Petrogenesis of Permian high-Mg diorites in the northern margin of the North China Craton: evidence of crust–mantle interaction

Min Li[1,2], Xisheng Xu[1,*], Richard M. Palin[3]

[1] State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing, 210023, China

[2] Tianjin Center, China Geological Survey (North China Center for Geoscience Innovation), Tianjin, 300170, China

[3] Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, United Kingdom

Abstract: The investigation of sanukitoids is particularly important for improving our understanding of crust–mantle interaction. This paper presents zircon and titanite U–Pb and bulk-rock major element, trace element, mineral major element and Sr–Nd–Pb–Hf isotope data for newly discovered Xinhure high-Mg diorite from the northern margin of the North China Craton (NCC). U–Pb dating of the southern Xinhure high-Mg diorite yielded ages of 284.8 (zircon) and 282.8 Ma (titanite), whereas the northern Xinhure high-Mg diorite crystallized at 265.8 Ma (zircon). The Early Permian and Middle Permian high-Mg diorite samples show a mantle signature, characterised by elevated $Mg^{\#}$ values (72.5–72.9, 67.3–68.9), Cr (695–785, 314–481 ppm) and Ni (106–122, 54–58 ppm) contents. Additionally, they exhibit enrichment in large ion lithophile elements, indicative of an enriched mantle source. Isotopically, both the Early Permian and Middle Permian high-Mg diorite samples display a relatively enriched radiogenic isotopic

composition, characterised by elevated initial $^{87}Sr/^{86}Sr$ ratios (0.7061–0.7063 and 0.7060–0.7066, respectively), negative $\varepsilon_{Nd}(t)$ values (−9.5 to −8.4 and −7.8 to −6.1, respectively) and broad zircon $\varepsilon_{Hf}(t)$ values (−10.1 to −4.1 and −6.0 to +5.3, respectively). The Nd–Hf isotopic compositions of the high-Mg diorites are decoupled as a consequence of interactions between subducting sediment-derived fluids and mantle peridotite. In light of the above, we propose a two-stage process for the formation of the Xinhure high-Mg diorite, comprising (1) partial melting of enriched mantle peridotite followed by (2) interaction between mantle-derived high-Mg diorite melts and continental crust-derived melts. Furthermore, this study provides new temporal constraints on the operation of subduction during the Late Paleozoic Paleo-Asian Ocean along the northern margin of the NCC.

Keywords: Sanukitoid; High-Mg diorite; North China Craton; Permian; Sr–Nd–Pb–Hf isotopes

1. Introduction

High-Mg andesites/diorites (HMAs) constitute a compositionally and geodynamically distinct series of rocks that occur throughout the geological record. They are characterised by elevated MgO, Cr and Ni contents, high $Mg^{\#}$ (100 × atomic Mg/[Mg + Fe]) values, and diverse trace element characteristics. They can be generally divided into four classes: high-Mg adakites, bajaites, boninites, and sanukitoids (e.g. Crawford, 1989; Defant and Drummond, 1990; Kamei et al., 2004; Kelemen, 1995, 2003; Rogers et al., 1985; Tatsumi, 1982, 2001, 2006; Tatsumi and Ishizaka, 1981). Adakites are defined by specific geochemical characteristics (Sr/Y ≥ 40 and La/Yb ≥ 20) and are named after magnesian andesites initially described by Kay (1978) from

Adak Island in the Aleutian Islands. Bajaites are distinguished by elevated concentrations of Ba (208–2300 ppm; mean ~1237 ppm) and Sr (506–3800 ppm), as well as elevated Sr/Y ratios (46–506) (Tang and Wang, 2010). They were initially identified in Baja, California (Rogers et al., 1985). In the classification proposed by Le Bas (2000), boninites are defined as rocks with SiO_2 > 52 wt. %, MgO > 8 wt. % and TiO_2 < 0.5 wt. %. The term 'sanukitoid' was initially introduced by Shirey and Hanson (1984) to describe a specific type of Archean intrusion associated with tonalite–trondhjemite–granodiorite magmatism. These sanukitoids exhibit a notable resemblance to the HMAs observed in the Setouchi Volcanic Belt (Tatsumi and Ishizaka, 1982). The rocks are predominantly diorite and andesite, characterised by high MgO (>5 wt. %) and Cr (>100 ppm) concentrations, as well as elevated Ba, Sr, and $Mg^{\#}$ (45~75) (Tatsumi, 2001, 2006; Martin et al., 2010). Sanukitoid and adakite exhibit comparable geochemical characteristics; however, sanukitoid displays a higher concentration of Mg, Cr, and Ni, which suggests that it can be directly formed by partial melting of mantle rocks, whereas adakite can only be formed by partial melting of basalt. Modern sanukitoids are scarce, whereas those of the Archaean are more prevalent. This indicates that the lithosphere or upper mantle that experienced melting and subduction in the Archaean may have had elevated temperatures compared to the present day (Zhang et al., 2005). Nevertheless, whether their origin is due to a single-stage process, in which the melt acquires the sanukitoid signature during passage to the surface, or a two-stage process, with melting preceded by a metasomatic event (Gómez-Frutos and Castro, 2022, and references therein), remains unresolved. These

aforementioned observations reflect the diverse possible petrogeneses of HMA magmas and also indicate the occurrence of abnormally hot thermal events that trigger flux- or decompression-melting.

Four principal models have been proposed to explain the genesis of HMAs. (1) Partial melting of enriched mantle is used to explain the genesis of sanukitoid in the Cenozoic Setouchi Island of Japan and numerous Archean greenstone belts (Tatsumi et al., 2002, 2003); (2) The reaction between subducted slab-derived melt with mantle peridotite (Rapp et al., 1999, 2010; Moyen et al., 2003; Tsuchiya et al., 2005) has been the subject of considerable research. Rapp et al., (1999) proposed that the primary differentiating factors between adakite, tonalite–trondhjemite–granodiorite, and sanukitoid are the extent of reaction between slab-derived melts and mantle peridotite; (3) delamination and partial melting of thickened, eclogite-facies lower crust, with the subsequent reaction of the melt with the mantle during its ascent (Gao et al., 2004; Streck et al., 2007; Xu et al., 2008, 2009; Huang et al., 2008); and (4) assimilation of mantle peridotite by felsic monzodiorite magma at crustal depths (Qian and Hermann, 2010). It is possible that the petrogenetic model for the fourth kind of high-Mg diorite may also be applicable to other HMAs in the eastern North China Craton (NCC). It is noteworthy that in models 1–3, initial partial melting of the mafic crust and/or assimilation of ultramafic rocks occurs at mantle depths (Qian and Hermann, 2010). In consideration of the diverse range of proposed mechanisms, it becomes evident that a multitude of potential tectonic settings may facilitate the formation of HMAs. For instance, the opening of a back-arc basin (Hanyu et al.,

2006; Tatsumi, 2006) represents one such possibility, whereas others include ridge subduction (Kamei et al., 2004) and post-subduction slab break-off (Heilimo et al., 2010; Kovalenko et al., 2005). Nevertheless, a consistent theme in all of these models and settings is the preponderance of HMAs in supra-subduction zones (SSZ) or SSZ-like locations ~~(e.g., greenstone belts)~~ along convergent plate margins of varying ages. Consequently, the identification and characterisation of HMAs may have significant implications for fingerprinting essential crust–mantle interactions and monitoring geodynamic regimes at ancient convergent plate margins.

The Late Paleozoic south-directed subduction of the Paleo-Asian Ocean resulted in the formation of a continental arc on the northern margin of the NCC (e.g., Zhang et al., 2007, 2009a, 2009b, 2012, 2013, 2016). The Late Paleozoic granitoid rocks and diorites in the continental arc are widespread (Zhang et al., 2016). The majority of researchers consider these plutons to reflect arc magmatism along an Andean-type active continental margin (e.g., Wang and Liu, 1986; Xiao et al., 2003, 2009; Li, 2006; Wang et al., 2007; Zhang et al., 2007, 2009; Bai et al., 2013; Ma et al., 2013; Zhang and Zhao, 2013). Some researchers, however, propose a post-collisional or post-subduction environment (Luo et al., 2009; Zhang et al., 2012; Shao et al., 2016). The compositions of these rocks are mostly diorite, quartz diorite, granodiorite, and granite, with minor gabbro and tonalite. With the exception of a few minor intrusions (Zhang et al., 2009; Zhou et al., 2009), mafic-ultramafic rocks and high-Mg diorites are rare along the northern margin of the NCC. Two high-Mg diorite plutons were identified in the Xinhure area during our geological survey (Fig. 1); however, the

petrogenesis and geodynamic significance of these rocks remain unclear.

In this contribution, we conducted an integrated study of *in-situ* analyses of titanite and zircon U–Pb and Hf isotope compositions, as well as petrology and whole-rock geochemical compositions, Sr–Nd–Pb isotope compositions, and mineral major element data for newly discovered Xinhure high-Mg diorites from the northern margin of the NCC. Our results demonstrate that these units are a member of the sanukitoid family and formed by partial melting of metasomatised mantle during slab roll-back of the Late Paleozoic Paleo-Asian Ocean. These mantle-derived melts subsequently interacted with continental crust-derived melts to form the Xinhure high-Mg diorites.

2. Geological background and sample description

2.1. Geological background

The NCC is one of the oldest cratons in the world, preserving crustal rocks as old as 3.8 Ga, and retains a complex history of crustal evolution, cratonization and stabilization (Santosh et al., 2016; Zhai and Santosh, 2011; Zhao et al., 2005; Zhao and Zhai, 2013). Following its cratonization, the NCC remained stable from the Mesoproterozoic to the Early Triassic, except for its northern margin, where extensive magmatism has occurred since the Late Paleozoic (Davis et al., 2001; Rudnick et al., 2004; Wu et al., 2008; Yang et al., 2008). The NCC and the Bainaimiao arc belt are separated by the E–W-trending Bayan Obo-Chifeng fault zone (Zhang et al., 2016).

The basement of the NCC is composed of highly metamorphosed Archean and Paleoproterozoic rocks, which were covered by the Meso-Neoproterozoic and Cambrian–Ordovician marine clastic and carbonate platformal sedimentary rocks, Middle Carboniferous to Triassic fluvial and deltaic sedimentary rocks, and Jurassic–Cretaceous and younger volcanic and sedimentary rocks. The Early Paleozoic Bainaimiao arc belt formed upon a Precambrian microcontinent with a tectonic affinity to the Tarim or Yangtze cratons, which was accreted to the northern NCC during the Late Silurian–Early Devonian by arc-continent collision (Zhang et al., 2014). The northern margin of the NCC played a pivotal role in the Paleozoic evolution of the Central Asian orogenic belt (CAOB) with the emplacement of a multitude of granitoid plutons during the Late Paleozoic.

Carboniferous–Permian calc-alkaline granitoid plutons are particularly prevalent in the northern NCC, occupying over 20% of the outcrop areas (Zhang et al., 2016). These plutons intruded into Precambrian rocks in the northern margin of the NCC, as well as into Early Paleozoic rocks in the Bainaimiao arc belt. Their geochemical features can be described as calc-alkaline or high-K calc-alkaline, metaluminous or weakly peraluminous.

2.2. Field occurrence and sample description

The study area, situated to the south of the Bayan Obo–Duolun–Chifeng Fault, belongs to the northern margin of the NCC (Fig. 1a). The area is primarily composed of Permian intrusive rocks, Paleoproterozoic metamorphosed basement rocks, and

Mesoproterozoic sedimentary rocks. The sample in this study were obtained from four Permian plutons, comprising the northern high-Mg diorite, the southern high-Mg diorite and two quartz diorites (Fig. 1b). The southern high-Mg diorite (Fig. 2a) occurs as a number of small stocks, each being exposed over an area of less than 1 m^2, which were intruded by Early Permian medium-fine-grained tonalite. Two quartz diorites are present on the east side of the northern high-Mg diorite pluton. These samples are included as comparison groups, with the samples numbered 0034-1 (in proximity to the northern high-Mg diorite) and 0041-1. The northern high-Mg diorite (Fig. 2b) intrudes into metamorphosed Paleoproterozoic basement rocks and is exposed over an area of approximately 20 m^2. The presence of chilled margins within the tonalite, in contact with the high-Mg diorite, indicates that the latter was emplaced earlier than the former. The two high-Mg diorite plutons are primarily composed of plagioclase (~40%) and amphibole (~60%), the latter of which occurs as coarse, euhedral columns measuring 4–10 mm in length (Fig.2c and 2d). The two quartz diorite plutons are primarily composed of plagioclase (~50%), biotite (~20%), amphibole (~20%) and quartz (~10%) (Fig.2e and 2f).

3. Sample analysis methods

3.1. Zircon U–Pb and Hf isotope analyses

The zircon separation process was completed by the Langfang Geological Survey Institute of Hebei Province, China. The samples were crushed and washed, and the zircon was separated using conventional magnetic separation and heavy liquid

separation techniques. Subsequently, zircon fractions with a purity of greater than 99% were selected by picking under a binocular lens. All grains were examined by transmitted light, reflected light, and cathodoluminescence imaging using electron micropcope and JXA-8800R (JEOL, Beijing, China) electron microprobe at the Tianjin Geological Survey Center (TGSC), China. The U–Pb dating of samples (Tw0032-1, Tw0044-1, Tw0034 and Tw0041) was also completed at the TGSC. Zircon U–Pb isotopic analyses were conducted using a laser ablation inductively coupled plasma–mass spectrometry (LA- ICP-MS). The laser used was a NEWWAVE 193 nm FX, manufactured in Fremont, California, USA, while the mass spectrometer used was the NEPTUNE, produced by Thermo Fisher (Geng et al. 2011). The laser spot diameter employed in the analysis was 35 μm, and helium was used as the carrier gas of the erosion material. The standard samples employed for U–Pb geochronological analysis are GJ1 and Plešovice (Hou et al., 2009). Eight samples were analyzed after one Plešovice zircon and two GJI zircons, and then two GJI zircons and another eight samples were analyzed. In this order, 24 samples were analyzed, followed by two GJI zircons and one Plešovice zircon. The analytical procedure is described in more detail by Yuan et al. (2004). Off-line processing of the final test data was conducted using ICPMSDataCal software (Liu et al. 2010). U–Pb age concordance graphs were generated using ISOPLOT 3.0 (Ludwig, 2003) and the average weighted age was calculated.

Zircon Hf isotope analysis was conducted in the Isotope Laboratory of the TGSC using a Neptune (MC-ICP-MS) system, with measurements taken in the same

192 localities used for U–Pb dating. The diameter of the laser beam was 35 μm, and the
193 frequency of the laser pulse was 8~10 Hz. During analysis, the $\varepsilon_{Hf}(t)$ value was
194 calculated on the basis of the zircon U–Pb age at the measuring point. The ^{176}Lu decay
195 constant is 1.867×10^{-1} $year^{-1}$ (Soderlund et al., 2004), the $^{176}Hf/^{177}Hf$ ratio of
196 chondrite is 0.282785 (Bouvier et al., 2008), and the $^{176}Lu/^{177}Hf$ ratio is 0.0336
197 (Bouvier et al., 2008). The calculation of the model age of the depleted mantle (T_{DM})
198 was based on the current depleted mantle $^{176}Hf/^{177}Hf$ ratio of 0.28325 and the
199 $^{176}Lu/^{177}Hf$ ratio of 0.0384 (Griffin et al., 2000, 2002).

200 3.2. Titanite U–Pb analysis

201 The external standard substance MKED1 was employed for U–Pb fractionation
202 correction of the data obtained under diverse laser ablation test conditions. The U–Pb
203 isotope ratios of all analysis points were corrected for elemental fractionation and
204 calculated using the ICPMSDataCal program, as described by Liu et al. (2008). Tera–
205 Wasserburg concordia diagrams were employed to perform a linear fit of the
206 measured data. The upper intersection point represents the common lead composition
207 of the sample, while the lower intersection point represents the age of the sample
208 (Tera and Wasserburg, 1972). Furthermore, based on the initial $^{207}Pb/^{206}Pb$ isotope
209 composition obtained from the upper intersection, a ^{207}Pb correction was performed
210 on samples enriched in common Pb in order to obtain their $^{206}Pb/^{238}U$ age (Sun et al.,
211 2010). The composition of common Pb in the MKED1 and OLT1 samples is relatively
212 uniform, and the deduction of common lead is based on the two-stage evolution

model of Pb isotopes proposed by Stacey and Kramers (1975).

3.3. Whole-rock Sr–Nd–Pb isotopes

Sr–Nd–Pb isotope analyses were conducted at the Isotope Laboratory of the TGSC using a Triton thermal ionizer (Perkin Elmer, Waltham, Massachusetts, USA). The accuracy of the analysis was better than 0.002%. The dissolution of the sample was conducted using acid digestion, employing a solution of hydrofluoric acid, perchloric acid, and nitric acid. The separation of Rb and Sr was conducted using AG50W × 12 strongly acidic cation exchange resins. Nd and Pb were separated and purified by using a HEHEHP resin (P507) and a Sr-specific resin, respectively. The isotope measurements of the background were conducted with a margin of error that was within the acceptable range. The results of the analyses conducted on the international standard sample BCR-2 are presented below: $^{143}Nd/^{144}Nd$ = 0.512630 ± 4 (2σ), $^{87}Sr/^{86}Sr$ = 0.704985 ± 7 (2σ), $^{206}Pb/^{204}Pb$ = 18.7472 ± 0.0016 (2σ), $^{207}Pb/^{204}Pb$ = 15.6244 ± 0.0016 (2σ), and $^{208}Pb/^{204}Pb$ = 38.7269 ± 0.0056 (2σ).

3.4. Whole-rock geochemistry

A total of 27 samples were subjected to analysis for major and trace elements at the TGSC, with all results presented in Table 3. Firstly, all weathered surfaces were removed, leaving behind only the fresh parts of each sample. These were then individually crushed and ground to powder (less than 200 mesh) by a ball mill, in order to analyse the major and trace elements. The major elements were quantified by X-ray fluorescence (XRF), while the proportion of FeO was determined by the

volumetric method, which involved the use of hydrofluoric acid-sulfuric acid solution and potassium dichromate titration. The degree of accuracy achieved in the analyses was better than 2%. The analysis of trace elements was conducted using ICP-MS, which has an analysis accuracy of better than 5%. The detailed analytical procedures are outlined in Gao et al. (2003).

4. Analytical results

4.1. Zircon and titanite U–Pb geochronology

4.1.1. Zircon U–Pb geochronology

Zircon grains that were free of cracks, inclusions, and exhibited euhedral crystal shapes were selected for U–Pb analysis via LA-ICP-MS. The full set of results is presented in Table 1.

The majority of zircon grains from the examined samples exhibited well-developed automorphism, and elongated columnar shapes. However, some of the grains were relatively short and stunted in morphology. The long axes of the zircon grains ranged from 150 to 300 μm, with length/width ratios between 1.5 and 4. As illustrated in Fig. 3, CL images reveal an oscillatory structure, which is characteristic of magmatic zircon. The Th/U ratios of all zircons range from 0.24 to 2.04, which is indicative of a magmatic origin.

A total of nine analyses were obtained from southern high-Mg diorite sample Tw0044 (Fig. 3a). The $^{206}Pb/^{238}U$ spot ages exhibited a high degree of consistency, with a range of 281 ± 3 to 287 ± 3 Ma. The concordia age of the nine zircons at the

95% concordance level is 284.8 ± 0.96 Ma (MSWD = 0.088). The weighted mean $^{206}Pb/^{238}U$ age of 18 zircons from the northern high-Mg diorite sample Tw0032 is 265.8 ± 2.6 Ma (MSWD = 3.1) (Fig. 3b). Twenty-four zircon analyses from quartz diorite sample Tw0034 yielded $^{206}Pb/^{238}U$ ages ranging between 273 and 280 Ma, with a concordia age of 276.3 ± 0.58 Ma (Fig. 3c). The $^{206}Pb/^{238}U$ ages of the zircon grains in quartz diorite Tw0041 lie predominantly within the range 274–284 Ma. All ages are plotted on the concordia curve, and the concordia age of the 22 zircon grains is 276.7 ± 0.72 Ma (MSWD = 0.78) (Fig. 3d).

4.1.2. Titanite U–Pb geochronology

Backscattered electron images demonstrate that the majority of titanite grains from the examined samples are euhedral, wedge-shaped, and occur in association with hornblende (Fig. 4a). The long axis of the titanite grains range from 50 to 200 μm, with length/width ratios spanning from 1.5 to 3. The lower intersection point of the spot analyses from 33 titanite grains in high-Mg diorite sample Tw0044 is 282.8 ± 2.0 Ma (MSWD = 4.3) (Fig. 4b).

4.2. Major and trace elements

Major and trace element data for nine representative samples of the southern high-Mg diorite and northern high-Mg diorite, and eight samples of quartz diorite, are presented in Table 3. The samples display sub-alkaline geochemical characteristics (Fig. 5a).

The high-Mg diorite samples display intermediate SiO_2 (51.5–54.6 wt. %), TiO_2 (0.62–0.93 wt. %), Al_2O_3 (12.2–15.2 wt. %) and total alkali (Na_2O+K_2O = 2.5–2.9 wt. %) contents, indicative of compositions characteristic of intermediate rocks. The samples record a high Na_2O content, with Na_2O/K_2O ratios ranging from 2.1 to 4.9. In the SiO_2 versus K_2O diagram, the high-Mg diorites display high-K to calc-alkaline characteristics (Fig. 5b). These rocks have high MgO contents (8.3–10.4 wt. %), with $Mg^{\#}$ values of 67.3–72.9, and they are situated within the domain of high-Mg andesite (HMA) (Fig. 5c; McCarro and Smellie, 1998). The SiO_2 versus FeO^T/MgO diagram (Fig. 5d) illustrates a low-iron calc-alkaline series (LF-CA), which further conforms to the definition of high-Mg diorite.

All high-Mg diorite samples exhibit low total rare-earth element (ΣREE) contents, with mean values in the range 72.4–90.5 ppm. Additionally, there is an enrichment of light rare earth elements (LREE) relative to heavy rare earth elements (HREE), with LREE/HREE of 4.7–6.3. The REE patterns of these samples are moderately fractionated ($(La/Yb)_N$ = 4.8–7.4), with slight Eu anomalies (δEu = 0.9–1.2) (Fig. 6a). The samples display relatively high $Mg^{\#}$ (67.3–72.9), Cr (314–785 ppm) and Ni (54–122 ppm) contents (Table 3), indicative of a primitive melt composition.

In comparison to the high-Mg diorite samples, the quartz diorite samples display higher SiO_2 (54.5–56.0 wt. %), Al_2O_3 (18.7–19.3 wt. %) and total alkali ($Na_2O + K_2O$ = 5.1–5.4 wt. %) contents. The samples also exhibit relatively low MgO (3.9–4.2 wt. %), $Mg^{\#}$ (51.3–53.0), Cr (18–49 ppm), and Ni (6–15 ppm), which plot in the field of

andesite (Fig. 5c). The quartz diorite samples display an enrichment in LREEs relative to HREEs with $(La/Yb)_N$ ratios of 6.8–9.7 with weak positive Eu anomalies (Eu/Eu* = 1.0–1.3) (Fig. 6c). The quartz diorite samples display comparable characteristics to those of the high-Mg diorites on a N-MORB-normalized multi-element diagram, exhibiting enrichment in Cs, Ba, Th, K, Pb and depletion in Nb, Ta and Ti (Fig. 6b, d). It is noteworthy that both the high-Mg diorite and quartz diorite plutons exhibit compositional similarities with the bulk continental crust (Fig. 6b, d).

4.3. Zircon Hf isotopes

Representative zircon samples from the northern high-Mg diorite (sample 0044-1), southern high-Mg diorite (sample 0032-1) and quartz diorite (sample 0034-1 and 0041-1) were collected for in situ multicollector ICP-MS Hf isotope analysis (Table 4). The measured $^{176}Lu/^{177}Hf$ ratios are all less than 0.02 (0.0002–0.0061), indicating that very little radioactive zircon Hf accumulated after its formation.

Nine analyses of zircon grains from the southern high-Mg diorite (0044-1) yielded negative $\varepsilon_{Hf}(t)$ values ranging from −10.06 to −4.36 (with an average of –6.79) (Fig. 7a), and corresponding Hf model ages of 1326–1093 Ma (Fig. 8). A total of 16 zircon grains from the northern high-Mg diorite pluton (0032-1) were analyzed for their Lu–Hf isotopic compositions. The resulting data exhibited a considerable range in $\varepsilon_{Hf}(t)$ values from −3.85 to +5.28 (Fig. 8b), and Hf model ages of 1021–738 Ma (Fig. 8). Sixteen analyses of the quartz diorite (sample 0034-1) zircons yielded $\varepsilon_{Hf}(t)$ values of between −15.4 and −3.7 (with an average of –8.1) (Fig. 7c), with Hf

model ages of between 1604 and 1061 Ma. Sixteen analyses zircon in quartz diorite sample 0041-1 yielded similar $\varepsilon_{Hf}(t)$ values of −20.1 to −12.4 (average – 16.7) (Fig. 7d) and Hf model ages of 1704–1399 Ma. Overall, the Hf isotopic compositions are distinguishable between the high-Mg diorite and quartz diorite samples.

4.4. Sr–Nd–Pb isotopes

Sr–Nd–Pb isotopic data for 13 samples of the high-Mg diorites and quartz diorites are presented in Table 5 and illustrated in Fig. 9. The $f_{Sm/Nd}$ values are situated between −0.6 and −0.2, indicating an absence of discernible differentiation between the high-Mg diorite and quartz diorite.

The southern high-Mg diorite samples (0044-1) and the quartz diorite samples (0034-1) exhibit comparable Sr–Nd isotopic compositions, with $(^{87}Sr/^{86}Sr)_i$ values ranging from 0.706082 to 0.706311 and 0.706415 to 0.706442, respectively. Additionally, they display similar $\varepsilon_{Nd}(t)$ values, spanning from −9.5 to −8.4 (Fig. 9a). Their T_{DM} ages range from 2974 to 1967 Ma. The northern high-Mg diorite samples also exhibit elevated $(^{87}Sr/^{86}Sr)_i$ values of 0.706000–0.706611, elevated $\varepsilon_{Nd}(t)$ values of −7.8 to −6.0, and Nd model ages (T_{DM}) of 2811–2007 Ma. The quartz diorite samples (0041-1) exhibit elevated $(^{87}Sr/^{86}Sr)_i$ values of 0.707350–0.707464, negative $\varepsilon_{Nd}(t)$ values of −13.2 to −12.8, and older T_{DM} ages of 2154–2084 Ma. In general, all samples can plot within the field of mafic lower crust rocks in NCC (Fig. 9b). However, the northern high-Mg diorite samples (0032-1) display elevated $\varepsilon_{Nd}(t)$ values in comparison to the Carboniferous–Permian intrusive rocks observed along

the northern margin of the NCC (Fig. 9; Zhang et al., 2016), with the former located near the field of the SCLM beneath the northern NCC during the Early Permian.

The Pb isotopic compositions of the northern high-Mg diorite samples (0032) demonstrate a degree of variability, exhibiting ranges of 17.869–17.923 for $^{206}Pb/^{204}Pb$, 15.530–15.553 for $^{207}Pb/^{204}Pb$, and 38.090–38.129 for $^{208}Pb/^{204}Pb$. These values are plotted between the orogen and mantle curves in Fig. 9c and between the mantle and lower crust curves in Fig. 9d. The values for the southern high-Mg diorite samples (0044) exhibit ranges of 18.015–18.131, 15.523–15.498, and 38.027–38.159 for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ respectively. These values are between the orogen and mantle curves (Fig. 9c), and also plot between the mantle and lower crust curves in Fig. 9d.

4.5. Mineral Compositions

4.5.1. Plagioclase

Plagioclase present in the high-Mg diorites displays a considerable range of compositions (Fig. 10), with An [=Ca/(Ca + Na+ K)] contents varying between 29 and 82 (Table S1; Fig. 11). These plagioclases can be classified into two distinct groups: (1) high-An cores (Fig. 10 and Fig. 11) and (2) low-An rims (Fig. 10 and Fig. 11). The high-An cores are bytownite (An_{72} to An_{82}), while the majority of the low-An rims are andesine (An_{29} to An_{51}). The majority of the calcic cores in sample 0032-1 are simply zoned, typically comprising a flat or normally zoned core (Fig. 11c-d). However, a small proportion of the calcic cores in sample 0032-1 and majority of

those in sample 0044-1 contain multiple internal resorbed surfaces and patchy zoning (Fig.11a-b). Both types of cores are mantled by a normally zoned or flat rim (Fig.11). The transition between the cores and rims is marked by a pronounced decrease in An content, ranging from 40 to 50 over a scale of approximately 2 μm (Fig.11). This is corroborated by the distinct boundaries observed between the bright BSE images of the cores and the dark rims (Fig.11).

4.5.2. Hornblende

Hornblende from high-Mg diorite samples 0044-1 and 0032-1 exhibits a restricted range of composition, lying predominantly within the magnesiohornblende field as defined by Leake et al. (1997). However, one analysis from 0032-1 falls within the field of tschermakite (Fig.12). The hornblende from the southern high-Mg diorite samples (0044) displays a greater enrichment in MgO (14.2–17.2 wt. %), Cr_2O_3 (0.028–1.606 wt. %), and SiO_2 (47.5–54.1 wt. %) than the hornblende from the northern samples. The northern high-Mg diorite samples (0032-1) display MgO, Cr_2O_3, and SiO_2 contents of 11.4–15.0 wt. %, 0.002–1.040 wt. %, and 44.4–50.2 wt. %, respectively (Table S2).

5. Discussion

5.1. Origin of calcic plagioclase cores

The An content of plagioclase in the Xinhure high-Mg diorites shows abrupt variations from core to rim zones (Fig. 11). However, variations in element

concentrations in plagioclase can form due to either variations in melt composition or intracrystal diffusional relaxation of previously formed gradients (Bezard et al., 2017; Ginibre and Wörner, 2007). Therefore, prior to utilising plagioclase for fingerprinting magma chemistry, it is essential to consider the impact of diffusion processes.

It is possible that post-crystallisation diffusion may have resulted in modifications or partial homogenisation of the element compositions of neighbouring crystal domains. The diffusion coefficients of elements are strongly dependent on plagioclase composition (Giletti and Casserly, 1994). In particular, paired CaAl–NaSi diffusion exchange is relatively slow within the plagioclase crystal structure (Liu and Yund, 1992), ~~and the concentrations of these elements are unlikely to have been modified during magma evolution~~. This is consistent with the significant and abrupt changes in the An% observed between the core and rim zones (Fig. 11). The experimental data indicate that K and Mg diffuse at a considerably faster rate (Giletti and Shanahan, 1997; Van Orman et al., 2014). The K_2O gradients between the core and rim zones are expected to be approximately similar. However, the preservation of sharp K_2O gradients between the core and rim zones (Table S1) demonstrates that negligible diffusion has occurred between the domains (Shane et al., 2019).

Therefore, steep gradients in slowly diffusing elements (Si, Na, Ca, and Al) indicate a change in magma composition, rather than recording diffusional processes, and can be employed to track the growth conditions of the crystals. Furthermore, given that such elements require a considerable length of time to re-equilibrate with their host magma, they can provide information about magma mixing processes. The

diffusion rate associated with NaSi–CaAl exchange in volcanic plagioclase is exceedingly slow (Liu and Yund, 1992), which allows for the common preservation of zoning patterns in An%, Na, Si, Ca and Al content (Fig. 13). These patterns may be assumed to represent magmatic conditions at the time of their formation (Coote and Shane, 2016). The presence of calcic cores (An% >72) in the plagioclase grains in the Xinhure high-Mg diorite gives rise to the question of whether these calcic zones are in equilibrium with the host diorites or have been introduced from a more mafic source (Izbekov et al., 2002).

Calcic plagioclase cores in the Xinhure high-Mg diorites are commonly resorbed (Fig. 13). Such resorption textures observed in plagioclase are typically attributed to magma mixing (Tsuchiyama, 1985) or magmatic decompression (Nelson and Montana, 1992). The plagioclase crystals studied here exhibit a pronounced decline in An contents (Fig. 11), which is thought to have resulted from reaction with a colder or more acidic magma. However, when an H_2O-undersaturated magma ascends rapidly through the crust during decompression, the $P(H_2O)$ of the system increases, reducing the stability of plagioclase and causing dissolution (Pietraniksup and Waight, 2008). It is noteworthy that remarkably similar textures of high An% and resorbed or patchy-zoned plagioclase cores surrounded by lower An rims have been observed in other terrains worldwide (e.g., Humphreys et al., 2006; Pietraniksup and Waight, 2008; Waight and Tørnqvist, 2018) and have been attributed to decompression-induced resorption (Waight and Tørnqvist, 2018). It can therefore be posited that the high-An % plagioclase cores initially crystallized in deep-seated mafic magmatic systems

426 within the crust. The formation of their resorption textures is thought to have occurred
427 during a period of rapid ascent and mixing between melt fractions (e.g., Waight and
428 Tørnqvist, 2018). It is probable that these crystals were entrained by ascending melts
429 (Davidson et al., 2007; Humphreys et al., 2006) and transported rapidly to a relatively
430 shallow magma chamber, where decompression led to plagioclase resorption (e.g.,
431 Annen et al., 2006; Humphreys et al., 2006; Pietranik and Waight, 2008; Waight and
432 Tørnqvist, 2018).

433 5.2. Petrogenesis of the high-Mg diorites

434 HMA can be further subdivided into adakitic HMA, bajaite, boninite, and sanukite
435 (sanukitoid) based on their geochemical characteristics (Kamei et al., 2004). The
436 following observations indicate that the Xinhure high-Mg diorites represent a typical
437 sanukitoid. (1) Adakitic HMA is formed through the assimilation of mantle peridotite
438 by slab-derived melts (Kelemen, 1995), which are characterised by high Sr and low
439 Yb and Y concentrations, and high La/Yb and Sr/Y ratios. The Xinhure high-Mg
440 diorites do not exhibit these characteristics and plot within the arc magmatic field in a
441 Sr/Y–Y diagram (Fig.15a). (2) Bajaites are a rare type of rock, generally considered to
442 be formed by an unbalanced reaction between mantle peridotite and Si-rich melt
443 derived from partially melted subducting plates (Rogers et al. 1985). The trace
444 element characteristics of bajaitic HMA and adakitic HMA are similar (Zhang et al.,
445 2005), and their genesis is analogous to that of adakite (Drummond and Defant 1990).
446 Furthermore, bajaites are distinguished by elevated concentrations of Ba (208–2300

ppm; mean ~1237 ppm) and Sr (506–3800 ppm), as well as elevated Sr/Y ratios (46–506) (Tang and Wang, 2010). However, the Xinhure high-Mg diorites exhibit considerably lower concentrations of both Ba (200–403 ppm) and Sr (310–512 ppm). (3) Boninite is the product of early intra-oceanic subduction. In accordance with the International Union of Geological Sciences classification system, boninites are defined as having a SiO_2 content exceeding 52 wt. %, MgO concentration above 8 wt. %, and TiO_2 concentration below 0.5 wt. % (Tang and Wang, 2010; Bas, 2000). The low TiO_2 concentrations are of particular significance in differentiating these from other types of HMA. Indeed, the Xinhure high-Mg diorites exhibit TiO_2 concentration of 0.62–0.93 wt. %, which is distinct from that observed in boninites. (4) The data for the Xinhure high-Mg diorites predominantly fall within the typical sanukite area in discrimination diagrams (Fig. 14). Accordingly, the Xinhure high-Mg diorites are classified as sanukitoids, characterised by a high MgO/TiO_2 ratio (9.0~16.6) and low SiO_2, high Y, high Mg, high Cr and high Ba+Sr contents. This further supports the inference that they are low-Ti sanukitic HMA. Moreover, the characteristics of the high-Mg diorites presented in this paper are consistent with the initial definition of sanukitoids proposed by Shirey and Hanson (1984). This definition includes the following criteria: $Mg^{\#} > 60$, Ni and Cr > 100 ppm, enrichment in LREE, and no or weak Eu anomaly.

Three main models have been proposed to explain the petrogenesis of sanukitic HMA: (1) direct partial melting of an enriched mantle peridotite (Tatsumi et al., 2002, 2003; Mitchell and Grove, 2015); (2) interaction between subducted slab melt with

mantle peridotite (Rappet al., 2010; Moyen et al., 2003; Tsuchiya et al., 2005); (3) and delamination and partial melting of thickened eclogite-facies lower crust, with the resulting melt reacting with the mantle during ascent (Gao et al., 2004, 2006; Streck et al., 2007; Xu et al., 2008, 2009; Huang et al., 2008; Tiepolo et al., 2011).

Given the following observations, it can be posited that the Xinhure high-Mg diorites are the result of interaction between slab-derived fluids or subducting sediment-derived fluids and mantle peridotite. The southern (0044-1) and northern (0032-1) Xinhure high-Mg diorites yield $\varepsilon_{Hf}(t)$ values of between −10.1 and −4.1 and between −6.0 and +5.3, respectively. These values are both lower than those of typical HMAs formed by direct melting of enriched mantle peridotite (Wood and Turner, 2009). The Nd-Hf isotopic compositions of the high-Mg diorites are decoupled, and it is probable that this is due to the inheritance of mantle-derived material with decoupled Nd-Hf isotopic compositions (Xie et al., 2020; Pang et al., 2021; Hao et al., 2022; Sun et al., 2024). This hypothesis suggests that the decoupled compositions are inherited from the interaction between fluids and the lithospheric mantle. The former are characterised by high Nd/Hf ratios, which are derived from subducting sediments or slab (Chauvel et al., 2009; Xie et al., 2020). This is due to the fact that Hf is generally less mobile in slab-derived fluids than Nd, leading to the re-enrichment of the Nd isotope. Consequently, the addition of fluids derived from subducted sediments or oceanic crust to the mantle wedge would result in melts that are typified by elevated ε_{Hf} and diminished ε_{Nd}, indicative of the decoupling of ε_{Nd} and ε_{Hf} (Chauvel et al., 2009; Xie et al., 2020). The extracted zircon from both suites displays

491 elevated U and Th concentrations relative to those observed in enriched mantle
492 peridotites, accompanied by high U/Yb ratios that are most similar to those observed
493 in zircon formed within continental crust. For example, samples of southern high-Mg
494 diorite yield Th/Yb ratios of 2.3–2.9 (Fig.15d), which is consistent with the addition
495 of subducted sediment, which has Th/Yb ratios of >2. The Xinhure high-Mg diorite is
496 of mantle origin; however, Pb isotope data indicate that its mantle source region is
497 significantly contaminated by crustal components, reflecting the recycling of crustal
498 Pb through the subduction of sediments (Fig. 9c and 9d). The entry of crustal Pb into
499 the high-Mg diorite mantle source occurs through fluid metasomatism. Furthermore,
500 the geochemical signatures of subducted sediment-derived fluids/melts and slab fluids
501 are discernible in the Ba/Th–$(La/Sm)_N$ and Ba/La–Th/Yb diagrams (Fig. 15bcd)
502 (Tatsumi, 2006). All high-Mg diorite samples plot within the supposed range for
503 mantle-derived melt (Fig.15e), and are consistent with the melting curve of spinel
504 peridotite (Fig.15f). Therefore, the Xinhure high-Mg diorites may have formed by
505 interactions between subducted sediment-derived fluids and mantle peridotite.

506 The crystallisation of olivine and pyroxene is the initial stage of mineral
507 formation in primitive water-saturated magmas (Grove et al., 2003). In the case of
508 basaltic magma derived from enriched mantle, high-Mg minerals are first separated
509 during fractional crystallization in the upper mantle/lower crust (Alonso-Perez et al.,
510 2009). This residual basaltic-andesitic magma then gradually becomes increasingly
511 water-rich during continued ascent, allowing hornblende to form. This mechanism is
512 thought to have permitted the formation of significant quantities of hornblende in the

513 samples from Xinhure. Additionally, the formation of substantial quantities of
514 hornblende causes an increase in the density of the magma, due to an increase in
515 crystallinity by approximately 40% (Barclay et al., 2004). Once the hornblende-rich
516 melt has formed in the lower crust, further ascent becomes highly challenging, leading
517 to a pronounced decline in the volume of ascending HMA magma. Consequently, the
518 volume of the Xinhure high-Mg diorites is notably constrained.

519 The plagioclase in the northern and southern high-Mg diorites exhibits a
520 considerable range of compositions, spanning from An_{29} to An_{82} (Table 6; Fig. 11).
521 Both samples display an abrupt transition between the cores and rims, with a decrease
522 of 40 to 50 mol.% An over a length scale of ~2 μm. This transition cannot be
523 attributed to source metasomatism and is interpreted to have resulted from a change in
524 melt composition. In addition to source metasomatism, the high-Mg diorite melt also
525 exhibited evidence of magma mixing.

526 In consideration of the aforementioned data, it can be concluded that the Xinhure
527 high-Mg diorites are of mantle origin, having ascended to the crust and subsequently
528 mixed with the crust-derived melt (Fig.16). An initial parental magma was formed at a
529 considerable depth by partial melting of enriched SCLM, which was altered by
530 metasomatism of subducted sediment-derived fluids. Following an initial period of
531 ascent, the magma experienced mixing and underwent various degrees of chemical
532 exchanges with continental crust-derived melt, prior to complete solidification. The
533 volume of the southern Xinhure high-Mg diorites that are exposed is very small. This
534 suggests that magma dispersed into various structurally controlled channels (e.g.

dikes) upon entering the brittle, shallow crust.

5.3. Tectonic evolution of the PAO subduction

HMAs (including adakitic HMAs, bajaites, boninites and sanukitoids) can form in a variety of tectonic settings. These include continental rifts, although this phenomenon is rare (e.g. Brown and Jenner, 1989), as well as intra-plate and convergent plate boundaries, which represent the majority of cases (e.g. Kay, 1978; Tatsumi and Hanyu, 2003). In general, most HMAs are associated with the subduction of young oceanic plates.

While there is still some debate concerning the specific processes that lead to the formation of sanukitoid-like high-Mg andesites and diorites, there is a relatively good understanding of the mechanisms behind the formation of sanukitoids. These mainly originate at convergent plate margins associated with the subduction of oceanic crust (Stern et al., 1989; Tatsumi, 2006; Heilimo et al., 2010; Martin et al., 2010). The subduction of oceanic crust and associated sediments adds considerable volumes of fluid (or melt) into the mantle wedge (Palin and White, 2016). This may result in the enrichment and metasomatism of the mantle, which could lead to a significant enrichment of large ion lithophile elements and a depletion of high field strength elements in derivative magmas. The new data demonstrate that the mantle source domain of the Xinhure high-Mg diorites underwent enrichment and metasomatism as a result of the subduction of marine sediment and associated melting. This also reflects a close correlation between the diagenetic background and oceanic crust

556 subduction. Nevertheless, partial melting of enriched lithospheric mantle above
557 subduction zone environments still necessitates the presence of elevated thermal
558 gradients. It has been demonstrated in related studies that anomalous high
559 temperatures in such environments may be associated with the subduction of oceanic
560 ridges (Tatsumi, 2006; Martin et al., 2010). Additionally, certain tectonic conditions
561 that occur during the final stages of oceanic crust subduction, leading to terrane
562 collision, may also be a contributing factor (Stern et al., 1989; Zhang et al., 2005;
563 Chiaradia et al., 2014). For example, the processes of subducted slab break-off, plate
564 roll-back and lithosphere delamination are all observed to occur at the end of plate
565 subduction (Heilimo et al., 2010; Laurent et al., 2014; Xiong et al, 2014). The
566 Permian magmatic rocks in the northern margin of the NCC display spatio-temporal
567 distribution and migration characteristics resulting from changes in subduction angle
568 over time, likely associated with a changing age of oceanic lithosphere entering the
569 trench. These characteristics lend support to the plate roll-back model (Zhang et al.,
570 2021), which is able to provide an explanation for the linear distribution of the
571 Permian magmatic rocks. The plate roll-back model is further supported by the spatio-
572 temporal distribution of high-Mg diorites in the Xinhure area, with Early Permian
573 diorites distributed in the south and Middle Permian diorites distributed in the north.
574 The southward subducting slab undergoes backward migration into the asthenospheric
575 mantle (roll-back), which leads to the upwelling of hot asthenospheric mantle and
576 decompression of enrichment mantle melting.

577 Based on other analyses of Permian magmatic rocks in the northern margin of the

NCC, we argue that the genesis of the Early Permian Xinhure high-Mg diorites (sample 0044-1) was not attributable to lithospheric delamination, but rather to the slab roll-back of the PAO. Lithospheric delamination can result in partial melting of thickened eclogite-facies continental crust, with the resulting melt potentially interacting with mantle peridotite to form high $Mg^{\#}$ and high Cr magmatic rocks (Rapp and Watson, 1995; Rapp et al., 1999; Xiong et al., 2014). However, this type of magma often exhibits geochemical characteristics that are indicative of high Sr, low Y, and low Yb (i.e. adakitic), and they often crystallise minerals in a reverse banded structure (Kamei et al., 2004; Tatsumi, 2006). This is significantly different from the geochemical and petrographic characteristics of the Xinhure high-Mg diorites in the northern margin of the NCC. Additionally, research on the genesis of intermediate-acidic intrusive rock suites dating to approximately 291–280 Ma also indicates the presence of significant continental arc magmatism in the Zhaojinggou area of the western segment of the northern NCC (Zhang et al., 2021).

The southward subduction of the eastern segment of the PAO in the southern CAOB was a continuous process until at least Carboniferous and probably lasted until the Early Permian (>~280 Ma). This inference is supported by the presence of Carboniferous and Early Permian calc-alkaline arc-related magmatic rocks in the region, including ~357–353 Ma Dahuabei pluton (Zhang et al., 2023), ~330–345 Ma diorite from Siziwangqi county (Chen et al., 2017), ~305 Ma tuff from the Daqingshan area (Zhang et al., 2018), ~280 Ma quartz diorite from the Wuchuan County (Yuan and Wang, 2006), and ~280–243.2 Ma A_2 type post-collisional

granitoids from the Bayan Obo area (Ling et al., 2014).

When considered collectively, the 284 Ma and 265 Ma Xinhure high-Mg diorites are deemed to have formed during the late stage of southward subduction of the PAO, with substantial quantities of crustal sediments being involved at greater depth beneath the north margin of the NCC. Nevertheless, partial melting of the enriched lithospheric mantle at a convergent margin necessitates an anomalously high temperature and dynamic environment. It is proposed that slab roll-back may have permitted asthenospheric upwelling with accompanying partial melting of the SCLM at approximately 280 Ma (Zhang et al., 2021). As a result of the increase in subduction angle and geothermal gradient, the oceanic slab underwent dehydration, leading to the generation of sediment-derived fluids with enriched Nd isotopic compositions and LILE-rich slab-derived fluids. A proportion of the sediment-derived or slab-derived fluid ascended and interacted with the overlying SCLM, resulting in modification of the latter to become a metasomatic SCLM with enriched elemental and isotopic signatures, which were superimposed by the metasomatic agents (Fig.16). Subsequently, partial melting of the metasomatized SCLM resulted in the formation of gabbroic to dioritic melts with high $Mg^{\#}$ values (72.5–72.9), high LILE contents, and elevated $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values in the Xinhure area. The $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values of the Xinhure high-Mg diorites exhibit a range of between −9.5 and −6.1 and between −10.1 and +5.3, respectively. These values are higher than those of contemporaneous quartz diorites (samples 0034 and 0041), which have values of −13.2 to −12.8 and −20.1 to −12.4, respectively.

6. Conclusions

The southern and northern Xinhure high-Mg diorites from the northern margin of the NCC formed at 284 Ma and 265 Ma, respectively. The petrology, bulk-rock geochemistry, Sr–Nd–Pb isotopes, as well as zircon Hf isotopes and mineral compositions collectively indicate that the Xinhure high-Mg diorites from the northern margin of the NCC are geochemically similar to the sanukitoids of the Setouchi Volcanic Belt in southwest Japan. They were generated by partial melting of enriched mantle during the slab roll-back stage of the southward-subducting PAO. Both the Early Permian and Middle Permian high-Mg diorite samples display a relatively enriched radiogenic isotopic composition, characterised by elevated initial $^{87}Sr/^{86}Sr$ ratios (0.7061–0.7063 and 0.7060–0.7066, respectively), negative $\varepsilon_{Nd}(t)$ values (−9.5 to −8.4 and −7.8 to −6.1, respectively) and broad ranges in zircon $\varepsilon_{Hf}(t)$ values (−10.1 to −4.1 and −6.0 to +5.3, respectively). The Nd-Hf isotopic compositions of the high-Mg diorites are decoupled as a consequence of the interaction between subducting sediment-derived fluids and mantle peridotite.

Major element traverses of zoned plagioclase and hornblende phenocrysts document two principal stages of formation. The initial stage is characterized by calcic plagioclase cores with high-An (An_{72} to An_{82}) and high-$Mg^{\#}$ hornblende with elevated Cr and Ni contents, which are associated with partial melting of enriched SCLM. The initial crystallization products of primitive mantle-derived magmas preserved in the lower crust are composed of high-$Mg^{\#}$ amphibole and plagioclase, which are important components. The amphibole represents the product of early

fractional crystallization in the evolution of a water-rich magmatic system. The second stage is recorded by low-An (An_{29} to An_{51}) plagioclase rims, which are believed to be the result of the melts mixing of mantle-derived high-Mg melt with crustal-derived magma. These data also provide new evidence regarding the duration of subduction of Late Paleozoic PAO oceanic crust along the northern margin of the NCC.

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Figure Captions

Fig. 1 (a) Simplified tectonic map of the Central Asian Orogenic Belt (modified after Jahn et al., 2000). (b) Geological sketch map of the Xinhure area in the Urad Zhongqi, Inner Mongolia

Fig.2 Field photographs and photomicrographs of the high-Mg diorites in the Xinhure area, Inner Mongolia. (a) southern high-Mg diorite (0044-1), (b) northern high-Mg diorite (0032-1), (c) photomicrograph of 0044-1, (d) photomicrograph of 0032-1, (e) photomicrograph of 0034-1, (f) photomicrograph of 0041-1. Abbreviations: Hbl, hornblende; Pl, plagioclase; Bi, biotite

Fig. 3 Zircon laser ablation inductively coupled plasma mass spectrometry U–Pb concordia diagrams for the

southern high-Mg diorite (0044-1), northern high-Mg diorite (0032-1), and quartz diorite (0034, 0041). MSWD, mean square weighted deviation.

Fig. 4 (a) BSE image of Tw0044, (b) LA-ICP-MS U–Pb dating results of titanite Tw0044. BSE: backscattered electron image

Fig. 5 Major element diagrams for the Xinhure high-Mg diorites. (a) Total alkalis versus SiO_2 diagram (after Middlemost, 1989), (b) K_2O versus SiO_2 diagram (after Peccerillo & Taylor, 1976), (c) MgO versus SiO_2 diagram, (d) FeO^T/MgO versus SiO_2 diagram. Literature data referenced from Shimoda et al. (1998), Tatsumi et al. (2003), Kamei et al. (2004), Yuan et al. (2016).

Fig.6 (a, c) Chondrite-normalized rare earth element patterns and (b, d) primitive mantle-normalized trace element spider diagrams. The chondrite and N-MORB values used for normalization are from Sun and McDonough (1989)

Fig. 7 Frequency distributions of zircon $\varepsilon_{Hf}(t)$ values of high Mg-diorite and quartz diorite in the Xinhure area

Fig. 8 Diagram of $\varepsilon_{Hf}(t)$ vs. zircon U–Pb age for high-Mg diorite and quartz diorite of the Xinhure area. Purple data are Hf isotopic compositions of zircons from Carboniferous–Permian intrusive rocks on the northern margin of the NCC (Zhang et al., 2016).

Fig. 9 Sr–Nd–Pb isotopic compositions of the high-Mg diorite and quartz diorite of the Xinhure area. (a) Plot of εNd(t) vs. age. (b) Plot of εNd(t) vs. ($^{87}Sr/^{86}Sr$)i. (c) $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and (d) $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$.

The Late Paleozoic intrusions in the northern margin of the NCC are referenced from Zhang et al. (2016). The SCLM beneath the NCC is approximated by xenoliths and perovskites in Paleozoic kimberlites (Yang et al., 2009 and references therein). The Archean mafic lower crust and TTG gneisses in the NCC are referenced from Griffin et al. (2002) and Chen et al. (2009), respectively.

Fig. 10 Ternary An–Ab–Or compositional end-member plot for plagioclase analyzed in this study. An: Anorthite, Ab: Albite, Or: Orthoclase

Fig.11 Representative backscattered electron (BSE) images of plagioclases in the high-Mg diorites. (a-b) Plagioclases with a partially resorbed, complexly zoned core overgrown by an oscillatory outer zone. (c-d) Plagioclases with a simple zoned calcic core, overgrown by an oscillatory outer zone. The An% profiles were measured by EMP analysis.

Fig 12 Classification diagram of hornblende (from Leake et al., 1997)

Fig.13 Phase composition mappings of the plagioclases in high-Mg diorite

Fig. 14 Discrimination diagrams for sanukitic, adakitic, boninitic and bajaitic HMA

Fig. 15 Data of the studied samples plotted on (a) Sr/Y vs. Y diagram (Tatsumi, 2006); (b) Ba/Th vs. $(La/Sm)_N$ diagram (Tatsumi, 2006); (c) $(Hf/Sm)_N$ vs. $(Ta/La)_N$ diagram; (d) Ba/La vs. Th/Yb diagram; (e) Ni vs. Cr diagram (Tsuchiya et al., 2005); (f) Gd/Yb vs. Dy/Yb diagram

Fig. 16 Schematic tectonic model for the petrogenesis of the southern high-Mg diorites (a) and northern high-Mg

diorites (b) in the northern margin of the NCC during the Early-Middle Permian. During the slab roll-back of the PAO beneath the NCC (ca. 285 Ma), the front of the hydrous oceanic slab was dehydrated and generated slab-derived fluids and sedimentary melts due to the increasing geothermal gradient. Slab-derived fluids and sedimentary melts metasomatized the SCLM, leading to partial melting of the enriched SCLM to produce mafic magma. The mantle-derived mafic magma rose to the continental crust, and mixed with andesitic magma in such tectonic settings.