Geochemistry of the Mesoproterozoic Intrusions, Geochronology and Isotopic Constraints on the Xiaonanshan Cu-Ni Deposit along the Northern Margin of the North China Craton

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ABSTRACT: Mesoproterozoic magma events in the Bayan Obo rift belt have remained poorly constrained and as a result, the Late Paleoproterozoic–Mesoproterozoic tectonic evolution of the rift belt has remained unclear. By a multiple-faceted regional geological investigation of this belt, we have resolved the stratigraphic sequence and geochronology of the Bayan Obo Group and made new discoveries including a three-stage mantle-derived magmatic sequence. Zircon and baddeleyite dating of Xiaonanshan hornblende pyroxenite emplaced into the Bayan Obo Group yields 207Pb/206Pb ages of ca. 1.34 and 1.33 Ga. The geochronological, geochemistry, Hf isotopic analyses place an important constraint on ages of the Late Paleoproterozoic–Mesoproterozoic strata and the evolution of the rift belt. Our field observations and U-Pb dating results suggest that mineralization is genetically related to Mesoproterozoic magmatism in North China Craton, i.e., 1.33–1.34 Ga. The δ44S values of sulphide from the ore-bearing ultra-mafic samples are about 6.2‰, whereas the 206Pb/208Pb, 207Pb/206Pb, and 208Pb/206Pb values vary in the ranges of 17.598–18.115, 15.496–15.501, and 37.478–37.952, respectively. The Late Paleozoic mafic gabbro and acidic granite porphyry intrusions are possible to bimodal magmatic event related to the extensional tectonic setting of the Central Asia in this period.

KEY WORDS: Bayan Obo rift belt, North China Craton, Late Paleoproterozoic–Mesoproterozoic tectonic evolution, Mesoproterozoic mineralization, Pb-S isotopic analysis.
The 1.33–1.31 Ga bimodal magmatic rocks appear to provide key evidence for the Mid-Mesoproterozoic breakup of the North China Craton from the supercontinent (Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009, 2007). Specifically, Wang et al. (2015) reported 1.23 Ga mafic dykes were likely related to continental rifting and possible breakup of the North China Craton in the transitional period between putative Columbia and Rodinia continents. Current models for Columbia configurations exclude the North China Craton or place it at the margin of the supercontinent with its paleo-position remaining controversial (e.g., Zhang et al., 2017, 2012, 2009; Wan et al., 2015; Kaur and Chaudhri, 2014; Pisarevsky et al., 2014; Zhai et al., 2014; Evans, 2013; Piper, 2013; Rogers and Santosh, 2002), mainly due to a paucity of well-established Paleoproterozoic–Mesoproterozoic geological units in the North China Craton suitable for paleogeographic reconstruction.

The anorogenic mafic rocks are the product of extensive lithospheric extension and can provide an important basis for identifying important tectonic events in the geological history (e.g., Wang J P et al., 2019; Wang S J et al., 2019; Ernst et al., 2016, 2008; Goldberg, 2010; Zhang et al., 2009; Hou et al., 2013; Rogers and Santosh, 2002), mainly due to a paucity of well-established Paleoproterozoic–Mesoproterozoic geological units in the North China Craton from the supercontinent (Zhang et al., 2017, 2012, 2009, 2007). Specifically, Wang et al. (2015) have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). The 1.33–1.31 Ga bimodal magmatic rocks appear to provide key evidence for the Mid-Mesoproterozoic breakup of the North China Craton from the supercontinent (Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013). Other researchers consider that breakup of the North China Craton from the supercontinent have occurred during the interval 1.35–1.20 Ga (e.g., Zhang et al., 2017, 2012, 2009; Li et al., 2013).
μm in depth. The ablated material was carried in helium into the Q-ICP-MS and MC-ICP-MS for simultaneous determination of U-Pb age and Hf isotopic values. Standard zircon 91500 was employed to correct for mass bias affecting 207Pb/206Pb, 206Pb/238U, 207Pb/235U, and 208Pb/232Th ratios (Ludwig, 2003). NIST SRM 610 glass was used for concentration information and the U/Th ratio determination. The fractionation correction and results were calculated using GLITTER 4.0, common Pb was corrected following the method described by Andersen (2002).

Twenty-four zircon and twenty baddeleyite grains from the Xiaonanshan hornblende pyroxenite sample (D445) were analyzed. The sample zircons are semitransparent, white subhedral prisms with a size of 100–120 μm and length/width ratio of 1.5 : 1 to 2.5 : 1 (Fig. 4a), whereas the baddeleyites are opaque or semitransparent, brown euhedral platy prisms with a size of 50–80 μm and length/width ratios of 1 : 1 to 2.5 : 1 (Fig. 4b). The analytical results are listed in Table S1 and plotted on the concordia diagrams in Figs. 4e and 4f. The zircon and baddeleyite grains exhibit high Th/U ratios and relative homogenous concentrations of Th and U (Table S1), respectively, showing no or weak oscillatory zoning in CL images (Figs. 4a and 4b). Twenty-four spots yield a weighted mean 207Pb/206Pb age of 1343±9 Ma (MSWD=0.75; Fig. 4e) which is interpreted as the crystallization age of this hornblende pyroxenite sample. The weighted mean 207Pb/206Pb age of the baddeleyite grains is 1333±14 Ma (MSWD=0.52; Fig. 4f), which is very similar to the zircon 207Pb/206Pb age obtained from the same sample reflecting the crystallization age of the Xiaonanshan hornblende pyroxenite.

Forty-four zircon grains from the Xiaonanshan gabbro sample (D181870-XNS) were analyzed, which are opaque or semitransparent, slight dark subhedral prisms with a size of 100–200 μm and length/width ratio of 1.5 : 1 to 3 : 1 (Fig. 4c). High Th/U ratios (Table S1) and weak oscillatory zoning (Fig. 4c) suggests the magmatic zircons. The forty-one spots yield a weighted mean 207Pb/206Pb age of 1331±11 Ma (MSWD=0.23, Fig. 4g), which is interpreted as the crystallization age of the gabbro. The other analyses were excluded because of discordance or low radiogenic Pb.

Twenty zircon grains from the Xiaonanshan granite porphyry sample (SHY) were analyzed, which are semitransparent or opaque, slight brown subhedral prisms with a size of 80–150 μm and length/width ratio of 1 : 1 to 2 : 1 (Fig. 4d). The weighted
mean U-Pb age of 12 concordant analyses is 271±3 Ma (MSWD=2.90), which is interpreted as the best estimate of a crystallization age of this granite porphyry sample. The age population near the upper intercept is concordant and yields a weighted mean 207Pb/206Pb age of 1798±48 Ma (MSWD=0.001, n=3; Fig. 4h), which is a possible inherited core age of this sample.

2.2 Geochemical Analyses

Bulk-rock major and trace element compositions, determined at the Chinese Academy of Geological Sciences, were obtained from igneous bodies to determine their source and tectonic setting. Complete detailed methods can be found in Dulski (1994), Norrish and Chappel (1977), and full geochemical analyses from 18 samples are summarized in Table S2.

The Jishengtai gabbro samples are characterized by high concentrations of FeO (12.40 wt.%–14.13 wt.%), CaO (9.56 wt.%–10.82 wt.%), medium concentrations of MgO (5.37 wt.%–6.94 wt.%), Al₂O₃ (13.51 wt.%–14.72 wt.%), and low contents of SiO₂ (50.21 wt.%–51.81 wt.%). The samples are plotted in the field of the gabbroic diorite on the TAS diagram (Fig. 5a). Although most of the samples fall in the field of the low-K tholeiitic series, few samples plot in the field of the tholeiitic series (Fig. 5b). The Jishengtai gabbro samples exhibit medium total rare earth element (ΣREE) values (52.07 ppm–
Figure 3. Microphotograph of the samples in the study. (a)-(c) Xiaonanshan hornblende pyroxenite; (d) granite porphyry; (e)-(f) Xiaonanshan gabbro; (g) Dajingpo gabbro; (h) Jishengtai gabbro. Noted abbreviations for different minerals: Qtz. quartz; Pl. plagioclase; Mag. magnetite; Px. Pyroxene; Hbl. hornblende; Py. pyrite; Clp. chalcopyrite. All the photomicrographs were taken under cross-polarized light.
Figure 4. Representative CL images of zircon grains and U-Pb concordia diagrams for zircons ((a), (e)) and baddeleyites ((b), (f)) from a Xiaonanshan, hornblende pyroxenite sample emplaced into the Jianshan Formation northeast to Dajingpo; ((c), (g)) Xiaonanshan gabbro and ((d), (h)) granite porphyry samples. Data-point error crosses are 2σ.
81.32 ppm) and weak enrichment in light rare earth elements (LREE) ((La/Yb)N=1.83–2.48) with no Eu anomalies (Eu/Eu*=0.93–1.00) (Table S2) (Fig. 5c). In the primitive mantle-normalised spider diagram (Fig. 5d), these rocks show moderate enrichment in high field strength elements (HFSEs; i.e., Zr and Hf) with positive Pb, Th and U but negative Nb and P anomalies.

The Longtoushan kimberlite samples have SiO₂=34.63 wt.%–35.99 wt.%, Al₂O₃=2.00 wt.%–2.19 wt.%, TiO₂=0.10 wt.%–0.11 wt.%, MgO=30.48 wt.%–34.40 wt.%, Na₂O+K₂O=0.12 wt.%–0.48 wt.% (Fig. 5a; Table S2), belonging to sub-alkaline and low-K tholeiitic series (Fig. 5b). The samples are enriched in LREEs and LILs (such as Rb, and K) as well as Pb, and depleted in LREEs and HFSEs (Figs. 5c and 5d; e.g., Nb, Ta, and Ti), with (La/Yb)N ratio and δEu value at 5.94–11.16 and 0.69–0.77, respectively, and low total REE abundances (ΣREE=26.67 ppm–30.61 ppm).

The Dajingpo gabbro samples are characterized by low SiO₂ (45.31 wt.%–52.41 wt.%), K₂O (0.14 wt.%–0.21 wt.%), and MgO (4.50 wt.%–6.30 wt.%), relatively high Na₂O (1.96 wt.%–2.42 wt.%), and Al₂O₃ (12.02 wt.%–16.30 wt.%). In a chondrite-normalized rare-earth element diagram (Fig. 5c), these rocks exhibit obviously LREE-enriched and relatively HREE-depleted patterns and positive Eu anomalies (1.10–1.60). In a primitive mantle-normalised trace element spider diagram (Fig. 5d), these rocks are enriched in Rb, Th, U, Sr and Ti, and depleted in K, Nb, Ta, and P. In contrast with the Dajingpo gabbro samples, the Xiaonanshan hornblende pyroxenite samples have low SiO₂ (43.55 wt.%–47.84 wt.%), Al₂O₃ (5.42 wt.%–8.70 wt.%), Na₂O (0.31 wt.%–1.24 wt.%), and CaO (4.97 wt.%–8.31 wt.%), relatively high MgO (13.97 wt.%–24.10 wt.%), and are depleted in Sr and Ba.

### 2.3 In-situ Zircon Hf isotopic Analyses

Zircon Hf analyses were also completed at MRL Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, using the method of Hou et al. (2007). Plesovice standard zircon was used as the reference standard (Sláma et al., 2008). The Hf isotope analysis results were reported with an error of 2σ with the mean and values of εHf(t) calculated using the method of Scherer et al. (2001). Depleted mantle model ages (TDM) were calculated based on Griffin et al. (2000). Crustal model ages (Tc) were calculated using the initial 176Hf/177Hf ratio of the zircon (Griffin et al., 2004). Full Hf...
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|      | 10 | 1311 | -1.128 | 32 | 0.024 | 0.007 | 0.007 | -1.328 | 10 | 0.008 | 0.003 | 0 | 0.283 | 0.000 | 0.004 |
analyses are shown in Table 1.

Zircons from 1.67 Ga Jishengtai gabbro show relatively higher initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and corresponding $\varepsilon_{\text{Hf}}(t)$ values range from -8.84 to 1.45 with the average is -1.67 (Zhou et al., 2018b), whereas the corresponding $T_{\text{DM}}$ model ages are 2068–2464 Ma (Fig. 6). The zircon grains with positive $\varepsilon_{\text{Hf}}(t)$ values yielded $T_{\text{DM}}$ model ages ranging of 2068–2076 Ma (Fig. 6). Zircons from ca. 1.34 Ga Dajingpo gabbro also yielded higher initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and corresponding $\varepsilon_{\text{Hf}}(t)$ values range from 2.72 to 5.48 (Zhou et al., 2018b), whereas the $T_{\text{DM}}$ model ages range from 1613 to 1716 Ma (Fig. 6).

Zircons from the Xiaonanshan hornblende pyroxenite sample D445 in this study, which yielded Pb-Pb age of ca. 1343 Ma, show relatively higher initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.281 995–0.282 158). The corresponding $\varepsilon_{\text{Hf}}(t)$ values range from -1.44 to 4.60 with the average of 2.24, whereas the corresponding $T_{\text{DM}}$ model ages are 1663–1851 Ma (Fig. 6; Table 1). One single zircon grain with negative $\varepsilon_{\text{Hf}}(t)$ values (-1.44) yielded $T_{\text{DM}}$ model age of 1914 Ma (Fig. 6; Table 1). Baddeleyites from the Xiaonanshan hornblende pyroxenite sample D445, yielded age of ca. 1333 Ma, showing relatively higher initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.281 872–0.282 427. The corresponding $\varepsilon_{\text{Hf}}(t)$ values range from -3.27 to 18.60 with the majority positive, whereas the corresponding $T_{\text{DM}}$ model ages are 146–1754 Ma (Fig. 6). Three baddeleyite grains with negative $\varepsilon_{\text{Hf}}(t)$ values (-2.62), (-3.27), (-3.04) yielded $T_{\text{DM}}$ model ages of 1907, 1892, 1925 Ma (Fig. 6; Table 1), respectively.
2.4 Sulphur and Lead Isotopic Compositions

Sulphur and lead isotopic compositions were determined at Beijing Institute of Nuclear Geological Research, China. Complete detailed methods can be found in Wu et al. (2015, 2014). The pyrite minerals collected from the Xiaonanshan hornblende pyroxenite samples were analyzed for sulphur and lead isotopic compositions. Their δ34S values are around 6.2‰, suggesting the typical of mantle sulphur. However, their δ18O values are within the ranges of 17.598–18.115, 15.496–15.501, and 37.478–37.952, respectively (Table 2).

3 DISCUSSION

3.1 Age Constraint on the Bayan Obo Group

Our new LA-ICP-MS dating on zircon and baddeleyite grains from the Xiaonanshan hornblende pyroxenite sample emplaced into the Jianshan Formation of Bayan Obo Group (Figs. 2a and 3c) yield a weighted mean 207Pb/206Pb age of 1.343 ± 0.009 Ma within error. Therefore, we infer that the Xiaonanshan hornblende pyroxenite sample is primary syn-magmatic and not inherited. We further report that the weighted mean 207Pb/206Pb age of the combined baddeleyite and zircon grains is 1.34 ± 0.07 Ma within error. Therefore, we infer that the Xiaonanshan hornblende pyroxenite within the Mesoproterozoic Bayan Obo Group sedimentary rocks were emplaced at ca. 1.34 Ga (Figs. 4a and 4b). Furthermore, the field occurrence shows the Xiaonanshan gabbro dike intrudes into the Dulahala Formation of Bayan Obo Group (Figs. 3a and 3b), which emplaced at ca. 1.33 Ga (Fig. 4c).

Recent exploratory studies on the geochronology of Mesoproterozoic strata in the Bayan Obo rift belt on the North China Craton (e.g., Zhou et al., 2019b, 2018a, 2016; Wu et al., 2018; Liu et al., 2017, 2015, 2014) yield a published geochronology of the Bayan Obo Group including depositional ages of Dulahala-Jianshan, Bilute, and Baiyinbaolage formations are summarized as follows: (1) detrital zircon U-Pb age analyses constrain the maximum depositional age of the Dulahala-Jianshan Formation as ca. 1.81 Ga (Zhou et al., 2018b), the sandstone layer was intruded by the ca. 1.67 Ga Jishengtai gabbro (Zhou et al., 2016), and the Dulahala-Jianshan Formation was deposited between ca. 1.81 and ca. 1.67 Ga; (2) detrital zircon U-Pb age analysis suggests the maximum depositional age of the Bilute Formation at ca. 1.58 Ga (Zhou et al., 2018b), and was intruded by the ca. 1.34 Ga Dajingpo gabbro (Zhou et al., 2016), and thus we suggest that the deposition period of the Bilute Formation was between ca. 1.58 and ca. 1.34 Ga; (3) Zhou et al. (2016) proposed that the lower age limit of Baiyinbaolage Formation is ca. 1.0 Ga, and Zhou et al. (2018b) proposed that the depositional interval of the Baiyinbaolage Formation ranges from ca. 1.25 to ca. 1.0 Ga. There is a relatively longer time span between the Halahuoge Formation and Bilute Formation, i.e., 200 Ma, indicating the likely the existence of unconformity.

3.2 Ore-Forming Material Source, Ages of Magmatism and Mineralization

Through field investigation and U-Pb dating results, combined with our new S and Pb isotopic tracing and whole-rock geochemistry analysis, we have demonstrated that ore sulphides of the Xiaonanshan Cu-Ni belt show the same S and Pb isotopic compositions as that of ore-bearing gabbro and hornblende pyroxenite samples. The δ18O values of pyrite minerals from our samples in this study are similar to that of magma hydrothermalism (Ohmoto and Goldhaber, 1997; Ohmoto and Rye, 1979). Their δ18O values are around 6.2‰ and are typical of mantle S (Ohmoto and Goldhaber, 1997). Our new Pb isotopic analyses are broadly consistent with the above interpretation (Table 2) (Ohmoto and Goldhaber, 1997; Ohmoto and Rye, 1979).

For the evolutionary sequence of magmatic rocks in the Xiaonanshan Cu-Ni deposit, the first concern is the intrusive age of ore-bearing magmatic rocks. The area of outcropping of gabbro is relatively large around the Xiaonanshan deposit, in contrast, outcrops of ultramafic are sporadic (e.g., Jiang et al., 2003). According to zircon U-Pb dating results of the latest gabbro, Dang et al. (2015) proposed that the Xiaonanshan Cu-Ni mineralization occurred approximately at ca. 273 Ma. However, the younger mafic gabbro and our acidic granite porphyry intrusions (Fig. 4h) are possible to bimodal magmatic event related to the Late Paleozoic extensional tectonic setting of the Central Asia. The age and isotopic composition of our ore-bearing gabbro and hornblende pyroxenite are identical within analytical error, indicating that the ultra-mafic emplacement and the Cu-Ni mineralization occurred approximately at the same time, i.e., ca. 1.330–1.340 Ma. In general, Ni mineralization is related to the ultramafic magmatic events in North China (e.g., Jiang et al., 2003), our field observations also show the evidence of Cu-Ni minerals developing within the Mesoproterozoic hornblende pyroxenite (Fig. 2c).

3.3 Tectonic Implications

The at least twice Paleoproterozoic collisional events and Late Paleoproterozoic–Mesoproterozoic accretionary events recorded in the North China Craton have been considered as one of evidences on assembly and outgrowth of the North China Craton within the Columbia supercontinent (e.g., Zhao G C et al., 2009, 2004, 2003a, b, 2002; Zhang et al., 2009; He et al., 2009; Ernst et al., 2008; Zhao T Pe et al., 2004; Fig. 7a). Most researchers agree that the North China Craton was formed by at least two Paleoproterozoic collisional events, with the earlier one forming the EW-trending khondalite belt along which the

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample description</th>
<th>Testing mineral</th>
<th>δ34S_CDT (‰)</th>
<th>206Pb/204Pb</th>
<th>207Pb/204Pb</th>
<th>208Pb/204Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>D181870-XNS</td>
<td>Gabbro</td>
<td>Pyrite</td>
<td>6.2</td>
<td>18.115</td>
<td>15.501</td>
<td>37.952</td>
</tr>
<tr>
<td>D445</td>
<td>Hornblende pyroxenite</td>
<td>Pyrite</td>
<td>6.2</td>
<td>17.598</td>
<td>15.496</td>
<td>37.478</td>
</tr>
</tbody>
</table>
Our new geochemistry analyses of the Jishengtai Hf isotopic compositions from Jishengtai gabbro (Zhou et al., 2016; Zhai et al., 2014), and is also supported by professional possibly related to the breakup of the supercontinent North China Craton probably experienced initial extensional possibly related to the breakup of the supercontinent (Zhou et al., 2018b). Further- more, the contact between the Jianshan and Halahuogete formations is parallel to the unconformity along the northern margin of the North China Craton (Jia et al., 2002) leading to our suggestion that the rift developed in the North China Craton. The later magmatic events (1.35–1.32 Ga) are characterized by bi-modal magmatism forming in an extensional tectonic setting and possibly associated with the rift process of the Columbia supercontinent (Zhang et al., 2017, 2012, 2009; Li et al., 2009b). We improve this interpretation from (1) our new geochemistry data for the Dajingpo gabbro and Xiaonanshan hornblende pyroxenite, Longtoushan kimberlite, Jishengtai and Dajingpo gabbros. Normalization values are from Sun et al. (2003) and Wang et al. (2001). Note: I. divergence margin of oceanic plate N-MORB; II. plate convergent margin (II1. oceanic island arc basalt; II2. continental margin island arc and continental margin volcanic arc basalts); III. oceanic intraplate basalt; IV. continental intraplate (IV1. intracontinental rift and epicontinental rift tholeiite basalts; IV2. continental extensional or initial rift; IV3. continent-continent collision basalt; IV4. continental rift basalt); V. mantle plume basalt.

Yinshan Block in the north and the Ordos Block in the south which amalgamated to form the Western Block at ca. 1.95 Ga and then collided with the Eastern Block along the central orogenic belt to form the coherent basement of the North China Craton at ca. 1.85 Ga (e.g., Zhou et al., 2018b; Wang et al., 2015; Zhang S H et al., 2009; Kröner et al., 2006; Xia et al., 2006; Zhao et al., 2005, 2001, 2000). The competing hypotheses consider that the collision between the Eastern and Western blocks occur at 2.5 Ga (e.g., Kusky et al., 2018, 2016; Wang et al., 2017), in addition, a new 1.9 Ga mélangé was reported as the evidence on that North China Craton became a component of the supercontinent starting at ca. 1.9 Ga (Wu et al., 2018). In any case, following final assembly at ca. 1.8 Ga, the North China Craton probably experienced initial extensional possibly related to the breakup of the supercontinent (Lu et al., 2016; Zhai et al., 2014), and is also supported by Hf isotopic compositions from Jishengtai gabbro (Zhou et al., 2018b). Our new geochemistry analyses of the Jishengtai gabbro indicate a continental intraplate tectonic setting (Figs. 7b and 7c) suggesting an intraplate extensional evolution feature during this time period.

Development of Mesoproterozoic Longtoushan kimberlite indicated that a thickness more than 150 km lithosphere existed in the Bayan Obo area during the Proterozoic Period, the North China Craton and the northern ancient craton, i.e., Siberia, had not begun to rift at ca. 1.55 Ga (Zhou et al., 2018a). Furthermore, the contact between the Jianshan and Halahuogete formations is parallel to the unconformity along the northern margin of the North China Craton (Jia et al., 2002) leading to our suggestion that the rift developed in the North China Craton. The later magmatic events (1.35–1.32 Ga) are characterized by bi-modal magmatism forming in an extensional tectonic setting and possibly associated with the rift process of the Columbia supercontinent (Zhang et al., 2017, 2012, 2009; Li et al., 2009b). We improve this interpretation from (1) our new geochemistry data for the Dajingpo gabbro and Xiaonanshan hornblende pyroxenite, and positive baddeleyite Hf isotopic values, which are characterized by isotopic compositions of depleted mantle (Fig. 6; e.g., Zhou et al., 2018b, 2016); (3) the existence of the baddeleyite within the Xiaonanshan hornblende pyroxenite suggests the characteristics of depleted mantle (Wingate and Compston, 2000). Wang et al. (2015) reported ~1.23 Ga mafic intrusions in the North China Craton and proposed that a regionally extensive and short-lived magmatic event occurred at this time within the craton.

4 CONCLUSIONS

(1) Our new zircon and baddeleyite dating on a hornblende pyroxenite sample emplaced into the Jianshan Formation yield weighted mean 206Pb/207Pb ages of 1343±9 and 1333±14 Ma, respectively, indicating that the emplacement of Xiaonanshan hornblende pyroxenite occurred at ca. 1.34 Ga. The Xiaonanshan gabbro intrudes into the Dulahala Formation, which emplaced at ca. 1.33 Ga.

(2) The age and isotopic composition of our ore-bearing gabbro and hornblende pyroxenite are identical, indicating that the ultra-/mafic emplacement and the Cu-Ni mineralization occurred at ca. 1.33–1.34 Ga. The Late Paleozoic mafic gabbro and our acidic granite porphyry intrusions are possible to bi-modal magmatic event related to the extensional tectonic setting of the Central Asia.

(3) Four stages of magmatic activities are recognized during the Late Paleoproterozoic–Mesoproterozoic in the North China Craton namely: the 1.8–1.78 Ga Xiong’er Igneous Province; 1.72–1.62 Ga anorogenic magmatism; the ca. 1.55 Ga Longtoushan kimberlite and 1.35–1.32 Ga mafic episode. The geochemistry results and Hf isotopic analysis suggest that the North China Craton and the northern ancient craton had not started rifting until ca. 1.55 Ga. The later magmatic events (1.35–1.32 Ga) are likely related to the breaking of the North China Craton away from the Columbia supercontinent.

Figure 7. (a) Comparison diagram of magmatic events during Late Paleoproterozoic–Mesoproterozoic with the Bayan Obo rift belt, North China Craton, southern Siberia Craton and northern Laurentia. Data from: Zhou et al. (2018a, 2016), Zhang et al. (2017, 2012, 2009), Ernst et al. (2016, 2008), Zhai et al. (2014), Li et al. (2013), Peng et al. (2010), He et al. (2009), Zhao T P et al. (2007). (b) Th/Hf-Ta/Hf and (c) Th/Zr-Nb/Zr identification diagrams for tectonic setting diagrams of Xiaonanshan hornblende pyroxenite, Longtoushan kimberlite, Jishengtai and Dajingpo gabbros. Normalization values are from Sun et al. (2003) and Wang et al. (2001). Note: I. divergence margin of oceanic plate N-MORB; II. plate convergent margin (II1. oceanic island arc basalt; II2. continental margin island arc and continental margin volcanic arc basalts); III. oceanic intraplate basalt; IV. continental intraplate (IV1. intracontinental rift and epicontinental rift tholeiite basalts; IV2. continental extensional or initial rift; IV3. continent-continent collision basalt; IV4. continental rift basalt); V. mantle plume basalt.
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