



# Article Early Permian Granitic Magmatism in Middle Part of the Northern Margin of the North China Craton: Petrogenesis, Source, and Tectonic Setting

Longxue Li<sup>1</sup>, Qingye Hou<sup>1,\*</sup>, Dingling Huang<sup>2</sup> and Xinyu Wang<sup>3</sup>

- School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China; longxueli@cugb.edu.cn
- <sup>2</sup> School of Field Engineering, Army Engineering University of People's Liberation Army of China, Nanjing 210001, China; huang\_dl@126.com
- <sup>3</sup> Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China; wangxinyu@cags.ac.cn
- \* Correspondence: qingyehou@cugb.edu.cn

Abstract: The late Palaeozoic was an important period of tectonic evolution for the northern margin of the North China Craton (NCC). The source(s) and tectonic setting of early Permian granitoid rocks emplaced along the northern margin of the NCC are still unclear. These granitoids formed between ~295.4–276.1 Ma (uncertainties ranging from  $\pm 1.5$  to  $\pm 7.8$  Ma) according to zircon laser ablation inductively coupled mass spectrometry (LA-ICP-MS) and sensitive high-resolution ion microprobe (SHRIMP) U-Pb data. The Dadongou (DDG) pluton is an A1-type granite and the Dananfangzi (DNFZ) pluton is an A2-type granite. The Erdaowa (EDW), Lisicun (LSC), Wuhai (WH) and Gehuasitai (GHST) plutons are I-type granites. The Yuanbaoshan (YBS) dykes are diorite and syenodiorite. All the granitoids are enriched in large ion lithophile elements and light rare earth elements, depleted in high field strength elements and have negative  $\varepsilon Nd(t)$  and  $\varepsilon Hf(t)$  values. The A1-type granite was formed by the melting of the mafic crust. The A2-type granite was derived from partial melting of tonalite gneiss from the NCC crust and mantle materials. The EDW, LSC, WH and GHST granites mainly originated from partially melted granulite, with some mantle input. The YBS dykes are formed by the magma mixing of hot mantle melt and the relatively cold crustal magma. The northern margin of the NCC experienced anorogenic and collision tectonic stages, and the structural setting started to transform to post-collision at the later period of early Permian.

Keywords: early permian; geochemistry; granitoids; North China Craton; petrogenesis

# 1. Introduction

The formation process and tectonic background of igneous rocks are important keys for understanding the geologic history of the continental margin. The northern margin of the North China Craton (NCC) is adjacent to the southern margin of the Xing Meng Orogenic Belt (XMOB) and within the eastern section of the Central Asian Orogenic Belt (CAOB), the largest Phanerozoic accretionary orogenic belt in the world. The CAOB formed by subduction-accretion during the Palaeozoic as a result of the closure of the Paleo-Asian Ocean (PAO) [1]. However, the timing of subduction, accretion and the PAO closure are uncertain. Previously proposed ages of the PAO closure include the late Silurian to Devonian [2], middle to late Devonian [3] and Permian to early Triassic [4–6]. Large volumes of Palaeozoic and Mesozoic magmatic rocks are distributed along the northern margin of the NCC. The evolution of the northern margin of the NCC was strongly influenced by the southward subduction and closure of the PAO from the early Palaeozoic to the Triassic [7,8]. Therefore, these magmatic rocks could provide insight into the timing of the PAO closure. Studies on early Permian magmatic rocks along the northern margin of the NCC have inferred that they were formed in different tectonic settings. Previous



Citation: Li, L.; Hou, Q.; Huang, D.; Wang, X. Early Permian Granitic Magmatism in Middle Part of the Northern Margin of the North China Craton: Petrogenesis, Source, and Tectonic Setting. *Minerals* **2021**, *11*, *99*. https://doi.org/10.3390/ min11020099

Received: 22 November 2020 Accepted: 17 January 2021 Published: 20 January 2021

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). researches on granites, granodiorites and diorites have proposed the presence of an active continental margin related to the subduction of the PAO [4–6,9–12], while others [13] have suggested that the rocks resulted from intraplate extensional processes along lithospheric faults on the northern margin of the NCC. The authors of [14] analysed the early Permian A-type granites and emphasized that the A-type granites formed within a post-collisional tectonic setting.

To further discuss the sources, petrogenesis and tectonic setting in which these early Permian magmatic rocks formed, we collected granitoid rock samples from the central region of the northern margin of the NCC and obtained data on their petrography, major and trace element contents, Sr-Nd-Pb isotopes, laser ablation inductively coupled mass spectrometry (LA-ICP-MS) zircon U-Pb geochronology and Hf isotopes compositions. These new data, combined with existing data from previous studies, enable us to constrain the geologic evolution of the northern margin of the NCC and the XMOB.

# 2. Geologic Background and Petrography

## 2.1. Geologic Setting

The NCC formed at ~3.8 Ga and was modified by several tectonic episodes from the Neoproterozoic to the early Mesozoic [15]. The basement of the NCC is composed of late Archean tonalite-trondhjemite-granodiorite suites (TTGs), ~2.6–2.5 Ga gneisses, mafic-ultramafic intrusive rocks and a few supracrustal rocks (including sedimentary and bimodal volcanic rocks), as well as early Proterozoic TTGs (2.4–2.5 Ga) [6], mafic granulites (1.8 Ga) [16] and syntectonic or post-tectonic granites [11]. The northern margin of the NCC is located adjacent to the eastern section of the CAOB (Figure 1), which is one of the largest Phanerozoic accretionary orogenic belts in the world [1,4].



**Figure 1.** Geological sketch map of the middle part of the north margin of the North China Craton (NCC) [5].

The northern margin of the NCC was strongly influenced by the PAO tectonic system between the Carboniferous and the Permian [7]. It is generally thought that the PAO subducted southward beneath the NCC [4], causing the formation of magmatic rock belts along the northern margin of the NCC during the late Palaeozoic and the early Mesozoic [7,11,17,18]. Magmatic rocks that formed in the late Carboniferous and early Permian are mainly diorites, quartz diorites, granodiorites and granites, as well as occasional tonalites and gabbros [18]. The granitoids are mostly I-type granites with small amounts of A-type granites [11].

Permian magmatic rocks are widely distributed in Inner Mongolia [17,19–39], forming an E-W trending belt that runs parallel to the northern margin of the NCC (Figure 2). The rock assemblages include diorite, quartz diorite and granite, followed by gabbro. Only a small amount of Permian volcanic rocks was emplaced in the northern margin of the NCC. Late Permian magmatic rocks are widely distributed on both sides of the Baiyun Obo–Chifeng–Fuxin Fault, which is considered the boundary between the northern margin of the NCC and the XMOB [4]. Early Permian ultramafic-mafic rocks occur on the northern margin of the NCC. Their distributions are controlled by the Jining–Chengde and Fengning–Longhua–Jianping faults, which are two long-term active lithospheric fault zones in the northern margin of the NCC. These ultramafic-mafic rocks intruded into lower carboniferous rocks and were penetrated by synchronous quartz diorites and granitoids.



**Figure 2.** Distribution of early Permian granitoids in the middle part of the northern margin of the NCC (modified from [40,41]).

We collected 32 whole rocks and 9 zircon samples from 8 early Permian intrusive granitoid rocks and dykes in the central region of the northern margin of the NCC (Figures 2 and 3a,b). The sampling transect was approximately 80 km along the northern margin of the NCC and 100 km in the vertical direction. The samples were from Dananfangzi (DNFZ), Dadonggou (DDG), Erdaowa (EDW), Lisicun (LSC), Gehuasitai (GHST), Wuhai (WH) and Yuanbaoshan (YBS) intrusive rocks and dykes. The early Permian intrusive rocks and dykes coexist with the early Palaeozoic magmatic rocks.

### 2.2. Petrography

The early Permian granitoids analysed in this study include alkali-feldspar granite, granite, diorite and syenodiorite. Alkali-feldspar granites are the dominant phase in the DNFZ and DDG intrusive rocks. They are characterized by leucocratic grey-coloured to reddish crystals and are medium- to coarse-grained. They consist mainly of slightly subhedral kaolinized K-feldspar (60–70%) and anhedral undulous quartz (25–35%), with accessory subhedral to euhedral heavily sericitized plagioclase (<8%) and small flakes of chloritized biotite (Figure 4c). EDW, LSC, WH and GHST granites are composed of medium- to coarse-grained granite that predominantly contain slightly sericitized plagioclase (25–60%), as well as K-feldspar (25–60%), anhedral quartz (20–30%) and biotite (3–9%) (Figure 4d–g).



**Figure 3.** Sketched geological maps of early Permian granitoids in the middle part of the northern margin of the NCC. (**a**) Erdaowa pluton (EDW), Gehuasitai pluton (GHST), Lisicun pluton (LSC); (**b**) Dadongou pluton (DDG); (**c**) Yuanbaoshan dikes (YBS); (**d**) Dananfangzi pluton (DNFZ).

YBS dykes are grained syenodiorite and diorite. Diorite is made up of near-idiomorphic amphibole (45%), subhedral to euhedral plagioclase (40%), subhedral biotite (10%), an-hedral quartz (5%) and biotite (<5%) (Figure 4h). Syenodiorite consists of near-idiomorphic amphibole (40%), subhedral plagioclase (30–35%), subhedral K-feldspar (15–20%) subhedral biotite (<5%) and anhedral quartz (<5%) (Figure 4i,j).



**Figure 4.** Representative field photos and photomicrographs of the Early Permian granitoids in the middle part of the northern margin of the NCC. (**a**) LSC pluton field photo; (**b**) YBS dyke field photo; (**c**) DNFZ, Dananfangzi pluton; HB-25, alkali-feldspar granite; (**d**) EDW, Erdaowa pluton; HB-75, granite; (**e**) LSC, Lisicun pluton; NMH15-2, granite; (**f**) WH, Wuhai pluton; HB-44, granite; (**g**) GHST, Gehuasitai pluton; HB-53, granite; (**h**) YBS, Yuanbaoshan dyke; HB-180, diorite; (**i**) YBS, HB179-3, syenodiorite; (**j**) YBS, HB178-3, syenodiorite. K fs, Potassium feldspar; Bt, biotite; Qz, quartz; Pl, plagioclase; Hb, hornblende and Ap, apatite.

## 3. Methods

## 3.1. Whole-Rock Analysis

Of the rock samples, 32 that did not contain veins or evidence of alteration were crushed and powdered using a pollution-free agate ball mill. Then, they were passed through a 200-mesh sieve. Major and trace elements were measured using X-ray fluores-cence (XRF) on a ZSX100e instrument (Rigaku Corporation, Tokyo, Japan), following the method of [42], and inductively coupled plasma mass spectrometry (ICP-MS) on an X SERIES II instrument (Thermo Electron Corporation, Waltham, MA, USA), respectively, at the Henan Rock and Mineral Testing Centre, China. FeO was determined using the potassium dichromate volumetric method. A set of standards was analysed to monitor instrument precision during XRF analyses and yielded precision better than 3%. The GSR21 and GSR22 [43] standards were analysed during all ICP-MS analyses and yielded precision typically better than 10%.

Whole Sr-Nd-Pb isotopic compositions of fifteen powdered rock samples were measured using isotope dilution thermal ionization mass spectrometry (ID-TIMS) at the Beijing Research Institute of Uranium Geology, China. The Sm-Nd isotopes used <sup>146</sup>Nd/<sup>144</sup>Nd = 0.7219 and the Rb-Sr isotopes used <sup>88</sup>Sr/<sup>86</sup>Sr = 8.37521 to correct for fractionation. Analyses of standard samples had the following results: The JMC standard (Nd<sub>2</sub>O<sub>3</sub>) yielded <sup>143</sup>Nd/<sup>144</sup>Nd = 0.512109  $\pm$  3; the NBS987 standard (SrCO<sub>3</sub>) yielded <sup>87</sup>Sr/<sup>86</sup>Sr = 0.710250  $\pm$  7; and the NBS981 standard yielded <sup>206</sup>Pb/<sup>204</sup>Pb = 16.917  $\pm$  2, <sup>207</sup>Pb/<sup>204</sup>Pb = 15.468  $\pm$  7, and <sup>208</sup>Pb/<sup>204</sup>Pb = 36.625  $\pm$  15 (all ratios are weighted means with 2 $\sigma$  errors). Whole-rock major and trace element data and Sr-Nd-Pb isotopic compositions [44,45] are listed in Table S1 and Table S2, respectively.

#### 3.2. Zircon Analyses

Zircons were separated from 9 rock samples using standard methods (e.g., crushing, panning, magnetically separating and processing through heavy liquids) at the Hebei Institute of Regional Geology and Mineral Resources Survey, China. Approximately 100 zircon grains were handpicked from each sample using a binocular microscope. The grains were mounted on an epoxy resin disc along with several grains of the TEMORA [46] zircon standard, ground down to expose their interiors and polished. The zircon grains were then imaged using cathodoluminescence (CL) at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The zircons were mostly euhedral stubby to long prismatic grains, but some grains had slightly or variably rounded terminations (Figure 5). The photomicrographs showed excellent crystal morphology under CL, with variable textures from shared oscillatory zoning to sector zoning, as was the case for magmatic zircons. The different zircon shapes and internal structures reflected variable transport and relatively heterogeneous source rocks. Magmatic zoning was characterized by moderate Th/U, which was ubiquitous under CL. Some of the grains were dark (high-U) or had dark rims and light-grey (low-U) cores. The U content of the analysed zircons was highly variable, ranging from 32.98 ppm to 3608.6 ppm (Table S3).

## 3.2.1. SHRIMP Zircon Analyses

Sample NMH9-5 from the DDZ was dated using a sensitive high-resolution ion microprobe (SHRIMP) with an accelerating voltage of ~10 kV, an ion beam current of ~7.5 nA and a beam diameter of 25–30  $\mu$ m at the Beijing SHRIMP Centre, Institute of Geology, Chinese Academy of Geological Sciences. Data obtained from the SHRIMP analyses were processed and analysed using the PRAWN software package from the Australian National University [47].



**Figure 5.** Cathodoluminescence (CL) images of representative zircons analysed from various granitoids or dykes in the middle part of the north margin of the NCC. The U-Pb ages and  $\varepsilon$ Hf(t) values are given for each spot. The scale bar in all CL images is 100 µm. (a) DNFZ pluton, HB25-2; (b) DDG pluton, NMH9-5; (c) EDW pluton, HB75-2; (d) WH pluton, HB44-2; (e) LSC pluton, NMH15-1; (f) GHST pluton, HB53-2; (g) YBS dyke, HB179-2; (h) YBS dyke, HB179-4.

# 3.2.2. LA-ICP-MS Zircon Analyses

The other zircon samples were dated using laser ablation (LA) single collector ICP-MS with an acceleration voltage of ~15 kV, an ion beam current of ~4 n, and a beam diameter of ~32 µm at the China University of Geoscience, Wuhan, China. The zircon standards 91500 (primary standard ~1065 Ma) [48] and GJ-1 (~608 Ma) [49] were also analysed at regular intervals throughout each run to assess the reproducibility and accuracy of the measured isotopic ratios and to correct for U/Pb fractionation. The weighted mean ages of the 91500 and GJ-1 zircon standards were 1061.8  $\pm$  2.2 Ma (n = 74, MSWD = 0.49) and 598.6  $\pm$  4.4 Ma (n = 35, MSWD = 7.8), respectively (all errors are 2 $\sigma$ ). The analytical procedure for U-Pb dating has been described in detail previously [50]. The measured <sup>204</sup>Pb was used to correct for common Pb. Data obtained from the LA-ICP-MS analyses were processed using the ICPMSDataCal software package [50].

Zircon Hf isotopic analyses were performed in situ on the same samples used for U-Pb dating using a Newwave UP213 laser-ablation microprobe (Elemental Scientific, Omaha, NE, USA) attached to a Finnigan Neptune multi-collector ICP-MS (Thermo Fisher Scientific, Germany), following the analytical procedures of [51], at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, China. A stationary spot with a beam diameter of 55  $\mu$ m was used. The ablated sample was transported, using He as the carrier gas, from the laser-ablation cell to the ICP-MS torch via a mixing chamber filled with He. The GJ-1 zircon standard was also analysed, and yielded <sup>176</sup>Hf/<sup>177</sup>Hf ratios

indistinguishable from the weighted mean  $^{176}$ Hf/ $^{177}$ Hf ratio of 0.282006  $\pm$  14 (2 $\sigma$ ). Care was taken to ablate spots immediately adjacent to those used for U-Pb determination within the same CL imaged zone. LA-ICP-MS zircon U-Pb ages and Lu-Hf isotopic data [52–55] are listed in Table S3 and Table S4, respectively. All reported errors include only the analytical error.

#### 4. Results

## 4.1. Zircon U-Pb Geochronology

We report the zircon  $^{206}$ Pb/ $^{238}$ U age as the best ages for grains younger than 1000 Ma and the  $^{207}$ Pb/ $^{206}$ Pb age for grains older than 1000 Ma [56]. Figures 5 and 6 show representative CL images of the zircon samples, zircon U-Pb Concordia diagrams and weighted mean  $^{206}$ Pb/ $^{238}$ U ages. The majority of the samples were within 10% concordance and most of the ages were well grouped (Figure 6).

#### 4.1.1. Alkali-Feldspar Granites

We found that 6 zircons from sample HB25-2 from the DNFZ provided concordant results, with a mean  $^{206}$ Pb/ $^{238}$ U age of 284.7  $\pm$  7.8 Ma (Figure 6a), whereas 12 concordant zircon grains from sample NMH9-5 from the DDG yielded a mean age of 295.4  $\pm$  4.7 Ma (Figure 6b). No inherited cores were involved in the calculation (Figure 5).

## 4.1.2. Granites

Six analysed zircon grain spots from sample HB75-2 from the EDW were calculated. Analysis spots were located on zircon rims with oscillatory zoning, which provided concordant results with a mean  $^{206}$ Pb/ $^{238}$ U age of 278.1  $\pm$  5.3 Ma (Figure 6c). Three dark (high-U) inherited cores yielded much older ages of 902  $\pm$  17 Ma, 1028  $\pm$  79 Ma, and 2420  $\pm$  38 Ma, and may have been associated with the Proterozoic magmatic thermal event (2.4–1.8 Ga) [16,57] on the northern margin of the NCC. The inherited ages suggest that the continental basement was involved in later magmatic processes.

Eight well-zoned magmatic zircon grains from sample NMH15-1 from the LSC provided concordant data, with a weighted mean <sup>206</sup>Pb/<sup>238</sup>U age of 281.9  $\pm$  1.5 Ma (Figure 6d). Ten zoned zircon grains from sample HB53-2 from the GHST provided concordant results, with a mean <sup>206</sup>Pb/<sup>238</sup>U age of 276.1  $\pm$  3.2 Ma (Figure 6e). Eight zircons analysed from sample HB44-2 from the WH yielded a weighted mean <sup>206</sup>Pb/<sup>238</sup>U age of 279.8  $\pm$  4.3 Ma (Figure 6f).

#### 4.1.3. Diorite and Syenodiorite

Ten zircon grains from sample HB179-2 from the YBS syneodiorite dyke yielded a weighted mean age of  $284.4 \pm 5.2$  Ma (Figure 6g). Eleven zircon spots from sample HB179-4 from the YBS diorite dyke provided concordant results, with a mean  $^{206}$ Pb/ $^{238}$ U age of  $282.2 \pm 4.3$  Ma (Figure 6h).

## 4.2. Major and Trace Element Contents

The alkali-feldspar granites had high SiO<sub>2</sub> (68.71–76.58%), Al<sub>2</sub>O<sub>3</sub> (12.04–14.66%) and K<sub>2</sub>O content and low TFe<sub>2</sub>O<sub>3</sub>, MgO and CaO content. As shown by the diagram of K<sub>2</sub>O vs. SiO<sub>2</sub> (Figure 7a), most of the samples fell into the high-K calc-alkaline and shoshonite series. They had K<sub>2</sub>O/Na<sub>2</sub>O ratios of 0.89–2.17, their Al<sub>2</sub>O<sub>3</sub>/(CaO + Na<sub>2</sub>O + K<sub>2</sub>O) ratios (A/CNK) were 0.85–1.08 and their Al<sub>2</sub>O<sub>3</sub>/(Na<sub>2</sub>O+K<sub>2</sub>O) ratios (A/NK) were 0.88–1.22. Most of the samples were peraluminous, and the DDG alkali-feldspar granites were metaluminous (Figure 7b). The DNFZ and DDG alkali-feldspar granites had total rare earth element (REE) concentrations of 162.34–398.48 ppm, with enriched light REEs (LREEs) [(La/Yb)<sub>N</sub> = 8.80–33.02] and negative Eu anomalies (Eu/Eu\* = 0.12 – 0.58) (Figure 8a). All alkali-feldspar granite samples displayed depletions in Sr, P and Ti (Figure 9a,b).



**Figure 6.** Zircon U-Pb Concordia diagrams of various granitoids or dykes in the middle part of the northern margin of the NCC. (a) HB25-2; (b) NMH9-5; (c) HB75-2; (d) HB44-2; (e) NMH15-1; (f) HB53-2; (g) HB179-2; (h) HB179-4. Sensitive high-resolution ion microprobe (SHRIMP) age for sample NMH9-5. All other ages were determined by laser ablation inductively coupled mass spectrometry (LA-ICP-MS).



**Figure 7.** Classification diagrams for early Permian granitoids in the middle part of the north margin of the NCC. (a) Plot of  $K_2O$  vs. SiO<sub>2</sub>; (b) plots of Al<sub>2</sub>O<sub>3</sub>/(Na<sub>2</sub>O+K<sub>2</sub>O) ratios (A/NK) vs. Al<sub>2</sub>O<sub>3</sub>/(CaO+Na<sub>2</sub>O+K<sub>2</sub>O) ratios (A/CNK) ratios.



**Figure 8.** Chondrite-normalized rare earth element (REE) patterns for early Permian granitoids in the middle part of the north margin of the NCC. (a) Plot of DNFZ pluton and DDG pluton; (b) Plot of EDW pluton; (c) Plot of LSC pluton, GHST pluton and WH pluton; (d) Plot of YBS dykes. Chondrite normalized data are from [58].



**Figure 9.** Primitive mantle-normalized trace element diagrams for early Permian granitoids in the middle part of the north margin of the NCC. (a) Plot of DNFZ pluton and DDG pluton; (b) Plot of EDW pluton; (c) Plot of LSC pluton, GHST pluton and WH pluton; (d) Plot of YBS dykes. Primitive mantle normalized data are from [58].

The granites had a high and restricted SiO<sub>2</sub> range from 72.34–77.37%, with high Al<sub>2</sub>O<sub>3</sub> (13.05–14.53%) and total alkalis (6.19–8.92%) and low MgO and TiO<sub>2</sub> concentrations. Most of the samples showed a high-K calc-alkaline character and were peraluminous, with A/CNK from 0.99 to 1.27 (Figure 7). They had lower total REE concentrations (27.53–140.31 ppm) than the DNFZ and DDG rocks, with enrichment in LREEs [(La/Yb)  $_{\rm N}$  = 2.16–20.08], and negative Eu anomalies (Eu/Eu\* = 0.41–1.49) (Figure 8b,c). All the granite samples displayed similar trace element patterns, with depletions in Nb, Ta, Sr, P and Ti and enrichments in Th, K, Zr and Hf (Figure 9b,c).

The YBS dykes exhibited relatively low SiO<sub>2</sub> content, ranging from 52.48–59.14%, variable total alkalis and high TFe<sub>2</sub>O<sub>3</sub> content and Mg#. Total REE content of the YBS dykes ranged from 109.42–224.90 ppm. They were enriched in LREEs [(La/Yb)  $_{\rm N}$  = 9.62–16.20], without a significant Eu anomaly (Figure 8d). They also showed enrichments in large-ion lithophile elements, such as Sr and LREEs, and strong depletions in Th, Nb, Ta, Hf and Ti (Figure 9d).

## 4.3. Sr-Nd-Pb Isotopic Compositions

Whole-rock Sr-Nd-Pb isotopic compositions and calculated initial Sr-Nd-Pb isotopic compositions based on the zircon U-Pb ages are presented in Table S2.

Alkali-feldspar granites had a wide range of  $({}^{87}\text{Sr}/{}^{86}\text{Sr})_t$  from 0.70591 to 0.71694, negative  $\epsilon_{Nd}(t)$  values of -12.37 to -7.86, model ages  $(T_{DM}{}^C)$  from 2057 Ma to 1700 Ma, initial  ${}^{206}\text{Pb}/{}^{204}\text{Pb}$  ratios of 16.858 to 18.060, initial  ${}^{207}\text{Pb}/{}^{204}\text{Pb}$  ratios of 15.301 to 15.539 and initial  ${}^{208}\text{Pb}/{}^{204}\text{Pb}$  ratios of 37.191 to 38.226. Granites exhibited initial  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  ratios of 0.70970 to 0.71745, negative  $\epsilon_{Nd}$  (t) values of -12.63 to -10.68, model ages  $(T_{DM}{}^C)$  from

2066 Ma to 1916 Ma, initial <sup>206</sup>Pb/<sup>204</sup>Pb ratios of 17.881 to 18.638, initial <sup>207</sup>Pb/<sup>204</sup>Pb ratios of 15.515 to 15.569 and initial <sup>208</sup>Pb/<sup>204</sup>Pb ratios of 37.715 to 37.939. YBS quartz dykes were characterized by initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios of 0.68938 to 0.70692, negative  $\varepsilon_{Nd}(t)$  values of -12.59 to -10.64, model ages (T<sub>DM</sub><sup>C</sup>) from 2073 Ma to 1916 Ma, initial <sup>206</sup>Pb/<sup>204</sup>Pb ratios of 17.025 to 17.633, initial <sup>207</sup>Pb/<sup>204</sup>Pb ratios of 15.335 to 15.429 and initial <sup>208</sup>Pb/<sup>204</sup>Pb ratios of 37.162 to 37.550.

#### 4.4. Zircon Hf Isotopic Compositions

Some concordant zircons dated using LA-ICPMS were also analysed for their Hf isotopic compositions. The zircon Lu-Hf isotopic data, depleted mantle extraction ( $T_{DM}$ ) and crustal model ages ( $T_{DM}^{c}$ ) of these samples are listed in Table S4 and plotted in Figure 10.



**Figure 10.**  $\varepsilon$ Hf(t) vs. U-Pb age plot for zircons from the early Permian granitoids in the middle part of the north margin of the NCC. Basement data source: [16,59–61].

Alkali-feldspar granites had  $\varepsilon_{\text{Hf}}$  (t) values of -19.4 to -5.7, with crustal model ages ( $T_{\text{DM}}^{\text{C}}$ ) of 2530–1664 Ma. Granites had  $\varepsilon_{\text{Hf}}$  (t) values from -26.8 to -7.4 and crustal model ages ( $T_{\text{DM}}^{\text{c}}$ ) of 2665–1506 Ma. The YBS dykes exhibited  $\varepsilon_{\text{Hf}}$  (t) values of -11.6 to -3.1, corresponding to crustal model ages ( $T_{\text{DM}}^{\text{c}}$ ) of 2030–1496 Ma.

# 5. Discussion

# 5.1. Rock Classification

5.1.1. Alkali-Feldspar Granites

DNFZ and DDG alkali-feldspar granites contain high percentages of alkaline feldspars and are high in SiO<sub>2</sub>, K<sub>2</sub>O, K<sub>2</sub>O+Na<sub>2</sub>O, K<sub>2</sub>O/Na<sub>2</sub>O and TFeO/MgO. These samples have low contents of Al<sub>2</sub>O<sub>3</sub>, CaO, MgO and P<sub>2</sub>O<sub>5</sub>. The P<sub>2</sub>O<sub>5</sub> content is negatively correlated with the SiO<sub>2</sub> content. They have large negative anomalies in Nb, Ta, Sr, P, Ti and Eu. Their Rb, Ga, Y and Zn contents are relatively high. The samples are plotted in the field of the A-type granite (Figure 11) [62,63].



**Figure 11.** Plots of oxides or trace elements vs.  $10000 \times \text{Ga/Al}$  for the DNFZ and DDG plutons [63]. (a) Plot of K<sub>2</sub>O/MgO vs.  $10000 \times \text{Ga/Al}$ ; (b) Plot of FeO<sup>T</sup>/MgO vs.  $10000 \times \text{Ga/Al}$ ; (c) Plot of Na<sub>2</sub>O + K<sub>2</sub>O (wt%) vs.  $10000 \times \text{Ga/Al}$ ; (d) Plot of (Na<sub>2</sub>O + K<sub>2</sub>O)/CaO vs.  $10000 \times \text{Ga/Al}$ ; (e) Plot of Zn (×10<sup>-6</sup>) vs.  $10000 \times \text{Ga/Al}$ ; (f) Plot of Nb (×10<sup>-6</sup>)vs.  $10000 \times \text{Ga/Al}$ . The oxide contents were recalculated to 100 wt.% on an anhydrous basis.

DNFZ and DDG plutons have high contents of REE, large negative Eu and Sr anomalies and strong depletions in high field strength elements (HFSEs) such as Nb and Ti. Both A-type granites and highly differentiated granites could exhibit these geochemical characteristics. A-type granites have high TFe<sub>2</sub>O<sub>3</sub> (>1%), while TFe<sub>2</sub>O<sub>3</sub> is usually low (<1%) in highly fractionated granites [64]. The DNFZ and DDG plutons also have relatively high TFe<sub>2</sub>O<sub>3</sub> (1.87% on average) content. Furthermore, the samples from the DNFZ and DDG contain no elbaite, lepidolite, lithium muscovite or beryl, which are lithogenous mineral markers of highly fractionated granites [65]. The zircons in highly fractionated granite are usually anhedral because of their late crystallization [65,66]. The zircon grains of samples are also mostly euhedral. Therefore, the DNFZ and DDG plutons are interpreted as A-type granites rather than highly fractionated granites.

The source area of A1-type granite is similar to that of ocean island basalts, while the source area of A2-type granite is derived from the continental crust or curst formed by underplating [67]. The Y/Nb ratio can be used to distinguish two subtypes of A-type granites because the Y/Nb ratio is mainly controlled by the source rock types, and the influence of crystallization differentiation of pyroxene, amphibole and opaque minerals on the Y/Nb ratios is relatively weak [67]. A1-type granites are rich in Nb, while A2-type granites are rich in Y [67]. The DDG pluton is high in Nb while it is low in Y, displaying an A1-type feature. The DNFZ pluton has high values of Y and can be classified as A2type granite. The DDG pluton shows more distinctive A-type features than the DNFZ pluton, is peralkaline and has low contents of Al<sub>2</sub>O<sub>3</sub> and CaO. The DDG pluton appears to be a peralkaline A1-type granite. The DNFZ pluton contains perthite without alkaline melaminerals, such as arfvedsonite or riebeckite, and is metaluminous-peraluminous. The DNFZ pluton appears to be an aluminous A2-type granite.

## 5.1.2. Granites

The granites have higher SiO<sub>2</sub> contents and large A/CNK ranges, are generally weakly peraluminous and contain small amounts of normative corundum (typically < 1%). The majority of the samples belong to the high-K calcium alkaline series and display I-type granite characteristics in a K<sub>2</sub>O-Na<sub>2</sub>O diagram [62]. The granites contain no alkaline melaminerals and have low ratios of 1000×Ga/Al. The samples contain biotite and iron oxides rather than muscovite, cordierite and other strong aluminium diagnostic minerals. When the SiO<sub>2</sub> content of granite is above 75%, the P<sub>2</sub>O<sub>5</sub> content of I-type granites is less than 0.05%, whereas the P<sub>2</sub>O<sub>5</sub> content of S-type granites is greater than 0.1% [68]. The majority of our samples had P<sub>2</sub>O<sub>5</sub> contents less than 0.1% (mostly < 0.05%), and the P2O5 was content negatively correlated with the SiO2 content. Thus, our samples were interpreted to be I-type granites.

#### 5.2. Petrogenesis and Magma Sources

## 5.2.1. Alkali-Feldspar Granites

A-type granite magmas can be produced by (1) the melting of crustal igneous rocks [69], including tonalities, granodiorites [70] and tonalitic gneisses [71]; (2) mantle-derived alkaline basaltic magma [67]; or (3) the mixing of mantle-derived alkaline basaltic magma and crustal anatectic magma [72]. It is unlikely that the fractional crystallization of mantlederived alkaline basaltic magma formed DNFZ and DDG pluton. First, A-type granite formed by the crystallization differentiation of mantle-derived basic magma is usually accompanied by large-area contemporaneous basic-ultrabasic rocks [73]. However, only the basic dykes were exposed in the study area without the large-scale exposure of contemporaneous basic rocks. The differentiation and assimilation of mantle basic magma usually produce a series of rocks which change continuously from basic to intermediate and acidic [74]. There were no intermediate rocks accompanying the A-type granite plutons in study area. The DNFZ and DDG plutons had high Pb content, large negative Eu and Sr anomalies and strong depletions in high field strength elements (HFSEs) such as Nb and Ti. These characteristics indicate that plagioclase remained in the magma source and the granites formed at low pressure [75], which does not correlate with the results of differentiation and evolution of a mantle-derived basaltic magma [76].

The DDG A1-type granite was characterized by high SiO<sub>2</sub>, K<sub>2</sub>O and Na<sub>2</sub>O, while it was low in CaO, Mg<sup>#</sup>, Cr and Ni, showing major element characteristics reflecting middle-lower crustal partial melting [77]. The Sr and Nd isotopic compositions were similar to those of the lower crust in the northern margin of the NCC (Figure 12). Relatively low  $\varepsilon_{Nd}(t)$  values and older crustal model ages for the zircon Hf data show that the magma dominantly originated from ancient crustal intermediate rocks. The DDG pluton had relatively high contents of Nb and Ta, suggesting that the melting of mafic crust was involved in the formation.



**Figure 12.** Plots of Sr-Nd-Pb isotopic compositions of the early Permian granitoids in the middle part of the north margin of the NCC. (a)  $\varepsilon$  Nd(t) vs. (87Sr/86Sr)t; (b) 207Pb/204Pb vs. 206Pb/204Pb. Data sources: Mafic lower crust in the NCC from [78].

The DNFZ A2-Type granite was high in SiO<sub>2</sub>, K<sub>2</sub>O, Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub> and Pb. The DNFZ pluton had low contents of Eu, Ni, Nb and Ta, showing the features of felsic crust source. In the study area, exposed tonalite gneisses formed at 2.5–2.4 Ga [16]. Therefore, we consider the tonalite gneisses present in the lower NCC crust as a main source of the observed A2-type granite. The DNFZ granite had more significant mantle feature than DDG granite through Hf isotopic composition. The zircon Hf data of the DNFZ pluton show a mixture source of mantle and crust (Figure 10). The DNFZ granite, as the later pluton, had more mantle input, implying that the mantle activity became more intense later. The mantle magma provided heat that led to the crust melting and mantle material input during the formation of A2-type granites.

## 5.2.2. Granites

The granites had low Sr and Yb contents (<2 ppm), suggesting that they formed at medium to low pressures [70]. The partial melting of pre-existing crustal igneous rocks played a key role in the formation of I-type granitic magma [79]. High-K calc-alkaline mafic-intermediate rocks such as pyroxene granulites can evolve into a magma source for granite [80]. Petrologic data [80] have shown that the Neoarchean and Paleoproterozoic continental crust of the NCC is mainly composed of TTG and granulites metamorphosed from high-K calc-alkaline mafic-intermediate rocks. However, high-K calc-alkaline I-type granites can only evolve from the partial melting of calc-alkaline to high-K calc-alkaline mafic to intermediate metamorphosed from high-K calc-alkaline mafic intermediate metamorphosed from high-K calc-alkaline mafic-intermediate rocks [81]. The granites were likely formed by the partial melting of granulites metamorphosed from high-K calc-alkaline mafic-intermediate rocks in the NCC. A slight negative Eu anomaly and depletion in HFSEs such as Ti, P, Nb, and Ta indicate that residual plagioclase, rutile, titanite, apatite, and amphibole remained in the magma source. The strong depletions in Nb and Ta also show a crustal origin or magma that was contaminated by crustal material [82].

The ratios of K/Rb, Zr/Hf, Nb/Ta and Y/Ho are invariant in ordinary magma systems [83], while they are largely reduced in highly fractionated granites [66,84,85]. In this study, the average elemental ratios were 52.77 (Zr/Hf), 11.09 (Nb/Ta) and 29.29 (Y/Ho), which is not similar to the elemental ratios of highly fractionated granites. The ratios of Zr/Hf (>26) and Nb/Ta (<5), along with the low Be content, support that the granites mainly formed due to initial partial melting without strong fractional crystallization [84,86].

The Nd model ages and zircon  $\varepsilon_{Hf}(t)$  values of most of the samples are consistent with the ancient lower NCC crust. The zircon  $\varepsilon_{Hf}(t)$  values of granites were distributed between the lower crust and depleted mantle lines (Figure 10), implying that the crust was the main origin and that the mantle played a small part. The granites had a few ancient inherited zircons, which indicate the old crustal source. The samples had Hf crust model ages peaking at 2.2–1.8 Ga, corresponding to a period of NCC continental crustal accretion [57,87,88]. High SiO<sub>2</sub> and low concentrations of MgO, Ni and V indicate little or no mantle materials in the source. Thus, the granites in this study mainly originated from partial melting of the ancient mafic crust with a small added component of mantle material.

## 5.2.3. Diorite and Syenodiorite

Acicular apatites were developed in YBS syenodiorite, showing the process of fast cooling. Acicular apatites imply that the hot basic magma was injected into relatively cold acidic magma and crystallized rapidly. In the TFeO/MgO plot (Figure 13a), the samples followed the magma mixing trend [89]. The YBS diorite and syenodiorite had high Mg<sup>#</sup>, MgO, FeO, Cr and Ni content. The Mg<sup>#</sup> (48.57–55.61) of the YBS rocks was higher than those of the experimental melt formed by partial melting of basalt and eclogite at different pressures [90], suggesting that both crustal melting and mantle-derived magma acted as the magmatic source. The high ( $^{87}$ Sr/ $^{86}$ Sr)<sub>t</sub> and lower  $\varepsilon_{Nd}(t)$  and  $\varepsilon_{Hf}(t)$  also illustrate a mixture of mantle-derived components and crustal materials. Thus, we state that the YBS dykes were formed by the magma mixing of mantle basic magma and crust magma. The low SiO<sub>2</sub> and high Mg<sup>#</sup> content show that the mixed magma was dominated by mantle materials. The divergence of chemical composition between diorite and syenodiorite were caused by the different degrees of magma mixing.



Figure 13. (a) Plot of TFeO vs. MgO [89]; (b) plot of Ba vs. Nb/Y; (c) plot of Ba/Y vs. Nb/Y.

The  $Al_2O_3$  content in the YBS dykes was high and may have been caused by the melting of enriched mantle (EM) or plagioclase accumulation. However, the absence of an Eu anomaly in these samples indicates that plagioclase accumulation was not significant, and that the high Al content was likely from the mantle part of the magma source of the dykes. The YBS dykes were depleted in Nb, Ta and Ti, which was caused by lithospheric mantle metasomatism by a fluid or by crustal contamination. Furthermore, the YBS dykes had high Ba content, ranging from 832–1821 ppm, reflecting a large fluid-related enrichment, while the nearly constant Th/Nb ratio showed a limited melt influence [91]. The plots of Ba-Nb/Y and Ba/Y-Nb/Y (Figure 13b,c) suggest that the YBS dykes were partly the result of fluid-related partial melting. Aqueous fluids were responsible for the enrichment of LREE and REE in these rocks [91]. The subducted PAO slab likely supplied fluid for partial mantle melting and enrichment.

#### 5.3. Tectonic Implications

The A1-type granites, in general, represent an anorogenic magmatism of continental rift or intraplate environment [67]. In this study, the DDG A1-type granite suggests that an anorogenic environment was present. The DDG granite is plotted in the anorogenic field in the R1-R2 diagram and within the plate granite field in the Rb-(Y+Nb) diagram (Figure 14). The tectonic setting of study area was likely to be anorogenic in the early period of the early Permian (295.4 Ma). It is generally believed that the A2-type granite formed in a post-orogenic environment or island arc environment and could be genetically related to subduction-related crustal melting or regional-scale mantle upwelling in the CAOB [92,93]. The DNFZ A2-type granite (284.7 Ma) showed the trend of post-collision or arc granite to syncollision granite (Figure 14). The DNFZ pluton was likely formed at the transient structural relaxed stage of subduction before the final suture of the PAO.



Figure 14. (a), Multicationic R1-R2 diagram [94]; (b), Rb-(Y+Nb) diagram [95].

The YBS dykes (284.4–282.2 Ma) formed though magma mixing and fluid-related partial melting (Figure 13). The fluid evolved as the result of dehydration of the subducting slab following the subduction of the CAOB. The YBS dykes in the pre-orogenic and volcanic arc granite field are plotted in Figure 14. The collision had not happened but was about to start between 284.4–282.2 Ma.

The LSC, WH, EDW and GHST granites (281.9–276.1Ma) mainly had the features of syncollision granites (Figure 14). These granites showed the trend of volcanic arc granites to syncollision granites and had slight post-collision granite features at the late period of early Permian. We hypothesized that the collision of the Siberian plate and the North China plate in study area occurred during the middle-late period of early Permian (281.9–276.1 Ma), while the remnant arc may have still existed in some areas. In the study area, granites (272–270 Ma) [32–35] that were formed slightly later than the LSC, WH, EDW and GHST plutons were formed in a post-collision background. These post-collision granites indicate that the closure of Paleo Asian Ocean was likely to take place before 272 Ma.

The closure time of the Paleo Asian Ocean has not been determined yet. The unconformable contact relationships and different deformation modes of the late Devonian molasse formation and ophiolitic mélange show that the collision and suture took place during the Devonian at the latest [96]. Other researchers agree the PAO was closed during the late Permian and early Triassic according to the geochronology and geochemistry of the late Palaeozoic basic-ultrabasic rocks and granitoids [7,11,97]. The geochemistry of granitoids mainly represents the features of source rocks and the information of the tectonic environment [95]. We speculate that the collision of the Siberian plate and the North China plate had not yet happened at 295.4–282.2 Ma and was likely to take place between 281.9–276.1 Ma. The structural setting started to transform to post-collision at the later period of the early Permian. The Paleo Asian Ocean was closed before the middle Permian in the middle part of the northern margin of the NCC, and the study area was in the post-collision setting during the middle Permian [32,98]. The early Permian granitoids with negative whole-rock  $\varepsilon_{Nd}(t)$  and zircon  $\varepsilon_{Hf}(t)$  values [7,11,27,50] with crustal characteristics are widely distributed in the eastern CAOB, Southern Mongolia, and the western CAOB [91,99,100]. Numerous researches have proven that the late Paleozoic magmatism in the northern margin of the NCC is related to the southward subduction of the PAO plate [7,11]. Large-scale magmatism indicates the occurrence of regional scale crustal remelting. Therefore, we suggest that the dehydration of the subducted PAO slab induced the interaction between fluids and the lower crust, causing partial melting of the lower crust. Accumulation of subducted slabs at the base of the mantle could cause widespread mantle upwelling events [101]. Subsequently, mantle upwelling aggravated the melting of crust.

#### 6. Conclusions

The integrated geochronological, major and trace elemental, and Sr-Nd-Pb isotopic and zircon Hf isotopic compositions of the granitoids from the central region of the northern margin of the NCC allowed us to reach the following conclusions:

(1) These granitoids can be classified as alkali-feldspar granites, granites, diorit, and syenodiorite. Geochronological analyses suggest that the alkali feldspar granites formed at 295.4–284.7 Ma, the granites formed at 281.9–276.1 Ma, and the diorite and syenodiorite formed at 284.4–282.2 Ma.

(2) The DDG pluton appeared to be A1-type granite, while the DNFZ pluton had a pronounced A2-type granite affinity. The A1-type granite was formed by the melting of the mafic crust. The A2-type granite was derived from partial melting of tonalite gneiss from the NCC crust and mantle materials. Granites mainly originated from partially melted granulite, with some mantle input. The YBS dykes were formed by the magma mixing of hot mantle melt and the relatively cold crustal magma. Our findings showed that the early Permian crustal evolution in northern margin of the NCC included a few juvenile crust inputs besides intracrustal circulation.

(3) The subduction and slab breakoff of the PAO led to widespread mantle upwelling events, and this mantle upwelling initiated large-scale remelting of the lower crust. The northern margin of the NCC experienced anorogenic and collision tectonic stages, and the structural setting started to transform to post-collision at the later period of early Permian. The studies of basic rocks, xenoliths and minerals are needed to better constrain our findings.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/2075-163 X/11/2/99/s1, Table S1: Whole-rock major (%) and trace-element (ppm) data of the Early Permian plutons in the middle segment of the north margin of the NCC, Table S2: Whole-rock Sr–Nd–Pb isotopic compositions of the Early Permian plutons in the middle segment of the north margin of the NCC, Table S3: Zircon U-Pb data of the Early Permian plutons in the middle segment of the north margin of the NCC, Table S4: Zircon Hf isotopic data of the Early Permian plutons in the middle segment of the north margin of the NCC.

**Author Contributions:** Conceptualization, Q.H.; Sampling and Experiments, L.L., D.H. and X.W.; writing—original draft preparation, L.L.; writing—review and editing, Q.H.; funding acquisition, Q.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Key R&D Program of China (2016YFC0600604) and SinoProbe-04-02.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

**Data Availability Statement:** The data presented in this study are openly available in [Supplementary File] at [10.5281/zenodo.4432839].

Acknowledgments: We are most grateful to Liu Jinbao, Nie Lanshi, Liu Dongsheng for help with the field trip and sample collection. We thank Hu Zhaochu and Luo Biji for help with LA-ICP-MS

zircon U-Pb dating and zircon Hf isotopic analysis. The authors also thank Zhang Wei for help with SHRIMP zircon U-Pb dating. We thank Yan Hongling and Liu Mu for help during Sr-Nd-Pb isotope, ICP-MS, and XRF analyses.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

### References

- Windley, B.F.; Alexeiev, D.; Xiao, W.; Kröner, A.; Badarch, G. Tectonic models for accretion of the Central Asian Orogenic Belt. J. Geol. Soc. 2007, 164, 31–47. [CrossRef]
- 2. Yue, Y.; Liou, J.G.; Graham, S.A. Tectonic correlation of Beishan and Inner Mongolia orogens and its im-plications for the palinspastic reconstruction of north China. *Mem. Geol. Soc. Am.* **2001**, *194*, 101–116.
- 3. Xu, B.; Chen, B. The structure and evolution of the Middle Paleozoic orogenic belt between the North China plate and the Siberia plate in northern Inner Mongolia. *Sci. China Ser. D* **1997**, *27*, 227–232. (In Chinese)
- 4. Xiao, W.J.; Windley, B.F.; Hao, J.; Zhai, M. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. *Tectonics* **2003**, *22*, 1–20. [CrossRef]
- Xiao, W.; Windley, B.F.; Huang, B.C.; Han, C.M.; Yuan, C.; Chen, H.L.; Sun, M.; Sun, S.; Li, J.L. End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaids: Implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia. *Int. J. Earth Sci.* 2009, *98*, 1189–1217. [CrossRef]
- Jian, P.; Liu, D.; Kröner, A.; Windley, B.F.; Shi, Y.; Zhang, W.; Zhang, F.Q.; Miao, L.C.; Zhang, L.Q.; Tomurhuu, D. Evolution of a Permian intraoceanic arc-trench system in the Solonker suture zone, Central Asian Orogenic Belt, China and Mongolia. *Lithos* 2010, 118, 169–190. [CrossRef]
- Zhang, S.-H.; Zhao, Y.; Song, B.; Hu, J.; Liu, S.-W.; Yang, Y.-H.; Chen, F.-K.; Liu, X.-M.; Liu, J. Contrasting Late Carboniferous and Late Permian-Middle Triassic intrusive suites from the northern margin of the North China craton: Geochronology, petrogenesis, and tectonic implications. *Geol. Soc. Am. Bull.* 2009, *121*, 181–200. [CrossRef]
- 8. Wang, Y.Y.; Xu, B.; Cheng, S.D.; Liao Shao, W.J.; Wang, Y. Zircon U-Pb dating of the mafic lava from Wudaoshimen, Hexigten, Inner Mongolia and its geological significance. *Acta Petrol. Sin.* **2014**, *30*, 2055–2062. (In Chinese)
- 9. Wang, A.; Liu, Y. Neoarchean (2.5–2.8 Ga) crustal growth of the North China Craton revealed by zircon Hf isotope: Asynthesis. *Geosci. Front.* 2012, *3*, 147–173. (In Chinese) [CrossRef]
- Wang, W.Q. Late-Paleozoic Tectonic Evolution of the Central-Northern Margin of the North China Craton: Constraints from Zircon U-Pb Ages and Geochemistry of Igneous Rocks in Ondor Sum-Jining Area. Ph.D. Thesis, Jilin University, Jilin, China, 31 May 2014. (In Chinese)
- 11. Zhang, S.-H.; Zhao, Y.; Liu, X.-C.; Liu, D.-Y.; Chen, F.K.; Xie, L.-W.; Chen, H.-H. Late Paleozoic to Early Mesozoic mafic–ultramafic complexes from the northern North China Block: Constraints on the composition and evolution of the lithospheric mantle. *Lithos* **2009**, *110*, 229–246. [CrossRef]
- 12. Zhang, S.-H.; Zhao, Y.; Kröner, A.; Liu, X.-M.; Xie, L.-W.; Chen, F.-K. Early Permian plutons from the northern North China Block: Constraints on continental arc evolution and convergent margin magmatism related to the Central Asian Orogenic Belt. *Int. J. Earth Sci.* **2009**, *98*, 1441–1467. [CrossRef]
- 13. Shao, J.A.; He, G.Q.; Tang, K.D. The evolution of Permian continental crust in northern part of North China. *Acta Petrol. Sin.* **2015**, *31*, 47–55. (In Chinese)
- 14. Luo, H.L.; Wu, T.R.; Zhao, L. Zircon SHRIMP U-Pb dating Wuliangsitai A-type granite on the northern margin of the North China Plate and tectonic significance. *Acta Petrol. Sin.* **2009**, *25*, 515–526.
- 15. Jian, P.; Zheng, J.; Griffin, W.L.; O'Reilly, S.Y.; Lu, F.; Wang, C.; Zhang, M.; Wang, F.Z.; Li, H.M. 3.6 Ga lower crust in central China: New evidence on the assembly of the North China craton. *Geology* **2004**, *32*, 229–232. [CrossRef]
- Jiang, N.; Guo, J.H.; Zhai, M.G.; Zhang, S.Q. ~2.7 Ga crust growth in the North China craton. *Precambrian Res.* 2010, 179, 37–49. [CrossRef]
- 17. Wang, H.C.; Zhao, F.Q.; Li, H.M.; Sun, L.X.; Miao, L.C.; Ji, S.P. Zircon SHRIMP U-Pb age of the dioritic rocks from northern Hebei: The geological records of late Paleozoic magmatic arc. *Acta Petrol. Sin.* **2007**, *23*, 597–604. (In Chinese)
- 18. Zhang, S.-H.; Zhao, Y.; Song, B.; Yang, Z.-Y.; Hu, J.-M.; Wu, H.C. Carboniferous granitic plutons from the northern margin of the North China block: Implications for a late Palaeozoic active continental margin. *J. Geol. Soc.* **2007**, *164*, 451–463. [CrossRef]
- 19. Wang, X.L. Research of Dengshenmiao Granitoids of Permian. Master's Thesis, Peking University, Beijing, China, 14 June 2007. (In Chinese)
- 20. Zhang, Y.Q. The Geochemistry and Tectonic Significance of Granitioid-Dioritoid Rocks in the Western of Langshan Mt., Inner Mongolia. Master's Thesis, Lanzhou University, Lanzhou, China, 18 June 2012. (In Chinese)
- 21. Luo, H.L. On the Permian Magmatism of the Middle Segment of the Northern Margin of the North China Plate and Its Tectonic Implication. Ph.D. Thesis, Peking University, Beijing, China, May 2007. (In Chinese)
- Ling, M.X.; Zhang, H.; Li, H.; Liu, Y.L.; Liu, J.; Li, L.Q.; Li, C.Y.; Yang, X.Y.; Sun, W.D. The Permian-Triassic granitoids in Bayan Obo, North China Craton: A geochemical and geochronological study. *Lithos* 2014, 190–191, 430–439. [CrossRef]

- 23. Zeng, J.J.; Zheng, Y.Y.; Qi, J.H.; Dai, F.H.; Zhang, G.Y.; Pang, Y.C.; Wu, B. Foundation and geological significance of Adakitic Granite at Guyang of Inner Mongolia. *Earth Sci.* 2008, *33*, 755–763. (In Chinese)
- 24. Yuan, G.B.; Wang, H.C. Magmatic Activity and It's Tectonic Implications During the Early Permian in the Northwestward of Wuchuan, Inner Mongolia. *Geol. Survey Res.* 2006, *29*, 302–310. (In Chinese)
- 25. Zhang, Y.Q.; He, Z.Y.; Zhang, J.; Chen, S.H. Discussion on tectonic Setting of the quartz diorite in Shilanhada, northern Daqingshan Mountain in Inner Mongolia. *Geol. Survey Res.* 2007, *3*, 22–26. (In Chinese)
- 26. Feng, L.X.; Zhang, Z.C.; Han, B.F.; Ren, R.; Li, J.F.; Su, L. LA-ICP-MS zircon U-Pb ages of granitoids in Darhan Muminggan Joint Banner, Inner Mongolia, and their geological significance. *Geol. Bull. China* **2013**, *32*, 1737–1748. (In Chinese)
- 27. Zhao, Q.Y.; Liu, Z.H.; Wu, X.W.; Chen, X.F. Characteristics and origin of Halaheshao pluton in Daqingshan region, Inner Mongolia. *J. Mineral. Petrol.* **2007**, 27, 46–51. (In Chinese)
- 28. Liu, C.F.; Liu, W.C.; Zhou, G.Z. Geochronology, geochemistry and tectonic setting of the Paleozoic Early Mesozoic intrusive in Siziwangqi, Inner Mongolia. *Acta Petrol. Sin.* **2014**, *88*, 992–1002. (In Chinese)
- Zhang, Y.M.; Zhang, H.F.; Zhou, Z.G.; Liu, W.C. Genetic and Tectonics significance of the Damiao granodiorite, Siziwangqi, Inner Mongolia. J. Mineral. Petrol. 2008, 28, 28–38. (In Chinese)
- Li, L.Y. Geological characteristics and tectonic significance of Gonghuduge granite rock body in Siz-iwangqi, Inner Mongolia. *Geol. Resour.* 2005, 14, 97–102. (In Chinese)
- 31. Liu, C.F.; Zhou, G.Z.; Zhang, H.F.; Liu, W.C.; Zhang, L. Petrochemical characteristics and timing of Wuertagaolemiao granitoids, Siziwangqi, Inner Mongolia. *J. Mineral. Petrol.* **2011**, *31*, 34–43. (In Chinese)
- 32. Feng, F.; Xu, Z.Y.; Dong, X.J.; Shi, Q.; Wang, S.J.; Li, C.H. LA-ICP-MS Zircon U-Pb dating, Hf isotopic compositions of granite porphyry in Wenduermiao-Jining Arae, Inner Mongolia and its geological significance. *Earth Sci.* **2020**. accepted. (In Chinese)
- Wang, W.Q.; Xu, Z.Y.; Liu, Z.H.; Zhao, Q.Y.; Jiang, X.J. Early Middle Permian tectonic evolution of the Central-Northern margin of the North China Craton: Constraints from zircon U-Pb ages and geochemistry of the granitoids. *Acta Petrol. Sin.* 2013, 29, 2987–3003. (In Chinese)
- 34. Hong, D.; Wang, T.; Tong, Y. An outline about granitoids in china. *Geol. Rev.* 2007, 53, 9–16. (In Chinese)
- 35. Jiang, X.J. Characteristics of Middle Permian Granitoids in Jining, Inner Mongolia and Their Geological Significance. Master'sThesis, Jilin University, Changchun, China, 10 June 2014. (In Chinese)
- 36. Wang, S.J.; Xu, Z.Y.; Dong, X.J.; Wang, W.Q.; Li, P.C. Geochemical characteristics and zircon U-Pb age of the granodiorite-norite gabbro in the northern margin of the North China Block and their formation mechanism. *Earth Sci.* **2018**, *43*, 3267–3284. (In Chinese)
- Peng, Y.B.; Jiang, X.J.; Yan, P.B.; Dai, M.J.; Xing, Y.J. LA-ICP-MS zircon-Pb ages, geochemical characteristics of middle Permian Qianhuhetaolegai granite in Zhengxiangbaibanner, Inner Mongolia and their tectonic significances. *Geol. Rev.* 2018, 64, 1379–1392. (In Chinese)
- 38. Xia, Y.J.; Wu, Q.H.; Xi, X.S. Zircon geochronology and trace Element characteristics of the Woniushan granites in Taibus Banner, Inner Mongolia, and their geological significance. *Geol. Bull. China* **2016**, *35*, 943–952. (In Chinese)
- Zhang, S.H. The Late Paleozoic Early Mesozoic Tectonomagmatie Activities in the Eastern Segment of the Inner Mongolian Uplift in the Yanshan Tectonic Belt and Their Geological Significance. Ph.D. Thesis, Chinese Academy of Geological Sciences, Beijing, China, 8 June 2004. (In Chinese)
- 40. Zhang, X.H.; Zhai, M.G. Magmatism and its metallogenetic effects during the Paleozoic continental crustal construction in northern North China: An overview. *Acta Petrol. Sin.* **2010**, *26*, 1329–1341. (In Chinese)
- 41. Hua, B.; Gao, X.; Hu, Z.G.; Mei, Z.H.; Zhang, Z.W.; Meng, Y.S.; Zhang, B.T.; Zhao, L. Petrogenesis and tectonic setting of the Wuzhuxinwusu granite, western Xing-Meng Orogenic Belt: Evidences from geochemistry, zircon U-Pb geochronology and Sr-Nd-Hf isotopes. *Acta Petrol. Sin.* **2020**, *36*, 1426–1444. (In Chinese)
- 42. Norrish, K.; Chappell, B.W. X-ray fluorescence spectrometry. In *Physical Methods in Determinative Mineralogy*; Zussman, J., Ed.; Academic Press: London, UK, 1977; pp. 201–272.
- 43. Govindaraju, K. Compilation of working values and sample description for 383 standards. *Geostand. Geoanal. Res.* **1994**, *18*, 1–158. [CrossRef]
- 44. Steiger, R.H.; Jäger, E. Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett.* **1977**, *36*, 359–362. [CrossRef]
- 45. Lugmair, G.W.; Marti, K. Lunar initial 143Nd/144Nd: Differential evolution of the lunar crust and mantle. *Earth Planet. Sci. Lett.* **1978**, *39*, 3349–3357. [CrossRef]
- 46. Black, L.P.; Kamo, S.L.; Allen, C.M.; Aleinikoff, J.N.; Davis, D.W.; Korsch, R.J.; Foudoulis, C. TEMORA 1: A new zircon standard for Phanerozoic U–Pb geochronology. *Chem. Geol.* **2003**, 200, 155–170. [CrossRef]
- 47. Williams, I.S.; Buick, I.S.; Cartwright, I. An extended episode of early Mesoproterozoic metamorphic fluid flow in the Reynolds Range, central Australia. *J. Metamorph. Geol.* **1996**, *14*, 29–47. [CrossRef]
- 48. Wiedenbeck, M.; Allé, P.; Corfu, F.; Griffin, W.; Meier, M.; Oberli, F.; Von Quadt, A.; Roddick, J.; Spiegel, W. three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE Analyses. *Geostand. Geoanalytical Res.* **1995**, *19*, 1–23. [CrossRef]
- Yuan, H.L.; Gao, S.; Dai, M.N.; Zong, C.L.; Günther, D.; Fontaine, G.H.; Liu, X.M.; Diwu, C.R. Simultaneous determinations of U-Pb age, Hf isotopes and trace element compositions of zircon by excimer la-ser-ablation quadrupole and multiple-collector ICP-MS. *Chem. Geol.* 2008, 247, 100–118. [CrossRef]

- Liu, S.; Hu, R.; Gao, S.; Feng, C.; Feng, G.; Coulson, I.M.; Li, C.; Wang, T.; Qi, Y. Zircon U–Pb age and Sr–Nd–Hf isotope geochemistry of Permian granodiorite and associated gabbro in the Songliao Block, NE China and implications for growth of juvenile crust. *Lithos* 2010, 114, 423–436. [CrossRef]
- 51. Hou, K.J.; Li, Y.H.; Xie, G.Q. Laser Ablation-ICP-MS technique for Hf isotope microanalysis of zircon and its geological applications. *Acta Petrol. Sin.* 2007, 23, 2595–2604. (In Chinese)
- 52. Scherer, E.; Münker, C.; Mezger, K. Calibration of the Lutetium-Hafnium Clock. Science 2001, 293, 683–687. [CrossRef] [PubMed]
- 53. Blichert-Toft, J.; Chauvel, C.; Albarède, F. Separation of Hf and Lu for high-precision isotope analysis of rock samples by magnetic sector-multiple collector ICP-MS. *Contrib. Miner. Pet.* **1997**, 127, 248–260. [CrossRef]
- 54. Griffin, W.L.; Pearson, N.J.; Belousova, E.; Jackson, S.E.; van Achterbergh, E.; O'Reilly, S.Y.; Shee, S.R. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochim. Cosmochim. Ac.* 2000, 64, 133–147. [CrossRef]
- 55. Griffin, W.L.; Wang, X.; Jackson, S.E.; Pearson, N.J.; O'Reilly, S.Y.; Xu, X.; Zhou, X. Zircon chemistry and magma mixing, SE China: In-Situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* **2002**, *61*, 237–269. [CrossRef]
- 56. Black, L.P.; Jagodzinski, E.A. Importance of establishing sources of uncertainty for the derivation of reliable SHRIMP ages. *Aust. J. Earth Sci.* 2003, *50*, 503–512. [CrossRef]
- 57. Geng, Y.S.; Shen, Q.H.; Ren, L.D. Late Neoarchean to Early Paleoproterozoic magmatic events and tec-tonothermal systems in the North China Craton. *Acta Petrol. Sin.* **2010**, *26*, 1945–1966. (In Chinese)
- 58. Sun, S.-S.; McDonough, W.F. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Geol. Soc. Lond. Spec. Publ.* **1989**, *42*, 313–345. [CrossRef]
- 59. Han, B.F.; Zhang, L.; Wang, Y.M.; Song, B. Enriched mantle source for Palcoproterozoic high Mg and low Ti-P mafic dykes in central part of the North China craton: Constraints from zircon Hf isotopic composi-tions. *Acta Petrol. Sin.* 2007, 23, 277–284. (In Chinese)
- 60. Liu, J.H.; Liu, F.L.; Ding, Z.J.; Liu, P.H.; Wang, F.; You, J.J. The zircon Hf isotope characteristics of~2.5Ga magmatic event, and implication for the crustal evolution in the Jiaobei terrane, China. *Acta Petrol. Sin.* **2012**, *28*, 2697–2704. (In Chinese)
- 61. Xia, X.; Sun, M.; Zhao, G.; Luo, Y. LA-ICP-MS U–Pb geochronology of detrital zircons from the Jining Complex, North China Craton and its tectonic significance. *Precambrian Res.* **2006**, 144, 199–212. [CrossRef]
- 62. Collins, W.J.; Beams, S.D.; White, A.J.R.; Chappell, B.W. Nature and origin of A-type granites with par-ticular reference to southeastern Australia. *Contrib. Mineral. Petr.* **1982**, *80*, 189–200. [CrossRef]
- 63. Whalen, J.B.; Currie, K.L.; Chappell, B.W. A-type granites: Geochemical characteristics, discrimination and petrogenesis. *Contrib. Miner. Pet.* **1987**, *95*, 407–419. [CrossRef]
- 64. Zhang, X.; Wei, R.; Xu, S.; Lei, S. Zircon U-Pb geochronology, geochemistry and petrogenesis of the Permian A–type granite in the Honggeer area, central Inner Mongolia. *Geochimica* 2017, *46*, 511–527. (In Chinese)
- 65. Wu, F.-Y.; Liu, X.; Ji, W.; Wang, J.; Yang, L. Highly fractionated granites: Recognition and research. *Sci. China Earth Sci.* 2017, 60, 1201–1219. (In Chinese) [CrossRef]
- 66. Breiter, K.; Lamarão, C.N.; Borges, R.M.K.; Dall'Agnol, R. Chemical characteristics of zircon from A-type granites and comparison to zircon of S-type granites. *Lithos* **2014**, *192–195*, 208–225. [CrossRef]
- 67. Eby, G.N. Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. Geology 1992, 20, 641–654. [CrossRef]
- 68. Chappell, B.W. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* **1999**, 46, 535–551. [CrossRef]
- 69. Creaser, R.A.; Price, R.C.; Wormald, R.J. A-type granites revisited: Assessment of a residual-source model. *Geology* **1991**, *19*, 163–166. [CrossRef]
- 70. Patiño Douce, A.E. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas? *Geol. Soc. Lond. Spec. Publ.* **1999**, *168*, 55–75. [CrossRef]
- 71. Skjerlie, K.P.; Johnston, A.D. Fluid-Absent Melting Behavior of an F-Rich Tonalitic Gneiss at Mid-Crustal Pressures: Implications for the Generation of Anorogenic Granites. *J. Pet.* **1993**, *34*, 785–815. [CrossRef]
- 72. Bonin, B. Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review. *Lithos* 2004, 78, 1–24. [CrossRef]
- 73. Turner, S.P.; Foden, J.D.; Morrison, R.S. Derivation of some A-type magmas by fractionation of basaltic magma: An example from the Padthaway Ridge, South Australia. *Lithos* **1992**, *28*, 151–179. [CrossRef]
- 74. Wu, Q.; Niu, M.L.; Zhu, G.; Wang, T.; Fei, L.L. Zircon U-Pb age, petrogenesis of the Changgang A-type granites in the Lujiang segment of the Tan-Lu fault zone and their implication. *Acta Petrol. Sin.* **2016**, *32*, 1031–1048. (In Chinese)
- 75. King, P.L.; White, A.J.R.; Chappell, B.W.; Allen, C.M. Characterization and origin of aluminous A—type granites from the Lachlan Fold Belt, Southeastern Australia. *J. Petrol.* **1997**, *38*, 371–391. [CrossRef]
- 76. Wu, F.Y.; Li, X.H.; Yang, J.H.; Zheng, Y.F. Discussions on the petrogenesis of granites. Acta Petrol. Sin. 2007, 23, 1217–1238. (In Chinese)
- 77. Wu, F.Y.; Sun, D.Y.; Li, H.; Jahn, B.M.; Wilde, S. A-type granites in northeastern China: Age and geo-chemical constraints on their petrogenesis. *Chem. Geol.* **2002**, *187*, 143–173. [CrossRef]
- 78. Jiang, N.; Guo, J.; Chang, G. Nature and evolution of the lower crust in the eastern North China craton: A review. *Earth-Science Rev.* **2013**, *122*, 1–9. [CrossRef]
- 79. Clemens, J.D.; Stevens, G. What controls chemical variation in granitic magmas? Lithos 2012, 134–135, 317–329. [CrossRef]
- 80. Deng, J.F.; Wu, Z.X.; Zhao, G.C.; Zhao, H.L.; Luo, Z.H.; Mo, X.X. Precambrian granite rocks, continental crust evolution and craton formation of the North China Platform. *Acta Petrol. Sin.* **1999**, *15*, 190–198. (In Chinese)

- 81. Roberts, M.P.; Clemens, J.D. Origin of high-potassium, calc-alkaline, I-type granitoids. Geology 1993, 21, 825–828. [CrossRef]
- 82. Sun, D.Y.; Wu, F.Y.; Zhang, Y.B.; Gao, S. The final closing time of the west Lamulun Riv-er-Changchun-Yanji plate suture zone: Evidence from the Dayushan granitic pluton, Jilin Province. *J. Jilin Univ.* **2004**, *34*, 174–181. (In Chinese)
- Green, J.C. Volcanic rocks of the Midcontinent Rift System: A review. In *Basement Tectonics 10. Proceedings of the International Conferences on Basement Tectonics*; Ojakangas, R.W., Dickas, A.B., Green, J.C., Eds.; Springer: Dordrecht, Germany, 1995; Volume 4, pp. 65–67.
- 84. Ballouard, C.; Poujol, M.; Boulvais, P.; Branquet, Y.; Tartèse, R.; Vigneresse, J.-L. Nb-Ta fractionation in peraluminous granites: A marker of the magmatic-hydrothermal transition. *Geology* **2016**, *44*, 231–234. [CrossRef]
- 85. Deering, C.D.; Keller, B.; Schoene, B.; Bachmann, O.; Beane, R.; Ovtcharova, M. Zircon record of the plutonic-volcanic connection and protracted rhyolite melt evolution. *Geology* **2016**, *44*, 267–270. [CrossRef]
- 86. London, D.; Evensen, J.M. Beryllium in Silicic Magmas and the Origin of Beryl-Bearing Pegmatites. *Rev. Miner. Geochem.* 2002, 50, 445–486. [CrossRef]
- Jian, P.; Kröner, A.; Windley, B.F.; Shi, Y.; Zhang, W.; Zhang, L.Q.; Yang, W.R. Carboniferous and Cre-taceous mafic–ultramafic massifs in Inner Mongolia (China): A SHRIMP zircon and geochemical study of the previously presumed integral "Hegenshan ophiolite". *Lithos* 2012, 142–143, 48–66. [CrossRef]
- 88. Zhai, M.G.; Liu, W. Palaeoproterozoic tectonic history of the North China craton: A review. *Precambrian Res.* 2003, 122, 183–199. [CrossRef]
- 89. Zorpi, M.J.; Coulon, C.; Orsini, J.B.; Cocirta, C. Magma mingling, zoning and emplacement in calc-alkaline granitoid plutons. *Tectonophysics* **1989**, 157, 315–329. [CrossRef]
- 90. Springer, W.; Seck, H.A. Partial fusion of basic granulites at 5 to 15 kbar: Implications for the origin of TTG magmas. *Contrib. Miner. Pet.* **1997**, 127, 30–45. [CrossRef]
- Zhao, Z.; Mo, X.; Dilek, Y.; Niu, Y.; DePaolo, D.J.; Robinson, P.; Zhu, D.; Sun, C.; Dong, G.; Zhou, S.; et al. Geochemical and Sr-Nd-Pb-O isotopic compositions of the post-collisional ultrapotassic magmatism in SW Tibet: Petrogenesis and implications for India intra-continental subduction beneath southern Tibet. *Lithos* 2009, *113*, 190–212. [CrossRef]
- 92. Cai, K.; Sun, M.; Yuan, C.; Xiao, W.; Zhao, G.; Long, X.; Wu, F. Carboniferous mantle-derived felsic intrusion in the Chinese Altai, NW China: Implications for geodynamic change of the accretionary orogenic belt. *Gondwana Res.* **2012**, *22*, 681–698. [CrossRef]
- Gao, R.; Xiao, L.; Pirajno, F.; Wang, G.-C.; He, X.-X.; Yang, G.; Yan, S.-W. Carboniferous–Permian extensive magmatism in the West Junggar, Xinjiang, northwestern China: Its geochemistry, geochronology, and petrogenesis. *Lithos* 2014, 204, 125–143. [CrossRef]
- Pearce, J.A.; Harris, N.B.W.; Tindle, A.G. Trace Element Discrimination Diagrams for the Tectonic Inter-pretation of Granitic Rocks. J. Petrol. 1984, 25, 956–983. [CrossRef]
- 95. Batchelor, R.A.; Bowden, P. Petrogenetic Interpretation of Granitoid Rock Series Using Multicationic Parameters. *Chem. Geol.* **1985**, 48, 43–55. [CrossRef]
- Xu, B.; Charvet, J.; Chen, Y.; Zhao, P.; Shi, G.Z. Middle Paleozoic convergent orogenic belts in western Inner Mongolia (China): Framework, kinematics, geochronology and implications for tectonic evolution of the Central Asian Orogenic Belt. *Gondwana Res.* 2013, 23, 1342–1364. [CrossRef]
- 97. Chen, B.; Jahn, B.M.; Wilde, S.; Xu, B. Two contrasting Paleozoic Magmatic belts in northern Inner Mongolia, China: Petrogenesis and tectonic implications. *Tectonophysics* 2000, 328, 157–182. [CrossRef]
- Liu, C.F. Paleozoic-Early Mesozoic Magmatic belts and Tectonic Significance in Siziwangqi Area, Inner Mongolia. Ph.D. Thesis, China University of Geosciences (Beijing), Beijing, China, 31 May 2010. (In Chinese)
- 99. Brown, M.S. Granite: From genesis to emplacement. Geol. Soc. Am. Bull. 2013, 125, 1079-1113. [CrossRef]
- Blight, J.H.S.; Crowley, Q.G.; Petterson, M.G.; Cunningham, D. Granites of the Southern Mongolia Car-boniferous Arc: New geochronological and geochemical constraints. *Lithos* 2010, *116*, 35–52. [CrossRef]
- 101. Condie, K.C. A planet in transition: The onset of plate tectonics on earth between 3 and 2 Ga? Geosci. Front. 2018, 9, 51–60. [CrossRef]