-ray fluorescence (XRF) spectrometer (AB–104L, PW2404), following Chinese national standard GB/T 14506.14–2010 for major element analyses, with precisions generally about 1%. Trace elements were determined using an ELEMENT XR ICP–MS following Chinese national standard GB/T 14506.30–2010 for trace element analyses, with precisions generally better than 5%.

In-situ major- and trace-element analyses were performed on 27 apatite crystals, of which seven are from the type-II nelsonite, ten from the type-III nelsonite and related oxide–apatite gabbronorite and pyroxenite, and another ten from the type-I nelsonite and related oxide–apatite gabbronorite. Electron microprobe analyses of apatite were conducted using a JEOL JXA-8230 Superprobe at the Institute of Mineral Resources, Chinese Academy of Geological Sciences in Beijing. Operating conditions during the quantitative analyses: accelerating voltage 15 kV, beam current 20 nA and beam size 5 μm. The standards used were albite for Si, hematite for Fe, MnTiO₃ for Mn, MgO for Mg, CaSiO₃ for Ca, jadeite for Na and apatite for P, F and Cl. Data were corrected using the atomic number-absorption-fluorescence (ZAF) software. For each sample, at least two spot analyses were conducted. In situ apatite trace element compositions were obtained using a New Wave Nd-YAG 193 nm laser attached to a Finnigan ELEMENT II ICP–MS at the National Research Centre for Geoanalysis in Beijing. Each analysis was acquired
with a 40 μm beam size, 45 s ablation time, 7 Hz repetition rate and 70 mJ energy. The Ca contents determined by electron microprobe were used as internal standard, and the NIST610, NIST612 and ML3B-G as external standards. The analytical uncertainties were smaller than 10% for all analyzed elements.

**RESULTS**

**Zircon U-Pb ages**

Full-details of zircon U-Pb analytical results are presented in supplementary tables S1 and S2.

Zircon grains extracted from sample XGL-15 display subhedral and prismatic morphology, and are 50–200 μm long and 30–50 μm wide. All of the grains appear to be homogeneous in CL images (Fig. 5A). Twenty-two analyses on 22 grains yielded \(^{207}\text{Pb}/^{206}\text{Pb} \) dates in the range of 1849–1338 Ma. These analyses have low concentrations of U from 5 to 35 ppm and Th from 2 to 79 ppm, with Th/U values varying from 0.44 to 3.72. Excluding 13 analyses that have relatively high proportions of common Pb \((f_{206} > 1\%)\) and/or high discordance \((> 5\%)\), the remaining 9 analyses give \(^{207}\text{Pb}/^{206}\text{Pb} \) dates from 1783–1636 Ma with a weighted mean at 1717 ± 30 Ma \((\text{MSWD} = 0.90)\) (Fig. 5A).

Zircon grains from sample XG11-21 show similar morphology to those from sample XGL-15. Most of the grains are homogeneous in CL images, but some show weak oscillatory zoning (Fig. 5B). Twenty analyses on 20 grains yielded \(^{207}\text{Pb}/^{206}\text{Pb} \) dates from 1787 to 1712 Ma, with a weighted mean at 1750 ± 13 Ma \((\text{MSWD} = 0.38)\) (Fig. 5B). These analyses are characterized by low proportions of common Pb \((f_{206} < 0.7\%)\), in spite of low concentrations of U (7–53 ppm) and Th (12–58 ppm), with Th/U values from 0.57 to 1.25.
Zircon grains from sample XG19-1 are subhedral and prismatic, and are 150–500 μm long and 80–200 μm wide. In CL images, most of the grains show weak oscillatory zoning (Fig. 5C). Fifty-three analyses on 53 zircon grains yielded $^{207}$Pb/$^{206}$Pb dates from 1883 to 1635 Ma. They have U concentrations from 28 to 431 ppm, Th concentrations from 26 to 706 ppm, and Th/U values from 0.30 to 3.15. Excluding 13 analyses that have relatively high discordance (> 5%), the remaining 40 analyses gave $^{207}$Pb/$^{206}$Pb dates ranging from 1792 Ma to 1689 Ma with a weighted mean of 1737 ± 10 Ma (MSWD = 1.13) (Fig. 5C).

**Whole-rock compositions**

Whole-rock geochemical data are presented in supplementary tables S3 and S4. The type-I nelsonite is characterized by constantly high Fe$_2$O$_3$ (54.54–56.97%), TiO$_2$ (11.53–14.16%), CaO (13.37–15.70%) and P$_2$O$_5$ (10.39–12.36%), but low SiO$_2$ (0.61–2.71%), Al$_2$O$_3$ (1.62–2.70%), NaO (< 0.11%) and K$_2$O (< 0.06%), consistent with a mineral assemblage dominated by Fe-Ti oxides and apatite. In contrast, the granite samples have high SiO$_2$ (72.00–73.24%), Al$_2$O$_3$ (12.84–13.33%), Na$_2$O (3.24–3.36%) and K$_2$O (4.89–5.87%), but low Fe$_2$O$_3$ (2.15–2.67%), TiO$_2$ (0.24–0.45%), CaO (0.98–2.11%) and P$_2$O$_5$ (0.03–0.11%). In the binary diagrams of whole-rock major element compositions (Fig. 6), the oxide–apatite gabbronorite has compositions intermediate between the two end-members defined by the type-I nelsonite and granite. However, the gabbronorite is characterized by higher MgO (3.44–6.23 %), reflecting the presence of orthopyroxene.

Transition metals (Sc, V, Cr, Co, Ni, Cu, Zn) are strongly enriched in the type-I nelsonite and oxide–apatite gabbronorite compared with the granite (Fig. 7). Except Sc,
all transition metals are more enriched in the type-I nelsonite than in the oxide–apatite
gabbronorite. The large ion lithophile elements (LILEs) display complex behavior. The
Sr concentrations of the three rock types are similar, whereas Rb concentrations gradually
increase from the type-I nelsonite through the oxide–apatite gabbronorite to the granite.
The oxide–apatite gabbronorite and granite have similarly elevated Ba concentrations,
much higher than the type-I nelsonite. For the high field strength element (HFSEs), the
Si-rich granite (5.60–10.10 ppm Nb, 0.23–0.42 ppm Ta, 2.12–2.35 ppm Th, 0.25–0.34
ppm U, 328–933 ppm Zr and 7.29–19.10 ppm Hf) have similar concentrations of Nb and
Ta but more abundant Th, U, Zr and Hf when compared with the Fe–Ti–P-rich type-I
oxide–apatite gabbronorite (4.91–11.00 ppm Nb, 0.08–0.38 ppm Ta, 0.21–0.46 ppm Th,
0.05–0.10 ppm U, 70.5–133 ppm Zr and 2.87–5.49 ppm Hf).

These three types of coexisting dike-like rocks display chondrite-normalized REE
patterns generally parallel to each other, which are characterized by enrichment of LREEs
relative to HREEs ($La_N/Yb_N = 5.83–14.19$), similar to other rock types in the Damiao
anorthosite complex (Fig. 8). The type-I nelsonite is characterized by the highest
abundances of total REEs (865–979 ppm) and conspicuous negative Eu anomalies
($Eu/Eu^* = 0.49–0.55$). The oxide–apatite gabbronorite associated with the type-I
nelsonite show chondrite-normalized REE patterns similar to the oxide–apatite
gabbronorite associated with the type-III nelsonite, with no significant Eu anomalies. The
granite samples plot between the early-stage anorthosite and oxide–apatite gabbronorite,
and also lack Eu anomalies. No obvious Ce anomalies are observed in any of the rock
types of the Damiao anorthosite complex.

Apatite compositions
Apatite compositions are listed in supplementary table S5.

Apatite crystals from all of the rock types are F-rich and contain similar CaO (53.29–56.30 %), P₂O₅ (39.75–41.89 %), F (2.21–4.75 %), FeO (0.02–1.03 %), SiO₂ (0.02–0.27 %) and Cl (0–0.13 %), consistent with their homogenous textures shown in BSE and CL images. Concentrations of other elements are close to, or below, the limits of detection. The F/Cl ratios of apatite show an overall increasing trend from type-II (17–392, average 156), through type-III (101–480, average 280) to type-I (88–1787, average 401) nelsonites.

Apatite from different rock types generally has parallel chondrite-normalized REE patterns, characterized by enrichment of LREEs relative to HREEs with La₉/Yb₉ in the range of 10.0–18.8 (Fig. 9).

The three types of Fe–Ti–P-rich rocks are also commonly characterized by variable apatite Sr contents, total REE contents and Eu anomalies, and display well-defined linear trends in the total REEs vs. Sr and Eu/Eu* diagrams (Fig. 10). Apatite from the oxide–apatite gabbronorite associated with the type-I nelsonite has the lowest Sr (240–480 ppm) and Eu/Eu* (0.34–0.47), but the highest total REEs (3730–4702 ppm). The Sr (509–975 ppm) and Eu/Eu* (0.62–0.98) of apatite from the oxide–apatite gabbronorite and pyroxenite associated with the type-III nelsonite are higher and more variable, but total REE contents (1314–3573 ppm) are lower.

The three types of nelsonites have different apatite Sr and total REE contents and Eu anomalies, defining continuous linear trends in the total REEs vs. Sr and Eu/Eu* diagrams (Fig. 10). Apatite from the type-I nelsonite is characterized by relatively constant Sr (457–680 ppm) and total REE contents (3676–5531 ppm), and prominent
negative Eu anomalies (Eu/Eu* = 0.44–0.55). Apatite of the type-III nelsonite exhibits higher Sr (541–791 ppm) and Eu/Eu* (0.50–0.84), but lower total REE contents (1847–3971 ppm). Apatite from the type-II nelsonite has highest Sr contents (699–1098 ppm) and Eu/Eu* values (0.80–1.06), but lower total REE contents (1451–2865 ppm).

**DISCUSSION**

**Comagmatic relationship of dike-like Fe–Ti–P-rich rocks**

In the Xiaogou mining district, the type-I nelsonite, oxide–apatite gabbro-norite and granite occur in the same dike and are closely inter-related on the outcrop scale (Fig. 2A–B). These rocks also have subparallel chondrite-normalized REE patterns (Fig. 8), suggesting that they are cogenetic.

Zircon U–Pb geochronology of the three types of rocks yielded crystallization ages at 1717 ± 30 Ma, 1750 ± 13 Ma and 1737 ± 10 Ma, which are identical within errors and confirm their close relationship in time. Age uncertainties of the samples are correlated with U concentrations of zircon, as previously documented in Proterozoic anorthosite complexes (Scoates and Chamberlain 2003; Li et al. 2019a). Since both the field relationships and geochronology results indicate a synchronous formation of the three types of rocks, combining the three datasets produces a weighted mean ^207^Pb/^206^Pb age at 1740 ± 7 Ma (MSWD = 0.93, n = 69) (Fig. 5D–E), which is considered as the best estimation of the magmatic event. This age is within uncertainty of the emplacement age of 1736 ± 3 Ma of the Damiao anorthosite complex, precisely constrained by baddeleyite from the type-II nelsonite (Li et al. 2019a). The oxide–apatite gabbro-norite associated with the type-I nelsonite displays chondrite-normalized REE patterns highly analogous to those of the oxide–apatite gabbro-norite and pyroxenite associated with the type-III
nelsonite (Fig. 8). These features are consistent with all of the dike-like Fe–Ti–P-rich rocks in the Damiao complex being originated from a residual magma after anorthosite segregation.

**Formation of type-I Fe–Ti–P-rich rocks by liquid immiscibility**

The binary diagrams of whole-rock major element compositions of the studied samples demonstrate significant compositional gaps in SiO$_2$ (47.7–72.0%), Fe$_2$O$_3$ (2.7–17.1%) and TiO$_2$ (0.5–3.2%) between the granite and the type-I Fe–Ti–P-rich rocks (Fig. 6).

Genetically related acidic rocks and Fe–Ti–P-rich rocks could be produced by late-stage fractional crystallization of residual magma that experienced variable felsic contamination/assimilation, as evidenced by experimental and geochemical studies (Vander Auwera et al. 1998; Bolle et al. 2003; Bybee et al. 2015). However, the $\varepsilon_{\text{Nd}(t)}$ values of the Damiao anorthosite complex are not correlated with their Th, U or K$_2$O contents, arguing against significant involvement of felsic contaminants (Li et al. 2019a). Also, a contaminated residual magma commonly produces a dioritic component besides acidic rocks and Fe–Ti–P-rich rocks (Bybee et al. 2015), but the studied rocks show apparent compositional gaps between granite and Fe–Ti–P-rich rocks. Therefore, this mechanism can be precluded in generating the type-I Fe–Ti–P-rich rocks and granite.

Liquid immiscibility between conjugate Fe- and Si-rich melts is an important petrogenetic process that can lead to major gaps of oxide contents, i.e., the absence of intermediate compositions (Veksler et al. 2007; Charlier et al. 2011, 2013; VanTongeren and Mathez 2012; Chen et al. 2013; Kamenetsky et al. 2013; Hou and Veksler 2015). Melt inclusion and experimental studies have shown that the immiscible Fe-rich melt is
composed of 30–50% SiO$_2$ and 18–32% Fe$_2$O$_3^T$, whereas the immiscible Si-rich melt comprises 60–76% SiO$_2$ and 4–13% Fe$_2$O$_3^T$ (Jakobsen et al. 2005; Charlier and Grove 2012). The major element compositions of the intimately associated oxide–apatite gabbronorite (41.49–47.74% SiO$_2$ and 17.14–24.69% Fe$_2$O$_3^T$) and granite (72.00–73.24% SiO$_2$ and 2.15–2.67% Fe$_2$O$_3^T$) associated with the type-I nelsonite in the Xiaogou mining district fit well with the assumption of two immiscible melts.

In this study, we chose the experimental products of Fe- and Si-rich melts of Charlier and Grove (2012) for comparison because of the compositional similarities between the starting materials (46–56% SiO$_2$ and 11.7–17.7% Fe$_2$O$_3^T$) and the residual magma of the Damiao anorthosite complex (48.13–49.00% SiO$_2$ and 15.38–15.61% Fe$_2$O$_3^T$, Zhao et al. 2009) (Fig. 6). In Figure 6, the granitic samples plot exactly into the fields of the experimental Si-rich melts, and the type-I oxide–apatite gabbronorite samples generally fall into the fields of the experimental Fe-rich melts except for Al$_2$O$_3$, which is likely a reflection of Al-spinel accumulation. The CaO/Al$_2$O$_3$ ratio is a sensitive indicator for immiscibility as fractionation between the two elements is very limited (Jacobsen et al. 2005; Coint et al. 2020). In the SiO$_2$–CaO/Al$_2$O$_3$ diagram, the type-I oxide–apatite gabbronorite and granite samples fall into the experimental Fe-rich and Si-rich melts, respectively (Fig. 6F). Previous experiments have also demonstrated that, compared with Si-rich melt, Fe-rich melt is strongly enriched in REEs, Sr and transition metals such as Sc, V, Cr, Co, Ni, Cu and Zn (Watson 1976; Veksler et al. 2006; Charlier and Grove 2012; Lester et al. 2013a; Veksler and Charlier 2015). This feature is also observed in contrasting compositions of the oxide–apatite gabbronorite (192–378 ppm REEs, 289–457 ppm Sr, 24.6–38.6 ppm Sc, 199–554 ppm V, 2.2–16.8 ppm Cr, 30.6–70.8 ppm Co,
8.5–46.5 Ni, 31.0–55.9 ppm Cu and 186–352 ppm Zn) and granite (84–139 ppm REEs, 73–281 ppm Sr, 1.7–4.2 ppm Sc, 14.8–16.0 ppm V, 1.0–1.2 ppm Cr, 2.5–2.8 ppm Co, 1.9–2.4 Ni, 3.2–4.0 ppm Cu and 26.0–38.1 ppm Zn) associated with the type-I nelsonite (Fig. 7). Collectively, these features indicate that the oxide–apatite gabbronorite and granite were directly crystallized from segregated Fe-rich and Si-rich immiscible melts that were evolved from the magma residual to anorthosite.

According to experiments, the HFSEs such as Th, U, Zr and Hf tend to concentrate in the Fe-rich melt, although partition coefficients can be affected by many parameters such as water content and oxygen fugacity (Watson 1976; Veksler et al. 2006; Lester et al. 2013b). In this study, however, the Si-rich granite has higher concentrations of Th, U, Zr and Hf than the Fe–Ti–P-rich type-I oxide–apatite gabbronorite. This is unexpected, but similar element behaviors have been documented elsewhere, e.g., in the Skaergaard intrusion of Greenland and Raftsund intrusion of Norway where liquid immiscibility has proven to be important (McBirney, 2002; Coint et al. 2020). This phenomenon can be attributed to the presence of specific accessory phase of zircon, which is more abundant and has higher concentrations of Th and U in the Si-rich granite than in the Fe–Ti–P-rich type-I oxide–apatite gabbronorite (Fig. 5). It is noteworthy that in the type-I oxide–apatite gabbronorite, Zr-bearing phase is represented initially by micron-sized baddeleyite hosted in crystallized melt inclusions (Fig. 4M), and later by coarse-grained zircon (Fig. 5B), reflecting enhanced input of Si during crystallization of the Fe-rich melt. This feature indicates that natural silicate liquid immiscibility is likely a transient phenomenon, and the segregated Fe-rich and Si-rich melts quickly hybridize as they crystallize. In this process, some of the most incompatible HFSEs tend to concentrate in the more stable and
mobile Si-rich melt rather than the more refractory Fe-rich melt, regardless of their
distribution during the preceding immiscibility stage.

Role of liquid immiscibility in Fe–Ti–P mineralization

Some fine-grained ferrodioritic dikes at the margins of the Damiao complex contain
48.13–49.00% SiO₂, 15.38–15.61% Fe₂O₃, 2.29–2.72% TiO₂ and 0.31–0.35% P₂O₅, and
are considered to represent the residual magma of the anorthosite complex (Zhao et al.
2009). As expected, they appear to fill in the compositional gaps between the oxide–
apatite gabbronorite and granite associated with the type-I nelsonite (Fig. 6–8). Residual
magma evolution from the initial melt to the Fe-rich immiscible melt led to significant
enrichment of Fe, Ti and P, and depletion of Si and Al. Therefore, liquid immiscibility
probably played an important role in Fe–Ti–P enrichment during residual magma
evolution.

Liquid immiscibility has been regarded as the controlling factor for the formation of
nelsonite, accounting for the features of discordant veins and dikes intruding anorthosites
(Philpotts 1967; Kolker 1982). However, recent experimental studies have negated the
existence of Fe-Ti oxide melt at geologically reasonable temperatures (< 1300 °C)
(Lindsley and Epler 2017; Wang et al. 2017). In the present study, the intimate
relationship between the type-I nelsonite and the oxide–apatite gabbronorite indicates that
the former is also a product derived from the Fe-rich immiscible melt. This interpretation
is further supported by the identical morphology and chondrite-normalized REE patterns
of apatite from both the nelsonite and oxide–apatite gabbronorite (Fig. 4E, 4G–H, 9–10).
The cross-cutting relationships of the nelsonite with hosting anorthosite or norite imply
that it was emplaced as crystalline mush through a squeeze-out process (Ashwal 1993;
Duchesne 1999; Lindsley and Epler 2017). The nelsonite likely represents cumulates evolved from Fe-rich immiscible melt rather than solidified Fe-rich immiscible melt, and the latter is interpreted to form the fine-grained oxide–apatite gabbronorite.

Therefore, the coexistence of oxide–apatite gabbronorite and nelsonite formed by liquid immiscibility affords an opportunity to explore the partition of elements from a Fe-rich melt to nelsonite. The nelsonite is enriched in REEs and transition metal elements (except for Sc), but depleted in LILE (Rb, Sr and Ba). This can be explained by early segregation of Sc-rich pyroxene and Rb–Sr–Ba-rich plagioclase from the Fe-rich melt. Apatite crystals from both the nelsonite and the oxide–apatite gabbronorite show similar chondrite-normalized REE patterns and total REE abundances, but those from the former are characterized by slightly higher Sr and less pronounced negative Eu anomalies. This observation can be explained by the partition of elements between coexisting apatite and plagioclase, as the latter mineral is also rich in Sr and typically has positive Eu anomalies (Li et al. 2015a). Apatite from both the oxide–apatite gabbronorite and the nelsonite displays similar Eu anomalies (Fig. 9, 10B), implying that fractional crystallization has minimal influence on the extent of apatite Eu anomalies.

Role of fractional crystallization in Fe–Ti–P mineralization

Large-scale nelsonites (type-II and III) are distributed in the Heishan–Dongdawa mining district. Field observations indicate that they either occur as conformable layers alternating with oxide–apatite pyroxenite, or sit at the end of the Fe–Ti–P-rich dikes with gradual contacts with oxide–apatite pyroxenite or oxide–apatite gabbronorite (Fig. 3D–G). Whole-rock compositions of the Fe–Ti–P-rich rocks show well-defined linear trends, with a Si–Al–Mg-rich end member and a Fe–Ti-rich end member (Fig. 6). This feature is
attributable to cumulate rocks formed by two-component mixing of plagioclase–pyroxene and Fe–Ti oxide members (Duchesne and Charlier 2005). As shown in Figure 6B, the Al₂O₃ contents of the oxide–apatite gabbronorite and the pyroxenite can be variable and are not necessarily correlated with SiO₂, suggesting that the aluminum contents in these rocks are also controlled by Al-spinel (60.14–62.05% Al₂O₃ and <0.11% SiO₂, Chen et al. 2013) apart from plagioclase. Field and geochemical evidences support the formation of large-scale nelsonite by extensive fractional crystallization with crystal accumulation.

The remarkable similarity in chondrite-normalized REE patterns between apatite and related Fe–Ti–P-rich rocks suggests that the REE budget of each sample is largely controlled by apatite (Fig. 9). Apatite crystals from all the three types of nelsonites, commonly show that Eu/Eu* values (0.44–1.06) and Sr contents (457–1098 ppm) are negatively correlated with their total REE contents (1451–5531 ppm), resulting in continuous linear trends (Fig. 10).

Variable negative Eu anomalies in apatite might be attributed to crystallization under different fO₂ conditions. However, abundant nelsonites have been shown to have crystallized constantly close to the FMQ buffer curve (Kolker 1982; McLelland et al. 1994; VanTongeren and Mathez 2012). Moreover, differences in fO₂ conditions, typically associated with variable Ce anomalies, are not observed in the apatite samples of this study. Therefore, we suggest that the variation in Eu anomalies shown by the samples is not related to fluctuation of oxygen fugacity.

Variable degrees of negative Eu anomalies in apatite can be explained by different proportions of prior plagioclase crystallization from the residual melt, because plagioclase is always on the liquidus in the magma parental to anorthosite suites (Ashwal
In the Damiao anorthosite complex, plagioclase in all types of plagioclase-bearing rocks is observed to be the first crystallized phase, and coarse-grained plagioclase crystals host abundant crystallized melt inclusions showing similar mineral assemblages with the interstitial melt (Fig. 4L–O). In the late-stage Fe–Ti–P-rich dikes, the Eu/Eu* values in the plagioclase aggregates (late-stage anorthosite) (0.99–2.01) are significantly higher than in the fine-grained oxide–apatite gabbronorite (0.74–1.00) (Li et al. 2015a), and thus prior crystallization of plagioclase would result in negative Eu anomalies in apatite subsequently crystallized from the residual melt. The plagioclase aggregates contain higher Sr (1025–1339 ppm vs. 285–481 ppm) but lower total REEs (51–131 ppm vs. 192–378 ppm) than the oxide–apatite gabbronorite (Li et al. 2015a). As a consequence of prior plagioclase crystallization, more REEs and less Sr would partition into apatite, a mechanism similar to the trapped liquid shift effect (Cawthorn 2013). We thus conclude that the linear trends observed in the total REEs vs. Sr and Eu/Eu* diagrams result from progressive plagioclase crystallization and Fe–Ti–P enrichment of the residual magma. This conclusion is consistent with the crystallization sequence from the oxide–apatite gabbronorite to the oxide–apatite pyroxenite associated with the type-III nelsonite, and eventually to the nelsonite as observed in the field (Li et al. 2015a).

**Role of hydrothermal process in Fe–Ti–P mineralization**

Extensive concentrations of Fe–Ti oxides and apatite with minor silicates cannot be simply explained by a gravity-controlled crystal sorting process, because of the similarity in density of apatite and pyroxene ($\rho_{\text{apatite}} = 3.1–3.3$, $\rho_{\text{Ca-poor pyroxene}} = 3.4–3.7$, $\rho_{\text{Ca-rich pyroxene}} = 3.3–3.5$, Deer et al. 1966) making it difficult to separate the two phases by gravity.
Lindsley and Epler (2017) proposed that FeO–TiO$_2$ and P$_2$O$_5$ mutually enhance their solubilities in silicate melts, and that Fe-Ti oxides and apatite tend to co-precipitate once the melts become saturated with either phase. They further suggest that the cross-cutting oxide-apatite bodies were probably emplaced as crystalline oxide-apatite mush, which was lubricated by small amounts of residual silicate liquid to facilitate its flow.

The mechanism above is not able to fully explain the occurrence of large-scale nelsonite in the Damiao anorthosite complex. The dikes or veins made up of nelsonite and massive Fe–Ti oxide ore have depth up to 200 m (Fig. 1D, 3A), which is less likely to be formed merely by a squeeze-out process. Moreover, the mineral proportions of apatite and oxides in each dike or vein are highly variable, with nelsonite generally distributed near the top and margin, while massive Fe–Ti oxide ore close to the bottom and center (Fig. 3B–C).

Considering that the nelsonite dikes or veins are controlled by fractures developed in early-stage anorthosite and commonly show chlorite-dominated alteration in the contact zone on both sides, hydrothermal processes have probably played a part in forming these features (Li et al., 2010). Based on the behavior of zirconium and silicon in magmatic–hydrothermal system and fluid inclusion studies, Li et al. (2019b) proposed that the Fe–Ti–P mineralization involved hydrous melts and magmatic–hydrothermal processes, with the Fe–Ti oxides being formed at the magmatic stage and apatite at the hydrothermal stage. Nevertheless, the substantial flow of Fe–Ti oxides along fractures appears to be contradictory with the generally-held views that Ti (and Al), which is rich in nelsonite, is immobile in hydrothermal fluids (Tropper and Manning 2007; Antignano and Manning 2008). However, Li et al. (2014) showed that Ti and Al could have been significantly
leached out during hydrothermal replacement of the early-stage anorthosite in the Damiao complex, an interpretation similar to the magnetite flotation model proposed for the Kiruna-type iron oxide-apatite deposits, which is characterized by the formation of a rising oxide suspension through preferred wetting of Fe–Ti oxides in hydrothermal fluid (Knipping et al. 2015, 2019).

IMPLICATIONS

The role of silicate liquid immiscibility in the petrogenesis of plutonic systems is a contentious issue, and previous works in support of this process have been mainly based on studies of crystal micro-structures or crystallized melt inclusions (e.g. Jakobsen et al. 2005; Holness et al. 2011; Borisov and Veksler, 2021). In this study, we present unambiguous, outcrop-scale, field evidences for the operation of liquid immiscibility process. We show that natural silicate liquid immiscibility is a transient phenomenon, and hybridization of the segregated Fe-rich and Si-rich melts effectively take place during their crystallization. This explains the inconsistent distribution of HFSEs such as Th, U, Zr and Hf between natural samples formed by liquid immiscibility and experimental immiscible melts.

Field relationships and geochemical characteristics of three types of nelsonites and related rocks in the Proterozoic Damiao anorthosite complex reveal the important role that liquid immiscibility and fractional crystallization have played in Fe–Ti–P mineralization. Our new results suggest that liquid immiscibility and fractional crystallization are not mutually exclusive during magma evolution, and giant magmatic Fe–Ti oxide deposits probably formed by combination of these two processes. In addition,
hydrothermal process may also have played a role in Fe–Ti–P mineralization. The
Eu/Eu* value, total REEs and Sr concentrations of apatite are probably a useful indicator
of Fe–Ti–P mineralization.

ACKNOWLEDGEMENTS AND FUNDING

This study was financially supported by National Natural Science Foundation of China
(42072112, 41873062, 41402067) and Basic Research Fund of MNR Key Laboratory of
Metallogeny and Mineral Assessment (KK2204). We thank Xiaoxiao Ling, Jiao Li and
Mingyue Hu for their assistance with analyses. We appreciate Nolwenn Coint, Ilya
Veksler and Charles Lesher (AE) for their insightful comments and detailed suggestions
which helped improve the paper.

REFERENCES CITED

H₂O-NaAlSi₃O₈ fluids at 0.7-2.0 GPa and 700–1000 °C: Implications for mobility of
nominally insoluble elements. Chemical Geology, 255, 283–293.


deposits formed in feeder conduits by removing cotectic silicates. Economic
Geology, 116 (3), 681–691.

Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., and

Borisov, A. and Veksler, I.V. (2021) Immiscible silicate liquids: K and Fe distribution as a test for chemical equilibrium and insight into the kinetics of magma unmixing. Contributions to Mineralogy and Petrology, 176, 47.


Hou, T., and Veksler, I.V. (2015) Experimental confirmation of high-temperature silicate
liquid immiscibility in multicomponent ferrobasaltic systems. American Mineralogist, 100(5–6), 1304–1307.


Li, X.H., Tang, G.Q., Gong, B., Yang, Y.H., Hou, K.J., Hu, Z.C., Li, Q.L., Liu, Y., and


Nasdala, L., Hofmeister, W., Norberg, N., Mattinson, J.M., Corfu, F., Dor, W., Kamo,
natural reference material for the ion microprobe U-Pb analysis of zircon.
Geostandards And Geoanalytical Research, 32, 247–265.

inclusions in olivine from the Panzhuhua and Hongge layered intrusions, SW China:
evidence for early saturation of Fe-Ti oxides in ferrobasaltic magma. Contributions
to Mineralogy and Petrology, 156, 307–321.

Geology, 62, 303–315.

constraints on the origin of monzonitic and related rocks in the Laramie anorthosite
complex, Wyoming, USA. Precambrian Research, 124, 269–304.

Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood,
M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B.,
reference material for U–Pb and Hf isotopic microanalysis. Chemical Geology, 249,
1–35.

of thick stratiform Fe–Ti oxide layers in layered intrusion and frequent
replenishment of fractionated mafic magma: evidence from the Panzhuhua intrusion,

The 4th geological team of Hebei (2007) Geological map of the Damiao–Heishan area in


in China. Science China: Earth Sciences, 64.


**FIGURE CAPTIONS**

**Fig. 1.** (A) Location of the Damiao anorthosite complex in the North China Craton (after Zhao et al. 2005). (B) Simplified geological map of the Chengde area (after Ye 1989). (C) Geological map showing the Western Body of the Damiao anorthosite complex and associated nelsonite (after the 4th geological team of Hebei 2007). (D) A profile of the Heishan–Dongdawa mining district showing the relationship between dike-like Fe–Ti–P orebodies and host anorthosite (after Li et al., 2015b).

**Fig. 2.** Photographs of the dike-like type-I nelsonite, type-I oxide–apatite gabbronorite and granite. (A) Type-I nelsonite coexisting with granite in a dike cross-cutting early-stage norite with smoothly curved contacts. (B) Type-I oxide–apatite gabbronorite enclosed by type-I nelsonite in a dike, with their width showing a
positive relationship. (C) Type-I nelsonite occurring as stockworks injecting into the fractures of early-stage norite. (D) Type-I nelsonite occurring in the contact between fined-grained type-I oxide–apatite gabbronorite and early-stage norite.

**Fig. 3.** Photographs of the type-II and III Fe–Ti–P-rich rocks. (A) Type-II nelsonite forming irregular orebodies in the fractures of early-stage anorthosite. (B, C) Development of mineralization zoning with apatite enriched in the upper level and center in an orebody composed of type-II nelsonite, as well as chlorite-dominated alteration on both sides of the contact zone between orebody and anorthosite. (D) Type-III dike-like Fe–Ti–P-rich rocks in the fractures of early-stage anorthosite, including nelsonite, oxide–apatite pyroxenite and oxide–apatite gabbronorite. (E) Type-III nelsonite occurring as conformable layer within layered oxide–apatite pyroxenite. (F, G) Type-III nelsonite locating in the end of Fe–Ti–P-rich-dikes.

**Fig. 4.** Photomicrographs of the type-I, II and III Fe–Ti–P-rich rocks. (A, B) Type-I nelsonite showing sharp contacts with early-stage norite. (B, C) Apatite developing planar orientation in the contacts between type-I nelsonite and coarse-grained plagioclase and orthopyroxene of early-stage norite. (D) Chlorite replacement fronts commonly developed in the contact between type-I nelsonite and early-stage norite. (E) Type-I nelsonite composed of Ti-magnetite, ilmenite, apatite and minor phases of zircon (Zrn) and sphalerite (Sph). (F) Oxide–apatite gabbronorite associated with the type-I nelsonite containing plagioclase, antiperthite (Atp), orthopyroxene, clinopyroxene, Fe–Ti oxides and apatite. (G) Granite composed of quartz (Qtz),
K-feldspar (Kf) and plagioclase. (H, I) Type-II nelsonite consisting of Ti-magnetite (Ti-Mag), ilmenite (Ilm) and apatite. (J) Oxide–apatite gabbronorite associated with the type-III nelsonite comprising plagioclase (Plag), orthopyroxene (Opx), clinopyroxene (Cpx), Fe–Ti oxides and apatite (Ap). (K) Oxide–apatite pyroxenite associated with the type-III nelsonite composed of clinopyroxene, Fe–Ti oxides and apatite. (L–O) Crystallized melt inclusions composed of clinopyroxene (Cpx), apatite (Ap), ilmenite (Ilm), magnetite (Mag), baddeleyite (Bdl) and chlorite (Chl) in plagioclase (Plag) of the early-stage anorthosite (L), type-I oxide–apatite gabbronorite (M), type-III oxide–apatite gabbronorite (N) and late-stage anorthosite (O). A–D, F, H, J and K, plane polarized light. G, crossed polarized light. E and I, reflected light. L–O, BSE image.

Fig. 5. (A–C) Tera-Wasserburg concordia plots of zircon U–Pb data for the type-I nelsonite (XGL-15), oxide–apatite gabbronorite (XG11-21), and granite (XG19-1). (D) Plots of U vs. $^{207}\text{Pb} / ^{206}\text{Pb}$ ages showing correlation of age uncertainties with U concentrations. (E) Age data histogram and relative probability plots of zircon.

Fig. 6. Binary diagrams of whole-rock major element compositions showing covariation of SiO$_2$ vs. TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3^T$, MgO, CaO and CaO/Al$_2$O$_3$ for different dike-like rock types. Our new geochemical results are plotted along with previously reported data of the Fe–Ti–P-rich rocks (Zhao et al. 2009; Chen et al. 2013; Li et al. 2015a; He et al. 2016) from the Heishan–Dongdawa mining district.
Fig. 7. Binary diagrams of whole-rock trace element compositions showing covariation of Cr+V vs. Sc, Co+Ni+Cu, Rb and Sr for different dike-like rock types. Our new geochemical results are plotted along with previously reported data of the Fe–Ti–P-rich rocks (Zhao et al. 2009; Li et al. 2015a; He et al. 2016) from the Heishan–Dongdawa mining district.

Fig. 8. Chondrite-normalized REE patterns of the coexisting type-I nelsonite, oxide–apatite gabbronorite and granite. Gray areas representing anorthosite and type-II oxide-apatite gabbronorite dikes are from Li et al. (2014, 2015a). Chondrite values are from Boynton (1984).

Fig. 9. Chondrite-normalized REE patterns of apatite from the type-I, II and III nelsonites, the oxide–apatite gabbronorite associated with the type-I nelsonite, and the oxide–apatite gabbronorite and oxide–apatite pyroxenite associated with the type-III nelsonite. The purple pattern representing initial residual magma (ferrodioritic dike) is from Zhao et al. (2009), gray areas representing the type-III oxide–apatite gabbronorite and pyroxenite are from Li et al. (2015a). Chondrite values are from Boynton (1984).

Fig. 10. Plots of total REE vs. Eu/Eu* and Sr of apatite from the type-I, II and III nelsonites, the oxide–apatite gabbronorite associated with the type-I nelsonite, and the oxide–apatite gabbronorite and oxide–apatite pyroxenite associated with the type-III nelsonite.
Figure 1

![Geological map of the study area with various rock types and fault lines.]

Legend:
- Neoarchean gneiss
- Early Paleoproterozoic quartz syenite
- 1735 Ma anorthosite
- 1735 Ma Fe–Ti–P-rich rocks (gabbronorite and pyroxenite)
- 1735 Ma mangerite
- 1735 Ma nelsonite and massive Fe–Ti oxide ore
- Late Paleozoic ultramafic rocks
- Mesoproterozoic sedimentary rocks
- Late Paleozoic granite
- Jurassic volcanic–sedimentary rocks
- Mesoziic diorite
- Thrust fault/normal fault
- Drill core
- Sample locations

Key locations:
- Beijing
- Damiao
- Maying

Geological features:
- Central body
- Western body
- Eastern body

Time periods:
- Early Paleoproterozoic
- Late Paleozoic
- Mesozoic
- Neoarchean
- Mesoproterozoic

Rock types:
- 1735 Ma mangerite
- Type-I nelsonite
- Type-II and III nelsonite
- Massive Fe–Ti oxide ore
- Mesoproterozoic sedimentary rocks
- Late Paleozoic granite
- Jurassic volcanic–sedimentary rocks
- Neoarchean gneiss
- Early Paleoproterozoic quartz syenite
- 1735 Ma anorthosite
- 1735 Ma Fe–Ti–P-rich rocks (gabbronorite and pyroxenite)
- Late Paleozoic ultramafic rocks
- Mesoziic diorite
Figure 2

A. Norite
Granite
Nelsonite
Norite

B. Norite
Nelsonite
Granite

C. Norite
Nelsonite
Norite

D. Norite
Nelsonite
Norite

Oxide–apatite gabbronorite
Nelsonite
Figure 3

A

B

C

D

E

F

G

Anorthosite

Alteration

Nelsonite

Anorthosite

Dike-like Fe–Ti–P-rich rocks with rhythmic layering

Oxide–apatite pyroxenite

Nelsonite

Oxide–apatite pyroxenite

Nelsonite

Anorthosite
Figure 4
Figure 5

A. XGL-15
Mean = 1717 ± 30 Ma
MSWD = 0.90, n = 9

B. XG11-21
Mean = 1750 ± 13 Ma
MSWD = 0.38, n = 20

C. XG19-1
Mean = 1737 ± 10 Ma
MSWD = 1.13, n = 40

D. Zircon from XGL-15
Zircon from XG11-21
Zircon from XG19-1

E. 1740 ± 7 Ma
MSWD = 0.93
n = 69

Always consult and cite the final, published document. See http://www.minsocam.org or GeoscienceWorld
Figure 6
Figure 7
Figure 8

The diagram shows the distribution of rare earth elements (REE) in different rock types and magma-related phases. The x-axis represents the REE in order of atomic weight, from La to Lu, while the y-axis represents the rock/chondrite ratio on a log scale. Different rock types, such as granite, nelsonite, oxide-apatite gabbronorite, and ferrodioritic dike, are plotted, each represented by a different symbol. The diagram also includes an anorthosite phase, indicated by a shaded area, showing its REE distribution.
Figure 9

La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Rock/Chondrite

Apatite from type-II oxide-apatite gabbro-norite
Apatite from type-I oxide-apatite gabbro-norite
Apatite from type-III oxide-apatite gabbro-norite
Apatite from type-III oxide-apatite pyroxenite
Apatite from type-II oxide-apatite pyroxenite
Apatite from type-I oxide-apatite pyroxenite

Type-I nelsonite (whole rock)
Type-I oxide-apatite gabbro-norite (whole rock)
Type-I oxide-apatite pyroxenite (whole rock)
Ferrodioritic dike (residual magma)

La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Figure 10

A. Sr (ppm) vs. Total REE (ppm) for Type-I nelsonite, Type-I oxide-apatite gabbronorite, Type-III nelsonite, Type-III oxide-apatite gabbronorite, Type-II nelsonite, and Type-III oxide-apatite pyroxenite.

B. Eu/Eu* vs. Total REE (ppm) for the same samples.