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Mesoproterozoic (ca. 1.3 Ga) A-Type Granites on the Northern Margin of the North China Craton: Response to Break-Up of the Columbia Supercontinent

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Abstract: Mesoproterozoic (ca. 1.3 Ga) magmatism in the North China Craton (NCC) was dominated by mafic intrusions (dolerite sills) with lesser amounts of granitic magmatism, but our lack of knowledge of this magmatism hinders our understanding of the evolution of the NCC during this period. This study investigated porphyritic granites from the Huade–Kangbao area on the northern margin of the NCC. Zircon dating indicates the porphyritic granites were intruded during the Mesoproterozoic between 1285.4 ± 2.6 and 1278.6 ± 6.1 Ma. The granites have high silica contents ($\text{SiO}_2 = 63.10\text{--}73.73$ wt.%), exhibit alkali enrichment (total alkalis = $7.71\text{--}8.79$ wt.%), are peraluminous, and can be classified as weakly peraluminous A2-type granites. The granites have negative Eu anomalies ($\delta\text{Eu} = 0.14\text{--}0.44$), enrichments in large-ion lithophile elements (LILEs; e.g., K, Rb, Th, and U), and depletions in high-field-strength elements (HFSEs; e.g., Nb, Ta, and Ti). $\varepsilon_{\text{Hf}}(t)$ values range from -6.43 to $+2.41$, with t_{DM2} ages of $1905\text{--}2462$ Ma, suggesting the magmas were derived by partial melting of ancient crustal material. The geochronological and geochemical data, and regional geological features, indicate the Mesoproterozoic porphyritic granites from the northern margin of the NCC formed in an intraplate tectonic setting during continental extension and rifting, which represents the response of the NCC to the break-up of the Columbia supercontinent.



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Keywords: A-type granite; porphyritic granite; Mesoproterozoic; Columbia break-up; Huade

1. Introduction

The assembly and break-up of supercontinents are fundamental processes in Earth's history and have affected continent formation and destruction, the global climate, biological evolution, and large-scale mineralization events. Over the past two decades, this field has become an important area of research [1,2]. Geological records indicate the past occurrence of at least four supercontinents: Kenorland, Columbia, Rodinia, and Pangaea [3–5]. The Columbia supercontinent was assembled by a series of global-scale collisional events during 2.1–1.8 Ga [6,7] and was subsequently affected by rifting from the Paleoproterozoic to Mesoproterozoic (1.8–1.3 Ga), followed by break-up at 1.3–1.2 Ga [2,6]. During this period, Columbia experienced extensive rifting, mafic magmatism, and numerous tectonothermal events [2,8,9].

The North China Craton (NCC) was a key part of the Columbia supercontinent and encompassed both the Palaeoproterozoic Khondalite Belt (ca. 1.95 Ga) and the Central

Orogenic Belt (ca. 1.85 Ga) [10,11], which are thought to have formed by convergent processes that accompanied the assembly of the supercontinent. However, due to a lack of reliable age data for the Mesoproterozoic magmatism and tectonism, controversy exists regarding the role of the NCC during the rifting of Columbia [12–14]. Some studies have proposed that the NCC had rifted from Columbia by 1.6 Ga [15,16], suggesting it was not involved in the final break-up of the supercontinent at 1.35–1.20 Ga. However, this inference is inconsistent with palaeomagnetic data [17,18]. Shao et al. [12] identified three extensional events in the NCC, based on the following: (1) the intrusion of 1.8–1.7 Ga basaltic sills; (2) 1.3–1.2 Ga alkaline magmatism; and (3) 0.8–0.7 Ga basaltic sills. Zhai et al. [11,13] proposed that the late Paleoproterozoic to the Neoproterozoic in the NCC was characterized by four magmatic events: a large igneous event at 1.78 Ga; anorogenic magmatism during 1.72–1.62 Ga; a mafic dyke swarm during 1.37–1.32 Ga; and a mafic dyke swarm at 900 Ma. They proposed that the NCC was predominantly in an extensional setting during the Meso-Neoproterozoic. Xiang et al. [14] identified five prominent magmatic events during the late Paleoproterozoic to Mesoproterozoic along the northern margin of the NCC. These include mafic dyke swarms at 1.80–1.77 Ga, anorthosite–mangerite–charnockite–rapakivi granite assemblages (AMCG assemblage) at 1.72–1.67 Ga, alkali granites and mafic dyke swarms at 1.63–1.62 Ga, mafic dyke swarms and A-type granites at 1.33–1.30 Ga, and mafic dykes at 1.23 Ga. They proposed that Mesoproterozoic magmatism was episodic. More recently, the discovery of 1.33–1.30 Ga dolerite sills and coeval A-type granites in the northern NCC has indicated the craton underwent rifting that was coeval with the rifting of Columbia [19–21].

Regionally extensive dolerite sills were intruded into the Yanliao area at ca. 1.3 Ga in the eastern part of the northern margin of the NCC, while coeval magmatism in the central and western parts was relatively small in volume and comprised mainly granites and gabbros. Previous studies have focused mainly on the dolerite sills in the eastern part of the northern margin of the NCC, whereas few studies have examined the granitic magmatism in the central part of the craton [8,16,19].

2. Geological Setting

The NCC is located in eastern China and is bordered by the Xingmeng orogenic belt to the north and the Qinling–Dabie orogenic belt to the south (Figure 1). The NCC is one of the oldest cratons in the world and consists primarily of Precambrian crystalline basement that is overlain by thick sedimentary cover rocks [22,23]. The formation of the crystalline basement of the NCC involved mainly three processes: (1) the formation of multiple dispersed continental nuclei; (2) the amalgamation of micro-blocks; and (3) cratonization [24,25]. The Eastern and Western blocks collided along the Trans-North China orogen at ca. 1.85 Ga, leading to the final assembly of the NCC basement and its incorporation into Columbia. The Precambrian basement consists mainly of Neoarchaeon–Palaeoproterozoic TTG (Tonalite–Trondhjemite–Granodiorite) rocks and 2.6–2.5 Ga granulites, amphibolites, and mafic–ultramafic intrusions [18,26]. The NCC was located on the edge of the Columbia supercontinent and adjacent to the Indian Craton [3]. During the middle to late Proterozoic, the NCC underwent large-scale extension. During this period, a radial swarm of mafic dykes formed during 1.78–1.68 Ga, and there were multiple periods of rifting, including the formation of the Yanliao, Xiong’er, and Zhaertei–Baiyunebo–Huade rifts in the NCC. The NCC experienced a period of magmatic quiescence at 1.6–1.4 Ga. The magmatism in the NCC at 1.4–1.3 Ga is mainly represented by dolerite sills and granites. The dolerite sills occur primarily in the Yanliao region, over an area that is >600 km long and 200 km wide, constituting a mafic large igneous province. The 1.3 Ga granites in the NCC are located mainly in the Shangdu area, Inner Mongolia [2].

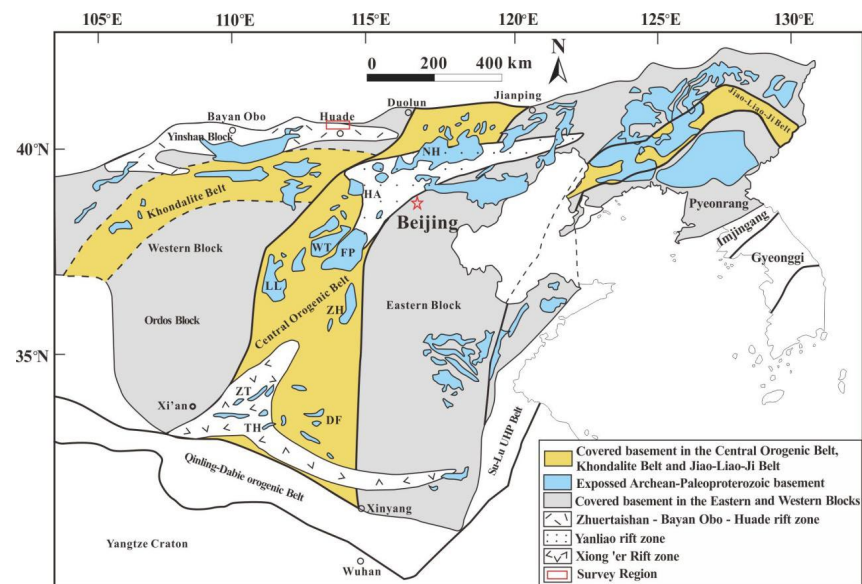


Figure 1. Schematic tectonic map of the NCC (modified after Zhao et al., 2001 [24]). Dengfeng (DF), Fuping (FP), Hengshan (HS), Huaian (HA), Lüliang (LL), Northern Hebei (NH), Taihua (TH), Wutai (WT), Zanghuang (ZH), and Zhongtiao (ZT).

The present study area is located at the northern margin of the NCC. Sedimentary rocks that crop out in the north of this area include the Mesoproterozoic Baoyintu Group, and lower Permian Sanmianjing and Elitu formations. Sedimentary rocks that crop out in the south of this area include the Mesoproterozoic Huade Group, with smaller exposures of the Middle Jurassic Tuchengzi Formation and Lower Cretaceous Zhangjiakou Formation. The Mesoproterozoic intrusions are located mainly in the northern area and trend NE–SW. Some of the intrusions have been mylonitized due to the activity of ENE–WSW-trending ductile shear zones (Figure 2).

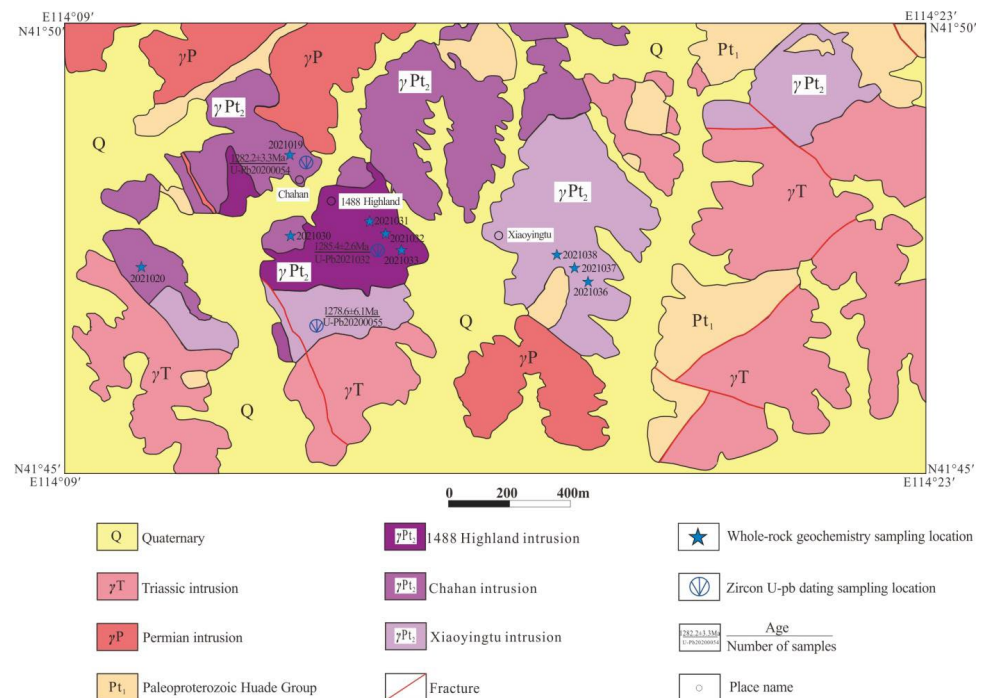


Figure 2. Simplified geologic map of the Huade area, Inner Mongolia.

3. Field Outcrops, and Petrology, and Mineralogy

Granitic samples were collected from the Huade area in Inner Mongolia and the Kangbao area in Hebei Province. Field investigations were conducted on the Xiaoyingtu, Chahan, and 1488 Highland intrusions in the study areas. These intrusions are stocks, with irregular elliptical shapes and spheroidal weathering (Figure 3a–e). Elliptical diorite xenoliths occur within the intrusions (Figure 3d).

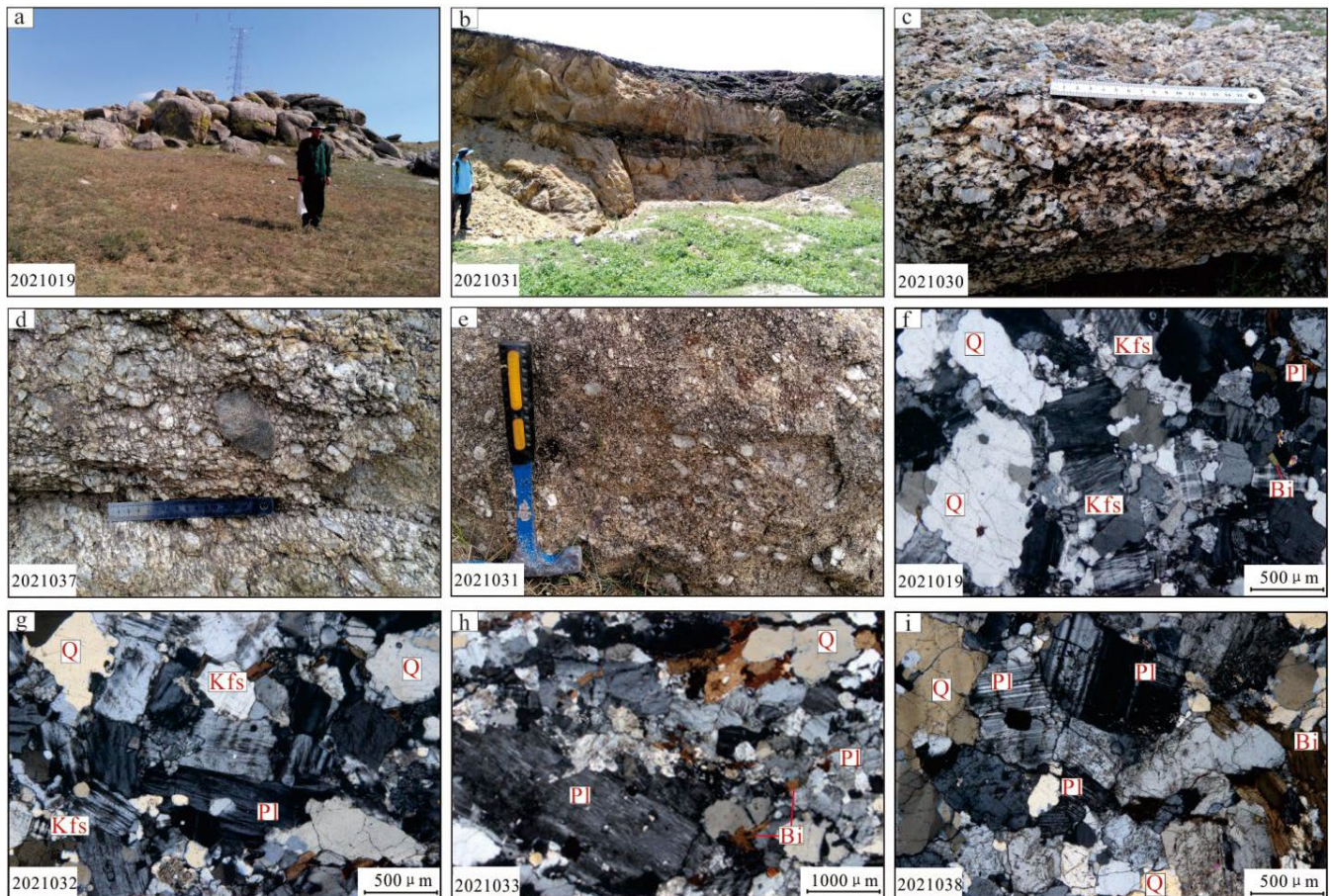


Figure 3. Representative field and photomicrographs of the Mesoproterozoic intrusions. (a) field characteristics of Xiaoyingtu intrusion; (b) pluton intruded into the strata of the Paleoproterozoic era Huade Group; (c) characteristics of medium-fine grained porphyritic biotite monzogranite granite hand specimen characteristics; (d) gray-black diorite inclusion; (e) medium-fine grained porphyritic biotite monzogranite; (f) porphyritic biotite syenogranite; (g) biotite syenogranite (orthogonal polarization); (h) medium-fine grained porphyritic biotite syenogranite (orthogonal polarization); (i) fine-grained porphyritic biotite monzogranite (orthogonal polarization).

3.1. Xiaoyingtu Pluton

The Xiaoyingtu pluton consists mainly of porphyritic granodiorite and is located in the central–eastern part of the study area over an exposed area of 18.30 km² (Figure 3b). The granodiorite is grey-yellow in color with a porphyritic texture and massive structure and consists mainly of plagioclase (50 vol.%), K-feldspar (25 vol.%), quartz (20 vol.%), and biotite and muscovite (5 vol.%). The samples are plotted in the granodiorite and quartz monzonite fields on the granite total alkalis–SiO₂ (TAS) diagram. Plagioclase phenocrysts range in size from 0.5 × 0.8 to 1 × 2 cm and are euhedral–subhedral, and they exhibit occasional multiple twinning. The quartz in the matrix is granular with a grain size of 2–4 mm. Plagioclase is euhedral–subhedral with grain sizes of 1 × 3 to 2 × 5 mm, and the distribution of biotite defines banding in the granodiorite (Figure 3f).

3.2. Chahan Intrusion

The Chahan intrusion crops out over an area of 20.47 km² in the central part of the study area and consists of fine–medium-grained porphyritic biotite syenogranite and medium–coarse-grained porphyritic biotite syenogranite. The biotite syenogranite is light grey-brown in color with a porphyritic texture and massive structure. The phenocrysts are K-feldspar, which are subhedral and have grain sizes of 0.4 × 1 to 0.5 × 2.5 cm and comprise ~10 vol.% of the sample. The matrix consists predominantly of K-feldspar (50 vol.%), plagioclase (15 vol.%), quartz (20 vol.%), and biotite (5 vol.%), with grain sizes of 2–4 mm. K-feldspar is subhedral and primarily microcline. Plagioclase is subhedral–euhedral and zoned, while biotite exhibits localized chloritization (Figure 3g–h).

3.2.1. Highland Intrusion

The 1488 Highland intrusion is located in the central part of the study area and is a stock that has an outcrop area of 7.07 km². The intrusion consists mainly of fine-grained porphyritic biotite monzogranite and itself has been intruded by the Chahan intrusion. The sample is yellow-brown in color and has a porphyritic texture and massive structure. It consists of K-feldspar (35 vol.%), plagioclase (40 vol.%), quartz (20 vol.%), biotite (5 vol.%), and minor muscovite and garnet. The phenocrysts are primarily subhedral microcline and minor amounts of plagioclase, which have grain sizes of 5–10 mm. Plagioclase occurs as subhedral crystals with grain sizes of 2–5 mm that occasionally exhibit zoning. Biotite has a weak shape-preferred orientation and a grain size of 0.2–2.0 mm (Figure 3i).

4. Sampling and Methodology

Whole-rock geochemical and zircon U–Pb dating and Hf isotope analyses were carried out on samples of the Xiaoyingtu, Chahancun, and 1488 Highland intrusions.

4.1. Whole-Rock Geochemistry

Whole-rock geochemical analysis was undertaken at the Regional Geological and Mineral Survey Institute, Hebei, China, using national standards and relevant industry analytical techniques. The analyzed samples were silicate rock samples, along with standards and blanks. Approximately 50 mg of representative sample material was weighed and placed in the inner container of a closed sample digestion vessel. Subsequently, 1 mL of HF and 0.5 mL of HNO₃ were added to the sample. The vessel was sealed and placed in an oven at a temperature of 190 °C for 24 h. After cooling, the inner container was removed and heated to 200 °C on a hotplate to evaporate the acids. Finally, 0.5 mL of HNO₃ was added and evaporated. This step was repeated and then an extra 5 mL of HNO₃ was added and the container was sealed and held at 130 °C for 3 h. After cooling, the container was opened, and the contents were transferred to a cleaned plastic bottle and diluted with 50 mL of water. The mixture was shaken thoroughly before determining the trace element contents by inductively coupled plasma–mass spectrometry (ICP–MS).

The major elements were determined by X-ray fluorescence spectrometry. Approximately 0.8 g of sample was weighed into a 25 mL porcelain crucible, along with an 8 g mixture of anhydrous lithium tetraborate and lithium fluoride. The mixture was then transferred into a Pt–Au crucible and melted and cooled into a fused glass disc. For the Fe analyses, ~0.3 g of sample was weighed and placed in a Pt crucible. The sample was wetted with water, and 5 mL of HF and 10 mL of H₂SO₄ were added. The crucible was covered, placed in a pre-heated electric furnace, heated and boiled for 10 min, removed from the furnace, and immediately placed in 200 mL of water containing 25 mL of saturated boric acid. For the loss-on-ignition analyses, 15 mL of thiophosphoric acid and two drops of 1% sodium diphenylamine sulfonate solution were added. Approximately 1.0 g of the sample was weighed into a porcelain crucible. The crucible was placed in a muffle furnace and heated at 980 °C for 2 h. After heating, the crucible was removed, transferred to a desiccator, allowed to cool to room temperature for 30 min, and then weighed. The ignition

process was then repeated for an additional 30 min and the crucible weighed again until a constant weight was achieved.

4.2. Zircon U–Pb Ages and Lu–Hf Isotopic Compositions

The zircon grains were separated and analyzed at the Hebei Regional Geological and Mineral Survey Institute. Subsequently, the zircons were subjected to cathodoluminescence (CL) imaging, U–Pb dating, and in situ Lu–Hf isotopic analysis at the Tianjin Geological Survey Center, China Geological Survey, Tianjin, China. The U–Pb dating was undertaken with a laser ablation (LA) system coupled to an ICP–MS (Agilent 7900) instrument (Agilent Technologies, Santa Clara, CA, USA). A RESolution LR (ASI) LA system comprising a 193 nm ArF excimer laser was used for the analyses. Ages and concordia diagrams were obtained with Isoplot 3.0 [27]. Hafnium isotopes were determined with an LA–multiple-collector–ICP–MS (LA–MC–ICP–MS) system. The LA system was a 193 nm ArF excimer laser (model UP193-FX; ESI Company, Santa Rosa, CA, USA). The MC–ICP–MS was a Neptune Plus (a product of Thermo Fisher Scientific, which is headquartered in Waltham, MA, USA). The Hf isotope data were processed using ICPMSDataCal 9.2 software. The laser beam diameter was 50 μm , the laser energy density was 3.5 J/cm², and the laser frequency was 8 Hz. The ablation time was 40 s, and the ablated material was transported into the mass spectrometer using He gas.

5. Results

5.1. Zircon U–Pb Ages

Three granitic samples were selected for zircon U–Pb dating: U–Pb2020054 (porphyritic biotite syenite; 41°47′09″N, 114°15′22″E), U–Pb2020055 (porphyritic biotite syenite; 41°46′30″N, 114°13′59″E), and U–Pb2021032 (porphyritic biotite monzonitic granite; 41°48′02″N, 114°14′01″). The results are listed in Appendix A Table A1. Rock samples with minimal alteration were collected. The zircon crystals are euhedral, short columnar in shape, 90 $\times$ 70 to 120 $\times$ 300 μm in size, and they contain few inclusions and fractures (Figure 4).

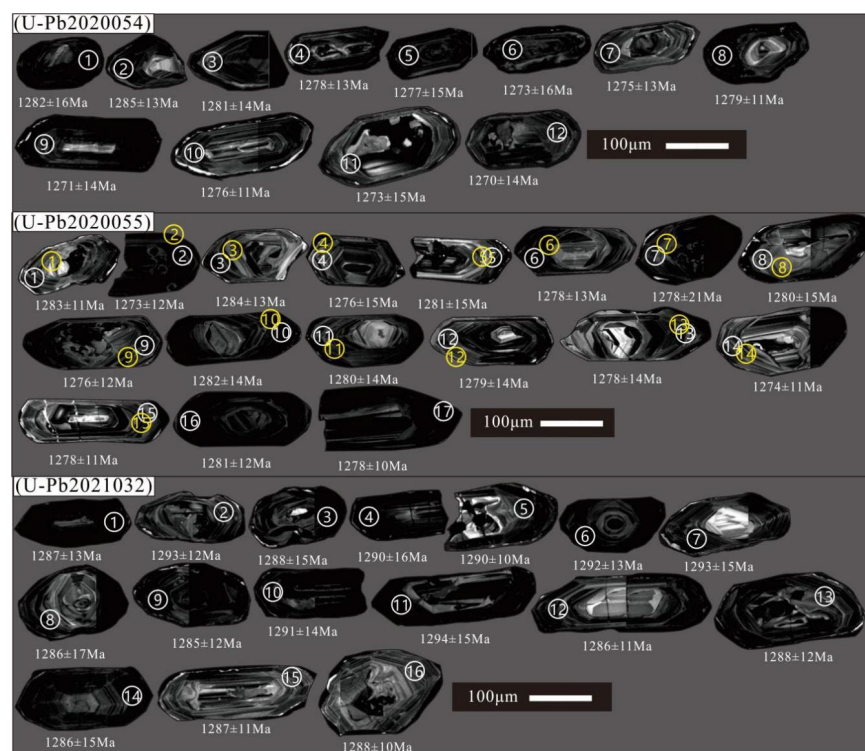


Figure 4. Cathode luminescence images of representative zircons from the Mesoproterozoic granites in the study area.

The CL images reveal oscillatory zoning, indicative of a magmatic origin. The U and Th contents are 248.93–769.10 and 17.91–308.87 ppm, respectively, with Th/U = 0.07–0.51, which are also consistent with a magmatic origin [28]. The U–Pb ages exhibit limited variations (Figure 5). The U–Pb ages for sample U–Pb2020054 range between 1270 ± 14 and 1285 ± 13 Ma, with a weighted mean age of 1282.2 ± 3.3 Ma ($n = 12$; MSWD = 0.008). The U–Pb ages of sample U–Pb2020055 vary between 1273 ± 12 and 1284 ± 13 Ma, with a weighted mean age of 1278.6 ± 6.1 Ma ($n = 17$; MSWD = 0.061). The U–Pb ages of sample U–Pb2021032 range between 1285 ± 12 and 1294 ± 15 Ma, with a weighted mean age of 1285.4 ± 2.6 Ma ($n = 16$; MSWD = 0.100). The zircon U–Pb ages of all samples are the same within error, suggesting the porphyritic granites are Mesoproterozoic in age.

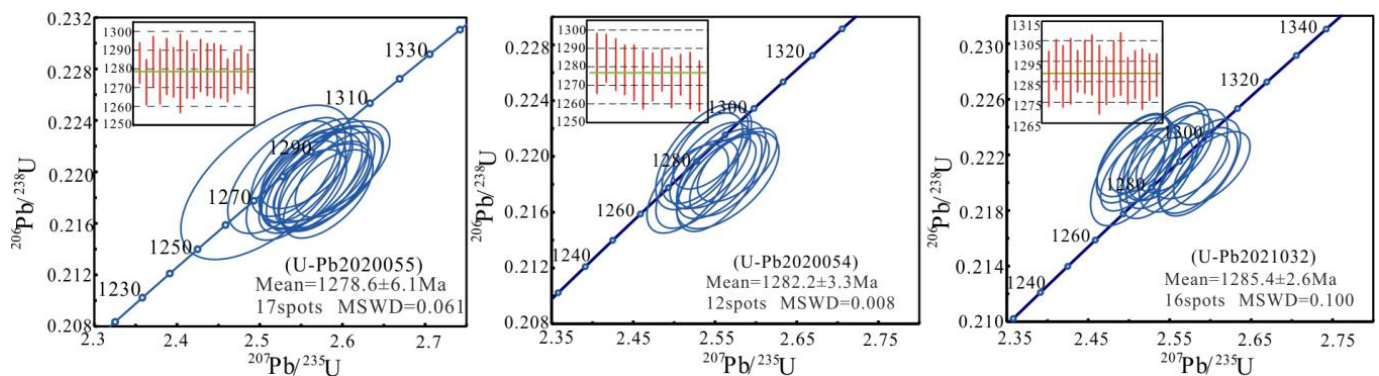


Figure 5. LA-ICP-MS zircon U–Pb concordia diagrams of the Mesoproterozoic granite samples in the study area.

5.2. Major Elements

The SiO₂ contents of the analyzed samples range from 63.10 to 73.73 wt.%. The total alkali (K₂O + Na₂O) contents are 6.28–8.79 wt.% (Figure 6a). The results are listed in Table A2. The Al₂O₃ contents are 12.04–17.64 wt.%, with an average of 14.54 wt.%. The A/CNK ratios are >1.0 (1.07–1.90; average = 1.22). Sample 2021037 has A/CNK > 1.90, potentially due to late-stage metamorphism, which led to the development of metamorphic minerals such as andalusite and sillimanite. The A/NK values range from 1.24 to 2.33, with an average of 1.54. All samples are plotted in the peraluminous field in an A/CNK versus A/NK diagram (Figure 6b). In a SiO₂–FeOT/(FeOT + MgO) diagram (Figure 6c), most samples are plotted in the magnesian granite field. In a SiO₂–K₂O diagram (Figure 6d), the samples are plotted in the shoshonite field.

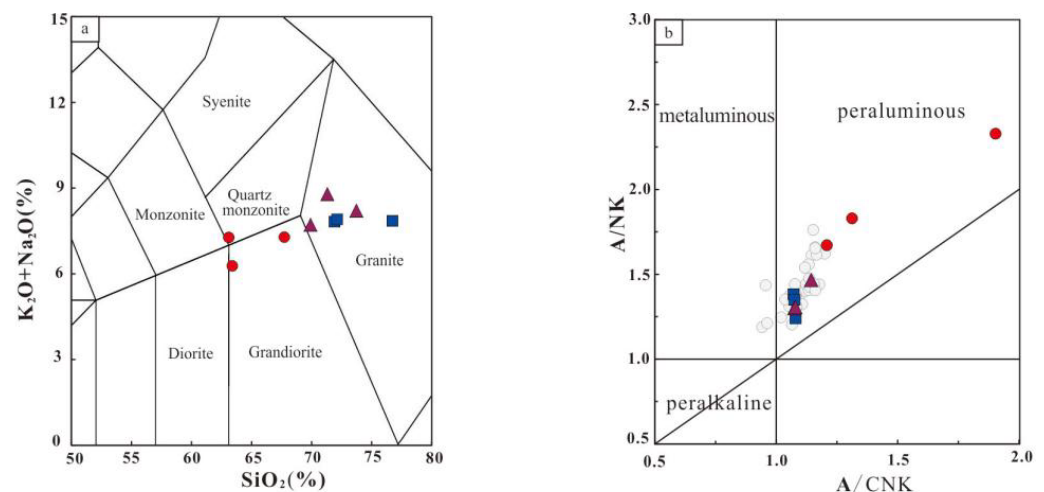


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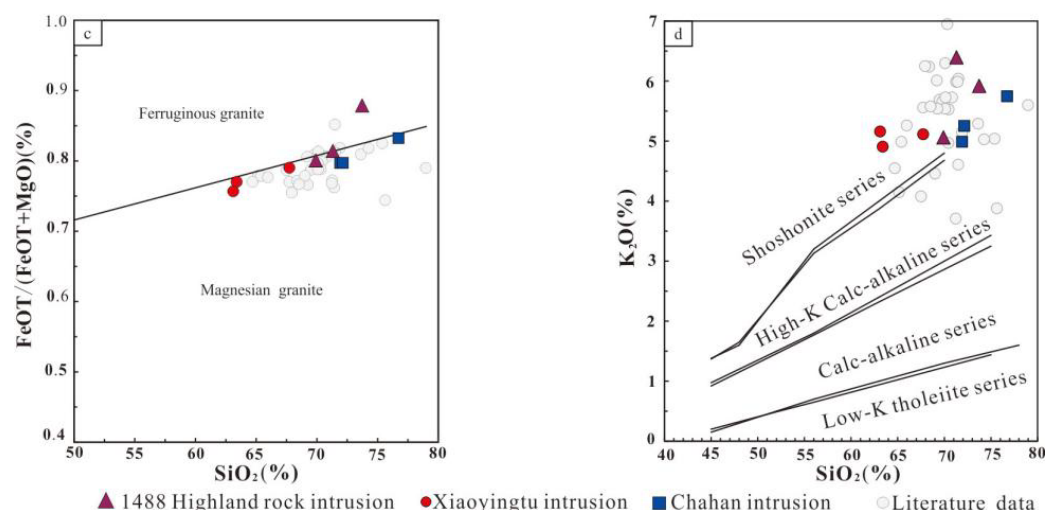


Figure 6. TAS (total-alkali-SiO₂) diagram (a), after Middlemost, 1994 [29]), A/CNK-A/NK diagram (b), after Maniar and Piccoli, 1989 [30]), SiO₂-FeO/(FeO + MgO) diagram (c), after Frost et al., 2001 [31]), SiO₂-K₂O covariant diagram (d), after Peccerillo and Taylor, 1976 [32]). Literature data from Zhang Shuanhong, 2014 [33]; Meng Baohang, 2016 [34]; Phase Vibration Group, 2020 [14].

5.3. Trace Elements

The total rare earth element (Σ REE) contents of the analyzed samples vary between 168.85 and 690.06 ppm, with an average of 374.64 ppm and significant variations between samples. The samples exhibit enrichments in light REE and depletions in heavy REE (Figure 7a), with ratios of light to heavy REE of 7.46–24.0. (La/Yb)_N ratios vary from 5.37 to 61.49, with an average of 22.87. The chondrite-normalized REE patterns exhibit negative Eu anomalies (δ Eu = 0.14–0.54), indicative of plagioclase fractionation. In a primitive-mantle-normalized multi-element diagram (Figure 7b), the samples are enriched in large-ion lithophile elements (LILEs; e.g., K and U) and exhibit small negative Zr and large negative Ti anomalies. In general, the trace element patterns of the studied granites are similar, indicating the granites are cogenetic.

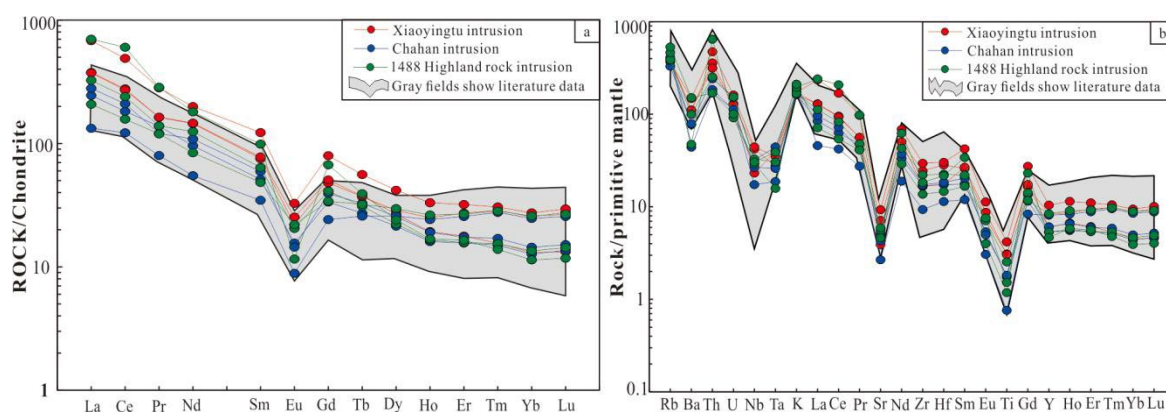


Figure 7. Chondrite-normalized REE patterns and (a) a primitive mantle-normalized multi-element diagram (b) of the Mesoproterozoic granites in the study area; standard reference values of chondrites and primitive mantle are from Sun and McDonough, 1989 [35]. Literature data from Zhang Shuanhong, 2014 [33]; Meng Baohang, 2016 [34]; Phase Vibration Group, 2020 [14].

5.4. Zircon Hf Isotopes

Hafnium isotopic compositions were determined for zircons in one granite sample (2021055). The results are listed in Table A3. The geochemical properties of Hf are similar to those of Zr, and Hf readily substitutes for Zr in the zircon crystal lattice, which results in low zircon Lu/Hf ratios. As such, the ¹⁷⁶Hf/¹⁷⁷Hf ratio changes little over time due to the in situ

decay of ^{176}Lu . Therefore, magmatic zircon effectively retains the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of the melt it crystallizes from [36]. The zircon $^{176}\text{Lu}/^{177}\text{Hf}$ ratios (Figure 8b) range between 0.0004 and 0.0017, and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios vary between 0.281807 and 0.282080. $^{176}\text{Yb}/^{177}\text{Hf}$ ratios are 0.0155–0.0671. Zircon $f_{\text{Lu}/\text{Hf}}$ and $\varepsilon_{\text{Hf}}(t)$ values and T_{DM1} and T_{DM2} ages vary from -0.98 to -0.95 , -6.43 to $+2.41$, 1676 to 2022 Ma, and 1905 to 2462 Ma (Figure 8a), respectively.

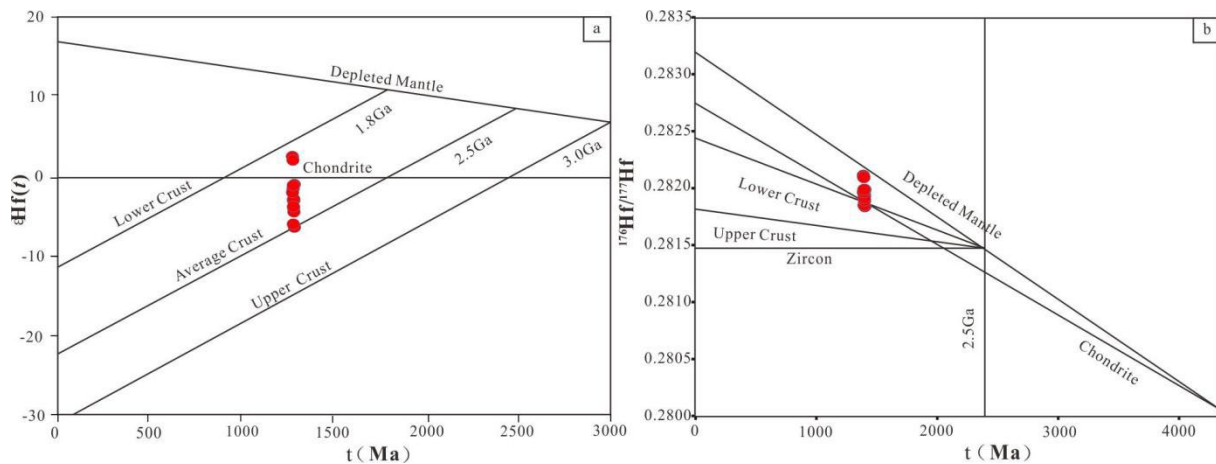


Figure 8. Correlation between Hf isotopic compositions and crystallization ages of porphyritic biotite monzogranite.

6. Discussion

6.1. Granite Petrogenesis

The primary minerals in the Mesoproterozoic granites are alkali feldspar, plagioclase, quartz, and biotite, with K-feldspar megacrysts present in most samples. Samples are enriched in Ga (19.50–28.46 ppm), with 1000 Ga/Al values of 2.64–3.10. Most samples are plotted in the A-type granite field on 10,000 Ga/Al–Ce, 10,000 Ga/Al–Zr, and 10,000 Ga/Al–K₂O/MgO diagrams (Figure 9a–c; [37]). Similarly, on a Zr + Nb + Ce + Y–TFeO/MgO diagram (Figure 9d), all samples are plotted in the A-type granite field. In addition, the absence of inherited zircons in the Mesoproterozoic granites, which are typically present in S-type granites, indicates the source region of the Mesoproterozoic granites underwent high-temperature melting. This characteristic is typical of A-type granites. Most samples are plotted in the A2-type granite fields in Nb–Y–Ce and Nb–Y–3Ga ternary diagrams (Figure 9e–f).

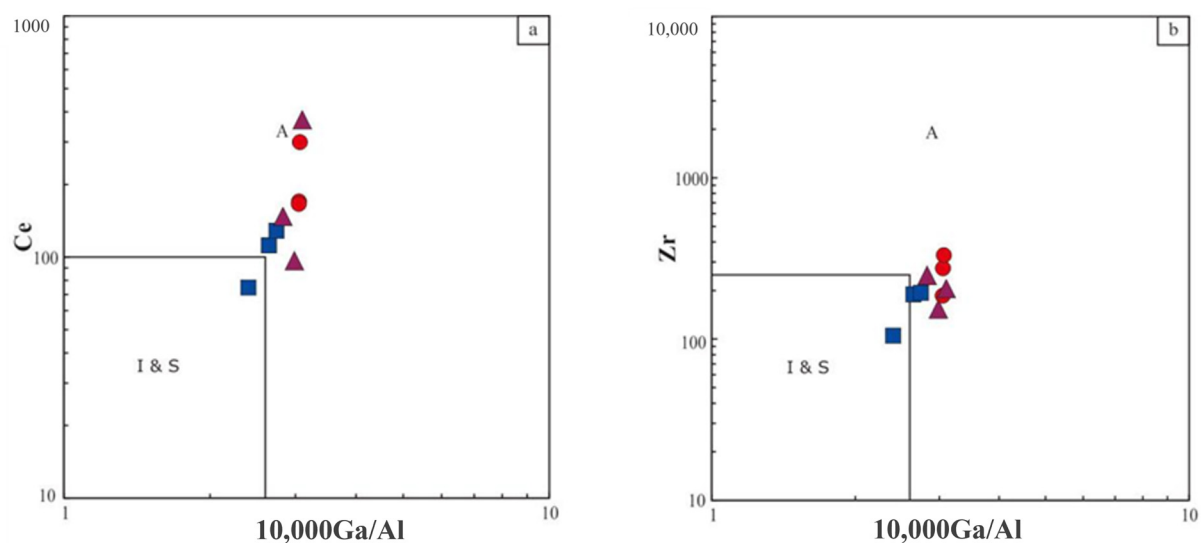


Figure 9. Cont.

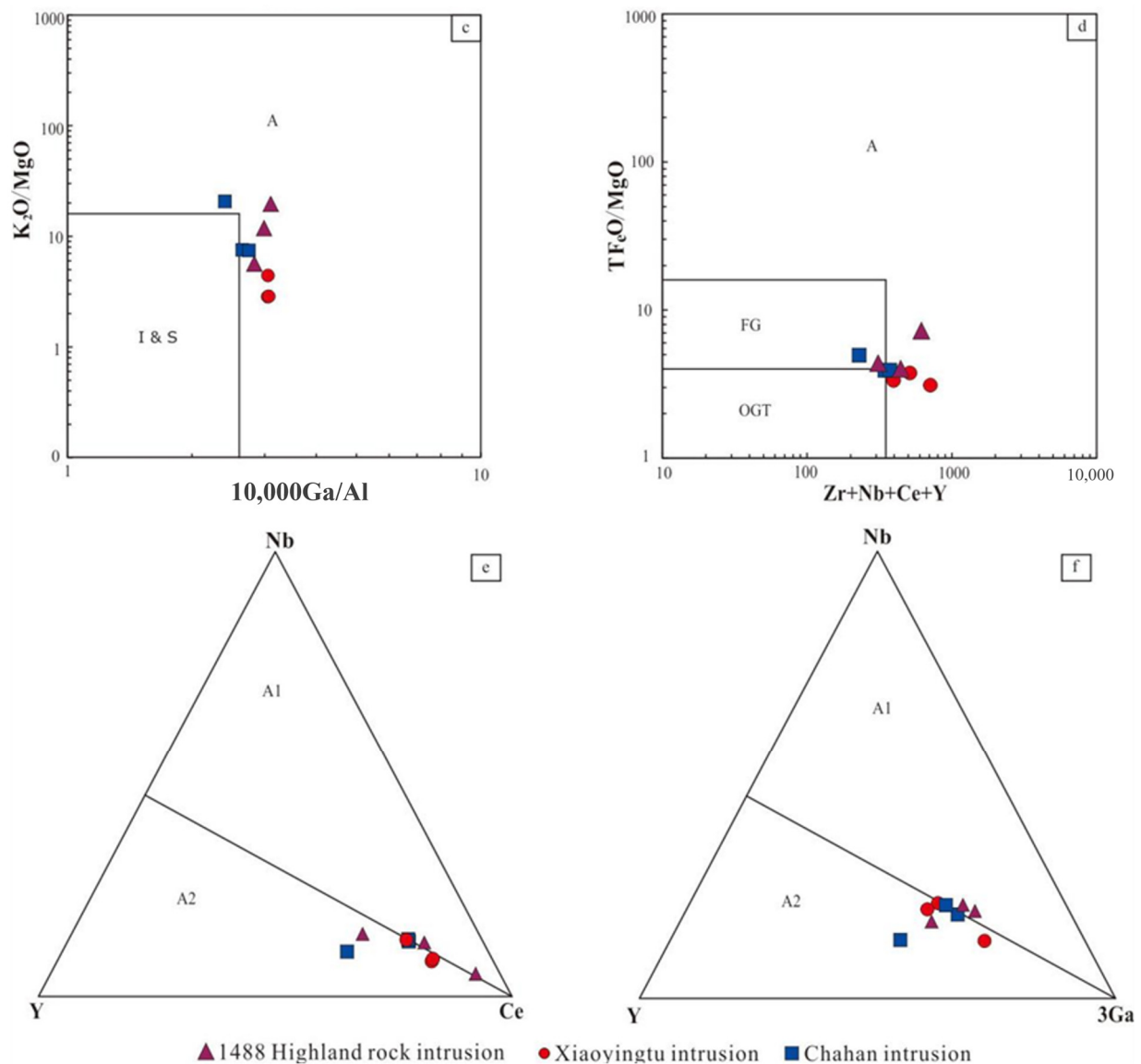


Figure 9. Classification diagrams for the genetic types of Mesoproterozoic granites in the study area: (a) 10,000 Ga/Al versus Ce; (b) 10,000 Ga/Al versus Zr; (c) 10,000 Ga/Al versus K_2O/MgO ; (d) (Zr + Nb + Ce + Y) versus $TFeO/MgO$; (e) Nb-Y-Ce; (f) Nb-Y-3Ga; (a–d) are after Whalen et al. (1987) [37], and (e) and (f) are after Eby. (1992) [38]; A-, I- and S-, A-, I- and S-type granite; FG. Differentiated I-type granite area; OGT. Undifferentiated I- and S-type granite area; A1. Non-orogenic granite; A2. Post-orogenic granite.

6.2. Magma Sources and Evolution

There are eight main hypotheses regarding the origins of A-type granites [39]: (1) differentiation of alkaline magmas derived from the mantle, resulting in residual A-type granitic melts [38,40]; (2) extreme differentiation of tholeiitic magma derived from the mantle or low-degree partial melting of tholeiitic rocks [41–43]; (3) interaction of alkali magmas derived from the mantle with crustal materials, leading to the formation of a syenitic magma source area, which is further differentiated or mixed with crustal materials [44,45]; (4) partial melting of F-rich granulite residue after extraction of I-type granitic magma from the lower crust [37]; (5) direct melts of igneous crustal rocks (i.e., tonalite and granodiorite) [46]; (6) melting of crustal rocks due to magmatic underplating [47,48]; (7) partial melting of lower crustal rocks due to the addition of volatiles from the mantle [49]; and (8) mixing between crust- and mantle-derived magmas [50].

The absence of coeval (ultra)mafic rocks precludes the involvement of mantle-derived (alkali) basalt magma. The granite samples have high SiO_2 and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ contents, and low TiO_2 , total Fe_2O_3 , and MgO contents. A/CNK ratios indicate the granites are strongly peraluminous. The depletions in Nb, Ta, Sr, and Ti and enrichments in K, Rb, Th, and U in the granites suggest their parental melt(s) were derived from the crust [51]. $\epsilon_{\text{Hf}}(t)$ values of -1.08 to -6.43 (except one analysis of 2.41) are indicative of a crustal source. The zircon T_{DM1} ages of 1676–2022 Ma (average = 1864 Ma) correspond to a period of uplift and rifting of NCC basement, and anorogenic magmatism. The zircon T_{DM2} ages of 1905–2462 Ma are consistent with the timing of development of the Palaeoproterozoic orogenic belt in the NCC [52]. Harker diagrams (Figure 10) exhibit negative linear correlations for TiO_2 , MgO , and Al_2O_3 . Furthermore, the trace element patterns all exhibit depletions in Ba, Nb, Ta, Sr, Ti, and Eu, indicating the sources of the granites were similar and that the generated magmas underwent significant fractional crystallization. In conclusion, the Mesoproterozoic granites were generated by the melting of crustal rocks due to magmatic underplating, and the parental magmas underwent significant crystal fractionation.

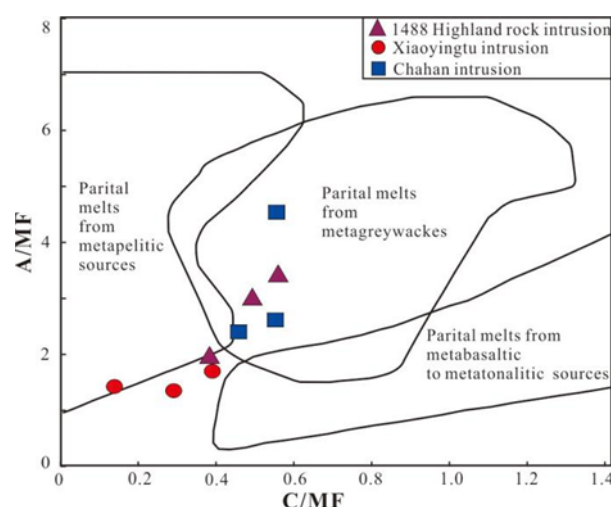


Figure 10. C/MF-A/MF diagram of Mesoproterozoic granite in the study area (Alther et al., 2000 [52]).

6.3. Tectonic Setting

The ca. 1.30 Ga magmatism along the northern margin of the NCC includes dolerite dykes and sills in the eastern part of the Yanliao rift, the Shangdu–Huade–Kangbao granite, and the Baiyun Obo carbonatite. Dolerite sills (1.33–1.30 Ga) associated with continental rifting have intruded the Shimaling, Tieling, Wumoushan, and Gaoqizhuang formations in the northern NCC [5,9,14]. In addition, 1.3 Ga carbonatite and mafic dykes occur in the Baiyun Obo area. Previous studies of carbonatites in the Baiyun Obo area, middle Mesoproterozoic granites, and large-scale dolerite sills from the northern margin of the NCC indicate that rifting persisted until the middle Mesoproterozoic [53,54].

The studied Mesoproterozoic granites are peraluminous A-type granites, and most studies consider that A-type granites form in extensional tectonic settings, such as those associated with post-orogenic extension, continental margins, and intraplate rifts. The Mesoproterozoic A-type granites have REE characteristics indicative of a crustal origin, similar to intraplate granites formed by the melting of continental crust. Eby [39] categorized A-type granites into two sub-types, A1 and A2. The A1 sub-type is thought to be derived by the differentiation of ocean island basalt magma, while the A2 sub-type may be derived by the interaction between mantle-derived magmas and continental crust. Granite samples from the study area plot in the A2 field in Nb–Y–Ce and Nb–Y–3Ga diagrams, indicating their formation in a stable extensional setting during the late stages of an orogeny. Pearce [55] used Yb + Ta–Rb, Nb + Y–Rb, Yb–Ta, and Y–Nb diagrams to identify the tectonic settings of granitic magmas. Most of the studied granites plot in the post-collisional to

intraplate fields in these diagrams (Figure 11a–d). Therefore, the Mesoproterozoic granites were formed in an intraplate tectonic setting during continental extension and rifting.

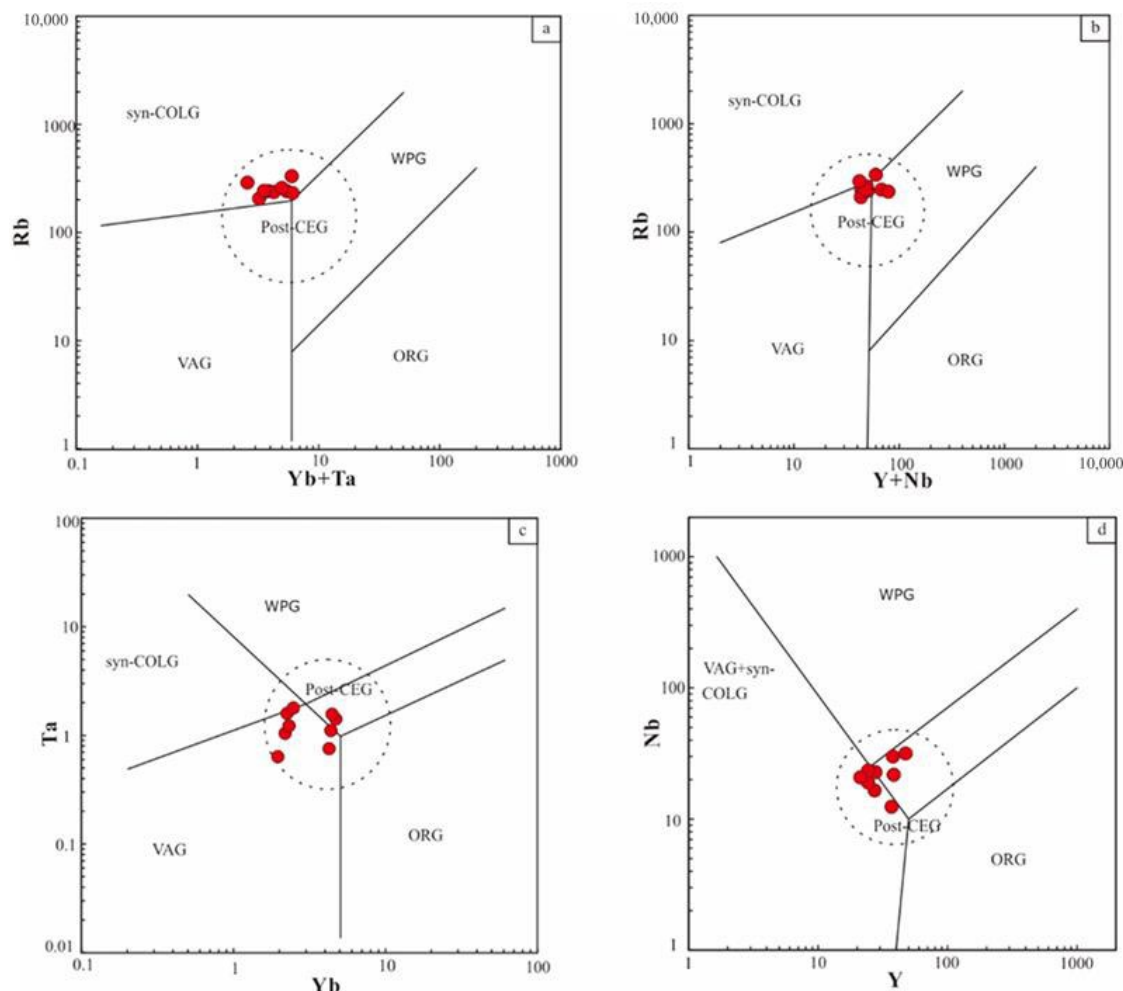


Figure 11. Diagrams of the tectonic environment of trace elements of Mesoproterozoic granite in the study area (after Pearce et al., 1984 [55]). WPG-within plate granite; ORG- ocean ridge granite; VAG- volcanic arc granite; syn-COLG-syn-collisional granite; Post-CEG-post collisional granite.

6.4. Relationship to the Break-Up of Columbia

The ca. 1.3 Ga magmatism was global in extent, suggesting the extensional/rifting event during this period was a global phenomenon. Mafic dyke swarms ranging in age from 1.3 to 1.2 Ga have been identified in the Mackenzie Mountains in Canada, the São Francisco craton in southeastern Brazil, and Australia [16,56,57]. In addition to mafic magmatism during the middle Mesoproterozoic along the northern margin of the NCC, granites were formed at this time in the study area and surrounding regions due to continental extension and rifting [8,18–20,53]. These late Mesoproterozoic dolerites, granites, and carbonatites form a bimodal magmatic assemblage in the NCC associated with the late-stage break-up of Columbia. Palaeomagnetic data for the period 1.77–1.50 Ga have shown that the palaeomagnetic poles of the NCC closely resemble those of North America (Laurentia) and Siberia [58]. However, during 1.35–1.20 Ga, the palaeomagnetic poles of North China exhibited a $\sim 90^\circ$ rotation relative to Laurentia (North America; [58]). Evans et al. [59] reconstructed the initial fragmentation of the Mesoproterozoic Columbia supercontinent based on tectonic, stratigraphic, and palaeomagnetic data for Siberia, Laurentia, and Baltica (Figure 12). Their findings indicate that the southern and eastern margins of Siberia were directly adjacent to the Urals margin of Baltica. Furthermore, they proposed the NCC may have fully separated from Columbia during the middle Mesoproterozoic (1.50–1.27 Ga).

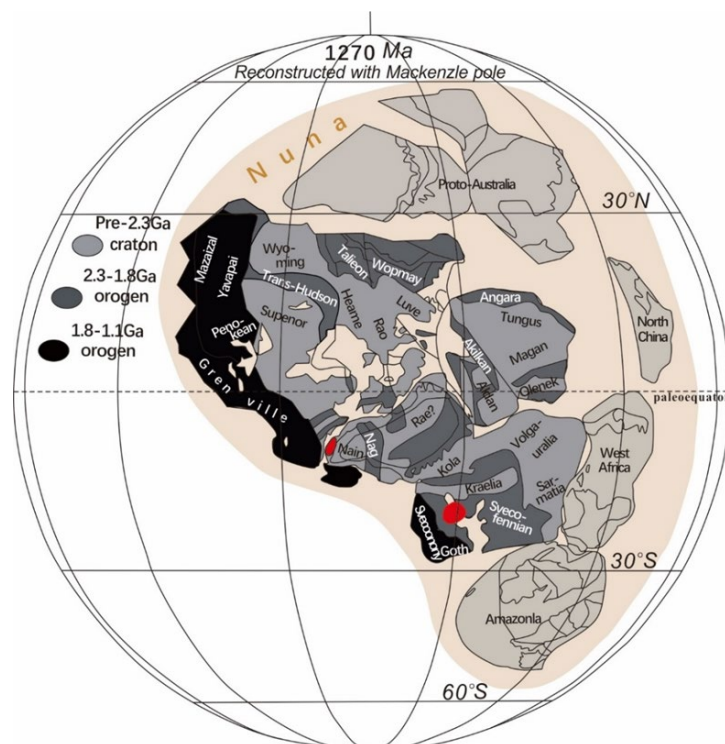


Figure 12. Reconstruction of the initial Mesoproterozoic fragmentation of the Columbia supercontinent (Modified by Evans, 2011 [59]).

In summary, it can be inferred that the Mesoproterozoic dolerite dykes along the northern margin of the NCC represent magmas derived from the mantle during continental rifting, whereas the granites represent the melting of the ancient crust. Both types of magmatism were related to the break-up of Columbia. The initial fragmentation of Columbia in different cratons may have varied in time. However, the ca. 1.30 Ga magmatic event in the study area likely corresponds to the last break-up phase of Columbia and highlights the response of the NCC to this final break-up event.

7. Conclusions

1. (Zircon U–Pb ages of porphyritic granites in the central part of the northern margin of the NCC range from 1285.4 ± 2.6 to 1278.6 ± 6.1 Ma; these are the same within error.
2. The Mesoproterozoic granites are weakly peraluminous A2-type granites. Trace element data suggest they were formed by partial melting of ancient crustal materials and may have formed in an intraplate tectonic setting affected by continental extension and rifting.
3. The Mesoproterozoic granites were formed in an extensional rift setting that also generated widespread coeval doleritic dykes in the NCC. These igneous rocks are also coeval with the 1.3–1.2 Ga extensional events that occurred worldwide. Therefore, the extensional setting at the northern margin of the NCC reflects a response to the late break-up stage of the Columbia supercontinent.

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Data Availability Statement: Data for this research are included in this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. LA-ICP-MS zircon U-Pb data of the volcanic rocks from the Mesoproterozoic granite-like zircon.

The Number of the Measurement Point	Elemental Content (10 ⁻⁶)				Isotope Ratio and 1σ								Isotope Age Values and 1σ								Confidence
	Pb	²³² Th	²³⁸ U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁸ Pb/ ²³² Th	1σ	²⁰⁸ Pb/ ²³² Th	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ			
U-Pb20200054.1	90	56	364	0.15	0.0831	0.0011	2.5340	0.0462	0.2200	0.0031	0.0831	0.0011	0.0640	0.0014	1282	13	1282	16	99%		
U-Pb20200054.2	124	48	489	0.10	0.0833	0.0011	2.5467	0.0392	0.2206	0.0024	0.0833	0.0011	0.0630	0.0013	1285	11	1285	13	99%		
U-Pb20200054.3	121	46	489	0.09	0.0831	0.0010	2.5345	0.0404	0.2199	0.0027	0.0831	0.0010	0.0648	0.0014	1282	12	1281	14	99%		
U-Pb20200054.4	108	138	405	0.34	0.0836	0.0010	2.5440	0.0404	0.2193	0.0025	0.0836	0.0010	0.0676	0.0013	1285	12	1278	13	99%		
U-Pb20200054.5	117	102	455	0.22	0.0843	0.0012	2.5576	0.0446	0.2190	0.0029	0.0843	0.0012	0.0684	0.0020	1289	13	1277	15	99%		
U-Pb20200054.6	121	120	469	0.26	0.0844	0.0010	2.5553	0.0425	0.2183	0.0030	0.0844	0.0010	0.0634	0.0015	1288	12	1273	16	98%		
U-Pb20200054.7	139	48	549	0.09	0.0858	0.0011	2.6046	0.0382	0.2186	0.0021	0.0858	0.0011	0.0673	0.0018	1302	11	1274	11	97%		
U-Pb20200054.8	183	46	702	0.07	0.0856	0.0013	2.6003	0.0404	0.2186	0.0022	0.0856	0.0013	0.0767	0.0029	1301	11	1274	12	97%		
U-Pb20200054.9	95	51	373	0.14	0.0845	0.0011	2.5676	0.0396	0.2187	0.0024	0.0845	0.0011	0.0652	0.0015	1291	11	1275	13	98%		
U-Pb20200054.10	162	309	593	0.52	0.0846	0.0012	2.5771	0.0398	0.2194	0.0022	0.0846	0.0012	0.0570	0.0011	1294	11	1279	11	98%		
U-Pb20200054.11	86	66	336	0.20	0.0864	0.0013	2.6158	0.0444	0.2181	0.0023	0.0864	0.0013	0.0586	0.0012	1305	13	1272	12	97%		
U-Pb20200054.12	121	56	498	0.11	0.0836	0.0011	2.5281	0.0412	0.2180	0.0026	0.0836	0.0011	0.0624	0.0014	1280	12	1271	14	99%		
U-Pb20200054.13	95	60	376	0.16	0.0840	0.0011	2.5523	0.0391	0.2188	0.0021	0.0840	0.0011	0.0651	0.0014	1287	11	1276	11	99%		
U-Pb20200054.14	125	45	493	0.09	0.0846	0.0013	2.5656	0.0512	0.2183	0.0028	0.0846	0.0013	0.0743	0.0035	1291	15	1273	15	98%		
U-Pb20200054.15	187	297	681	0.44	0.0834	0.0011	2.5166	0.0408	0.2177	0.0026	0.0834	0.0011	0.0627	0.0012	1277	12	1270	14	99%		
U-Pb20200055.1	129	42	511	0.08	0.0838	0.0010	2.5570	0.0365	0.2202	0.0020	0.0634	0.0012	1288	23	1288	10	1283	11	99%		
U-Pb20200055.2	144	182	541	0.34	0.0855	0.0009	2.5828	0.0357	0.2183	0.0023	0.0662	0.0010	1328	21	1296	10	1273	12	98%		
U-Pb20200055.3	84	30	328	0.09	0.0836	0.0009	2.5466	0.0376	0.2204	0.0025	0.0604	0.0015	1283	22	1285	11	1284	13	99%		
U-Pb20200055.4	79	32	324	0.10	0.0841	0.0009	2.5439	0.0397	0.2189	0.0028	0.0652	0.0014	1294	19	1285	11	1276	15	99%		
U-Pb20200055.5	84	36	344	0.11	0.0845	0.0010	2.5665	0.0432	0.2199	0.0028	0.0679	0.0014	1306	23	1291	12	1281	15	99%		
U-Pb20200055.6	99	39	400	0.10	0.0845	0.0009	2.5631	0.0401	0.2193	0.0025	0.0661	0.0014	1306	21	1290	11	1278	13	99%		
U-Pb20200055.7	68	22	270	0.08	0.0827	0.0016	2.5077	0.0680	0.2192	0.0040	0.0618	0.0021	1265	38	1274	20	1278	21	99%		
U-Pb20200055.8	62	18	249	0.07	0.0835	0.0011	2.5278	0.0438	0.2196	0.0029	0.0654	0.0019	1281	24	1280	13	1280	15	99%		
U-Pb20200055.9	141	47	545	0.09	0.0854	0.0009	2.5794	0.0369	0.2189	0.0023	0.0658	0.0013	1324	20	1295	11	1276	12	98%		

Table A1. Cont.

The Number of the Measurement Point	Elemental Content (10 ⁻⁶)				Isotope Ratio and 1σ								Isotope Age Values and 1σ								Confidence
	Pb	²³² Th	²³⁸ U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁸ Pb/ ²³² Th	1σ	²⁰⁸ Pb/ ²³² Th	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ			
U-Pb20200055.10	94	29	356	0.08	0.0849	0.0015	2.5782	0.0522	0.2200	0.0026	0.0812	0.0036	1322	34	1294	15	1282	14	99%		
U-Pb20200055.11	91	30	358	0.08	0.0854	0.0013	2.5834	0.0435	0.2196	0.0026	0.0850	0.0052	1326	29	1296	12	1280	14	98%		
U-Pb20200055.12	104	38	423	0.09	0.0853	0.0009	2.5807	0.0386	0.2195	0.0027	0.0670	0.0014	1324	21	1295	11	1279	14	98%		
U-Pb20200055.13	105	35	435	0.08	0.0848	0.0009	2.5694	0.0405	0.2193	0.0027	0.0697	0.0015	1311	16	1292	12	1278	14	98%		
U-Pb20200055.14	106	45	432	0.10	0.0846	0.0009	2.5520	0.0349	0.2185	0.0021	0.0647	0.0012	1306	20	1287	10	1274	11	98%		
U-Pb20200055.15	195	115	769	0.15	0.0842	0.0008	2.5487	0.0320	0.2192	0.0021	0.0586	0.0009	1298	19	1286	9	1278	11	99%		
U-Pb20200055.16	92	54	375	0.15	0.0856	0.0010	2.5956	0.0348	0.2198	0.0022	0.0657	0.0011	1329	21	1299	10	1281	12	98%		
U-Pb20200055.17	60	46	250	0.19	0.0851	0.0011	2.5744	0.0383	0.2192	0.0020	0.0645	0.0013	1318	26	1293	11	1278	10	98%		
U-Pb2021032.1	98	49	389	0.13	0.0845	0.0011	2.5846	0.0400	0.2209	0.0025	0.0687	0.0014	1306	25	1296	11	1287	13	99%		
U-Pb2021032.2	137	279	487	0.57	0.0830	0.0010	2.5563	0.0387	0.2221	0.0023	0.0654	0.0010	1269	19	1288	11	1293	12	99%		
U-Pb2021032.3	125	52	492	0.11	0.0845	0.0010	2.5871	0.0407	0.2211	0.0028	0.0667	0.0013	1306	24	1297	12	1288	15	99%		
U-Pb2021032.4	142	85	564	0.15	0.0835	0.0010	2.5668	0.0444	0.2216	0.0030	0.0630	0.0014	1281	23	1291	13	1290	16	99%		
U-Pb2021032.5	102	34	400	0.09	0.0820	0.0010	2.5176	0.0335	0.2216	0.0019	0.0672	0.0016	1256	24	1277	10	1290	10	98%		
U-Pb2021032.6	72	65	273	0.24	0.0814	0.0010	2.5063	0.0371	0.2220	0.0024	0.0636	0.0011	1232	23	1274	11	1292	13	98%		
U-Pb2021032.7	135	51	549	0.09	0.0827	0.0009	2.5456	0.0385	0.2221	0.0028	0.0679	0.0015	1261	21	1285	11	1293	15	99%		
U-Pb2021032.8	124	42	491	0.08	0.0861	0.0011	2.6303	0.0365	0.2203	0.0019	0.0986	0.0040	1343	25	1309	10	1284	10	98%		
U-Pb2021032.9	89	36	364	0.10	0.0818	0.0009	2.5056	0.0431	0.2208	0.0032	0.0640	0.0015	1240	20	1274	13	1286	17	99%		
U-Pb2021032.10	109	62	438	0.14	0.0820	0.0009	2.5048	0.0324	0.2207	0.0022	0.0632	0.0011	1244	28	1273	9	1285	12	99%		
U-Pb2021032.11	108	45	438	0.10	0.0815	0.0009	2.5055	0.0370	0.2217	0.0026	0.0665	0.0013	1233	22	1274	11	1291	14	98%		
U-Pb2021032.12	85	59	340	0.17	0.0826	0.0011	2.5459	0.0432	0.2222	0.0029	0.0667	0.0014	1259	26	1285	12	1294	15	99%		
U-Pb2021032.13	122	65	494	0.13	0.0829	0.0009	2.5374	0.0336	0.2207	0.0021	0.0658	0.0012	1266	16	1283	10	1286	11	99%		
U-Pb2021032.14	92	42	380	0.11	0.0825	0.0009	2.5258	0.0324	0.2213	0.0022	0.0672	0.0013	1257	22	1279	9	1288	12	99%		
U-Pb2021032.15	107	41	448	0.09	0.0829	0.0009	2.5373	0.0393	0.2208	0.0028	0.0665	0.0014	1278	22	1283	11	1286	15	99%		
U-Pb2021032.16	82	138	302	0.46	0.0867	0.0014	2.6398	0.0436	0.2203	0.0028	0.0723	0.0015	1354	31	1312	12	1284	15	97%		
U-Pb2021032.17	109	121	426	0.28	0.0851	0.0011	2.6017	0.0384	0.2210	0.0021	0.0626	0.0011	1318	26	1301	11	1287	11	98%		
U-Pb2021032.18	73	41	299	0.14	0.0843	0.0011	2.5772	0.0376	0.2212	0.0019	0.0468	0.0012	1298	26	1294	11	1288	10	99%		

Table A2. Analysis results of major elements (%), rare earth elements (10^{-6}), and trace elements (10^{-6}) of Mesoproterozoic granites in Inner Mongolia.

Sample	2021036	2021037	2021038	2021019	2021020	2021030	2021031	2021032	2021034
	(Xiaoyingtu Intrusion)			(Chahan Intrusion)			(1488. Highland Intrusion)		
SiO ₂	67.72	63.39	63.10	71.90	72.13	76.71	73.73	69.91	71.30
TiO ₂	0.67	0.66	0.91	0.38	0.40	0.16	0.26	0.55	0.33
Al ₂ O ₃	15.23	17.64	16.59	13.93	13.59	12.04	13.23	14.44	14.19
Fe ₂ O ₃	1.20	3.59	2.35	0.94	0.90	0.45	0.75	0.98	0.65
FeO	3.28	2.58	3.52	1.77	1.97	0.98	1.52	2.72	1.78
MnO	0.041	0.061	0.046	0.03	0.032	0.017	0.023	0.034	0.035
MgO	1.16	1.73	1.81	0.66	0.71	0.28	0.30	0.90	0.54
CaO	1.92	0.93	1.97	1.61	1.42	0.80	1.17	1.53	1.26
Na ₂ O	2.17	1.37	2.11	2.84	2.66	2.11	2.29	2.65	2.39
K ₂ O	5.11	4.91	5.16	4.99	5.25	5.75	5.92	5.06	6.39
P ₂ O ₅	0.164	0.091	0.098	0.15	0.136	0.051	0.049	0.122	0.170
LOI	0.78	2.58	1.72	0.49	0.46	0.47	0.51	0.65	0.58
Total	99.82	99.83	99.76	99.87	99.87	99.93	99.91	99.84	99.83
Rb	246	246	235	209.92	241	263	295	247	338
Ba	776	779	1036	540	552	308	331	698	1056
Th	30.4	26.9	40.2	15.75	20.6	14.40	54.9	21.5	14.4
U	2.72	2.65	3.39	2.36	3.18	2.37	1.92	3.23	2.11
Nb	30.1	16.5	31.7	19.00	22.8	12.40	20.8	23.4	21.8
Ta	1.13	1.63	1.44	1.07	1.82	0.77	0.65	1.25	1.60
La	89.3	88.5	162	58.1	66.4	31.47	166	76.94	49.25
Ce	170	166	299	112	128	74.70	369	147	96.3
Pr	15.5	15.5	26.9	13.1	11.5	7.58	27.1	13.2	11.4
Sr	150	82.4	196	90.6	108	56.5	97.5	118	125
Nd	67.8	68.2	93.2	44.8	50.8	25.60	84.3	58.2	39.3
Zr	275	186	331	189	193	105	205	248	153
Hf	8.77	5.40	9.35	5.37	5.68	3.53	6.72	6.94	4.53
Sm	11.5	11.9	18.8	7.83	9.06	5.31	15.1	9.77	7.41
Eu	1.27	1.47	1.90	0.90	0.84	0.52	0.67	1.19	1.27
Gd	9.87	10.4	16.4	6.89	8.07	4.97	13.8	8.45	7.00
Tb	1.39	1.41	2.10	1.02	1.22	0.96	1.46	1.16	1.20
Dy	7.25	6.80	10.6	5.43	6.50	6.57	6.10	5.66	7.54
Y	37.9	27.3	47.4	24.2	27.7	36.90	21.2	24.4	38.3
Ho	1.42	1.10	1.87	0.91	1.08	1.37	0.95	0.93	1.49
Er	4.51	2.94	5.29	2.58	2.88	4.24	2.72	2.60	4.44
Tm	0.73	0.40	0.78	0.38	0.43	0.70	0.35	0.39	0.72
Yb	4.32	2.22	4.66	2.16	2.45	4.20	1.93	2.29	4.39
Lu	0.70	0.34	0.75	0.35	0.38	0.65	0.30	0.36	0.68

Table A3. Zircon in situ Hf isotope analysis results of medium-grained porphyritic biotite monzogranite.

Periods	Age (Ma)	$\frac{^{176}\text{Yb}}{^{177}\text{Hf}}$	2 σ	$\frac{^{176}\text{Lu}}{^{177}\text{Hf}}$	2 σ	$\frac{^{176}\text{Hf}}{^{177}\text{Hf}}$	2 σ	$\epsilon_{\text{Hf}}(\text{t})$	$\epsilon_{\text{Hf}}(0)$	T _{DM1}	T _{DM2}	f _{Lu/Hf}
U-Pb20200055												
−1	1283	0.0310	0.0006	0.0008	0.0000	0.281956	0.000027	−1.08	−28.86	1812	2130	−0.98
−2	1273	0.0608	0.0010	0.0016	0.0000	0.282080	0.000031	2.41	−24.47	1676	1905	−0.95
−3	1284	0.0324	0.0004	0.0009	0.0000	0.281807	0.000032	−6.43	−34.13	2022	2462	−0.97
−4	1276	0.0594	0.0006	0.0016	0.0000	0.282065	0.000028	1.94	−25.00	1698	1936	−0.95
−5	1281	0.0354	0.0003	0.0010	0.0000	0.281906	0.000028	−3.07	−30.63	1891	2252	−0.97
−6	1278	0.0275	0.0003	0.0008	0.0000	0.281819	0.000023	−6.05	−33.70	2001	2434	−0.98
−7	1278	0.0671	0.0045	0.0017	0.0001	0.281925	0.000032	−3.07	−29.95	1900	2249	−0.95
−8	1280	0.0155	0.0002	0.0004	0.0000	0.281866	0.000026	−4.00	−32.04	1916	2309	−0.99
−9	1276	0.0303	0.0004	0.0008	0.0000	0.281945	0.000027	−1.62	−29.25	1827	2158	−0.98
−10	1282	0.0285	0.0003	0.0008	0.0000	0.281860	0.000022	−4.51	−32.25	1944	2342	−0.98
−11	1280	0.0187	0.0001	0.0006	0.0000	0.281902	0.000018	−2.90	−30.77	1877	2240	−0.98
−12	1279	0.0318	0.0004	0.0009	0.0000	0.281883	0.000020	−3.84	−31.44	1918	2298	−0.97
−13	1278	0.0317	0.0002	0.0008	0.0000	0.281946	0.000018	−1.54	−29.21	1826	2155	−0.98
−14	1274	0.0283	0.0003	0.0008	0.0000	0.281933	0.000018	−2.10	−29.67	1844	2186	−0.98
−15	1278	0.0310	0.0006	0.0008	0.0000	0.281956	0.000027	−1.20	−28.86	1812	2133	−0.98

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