

Article

Provenance of the He 8 Member of the Upper Paleozoic Shihezi Formation, Ordos Basin, China: Insights from Heavy Minerals, Paleocurrents, Detrital Zircon Chronology, and Hf Isotopes

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Abstract: The Ordos Basin is located in the western part of the North China Craton. The Upper Paleozoic Shihezi Formation, particularly the He 8 Member, is one of the main gas-bearing strata. However, the source areas for the north and south sections have not been clearly distinguished, which has constrained oil and gas exploration to some extent. Therefore, understanding the source rock evolution of He 8 Member in both the south and north basins will provide a favorable theoretical basis for oil and gas exploration. The provenance of the He 8 Member of the Shihezi Formation in the Ordos Basin has not been well defined until now. Seven wellbore sandstone samples and three field outcrop sandstone samples from the He 8 Member in the Ordos Basin were analyzed. Based on zircon U–Pb dating and Lu–Hf isotope analyses, zircon assemblages of 520–386 Ma and 350–268 Ma in the southern Ordos Basin might have originated from the North Qinling Orogenic Belt (NQinOB) and the North Qilian Orogenic Belt (NQiOB); the 350–268 Ma age group of zircons from the NQinOB, and a large number of ~320–260 Ma detrital zircons supplied to the southern Ordos Basin by the NQinOB suggest that NQinOB magmatic and/or metamorphic events may have occurred in the NQinOB during the ~320–260 Ma period. From ~320–260 Ma, the NQinOB might have experienced significant tectonic activity that has not been fully revealed thus far. The zircons from 2600–2300 Ma, 2000–1600 Ma, and 450–300 Ma in the northern Ordos Basin might have been derived from the Trans-North China Orogenic Belt (TNCO), the Khondalite Belt, the Yinshan Belt, and the Alxa Belt. The paleocurrent and heavy mineral analyses determined that there are certain differences between the northern Ordos Basin and southern Ordos Basin, with unstable minerals such as barite and pyrite, as well as moderately stable minerals such as garnet, showing an increasing trend from south to north. There are also differences in the dominant paleocurrent directions between the south and north parts of the basin, and the Hf isotope data in the Ordos Basin show two-stage Hf model ages (T_{DM2}) ranging from 918 Ma to 3574 Ma. As a result, the He 8 Member deposits in the southern Ordos Basin and northern Ordos Basin had different sources. The southern Ordos Basin might have derived from the NQinOB, the NQiOB, and the TNCO, and the northern Ordos Basin might have derived from the TNCO, the Khondalite Belt, the Yinshan Belt, and the Alxa Belt.

Keywords: provenance; detrital zircon; heavy mineral; U–Pb dating; in situ Lu–Hf isotope; Shihezi Formation; Ordos Basin



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1. Introduction

The Ordos Basin spans more than 250,000 km² [1], the second largest sedimentary basin in China [2], and is situated in the western part of the North China Craton (Figure 1a). Many giant gas fields, such as Sulige, Daniudi, and Wushenqi, have been found in the He 8 Member of the Middle Permian Shihezi Formation (Fm.) in the northern Ordos Basin (Figure 1a). The He 8 Member of the Lower Shihezi Formation in the Upper Paleozoic strata of the Ordos Basin is one of the main gas-producing strata. However, in the southern Ordos Basin (Figure 1a), only a few small natural gas fields, such as Qingyang and Yihuang, have been discovered in the He 8 Member in recent decades, indicating significant potential for further exploration and development in this area. The efficiency and success rate of gas exploration have been relatively low for a long time because of the unclear provenance. The material components of the provenance have a deep impact on the nature of the oil and gas reservoir strata [3]. Studying the sediment sources of the Ordos Basin helps in understanding the formation processes, sources, and evolution of the basin's sediments, which in turn affects the distribution and assessment of oil and gas resources. Understanding the provenance of the He 8 Member in the Ordos Basin is key for the successful exploration of oil and natural gas.

Researchers have conducted various studies on the provenance of the He 8 Member in the Ordos Basin via methods such as the analysis of sandstone detrital components [4–11], sandstone clastic compositions [8], heavy mineral components [5,7,9–14], rock geochemistry [4,10], paleocurrents [6,7,9–12,15–17], and sedimentary facies analyses [5,9,10,12]. In addition, a small number of scholars have utilized rare earth element analyses [14,18], major and trace element analyses [18], and U–Pb dating of detrital zircons [19–24]. Recent studies have indicated that the principal provenance areas of the southern Ordos Basin are the North Qinling Orogenic Belt (NQinOB), the North Qilian Orogenic Belt (NQiOB), and the Trans-North China Orogenic (TNCO). Most studies have shown that the primary provenance areas of the northern Ordos Basin are the Yinshan Belt (YB), the Khondalite Belt (KB), the Trans-North China Orogenic Belt (TNCO), and the Xingmeng Orogenic Belt. Some scholars believe that the Alxa belt (AB) has also contributed materials to the northern Ordos Basin. Despite the extensive research conducted [4–7,9–12], the source areas of the He 8 Member in the Ordos Basin, particularly in the southern Ordos Basin, have not been well defined to date.

For the past few years, the detrital zircon U–Pb dating, coupled with analyses of orogen–basin interactions, has proven effective in identifying sedimentary rock sources, particularly in situ zircon Lu–Hf isotope analysis [25–28]. Our study uses heavy mineral, paleocurrent, and detrital zircon U–Pb ages and Lu–Hf isotopes to gain an understanding of the provenance of the He 8 Member within the Ordos Basin.

2. Geological Background

The Ordos Basin is a collage of oceanic plateaus [29]. Additionally, the Ordos Basin was undergoing oceanic subduction or continental collision along its margins from the Paleozoic to Triassic [30,31]. In addition, the Ordos Basin is now a lithosphere-syncline basin that was kept intact by later tectonothermal events [32].

The Ordos Basin lies south of the KB and YB, east of the Helanshan–Liupanshan Thrust Belt, south of the Qinling Orogenic Belt (QinOB), and east of the TNCO [33] (Figure 1b). Paleozoic clastic deposits in the Ordos Basin are shown in Figure 1a [34]. During the Paleozoic era, clastic deposits, including the Carboniferous Benxi Fm., as well as the Permian Taiyuan Fm., Shanxi Fm., Shihezi Fm., and Shiqianfeng Fm., were deposited in the OB. The Shihezi Fm. comprises eight members, with the He 8 Member at its base (Figure 1a).

The lithologic description of clastic strata and the characteristics of thin sections in the He 8 Member of the southern Ordos Basin are detailed in reference [34]. The petrographic analysis revealed that most of the sandstone samples from the He 8 Member in the northern Ordos Basin are subangular, with quartz being the primary mineral and feldspars present,

indicating corrosion (Figure 2a). The samples also contain clastic fragments, predominantly volcanic, and metamorphic fragments. Additionally, detrital zircon U–Pb chronology and Lu–Hf isotope analyses of these samples were conducted. Research has revealed that most of the quartz is subangular, and most feldspars are subangular and corroded in the two samples from the northern Ordos Basin (Figure 2b). The longitude, latitude, and lithological descriptions of the samples can be found in Supplementary Table S1.

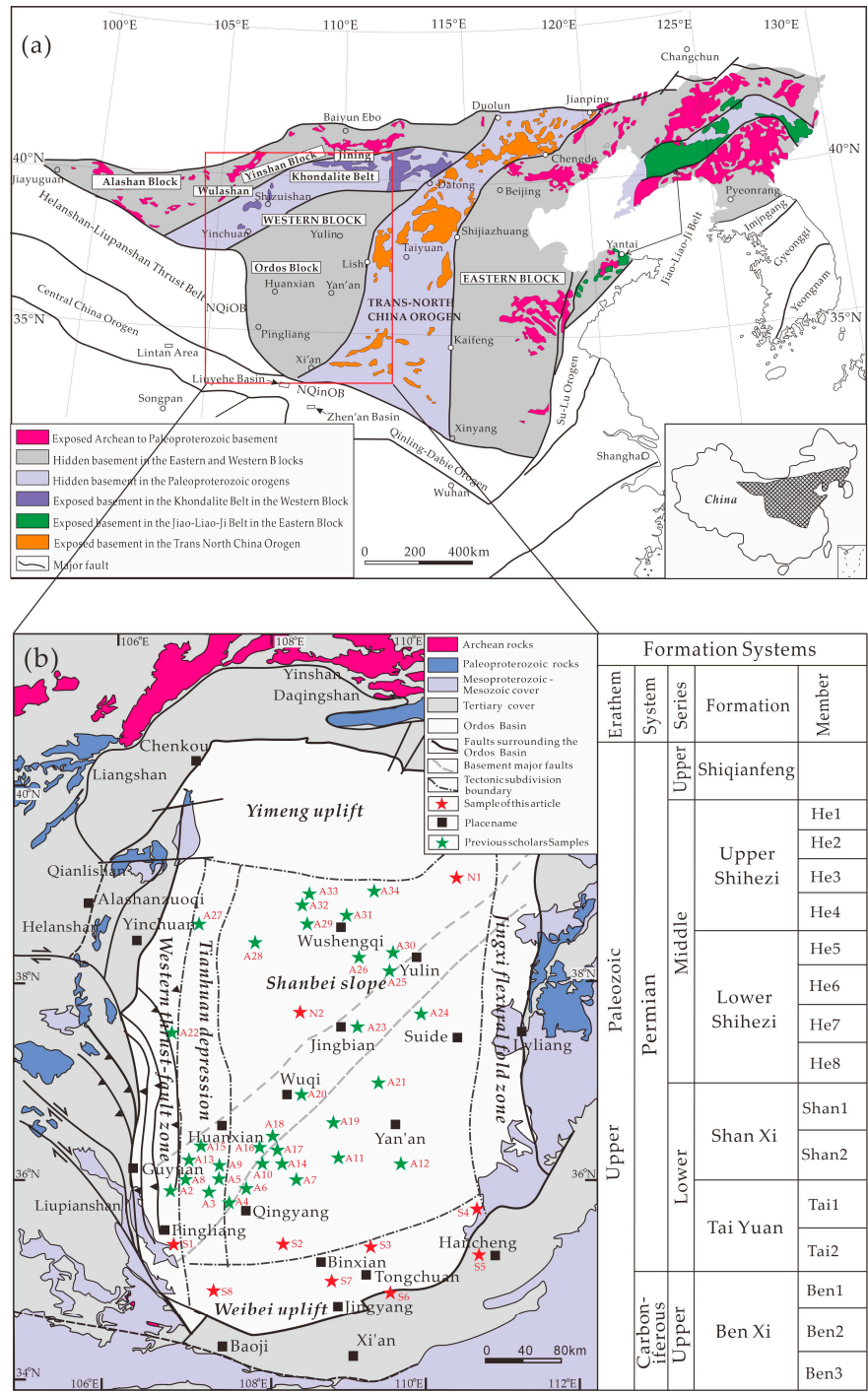


Figure 1. Schematic geological map showing the tectonic subdivision of the Ordos Basin ((a) modified from [34]) and TNCO ((b) modified from [35]) and the Ordos Basin with the Upper Paleozoic formation systems (modified from [13]).

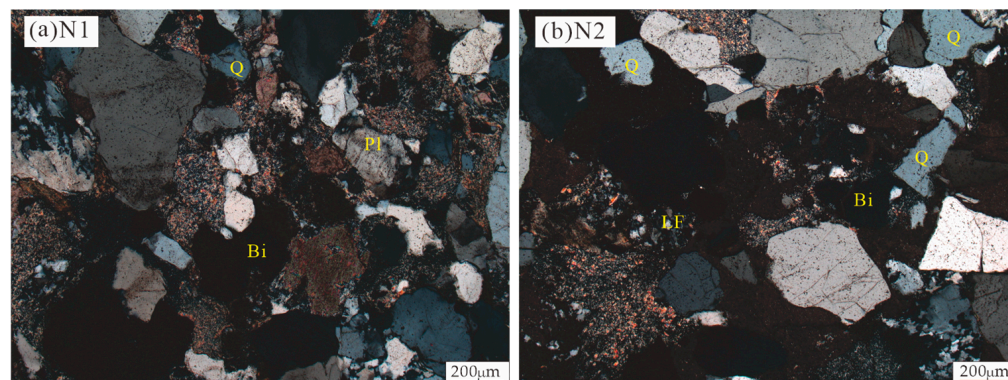


Figure 2. Microphotos of the sandstone samples N1 (a) and N2 (b) from the northern Ordos Basin. All are shown under cross-polarized light. Q: quartz, Pl: plagioclase, Bi: biotite, LF: lithic fragment.

3. Sampling and Methodology

3.1. Heavy Mineral Analysis

Heavy minerals offer valuable clues about potential sediment sources, and variations in their distributions throughout stratigraphic layers effectively demonstrate changes in sediment provenance [36]. We collected three field outcrop samples and twenty-one sets of drill core samples from the He 8 Member in the southern Ordos Basin for heavy mineral analysis. Additionally, we obtained two sets of drill core samples from the northern Ordos Basin for heavy mineral analysis. Furthermore, we acquired heavy mineral data from 184 groups of drill core samples collected by previous researchers at the Research Institute of Petroleum Exploration and Development, PetroChina Changqing Oilfield Company, Xi'an, China.

The separation and selection of heavy mineral samples were completed in the laboratory of the Hebei Regional Geological Survey Team (Langfang City, China). The main operational procedures are as follows:

- (a) Pretreatment: the samples were crushed to 30–100 mesh, the samples with a particle size between 0.25–0.63 mm were extracted, and the samples were treated with hydrogen peroxide and dilute hydrochloric acid.
- (b) Heavy liquid rough separation: bromoform was chosen as the heavy liquid and minerals were separated to obtain heavy minerals with a specific gravity greater than 2.89 g/cm^3 for identification under a microscope. Zircon, rutile, tourmaline, monazite, garnet, magnetite, hematite–limonite, leucoxene, titanite, epidote, anatase, pyrite, barite, apatite, ilmenite, mica, hornblende, cassiterite, zoisite, chloritoid, anhydrite, sphalerite, and siderite were counted, and the percentage contents of the samples were calculated.

We employed the provenance-sensitive index values of zircon–tourmaline–rutile (ZTR), apatite–tourmaline (ATi), and garnet–zircon (GZi) to determine the provenance, following the procedure outlined in reference [37]. The heavy mineral characteristic index can be used to analyze the properties of the parent rock and the source area effectively. In this study, the ZTR, ATi, and GZi were used for analysis. The ZTR index represents the maturity of heavy minerals, the ATi represents the source area of intermediate-acidic igneous rocks, and the GZi represents the source area of intermediate- to low-grade metamorphic rocks.

3.2. Paleocurrent Analysis

Paleocurrent analysis is one of the most effective tools for identifying depositional environments and reconstructing paleogeography, thereby helping to determine the locations of material sources [7]. This analysis is primarily applicable to field outcrop studies, with sedimentary markers in the study area mostly found in interbedded laminae [38]. The measurement points for the preexisting layers chosen from the profiles vary between 60 and 100, with at least 80 points indicating the maximum flat surface orientation of the shingled gravel. Importantly, the orientation of the shingled gravel plays a critical role in identifying the paleocurrent direction. Moreover, paleocurrent data comprising fewer than 60 sets are not statistically significant. Therefore, when gathering previous data, it is crucial to ensure that these criteria are fulfilled to accurately reflect the original paleocurrent. The data obtained through the measurement of paleocurrent-indicating structures are scattered and require processing. Stereo net software (version 11.6) was used for data processing and to correct paleocurrent recovery. The original paleocurrent direction obtained from paleocurrent rosette mapping was used to further determine the direction of the material sources in the research area [9,39]. Specifically, our research group tested three field paleoflows in reference [8]. Three paleocurrent measurements were conducted at well-exposed sections located in the southwest at Pingliang Erdaogou and in the southeast at the South Bukou town of Xuefengchuan in Hancheng. Additional data were collected in the southern Ordos Basin from reference [35]. The Shibao Gou section generally trends southeast, with the paleocurrent direction at San Yuan Qiao being relatively concentrated. In contrast, the paleocurrent directions at Pingliang Erdaogou, Kou Town, and Xiangshan are more dispersed and are oriented toward the north, east, and south, but overall, they converge toward the northeast and into the basin. Paleocurrent measurements were conducted at well-exposed sections in the south edge of the basin. There are 8 paleoflow data points in the northern Ordos Basin identified from the literature [4,15,16]. In the north part of the basin, paleoflow data were collected from five sections in the Lower Shihezi Formation, including Hulusitai, Shabatai, Haizemiao, Balougou, and Qianlishan.

3.3. LA-ICP-MS Zircon Dating and Zircon Lu-Hf Isotope Analysis

In the southern Ordos Basin, eight sandstone samples were collected from five boreholes (S2, S3, S4, S7, and S8) and three field outcrops (S1 outcrop, S5 outcrop, and S6 outcrop, Figure 1a). Research on petrographic characteristics, detailed mineral compositions, and textures can be found in reference [34]. The zircon U-Pb dating data of 32 well core samples from the He 8 Member of the Ordos Basin were collected from the Research Institute of Petroleum Exploration and Development, PetroChina Changqing Oilfield Company, as reported in reference [23].

The separation of zircon minerals was conducted in the laboratory of the Hebei Regional Geological Survey Team. Cathodoluminescence (CL) imaging, LA-ICP-MS zircon dating, and zircon Lu-Hf isotope analysis were performed at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China. The operating conditions and instrument parameters for zircon separation, CL imaging, LA-ICP-MS zircon dating, and zircon Lu-Hf isotope analysis were consistent with those described by [34]. The detailed analytical results can be found in Supplementary Table S2. The LA-ICP-MS zircon dating and zircon Lu-Hf isotope analysis data (younger than 550 Ma) of some samples (five borehole samples and three field outcrop samples from the southern Ordos Basin) have been published in an open journal. For detailed information, refer to reference [34]. Analysis was conducted via a Nu Plasma HR multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) equipped with a 193 nm laser on zircon samples that had undergone U-Pb dating. The laser beam spot diameter was 44 μm , the frequency was 10 Hz, the pulse energy was 80 mJ, and the ablation time was 50 s. The external standards used were zircon 91500, MON-1, and GJ-1 [40]. For the instrument operating conditions, detailed analytical procedures, and data precision, the RF forward power is set

to 1300 W, the reflected RF power is under 10 W, and the plasma gas flow rate is maintained at 13 L/min. The MC-ICP-MS instrument was operated in static mode. Before ablation for U–Pb dating, the zircon underwent preablation with two laser pulses to eliminate surface contamination, and corrections for instrumental mass bias and depth-dependent elemental and isotopic fractionation were made using zircon 91500 as the external standard. For other parameters, please refer to the literature [40], which also includes the calculation formulas for $\epsilon_{\text{Hf}}(t)$, T_{DM1} , T_{DM2} , and $f_{\text{Lu/Hf}}$ [41,42].

The zircons predominantly exhibit light rose and dark rose colors, with a few being brown and milky white. Some zircons contain gas and solid inclusions. Many zircons range from 30 to 370 μm in length (with most ranging between 60 μm and 200 μm) and 20 to 300 μm in width. These features are similar to those of magmatic zircons, which typically have the longest dimension falling between 20 μm and 250 μm [43,44].

4. Results

4.1. Heavy Mineral Analysis

The dominant heavy minerals include zircon, rutile, tourmaline, monazite, garnet, magnetite, hematite–limonite, leucoxene, titanite, epidote, anatase, pyrite, barite, and apatite (Figures 3 and 4a). Other heavy minerals, such as ilmenite, mica, hornblende, cassiterite, zoisite, chloritoid, anhydrite, sphalerite, and siderite, are found in limited numbers of samples. Additionally, monazite, magnetite, titanite, epidote, anatase, and apatite generally exhibit low abundances (Figures 3 and 4a).

Overall, based on the characteristics of heavy mineral assemblages and the heavy mineral characteristic index, the basin can be divided into six regions: (I) zircon + leucoxene + tourmaline + rutile + garnet, (II) leucoxene + zircon + hematite–limonite + magnetite + tourmaline, (III) other (chloritoid, siderite, pyrrhotite, mica, ilmenite, etc.) + zircon + leucoxene + anatase + magnetite, (IV) zircon + leucoxene + hematite–limonite + pyrite + garnet, (V) zircon + leucoxene + garnet + barite + tourmaline, and (VI) leucoxene + zircon + garnet + tourmaline + barite (Figures 3 and 4a). Zones I, II, and III are in the southern Ordos Basin, and Zones IV, V, and VI are in the northern Ordos Basin.

The zircon–tourmaline–rutile (ZTR) ratio of the southern Ordos Basin is slightly greater than that of the northern Ordos Basin (Figure 4b). The aluminum–titanium indices (ATis) of the northern Ordos Basin and southern Ordos Basin show noticeable differences, with a decreasing trend from the southern Ordos Basin to the northern Ordos Basin, indicating variations in material sources between the two areas, and indicating that there are differences between the southern Ordos Basin and the northern Ordos Basin in terms of the material sources (Figure 4b). The zircon–garnet index (ZGi) mainly ranges from 5–40 (Figure 4b) and tends to increase from the southern Ordos Basin to the northern Ordos Basin.

4.2. Paleocurrent Analysis

We obtained paleoflow data for 19 sites from the literature [4,8,9,15,16,20,35,39] to indicate the provenance direction (Figure 3). Paleoflow data were collected in Zone I, with the main profile pointing N and NE. In Zone II, there are four sets of paleoflow data, with the main profile pointing NE and NW. In Zone III, there are five sets of paleoflow data, with the main profile pointing W and NW. In Zone IV, there are three sets of paleoflow data, and the dominant directions of paleocurrents are SE and SW [8]. In Zone VI, there are six sets of paleoflow data, with the main profile pointing to the SE, NW, SW, and EW [8,15,16].

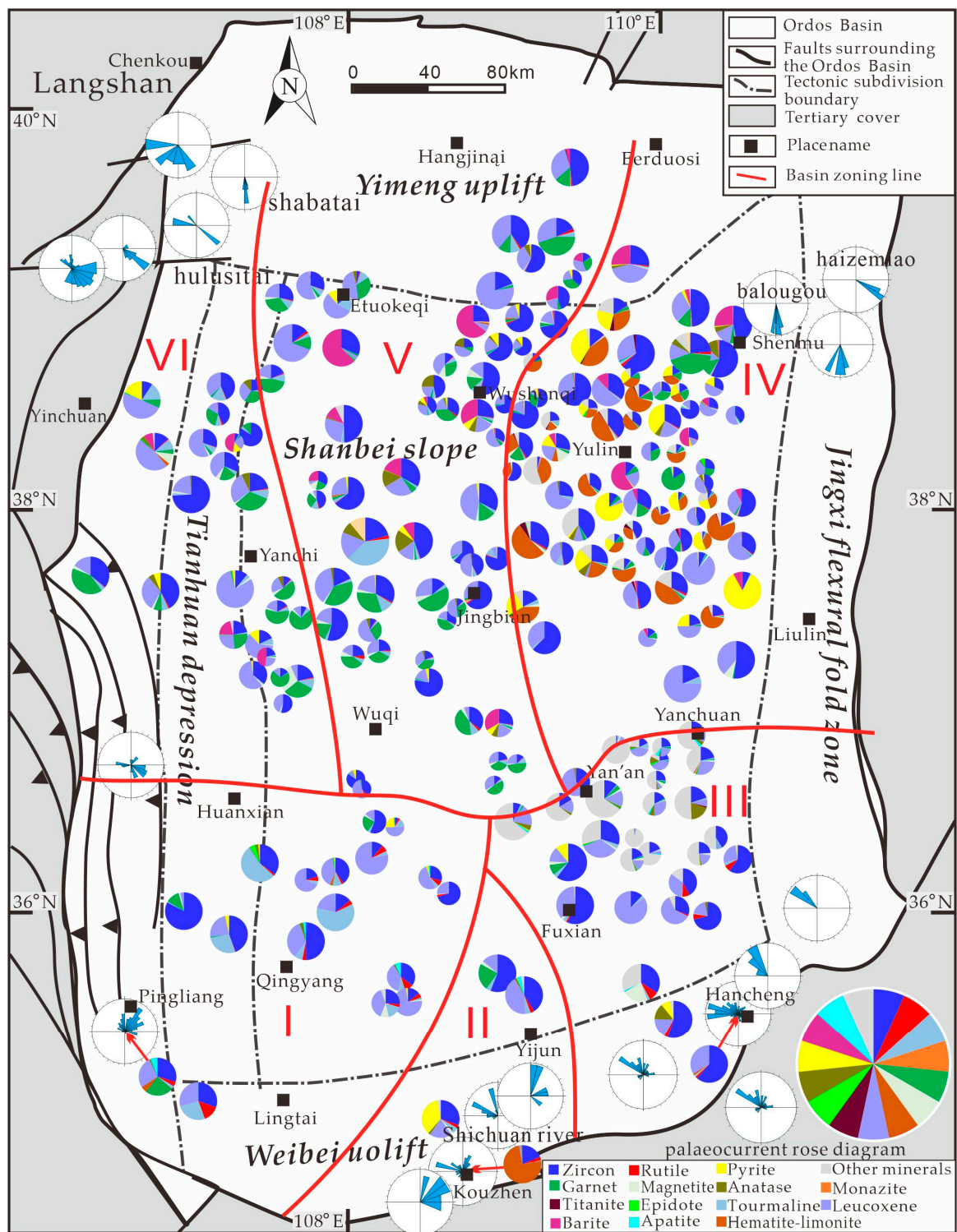


Figure 3. Heavy minerals sample distribution, paleocurrent direction, and distribution characteristics of heavy minerals of the He 8 Member in the Ordos Basin (base map modified from [34], paleocurrent direction according to [4,8,9,15,16,20,35,39]).

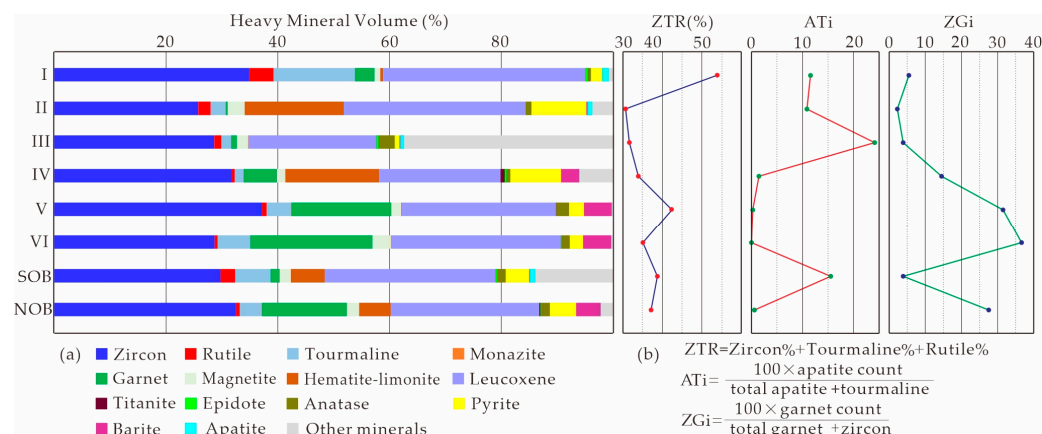


Figure 4. Heavy mineral assemblages (a) and heavy mineral indices (b) of the He 8 Member in the Ordos Basin.

4.3. Zircon U–Pb Ages

We analyzed 812 detrital zircons from eight representative samples taken from the southern Ordos Basin, of which 645 grains showed <10% discordance. Most of these zircons align with the concordant age curve (Figure 5a–h) and are detailed in Table S2. A total of 204 detrital zircons from two representative samples in the northern Ordos Basin were analyzed, with the ages of 178 grains found to be concordant. Most of these zircons also feature concordant curves (Figure 5i,j) and exhibit mainly light rose and dark rose colors. Most of these zircons are subrounded to round and angular-grained to subangular-grained in shape, with most lengths falling between 80 μm and 200 μm (Figure 6i,j). Some of these zircons have dark or blurry oscillatory zoning (Figure 6j, 72 points), with Th/U ratios > 0.4, suggesting a magmatic origin [42,43,45–47]. Additionally, a few grains display fan zoning structures (Figure 6c, 32 points), indicating that they recrystallized during late tectonothermal events or metamorphic events and likely experienced metamorphic growth [42,43,45,46]. In general, igneous zircons typically present Th/U ratios > 0.4, whereas metamorphic zircons present ratios < 0.1 [44,48,49]. Overall, the data indicate that most of the zircons in the He 8 Member have Th/U ratios greater than 0.4, except for 286 grains with ratios ranging from 0.1 to 0.4 and 8 zircons with ratios less than 0.1 (Figure 7), suggesting a primarily magmatic origin with a minority of zircons of metamorphic origin.

In our study, two boreholes were studied in the northern Ordos Basin, from which the number of concordant dated zircon grains totaled 178. U–Pb age data were collected from 14 sandstones in the southern Ordos Basin, where the number of concordant dates totaled 995, and from 32 sandstones in the northern Ordos Basin, where the number of concordant dated zircon grains totaled 1275.

All zircons dated, analyzed, photographed, and described were compared according to the six zones delineated by heavy mineral characteristics. Although the age distributions have little difference, they all show three main peak distributions (Figure 8a–f). There are specific main age peak values for each zone, including Zone I: 309 Ma, 1060 Ma, 1880 Ma, and 2380 Ma; Zone II: 307 Ma, 1855–1937 Ma, and 2455 Ma; Zone III: 310 Ma, 1858 Ma, and 2425 Ma; Zone IV: 319 Ma, 1830 Ma, and 2382 Ma; Zone V: 319 Ma, 1858 Ma, and 2422 Ma; and Zone VI: 340 Ma, 1830 Ma, and 2446 Ma (Figure 8a–f). Overall, they demonstrate three significant age populations of ~350–258 Ma (peaking at ~0.34–0.3 Ga), 2000–1600 Ma (peaking at ~1.94 Ga and ~1.88–1.83 Ga), and 2600–2300 Ma (peaking at ~2.52–2.38 Ga) and two secondary populations of 620–350 Ma (peaking at ~0.595 Ga and ~0.44–0.42 Ga) and 2300–2000 Ma (peaking at ~2.25–2.1 Ga) (Figure 8a–f). The youngest detrital zircons in the collected and test samples are 258 ± 2.5 Ma and 268.2 ± 3.3 Ma (sample S5), respectively. All 1640 harmonic zircon age data collected in the southern Ordos Basin, according to the age spectrogram, reveal that the main peaks are 305 Ma, 1853 Ma, and 2380–2507 Ma, whereas the secondary peaks are 440–600 Ma and 1934 Ma (Figure 8g). Similarly, all 1453 harmonic

zircon age data collected in the northern Ordos Basin display main peaks at 315, 1846, and 2431 Ma, along with a secondary age peak at 422 Ma (Figure 8h).

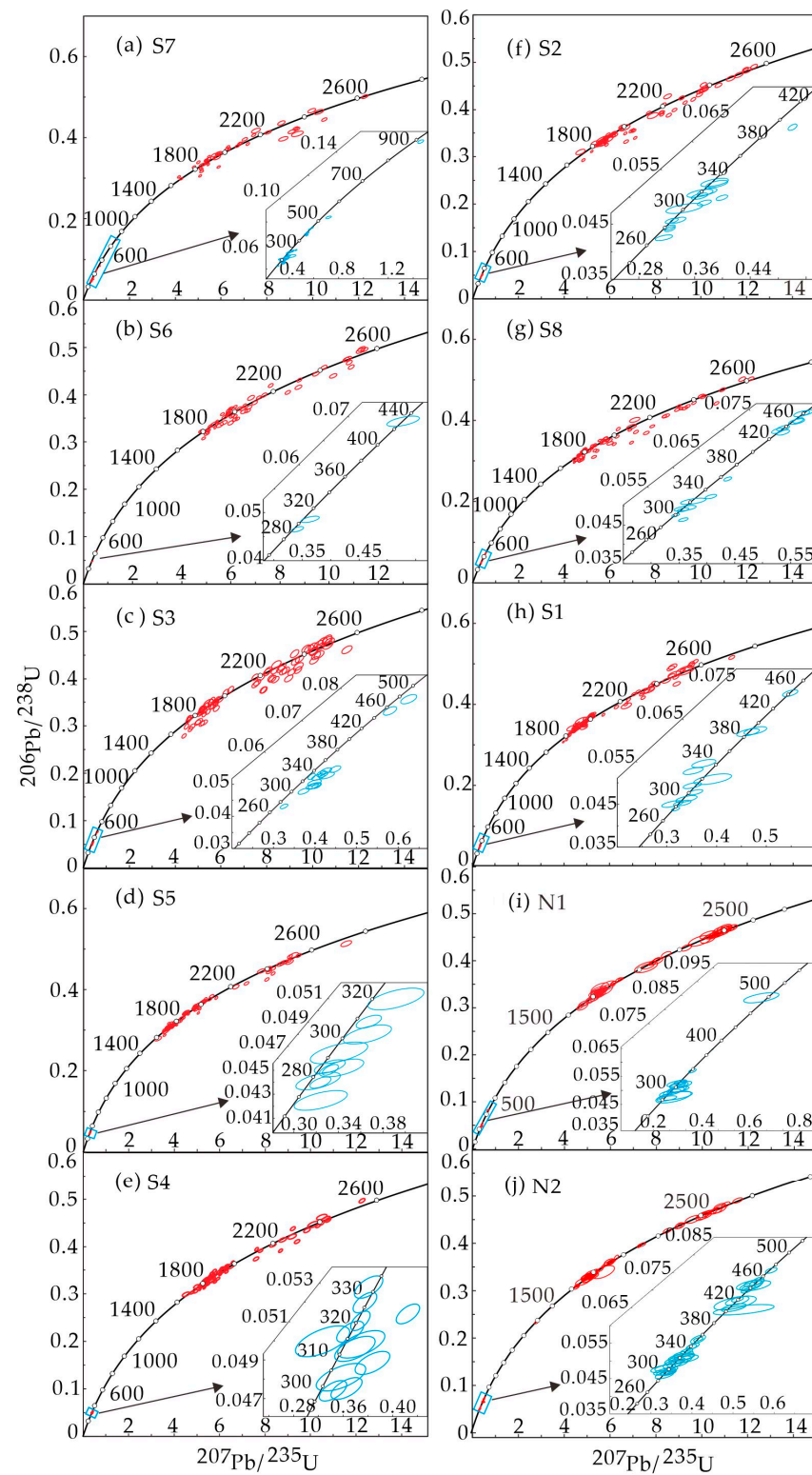


Figure 5. U-Pb harmonic diagrams of detrital zircons. Errors are quoted at 1 σ level.

(a) S7 <u>200μm</u>							
	41:287.7±2.4 32:-6.35±0.56	45:300.1±2.2 34:-10.79±0.50	98:304.9±2.8 26:-7.64±0.46	81:1864.6±25.5 19:-0.46±0.57	94:1935.0±23.0 23:6.60±0.61	32:2074.6±22.6 28:0.86±0.6	95:2441.8±19.7 24:2.50±0.47
(b) S6 <u>200μm</u>							
	63:1840.4±24.9 27:0.38±0.47	61:1925.4±23.9 25:-0.76±0.60	88:1947.0±32.1 31:-2.52±0.63	53:2019.3±24.8 21:1.63±0.51	54:2127.1±25.1 22:4.19±0.55	75:2516.2±21.5 30:-9.36±0.59	16:2579.4±18.5 7:6.74±0.51
(c) S3 <u>200μm</u>							
	79:331.1±4.3 21:-7.49±0.84	6:1942.4±37.8 3:1.18±0.83	32:1943.8±36.4 8:0.82±0.90	43:2232.5±36.8 12:1.05±1.16	53:2369.7±34.8 14:0.73±0.93	92:2429.5±35.4 25:-3.6±0.93	56:2438.7±35.7 16:0.57±0.81
(d) S5 <u>200μm</u>							
	57:1847.1±29.5 25:1.87±0.61	10:1849.1±23.6 7:-8.62±0.54	35:1854.3±36 18:-7.18±0.69	63:1884.5±20.7 32:-3.01±0.58	4:2063.1±19.1 3:-3.57±0.77	2:2257.4±27.5 2:8.64±0.77	87:2496.5±21.2 41:5.64±0.72
(e) S4 <u>200μm</u>							
	18:1816.0±25.3 5:-6.11±0.76	53:1818.1±22.2 18:-8.93±0.65	58:1827.7±22.0 21:-11.19±0.61	78:1829.3±25.1 28:-13.13±0.78	80:2214.3±23 30:-2.95±0.61	9:2245.6±20.2 3:0.82±0.80	3:2419.0±17.4 2:-0.64±0.64
(f) S2 <u>200μm</u>							
	73:328.8±2.7 19:3.83±0.80	18:1896.8±24.3 2:-4.45±0.75	60:2382.7±20.6 14:3.03±0.98	62:2392.5±18.9 15:0.74±0.81	87:2399.2±21.2 21:2.41±0.81	23:2460.8±20.7 5:0.82±0.86	95:2548.1±19.5 25:4.04±1.02
(g) S8 <u>200μm</u>							
	46:310.7±3.0 15:5.17±0.74	57:1741.7±23.6 19:-3.75±0.64	54:1752.3±26.2 17:-2.90±0.69	59:1763.2±26.2 21:-3.67±0.55	10:1828.6±23 2:2.27±0.60	35:1931.6±21.4 11:-2.39±0.61	20:2596.8±18.2 6:-3.50±0.58
(h) S1 <u>200μm</u>							
	15:386.3±3.6 11:-6.34±0.62	67:442.1±3.1 40:-6.31±0.80	35:1922.5±25.9 21:-0.72±0.75	94:1937.5±30.3 61:-5.47±0.64	79:1947.4±30.7 48:-5.20±0.63	56:1967.3±26.1 35:-2.20±0.79	69:2270.5±23.0 42:1.00±0.91
(i) N1 <u>200μm</u>							
	69:303.4±4.1 18:-3.75±0.81	20:353.6±2.8 6:-8.77±0.96	13:1849.0±67 4:-5.49±0.82	79:1917.0±21.0 19:-4.37±0.82	13:2355.0±41.0 3:2.45±1.00	38:2428.0±29.0 11:3.70±0.82	93:2455.0±18.0 23:-4.96±0.82
(j) N2 <u>200μm</u>							
	72:289.7±4.1 19:-13.35±1.13	4:294.3±3.1 1:-2.46±0.88	58:295.9±4.2 14:-2.63±0.85	26:440.0±3.2 21:-5.14±0.92	10:1790.0±71.0 3:-3.08±1.17	86:1851.0±59.0 24:-5.73±0.85	96:2530.0±15.0 29:2.47±0.78
○ LA-ICP-MS spots' location, analysis number and age(Ma) ○ LA-ICP-MS in situ Hf analytical site, number and $\epsilon_{\text{Hf}}(t)$ 3:2419±17.4 2:-0.64±0.64							

Figure 6. Representative cathodoluminescence (CL) images of the zircons from samples.

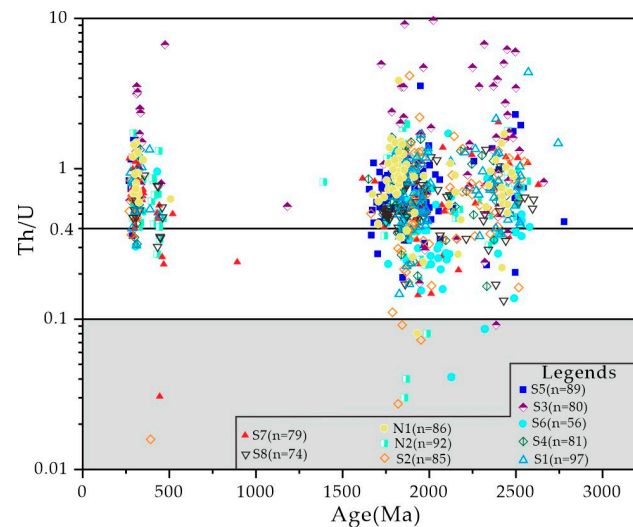


Figure 7. U–Pb age vs. Th/U ratio diagram. The shaded area denotes values for typical metamorphic zircons with Th/U < 0.1.

4.4. In Situ Zircon Hf Isotope Analyses

The Hf isotope data for 307 detrital zircons in the southern Ordos Basin are detailed in Supplementary Table S3. The samples exhibit $\epsilon_{\text{Hf}}(t)$ values spanning a broad range of -16.63 to 9.42 (average -2.72 , most $\epsilon_{\text{Hf}}(t) < 0$), along with two-stage Hf model ages (T_{DM2}) ranging from 992 to 3574 Ma. Among these points, 197 have negative $\epsilon_{\text{Hf}}(t)$: -16.63 to -0.44 (average -6.12), with T_{DM2} values of 1369 – 3574 Ma (average 2510 Ma). The remaining 110 grains display positive $\epsilon_{\text{Hf}}(t)$: 0.38 – 9.42 (average 3.37), with T_{DM2} values of 992 – 3139 Ma (average 2556 Ma, Table S3 and Figure 9). There are a total of 55 zircon grains with Lu–Hf isotope data in the northern Ordos Basin, with the $\epsilon_{\text{Hf}}(t)$ values ranging from -13.35 to 6.2 (average of -4.3) and T_{DM2} values ranging from 918 – 3266 Ma (average 2208 Ma). There are a total of 41 zircon grains that have negative $\epsilon_{\text{Hf}}(t)$: -13.35 to -0.38 (average -6.2), with T_{DM2} values of 1346 – 3266 Ma (average 2207 Ma), whereas the remaining 12 grains exhibit positive $\epsilon_{\text{Hf}}(t)$ values: 0.16 – 6.2 (average 2.5) and T_{DM2} values of 638 – 2880 Ma (average 2214 Ma).

The $\epsilon_{\text{Hf}}(t)$ and T_{DM2} values of the zircons indicate that their sources in the He 8 Member were dominated by Paleoproterozoic zircons, with a few Neoproterozoic and Neopaleozoic zircons also present.

There are a total of 121 zircons with Lu–Hf isotope data in Zone I, and the $\epsilon_{\text{Hf}}(t)$ values range from -12.75 to 7.93 (average -2.65), with T_{DM2} ages spanning from 992 to 3522 Ma (average 2546 Ma). Among these zircons, 83 exhibit negative $\epsilon_{\text{Hf}}(t)$ values, ranging from -12.75 to -0.58 (average -5.14), and their T_{DM2} ages range from 1369 to 3522 Ma (average 2521 Ma). Thirty-eight zircons have positive $\epsilon_{\text{Hf}}(t)$ values ranging from 0.74 to 7.93 (average 3.37), with T_{DM2} values ranging from 992 – 2919 Ma (average 2603 Ma).

There are a total of 107 zircons with Lu–Hf isotope data in Zone II, and the $\epsilon_{\text{Hf}}(t)$ values range from -16.63 to 9.42 (average -2.31), with a T_{DM2} of 1292 – 3574 Ma (average 2499 Ma). Among these zircons, 59 exhibit negative $\epsilon_{\text{Hf}}(t)$ values, ranging from -16.63 to -0.66 (average -6.9), and their T_{DM2} ranges from 1615 to 3574 Ma (average 2472 Ma). Among these zircons, forty-eight exhibit positive $\epsilon_{\text{Hf}}(t)$ values, ranging from 0.38 to 9.42 (average 3.33), with T_{DM2} values ranging from 1292 – 2957 Ma (average 2552 Ma).

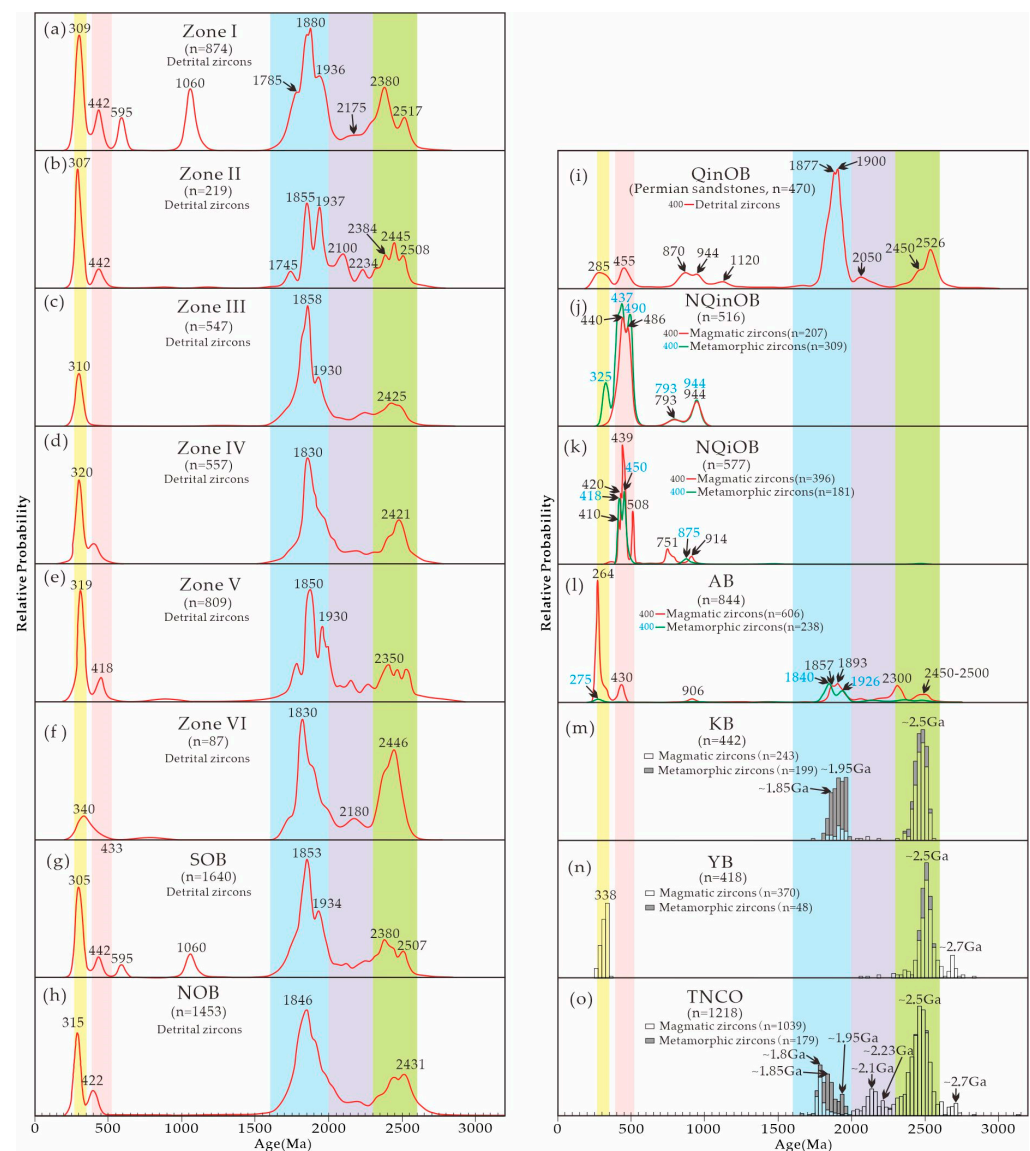


Figure 8. Zircon U–Pb age histograms. The ages with less than 10% discordance are used only. The yellow, pink, blue, gray, and green bars show the age groups of 350–268 Ma, 520–386 Ma, 2000–1600 Ma, 2300–2000 Ma, and 2600–2300 Ma, respectively. Data sources: the magmatic ages and metamorphic ages data of the Trans-North China Orogen (TNCO) are from [50–73], the magmatic ages data of the North Qinling Orogenic Belt (NQinOB) from [74–88], the metamorphic ages data of the NQinOB from [74,80,85,89–112], the magmatic ages data of the North Qilian Orogenic Belt (NQiOB) from [74,78,113–135], the metamorphic ages data of the NQiOB from [96,114,131–133,136–138], the magmatic ages data of the Khondalite Belt (KB) from [139–150], the metamorphic ages data of the KB from [68,142–145,147,151–164], the magmatic ages data of the Yinshan Block (YB) from [165–192], the metamorphic ages data of the YB from [169,170,176,177,179,192–194], the detrital zircon ages data of the northern Ordos Basin from [195], the detrital zircon ages data of the QinOB from [196–199] (the QinOB data include the Permian in Zhen’an Basin data in the South Qinling Orogenic Belt, the Liuye River Basin data in the NQinOB, and the Lintan area data in Western Qinling Orogenic Belt), the magmatic ages data of the AB from [165,179,200–293], the metamorphic ages data of the AB from [201–207,212,214,216,232,243,250,268,273,281,293–304], and the detrital zircon ages data of (a–h) from this study and the Research Institute of Petroleum Exploration and Development, PetroChina Changqing Oilfield Company. The relative probability curves were drawn with the DensityPlotter program (version 8.5) by using the model of kernel density estimation (KED). The width of one column in (m–o) is 25 Ma.

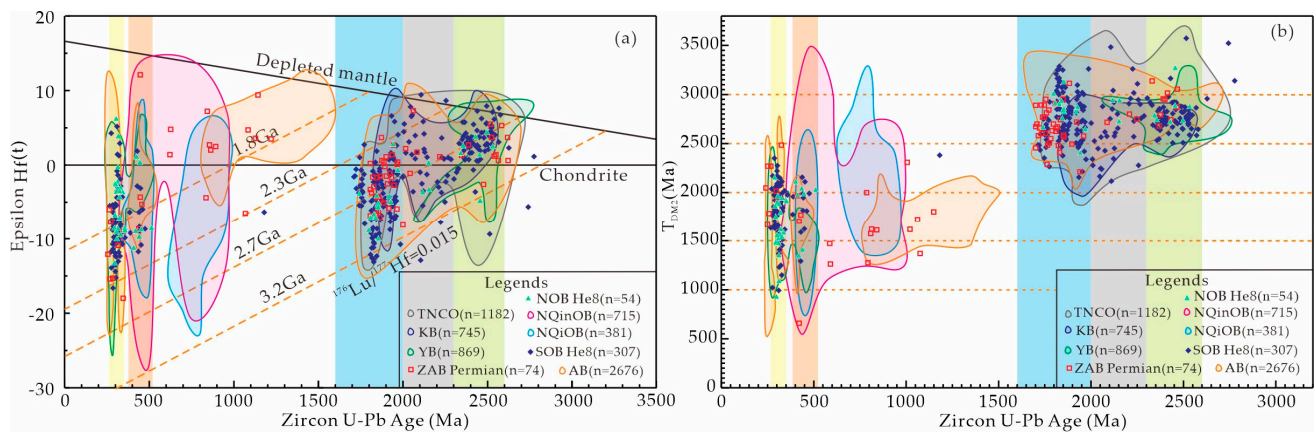


Figure 9. $\epsilon_{\text{Hf}}(t)$ values vs. U–Pb ages (a) and T_{DM2} vs. U–Pb ages (b). The yellow, orange, blue, gray, and green bars show the age groups of 350–268 Ma, 520–386 Ma, 2000–1600 Ma, 2300–2000 Ma, and 2600–2300 Ma, respectively. The Hf isotope evolution line for depleted mantle follows [305]. The Lu–Hf isotopic compositions of the TNCO are from [50–59], the NQinOB from [114,132,133,306], the NQiOB from [75,78,80,82,85,86], the KB from the references [139–150], the YB from [149,168,173,175,176,178,179,181,184–186,189], the AB from [149,168,173,175,176,178,179,181,182,184,186,200,203,260,291,307–310], the Permian in Zhen’an Basin (ZAB Permian) in South Qinling Orogenic Belt (SQinOB) from [199], and the southern Ordos Basin and northern Ordos Basin from this study.

There are a total of 79 zircons with Lu–Hf isotope data in Zone III, and the $\epsilon_{\text{Hf}}(t)$ values range from -13.54 to -0.44 (average -6.38), and their T_{DM2} values from 1514–3288 Ma (average 2550 Ma). Fifty-five of these zircons have negative $\epsilon_{\text{Hf}}(t)$ values, ranging from -13.54 – 8.64 , with T_{DM2} ages ranging from 1292 to 2959 Ma (average 2552 Ma). Twenty-four of these zircons have positive $\epsilon_{\text{Hf}}(t)$ values ranging from 0.53 to 8.64 (average 3.43), with T_{DM2} values ranging from 1148–3139 Ma (average 2491 Ma).

There are a total of 24 zircons with Lu–Hf isotope data in Zone IV, revealing $\epsilon_{\text{Hf}}(t)$ values ranging from -10.18 – 3.7 (average -4.78) and T_{DM2} values spanning 1346–3266 Ma (average 2289 Ma). Among these, twenty-one zircons have negative $\epsilon_{\text{Hf}}(t)$ values, ranging from -10.18 to -0.38 (average -5.05), with T_{DM2} values of 1346–3266 Ma (average 1949 Ma). Three zircons displayed positive $\epsilon_{\text{Hf}}(t)$ values, ranging from 0.16 to 3.7 (average 2.1), with T_{DM2} values ranging from 2717–2737 Ma (average 2725 Ma).

There are a total of 30 zircons with Lu–Hf isotope data in Zone VI, and the $\epsilon_{\text{Hf}}(t)$ values range from -13.35 to 6.2 (average -3.69), with T_{DM2} values ranging from 918–3004 Ma (average 2070 Ma). Twenty-one of these zircons have negative $\epsilon_{\text{Hf}}(t)$ values, ranging from -13.35 – 2.46 (average 6.4) and their T_{DM2} values ranging from 1464–3004 Ma (average 2081 Ma). Nine of these samples ranged from 0.31 to 6.2 (average 2.66), with T_{DM2} values ranging from 918–2880 Ma (average 2043 Ma).

5. Major Tectonothermal Event Analyses of Adjacent Regions

Numerous zircon U–Pb geochronology data have been obtained from adjacent regions of the NQinOB, the NQiOB, the KB, the AB, and the YB (Figure 1b), as well as the TNCO.

5.1. North Qinling Orogenic Belt (NQinOB)

Previous investigations of U–Pb geochronology in the NQinOB revealed one main peak with magmatism events dating from 500 Ma to 400 Ma, along with two secondary magmatism event peaks at 793 Ma and 944 Ma (Figure 8j). Within the 500–400 Ma main ages, two peaks at 440 Ma and 486 Ma are distinguished. These events were linked genetically to deep continental subduction at approximately 500 Ma, followed by crustal thickening and uplift from continent–continent collision at approximately 450 Ma and subsequent crustal uplift at approximately 420 Ma. The $\epsilon_{\text{Hf}}(t)$ values of the samples range from -27.5 to 14.6 (average -0.6), with T_{DM2} values ranging from 551 to 2759 Ma (average 1447 Ma, mostly

$T_{DM2} < 2.0$ Ga). This indicates reworking of Neoproterozoic–Neoproterozoic crustal materials (Figure 9). Additionally, metamorphic ages of 517–324 Ma, peaking at 490 Ma, 437 Ma, and 325 Ma, have been reported (Figure 8j). Notably, a few metamorphic ages are younger than 350 Ma. The NQinOB underwent metamorphism at approximately 500 Ma (Figure 8j). These magmatic and metamorphic events indicate that the NQinOB experienced multistage tectonic evolution [311–313].

The granitic magmatism in the QinOB can be categorized into four evolutionary periods: Neoproterozoic (979–711 Ma), Paleozoic (507–400 Ma), early Mesozoic (250–185 Ma), and late Mesozoic (160–100 Ma) [314]. There are two stages of Neoproterozoic granitic magmatism in the NQinOB: 979–911 Ma (peaking at 944 Ma) and 894–815 Ma. The Paleozoic granitic magmatism can be divided into three stages: 507–470 Ma (peaking at 486 Ma), 460–422 Ma (peaking at 440 Ma), and 415–400 Ma [315].

The age statistics of magmatic zircons in the NQinOB reveal four main age peaks: 944 Ma, 793 Ma, 486 Ma, and 440 Ma, and those of metamorphic zircons include five main age peaks: 944 Ma, 793 Ma, 490 Ma, 437 Ma, and 325 Ma (Figure 8j).

5.2. North Qilian Orogenic Belt (NQiOB)

In contrast to NQinOB, NQiOB shows multiple magmatic events peaking at 410 Ma, 420 Ma, 439 Ma, 508 Ma, 751 Ma, and 914 Ma, alongside metamorphic events peaking at 418 Ma, 450 Ma, and 875 Ma (Figure 8k). Among these ages, zircons with early Paleozoic ages are mentioned in reference [34]. Conversely, Neoproterozoic zircons have $\varepsilon_{Hf}(t)$ values ranging from -25.2 to 6.3 (average -2.2) and T_{DM2} ages ranging from 1366 Ma to 3282 Ma, indicating juvenile growth and reworking of ancient Archean–Mesoproterozoic crustal materials (Figure 9). Furthermore, two stages of metamorphism that occurred from 473–445 Ma and 445–410 Ma are widespread in the NQiOB, corresponding to early oceanic and later continental subduction processes from [316].

5.3. Khondalite Belt (KB) and Yinshan Block (YB)

The KB is an ~ 1.95 Ga collisional orogen between the YB and the Ordos Basin [314,317–320]. This region is characterized by tectonothermal events, with the most significant being 1.95–1.85 Ga metamorphism, featuring two age peaks at ~ 1.95 Ga and ~ 1.85 Ga, and associated coeval magmatism of 1.95–1.85 Ga (Figure 8n). Additionally, magmatism at ~ 2.5 Ga and 2.45–2.37 Ga, along with metamorphism at 1.95–1.85 Ga, is documented in some Archean blocks within the KB [163,314]. Both magmatic activities at ~ 2.5 Ga and ~ 1.95 Ga have $\varepsilon_{Hf}(t)$ values of -3.48 – 9.75 (average 3.75, mostly > 0) and -11.6 – 7.54 (average 0.36, mostly > 0), with corresponding T_{DM2} ranges of 2.382–2.806 Ga (average 2.639 Ga, predominantly > 2.6 Ga) and 2.082–3.009 Ga (average 2.398 Ga, mostly > 2.3 Ga), respectively. These findings indicate that crustal reworking was associated with minor juvenile growth from the late Neoproterozoic to the Paleoproterozoic (Figure 9).

YB represents a microcontinental fragment located immediately north of the KB [321]. In contrast with the KB, this block has ~ 2.7 Ga of granitic gneiss [177,322] (Figure 8n) and was subjected to two stages of magmatism, ~ 2.7 Ga and ~ 2.5 Ga, as well as subsequent metamorphism resulting from ~ 2.55 – 2.45 Ga metamorphic events (Figure 8n). The ~ 2.55 – 2.45 Ga metamorphic event is marked by $\varepsilon_{Hf}(t)$ values ranging from 0.5 to 7.1 and T_{DM2} values ranging from 2.67–3.0 Ga [323]. The ~ 2.5 Ga magmatism is marked by $\varepsilon_{Hf}(t)$ values from -7.58 to 8.83 (average 2.31, mostly > 0) and the T_{DM2} ages range from 2395 to 3294 Ma (average 2772 Ma, predominantly > 2.7 Ga), indicating an ancient block with important juvenile growth at 2.7 Ga as well as strong 2.6–2.5 Ga crustal reworking (Figure 9). In addition, widely late Paleozoic magmatism occurred from 350–260 Ma (Figure 8n), which was attributed to the Paleozoic orogenesis of the Central Asia Orogenic Belt [163,324,325].

5.4. Alxa Block (AB)

We collected a total of 844 zircons from the AB, including 606 magmatic zircons and 238 metamorphic zircons. The age peaks of magmatism are as follows: 264 Ma,

430 Ma, 906 Ma, 1850–1900 Ma, 2300 Ma, and 2450–2500 Ma (Figure 8l). Moreover, the age peaks of the metamorphism are 275 Ma and 1840–1930 Ma (Figure 8l). The $\epsilon_{\text{Hf}}(t)$ values of these zircons range from -26.8 to 15.9 (average 2.82), and their T_{DM2} from 323–3449 Ma (average 1105 Ma, Figure 9). The peak at approximately 260 Ma may represent the tectonothermal event of the late Paleozoic AB [321]. In recent years, a significant number of granites aged approximately 270–380 Ma have been discovered in the North AB [326]. Additionally, the widely developed early Permian syncollisional to postcollisional granites along the north margin of the AB further illustrate the final closure event of the Paleo-Asian Ocean in the north margin of the AB [327]. The 270–380 Ma samples have $\epsilon_{\text{Hf}}(t)$ values of 0.35 – 10.0 (average 5.5 , all $\epsilon_{\text{Hf}}(t) > 0$) and T_{DM2} values of 679–1314 Ma (average 977 Ma, predominantly > 800 Ma). The Longshoushan Mountain, Beidashan Mountain, Norkong, and Langshan Mountain areas in the AB experienced magmatic events at 460–390 Ma. Additionally, Longshoushan Mountain contains both 444–420 Ma granitoid and 424–421 Ma diabase [328]. These magmatic events are presently interpreted as being associated with subduction and sinking of the Qilian Ocean into the AB [329]. The 460–387 Ma diorites and granites are exposed primarily in the Beidashan Mountain and Norkong areas. Geochemical characteristics suggest an island-arc-related characteristic; hence, it is interpreted as being associated with subduction orogenic processes in the Paleo-Asian Ocean [256]. The 443–418 Ma granodiorite found in the Yamatu area and the Langshan Mountain areas east of the AB is thought to be associated with the convergence of the AB with the North China Craton [195,218]. Metamorphism at approximately 400 Ma has been recorded in the eastern AB, resulting from the collision between the AB and North China Craton [218]. Previous data also indicate that there are approximately 420 Ma metamorphic records in the North Mountain area of the western AB. The AB may have been affected by an orogenic belt, which can more reasonably explain the Late Silurian–Early Devonian metamorphic events in the East China and West China AB [297]. The ages of 460–390 Ma have $\epsilon_{\text{Hf}}(t)$ values of -13.5 – 13.9 (average 0.7) and T_{DM2} values of 487–1857 Ma (average 1161 Ma, most $T_{\text{DM2}} > 1.1$ Ga). The peak from 1850–1900 Ma represents the collision of the Alashan Massif (Yinshan Massif) and the Ordos Basin between 2.0 Ga and 1.9 Ga, forming the unified North China Plate [318].

5.5. Trans-North China Orogen (TNCO)

The TNCO underwent multistage magmatic events during the Neoproterozoic–Paleoproterozoic. The U–Pb zircons from the magmatic event are distributed among four age groups (Figure 8o). The 2.6–2.35 Ga group has $\epsilon_{\text{Hf}}(t)$ values of -20.72 – 16.18 (average of 1.98 , mostly > 0) and the T_{DM2} values range from 2101–3776 Ma (average of 2789 Ma, predominantly > 2.7 Ga). The 2.25–2.0 Ga age group has $\epsilon_{\text{Hf}}(t)$ values ranging from -22.55 to 9.28 (average 0.84 , mostly > 0) and T_{DM2} values ranging from 2181–3643 Ma (average 2565 Ma, predominantly > 2.4 Ga) (Figure 9). Strong metamorphism occurred from 1.95–1.80 Ga in the TNCO [184] (Figure 8o), with $\epsilon_{\text{Hf}}(t)$ values of -9.24 – 1.21 (average -5.03 , predominantly < 0) and T_{DM2} values of 2288–2832 Ma (average 2629 Ma, predominantly > 2.4 Ga). These findings indicate that crustal growth approximately 2.7 billion years ago and magmatic activity approximately 2.5 billion years ago arose from the reworking of young crust within the TNCO. This was succeeded by granitic magmatism spanning 2.25 to 2.0 billion years ago, associated with continental margins, and metamorphism between 1.95 and 1.80 billion years ago, triggered by the collision of the East and West Blocks in the TNCO [33].

6. Discussion

6.1. Provenance of the He 8 Member

6.1.1. Provenance Evaluation Based on the Heavy Mineral and Paleoflow Data

According to the paleocurrent direction and statistical analysis of the data, the paleocurrent directions in the profiles of Hulusitai and Shaba Tai on the northwestern margin of the Ordos Basin are mainly S and SE (Figure 3). This suggests that the AB on the

northwestern margin may have provided the materials for the research area. Paleocurrent directions in the eastern margin of the Ordos Basin, such as those in Balougou and Haize Miao, are mainly toward the S and SW, combined with the extension of the Permian river deltas into the basin in the SSW (Figure 3). This reflects that the YB and the KB might have provided materials for the northern Ordos Basin [330]. Moreover, the dominant direction in Pingliang Erdaogou is NE, that in Kouzhen is NW and NE, and that in Hancheng is NW (Figure 3). These findings indicate that NQiOB, NQinOB, and TNCO might have provided materials for the southern Ordos Basin.

The southern Ordos Basin is dominated by zircon, leucoxene, tourmaline, and other minerals (chloritoid, siderite, pyrrhotite, mica, ilmenite, etc.), which are present in greater abundance in the north part of Zone III (Figures 3 and 4a). The garnet content decreases from the northern Ordos Basin to the southern Ordos Basin. In the northern Ordos Basin, the garnet contents of Zones VI and V are slightly higher than those in Zone IV (Figures 3 and 4a). The pyrite content is relatively high in Zone IV. The zircon contents in Zones IV, V, and VI increase sequentially from east to west and north to south (Figures 3 and 4a). The garnet content is relatively high in the central part, west-central part, and northeastern part of the Ordos Basin (Figure 3). Overall, the barite content in the northern Ordos Basin decreases sequentially from east to west, and the content of the moderately stable heavy mineral garnet increases sequentially from the southern Ordos Basin to the northern Ordos Basin, suggesting that the sediments in the He 8 Members of Zones IV, V, and VI have mainly provenances from the north part of the basin and that secondary provenances appears to have existed in the eastern part [195]. The unstable mineral assemblages of barite and pyrite tend to increase from the southern Ordos Basin to the northern Ordos Basin. Additionally, the pyrite in the northern Ordos Basin shows a sequential increasing trend from west to east and south to north, indicating proximal deposition with a short transport distance.

The ZTR index of the whole basin clearly tends to increase (Figure 4b): the highest ZTR in Zone I (ZTR > 50%) indicates that Zone I is relatively far from the source area compared with the other regions. From Zone I to Zone III, the ZTR index shows a decreasing and then an increasing trend. In the northern Ordos Basin, it increases from Zone VI to Zone IV and then decreases. The ZTR indices of Zones IV, V, and VI in the northern Ordos Basin are significantly higher than those of Zones II and III in the southern Ordos Basin, suggesting that Zones II and III are relatively closer to the source area. Overall, the ZTR index in the southern Ordos Basin is lower than that in the northern Ordos Basin.

The ATi in the southern Ordos Basin tends to increase from Zone I to Zone III (Figure 4b), with average values ranging from 10.86 to 24.11, and Zone III has the highest ATi, with an average value of 24.11, indicating that the southern Ordos Basin is supplied with more medium-acidic magmatic rocks. In the northern Ordos Basin, the ATi shows a decreasing trend from Zone IV to Zone VI, with average values ranging from 0 to 1.46. There are obvious differences in ATi between the northern Ordos Basin and the southern Ordos Basin, with a decreasing trend from the southern Ordos Basin to the northern Ordos Basin. This variation is obviously due to differences in material sources, indicating that there is a distinction between the southern Ordos Basin and the northern Ordos Basin in terms of their provenance.

The ZGi primarily ranges from 5 to 40 (Figure 4b), with an increasing trend from the southern Ordos Basin to the northern Ordos Basin. The three zones in the southern Ordos Basin have lower ZGi values (mean values between 2 and 6), whereas the three zones in the northern Ordos Basin have higher ZGi values (mean values between 14 and 37). This indicates a limited supply of intermediate-grade and lower-grade metamorphic host rocks in the southern Ordos Basin and a greater supply of these rocks in the northern Ordos Basin, suggesting differences in material sources between the southern Ordos Basin and the northern Ordos Basin.

6.1.2. Evaluation of Provenance via U–Pb Aircon Ages and Hf Isotopes

(1) Sedimentary tectonic setting

Cawood et al. (2012) proposed a discriminant diagram to determine the sedimentary tectonic setting of sedimentary rocks by using the age distribution characteristics of detrital zircons [331]. The mapping process and parameters of the discriminant map are detailed in [20,331]. The results of the Cawood diagram show that the sedimentary tectonic setting of most samples in the Ordos Basin is a collisional setting (B), that of only three samples in Zones I, II, and V is a convergent setting (A), and that of five samples in Zones II, IV, V, and VI is an extensional setting (C, Figure 10).

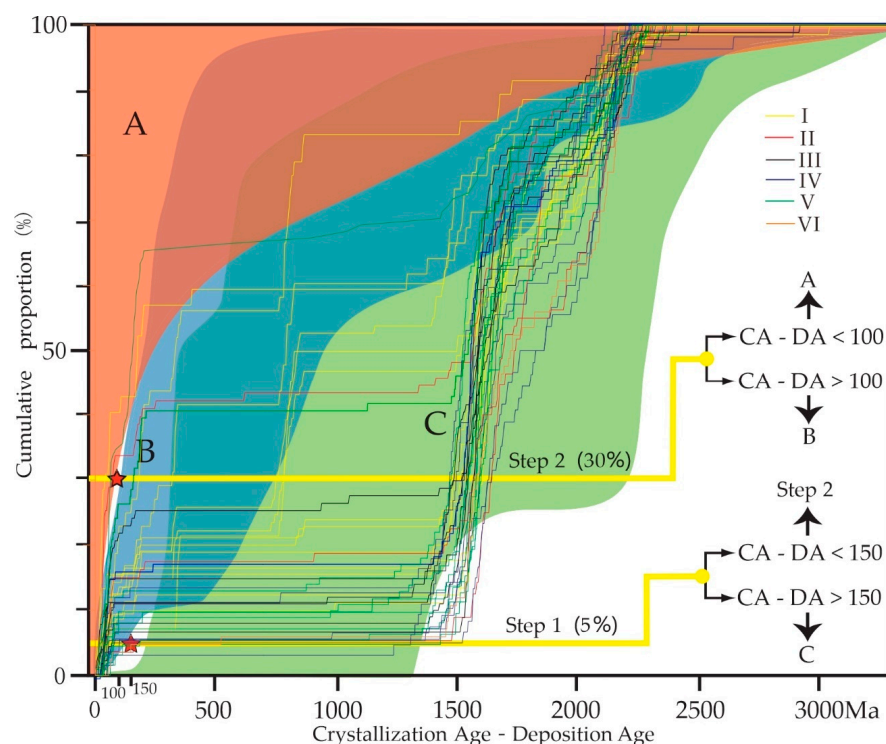


Figure 10. Cumulative probability curves of measured crystallization ages for detrital zircon grains relative to the depositional age of zircon samples from the Ordos Basin (basic map according to reference [331]). (A): Convergent setting; (B): Collisional setting; (C): Extensional setting.

(2) Neoproterozoic–Paleoproterozoic zircons (2600–1600 Ma)

In the Ordos Basin, 2377 zircon grains range in age from 2600 Ma to 1600 Ma, accounting for 76.85% of the total (3093). This age group accounted for 73.6% of the southern Ordos Basin and 80.5% of the northern Ordos Basin. Most of these grains exhibit typical magmatic zircon grains with evident magmatic oscillatory zoning (Figure 5).

There are 294 zircon grains with ages of 2600–2300 Ma (peaking at ~2.5–2.38 Ga) in the southern Ordos Basin, accounting for 17.9% of the total (1640). Most of these zircon grains show oscillatory zoning, indicating a distinctive origin from magma. The Lu–Hf isotopes of seventy-one zircons were analyzed, yielding $\epsilon_{\text{Hf}}(t)$ values ranging from -9.36 to 7.93 and T_{DM2} ages ranging between 2506 and 3574 Ma (most $T_{\text{DM2}} > \sim 2.7$ Ga, Table S3 and Figure 9). Among these, seven grains exhibited negative $\epsilon_{\text{Hf}}(t)$: -9.36 to -0.44 , with T_{DM2} ages of 2891–3574 Ma. Sixty-four grains displayed positive $\epsilon_{\text{Hf}}(t)$ values of 0.53 to 7.93 and T_{DM2} ages of 2506 to 2924 Ma, indicating that Neoproterozoic–Mesoarchean juvenile crust was involved in minor Eoarchean crustal materials.

There are 283 zircon grains with ages of 2600–2300 Ma (peaking at ~2.43 Ga) in the northern Ordos Basin (Figure 8h), accounting for 17.2% of the total (1453). Most of these show oscillatory zoning, indicative of a typical magmatic origin. Of the 178 zircon

samples from wells N1 and N2 in the northern Ordos Basin, there are 33 zircon grains with ages of 2600–2300 Ma (peaking at ~2.43–2.15 Ga), accounting for 18.5% of the total (178), with Th/U range of 0.22 to 1.80 (average 0.81, Figure 7). This suggests that these zircons are from magmatic rocks, with most of them having Th/U > 0.4, and showing typical magmatic characteristics with evident magmatic oscillatory zoning. Six grains yielded $\epsilon_{\text{Hf}}(t)$ values ranging from 1.35 to 4.37, their T_{DM2} ranging from 2717–2880 Ma (Figure 9). One grain yielded an $\epsilon_{\text{Hf}}(t)$ value of −4.96, with a T_{DM2} value of 3266 Ma. This implies that the corresponding magmas were influenced by materials from different source regions. The source regions of the magmas were both melted and supplemented by nascent terrestrial crust. There are 176 zircon grains with ages from 2300 Ma to 2000 Ma (peaking at ~2.25–2.1 Ga) in the southern Ordos Basin, accounting for 10.7% of the total (1640). Most of them are magmatic zircons. Fifteen grains exhibited negative $\epsilon_{\text{Hf}}(t)$ values, varying from −12.88 to −0.97, with a T_{DM2} ranging from 2709 to 3483 Ma (Table S3 and Figure 9). Conversely, twenty-three grains showed positive $\epsilon_{\text{Hf}}(t)$ values, ranging from 0.79–9.42, and a T_{DM2} between 2116 and 2782 Ma (Table S3 and Figure 9). Most T_{DM2} values are greater than ~2.4 Ga (Figure 9b). The Lu–Hf isotopes indicate that this group of zircons was mainly from a Neoarchean–Mesoarchean crust with minor Palearchean and Paleoproterozoic crustal materials.

There are 183 zircon grains with ages from 2300 Ma to 2000 Ma (peaking at ~2.25–2.1 Ga) in the northern Ordos Basin (Figure 8h), accounting for 11.97% of the total (1453). Of the 178 zircon samples from wells N1 and N2 in the northern Ordos Basin, there are 9 zircon grains with ages of 2300–2000 Ma (peaking at 2155 Ma, Figure 8i), accounting for 5.1% of the total (178), with Th/U ranging from 0.27 to 1.09 (average 0.63, Figure 7). The Lu–Hf isotope analysis of two zircons revealed negative $\epsilon_{\text{Hf}}(t)$ values of −3.8 and −3.32, along with T_{DM2} ages of 2934 Ma and 2936 Ma. One zircon exhibited an $\epsilon_{\text{Hf}}(t)$ value of 0.16, with T_{DM2} age of 2611 Ma (Figure 9). The Lu–Hf isotopic data suggest that this group of zircons is predominantly from the Neoarchean–Mesoarchean crust.

There are 737 zircon grains dated from 2000 Ma to 1600 Ma (peaking at ~1.95 Ga and ~1.85 Ga) in the southern Ordos Basin, accounting for 44.9% of the total (1640). The zircons are predominantly of metamorphic origin and also contain a lot of magmatic zircons. Of these, 105 grains exhibited negative $\epsilon_{\text{Hf}}(t)$ values ranging from −13.13 to −0.46, with T_{DM2} ranging from 2434 to 3288 Ma. Fifteen grains showed positive $\epsilon_{\text{Hf}}(t)$ values between 0.3 and 6.6, with T_{DM2} ages spanning from 2157 to 2538 Ma (Figure 9b), of which most of the $\epsilon_{\text{Hf}}(t)$ values are greater than zero, and most T_{DM2} > ~2.4 Ga. All suggest a Neoarchean to Mesoarchean crustal source with a small Palearchean and Paleoproterozoic crustal component.

A total of 1453 zircons are from the northern Ordos Basin, of which 703 zircons date between 2000 Ma and 1600 Ma (peaking at ~1850 Ma). Of the 178 grains from wells N1 and N2 in the northern Ordos Basin, 82 zircon grains had ages ranging from 2000 Ma to 1600 Ma (peaking at ~1830 Ma), accounting for 46.1% of the total (178), with Th/U ratio ranging from 0.03 to 3.90 (average 0.89). Combined with the zircon characteristics observed in CL images, it is inferred that the zircons are predominantly magmatic orogenic, with a few metamorphic zircons. Lu–Hf isotope analysis of 13 zircon samples revealed predominantly negative $\epsilon_{\text{Hf}}(t)$ values, spanning from −10.17 to −0.83, with T_{DM2} of 2641–3125 Ma. Additionally, one zircon exhibited an $\epsilon_{\text{Hf}}(t)$ value of −2.75, corresponding to a T_{DM2} age of 2399 Ma. Most $\epsilon_{\text{Hf}}(t)$ values are less than 0 and most T_{DM2} values are >2.4 Ga (Figure 9). Previous studies have suggested that ages of ~1950–1850 Ma correspond to ages of late Paleoproterozoic gneisses, mafic rocks, and forsterites in the Daqingshan–Wulashan and Yinshan areas [332].

In terms of the heavy mineral analysis, paleocurrent analysis, distribution of zircon crystallization ages, Lu–Hf isotope compositions, and Hf model ages, the groups of 2600–2300 Ma zircons are similar to those of the TNCO, AB, YB, and KB. The 2300–2000 Ma zircons are similar to the TNCO and AB, and the 2000–1600 Ma zircons similar are to the TNCO, AB, and KB (Figures 8 and 9).

(3) Late Mesoproterozoic zircons (1150–1000 Ma)

Only two zircons of this age group were found in the northern Ordos Basin (Zones IV and V), and the rest were found in the southern Ordos Basin (Zone I, Figure 8a–f). There are a total of 81 zircon grains from 1150 Ma to 1000 Ma (peaking at 1060 Ma, Figure 8g) in the southern Ordos Basin (Zone I), accounting for 4.9% of the total (1640). These zircon age data were collected from other researchers, and no zircons were found in our test samples. Zircons of this age group were found in other researchers' Pingliang samples that we collected, but no zircon was found in our test Pingliang sample. It is reasonable to speculate that zircons of this age group may be the result of mixed-age zircons due to the selection of test locations during zircon age testing. Therefore, we conclude that the 1150–1000 Ma age group has no provenance indication. Whether this age group is real or not needs further research.

(4) Late Neoproterozoic–Early Paleozoic zircons (671–375 Ma)

The north sample included 73 zircons in the age range of 671–350 Ma (peaking at 410–439 Ma) in the northern Ordos Basin, of which 14 zircons were our test data and 59 zircons were collected. There are a total of 13 zircon grains in the interval of 671–375 Ma (peaking at 439 Ma) in the northern Ordos Basin, accounting for 8.4% of the total (178). Nine zircons were subjected to Lu–Hf isotope analysis, revealing T_{DM2} values ranging from 1336 Ma to 2023 Ma, with the majority falling between 1.9 Ga and 2.1 Ga and only one zircon grain with $T_{DM2} < 1.9$ Ga (T_{DM2} of 1.3 Ga). Among these, seven zircons had negative $\epsilon_{Hf}(t)$: $-11.3 \sim -8.73$ (average -9.3), and their T_{DM2} ages ranged from 351 to 510 Ma. The remaining two grains exhibited positive values: 0.31 and 1.08 (average 0.7), with T_{DM2} values of 420 Ma and 440 Ma, respectively (Table 1).

Table 1. Summarized Hf isotopic composition.

Ages (Ma)	Parameters	YB	AB	Northern Ordos Basin	Southern Ordos Basin
520–370	$\epsilon_{Hf}(t)$ value	$-6.11 \sim -6.8$ ^a	$-13.5 \sim -13.9$	$-11.3 \sim -1.08$	$-11.73 \sim -1.87$
	$\epsilon_{Hf}(t)$ feature	1.03 ^b (35 ^c), 60% > 0, all from $-6.2 \sim -7$	0.74 (233), 58.37% > 0	-6.61 (7), 71.4% < -6.61 , 28.6% > 0	-6.7 (12), 50% < -6.2 , 5% > 10
	T_{DM2} value	1000–1793 ^d Ma	472–1857 Ma	1336–2103 Ma	1292–2155 Ma
	T_{DM2} feature	1361 Ma (35 ^c), all from 1.0–1.8 Ga	1166 Ma (233), 61.37% from 1.1–1.9 Ga	1834 Ma (7), 28.6% < 1.5 Ga, 71.4% > 1.8 Ga	1838 Ma (12), 90% from 1.1–1.85 Ga, 5% < 1.0 Ga
350–320	$\epsilon_{Hf}(t)$ value	$-9.18 \sim -3.2$	/	$-9.52 \sim (-3.18)$	$-12.33 \sim -2.91$
	$\epsilon_{Hf}(t)$ feature	-2.6 (141), all from $-10 \sim -3.2$, 73% < 0	/	-5.29 (6), 100% < 0	-6.66 (14), 90% < 0, 33% < -10
	T_{DM2} value	1131–1953 Ma	/	1535–1933 Ma	1148–2111 Ma
	T_{DM2} feature	1505 Ma, 91% from 1.2–1.85 Ga, all > 1.1 Ga	/	1666 Ma (6), 50% > 1.6 Ga	1755 Ma (14), 80% from 1.13–1.77 Ga, 10% < 1.1 Ga
320–285	$\epsilon_{Hf}(t)$ value	$-25.49 \sim (-3.97)$	0.35–10.0	$-13.35 \sim -6.2$	$-20.84 \sim -5.18$
	$\epsilon_{Hf}(t)$ feature	-7.85 (37), 81% from $-8.5 \sim (-4)$	5.94 (29), 100% > 0	-4.41 (14), 14.3% > 0	-8.25 (41), 95% < 0, 16.1% > -4.4 , 52% < -8.5 , 79% from $-15 \sim (-5)$
	T_{DM2} value	1529–2046 Ma	591–1702 Ma	918–2146 Ma	992–2349 Ma
	T_{DM2} feature	1746 Ma, 84% from 1.55–1.85 Ga, all > 1.52 Ga	955 Ma, 24.14% from 1.0–1.8 Ga	1592 Ma (14), 57.1% > 1.5 Ga	1841 Ma (41), 42% < 1.52 Ga, 89% from 1.1–1.85 Ga
285–260	$\epsilon_{Hf}(t)$ value	$-22.04 \sim -5.44$	1.4–7.4	/	$-13.88 \sim -4.3$
	$\epsilon_{Hf}(t)$ feature	-7.14 (250), 94% from $-16 \sim -5$	4.21 (44), 100% > 0, 29.5% > 5	/	-6.92 (7), 86% from $-14 \sim (-5)$
	T_{DM2} value	954–2470 Ma	814–1625 Ma	/	877–1804 Ma
	T_{DM2} feature	1772 Ma (250), 95% from 1.0–2.3 Ga	1047 Ma (44), 56.8% from 1.0–1.7	/	1450 Ma (7), 86% from 1.35–1.81 Ga

Note: The Lu–Hf isotopic compositions of the AB are from [34,191,275,306], the YB from [34], and the northern Ordos Basin and southern Ordos Basin from this study. “a” and “d” are numerical ranges of $\epsilon_{Hf}(t)$ and T_{DM2} , respectively; “b” is numerical averages of $\epsilon_{Hf}(t)$ and T_{DM2} , respectively; “c” is the number of data.

A total of 170 zircon grains have ages ranging from 671 Ma to 375 Ma, accounting for 5.5% of the total (3093). This age group accounted for 5.9% of the southern Ordos Basin (peaking at 441 Ma, 387 Ma, 327 Ma, 308 Ma, and 291 Ma; Figure 11g) and 4.7% of the northern Ordos Basin (peaking at 433 Ma, 410 Ma, 323 Ma, and 300 Ma; Figure 11h).

Small proportions of 520–386 Ma zircons were collected in the southern Ordos Basin. Twelve zircons were analyzed for Lu–Hf isotopes. Most of these zircons have Th/U ratios exceeding 0.4, with five grains having ratios from 0.1 to 0.4 and two grains having ratios less than 0.1 (Table S2 and Figure 5). These findings suggest that these rocks originated from both magmatic and metamorphic processes. Twelve Lu–Hf isotope data yielded T_{DM2} values from 1292 to 2155 Ma, and most of the T_{DM2} values were less than 2.0 Ga (Table 1 and Figure 12b). Among these zircons, 11 displayed negative $\epsilon_{Hf}(t)$ values of -11.73 to -2.81 , along with T_{DM2} values ranging from 1589 to 2155 Ma (Table 1 and Figure 12). The remaining zircon sample exhibited positive an $\epsilon_{Hf}(t)$ value of 1.87 and T_{DM2} age of 1292 Ma.

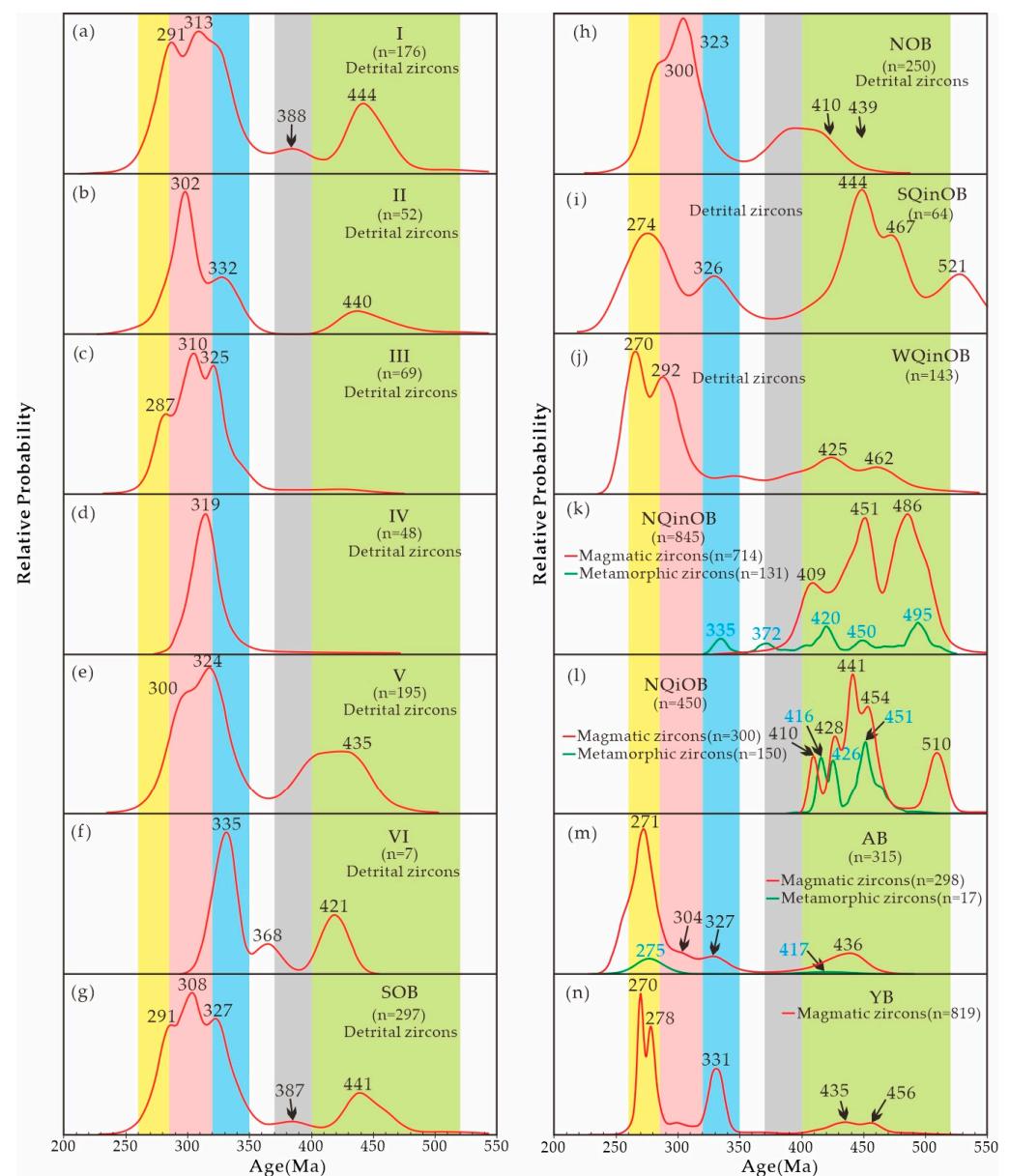


Figure 11. Zircon U–Pb age (200–550 Ma) distribution diagram (a–n). The ages with less than 10% discordance are used only. The yellow, orange, blue, gray, and green bars show the age groups of 285–260 Ma, 320–285 Ma, 350–320 Ma, 400–370 Ma, and 520–400 Ma, respectively. Data sources: the magmatic ages data of the NQinOB are from [74,75,78,80,87–89], the metamorphic ages data of the

NQinOB from [74,81,86,90–108,110,112,333], the magmatic ages data of the NQiOB from [114–121,123,126,128–135], the metamorphic ages data of the NQiOB from [131–133,136–138], the magmatic ages data of the YB from [165,166,172–175,179–182,184–187,189,190,192,334], the metamorphic zircon ages data of the AB from [180,232,273,281,294,299], the magmatic zircon ages data of AB from [173–220,222,224,235,256,258,260,265,268,280,291], the detrital zircon ages data of the South Qinling Orogenic Belt (SQinOB, the Permian in Zhen'an Basin) from [196,200], the Western Qinling Orogenic Belt (WQinOB, the Permian in Lintan area) from [197], the detrital zircon ages data of the Figure 8a–h from this study and the Research Institute of Petroleum Exploration and Development, PetroChina Changqing Oilfield Company.

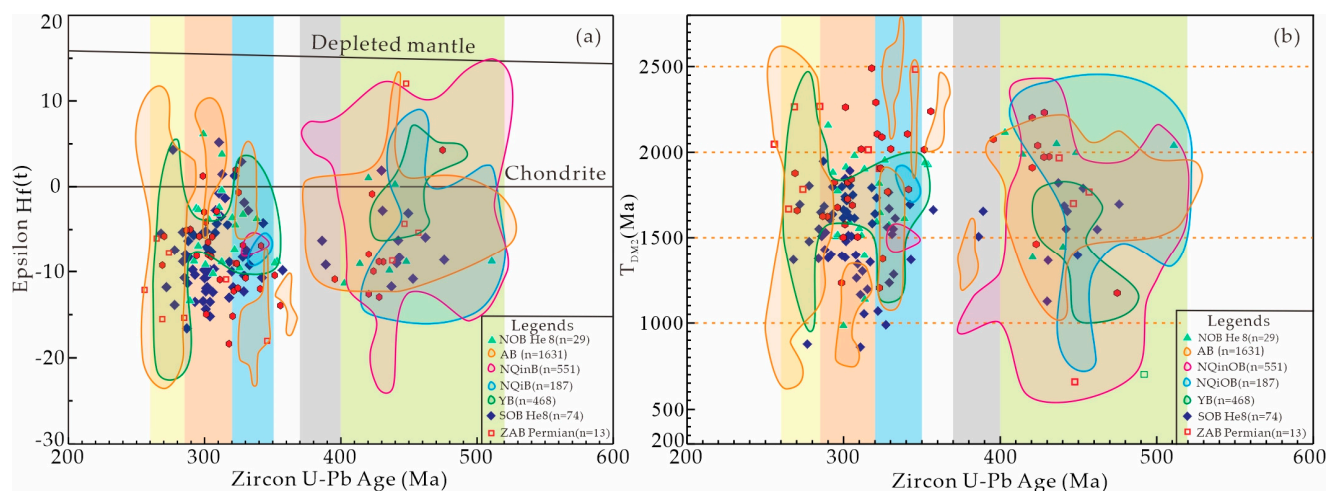


Figure 12. $\epsilon_{\text{Hf}}(t)$ values vs. U–Pb ages (200–520 Ma (a)) and T_{DM2} values vs. U–Pb ages (200–520 Ma (b)). The yellow, pink, blue, gray, and green bars show the age groups of 285–260 Ma, 320–285 Ma, 350–320 Ma, 400–370 Ma, and 520–400 Ma, respectively. The Hf–isotope evolution line for depleted mantle follows from [305]. The Lu–Hf isotopic compositions of the NQinOB are from [75,78,80,82,85,86], the NQiOB from [114,132,133,306], the YB from [173,175,179,181,182,184–186,189], the AB from [333] the Permian in Zhen'an Basin (ZAB Permian) in the South Qinling Orogenic Belt (SQinOB) from [199] and the southern Ordos Basin and northern Ordos Basin from this study.

Previous scholars have argued that the 520–378 Ma zircons originate from the NQinOB and the NQiOB [34]. It has been suggested that ~450 Ma and ~430–400 Ma have been documented in the NQinOB [102] and the NQiOB [191,335–341], and ~390 Ma metamorphic ages have been observed in the NQinOB [337]. We hypothesize that NQinOB provided the source of the 520–378 Ma zircons, although the contribution from NQiOB requires further investigation. Studies using sedimentological methods to trace sources in the southern Ordos Basin indicate that NQiOB contributes materials to the southern Ordos Basin [4–7,9–12]. Consequently, we infer that the 520–378 Ma ages are considered to have resulted from continental collision and accretion in the Paleozoic strata of the NQinOB and NQiOB regions.

We also infer that the zircon grains from 671–375 Ma in the northern Ordos Basin may have been from the YB and the AB. First, the zircon U–Pb isotope age system, Lu–Hf isotopes, and Hf modeled ages of the zircons correspond well to those of the YB and the AB (Figure 11n,m). In addition, there are 14 zircons with ages of 520–400 Ma, with 12 zircons with Th/U ratios > 0.4, which are magmatic zircons. Two zircons with a Th/U > 0.1 but less than 0.4 (Figure 7) are indicative of a magmatic event. These magmatic zircons laterally reflect the magmatic event of the AB from 460 Ma to 397 Ma. At the same time, according to the paleocurrent direction in the northern Ordos Basin, we can infer that the provenance is from the northwestern and northeastern parts of the basin. The heavy mineral assemblage shows that Zone IV in the northern Ordos Basin is characterized by zircon + leucoxene + hematite–limonite + pyrite + garnet; Zone V is characterized by zircon + leucoxene +

garnet + tourmaline + barite; and Zone VI is characterized by leucoxene + zircon + garnet + tourmaline + barite. The ZTR index of Zone V is slightly greater than those of Zones IV and VI, which can be regarded as closer to the provenance area.

(5) Carboniferous–Middle Permian zircons (~350–268 Ma)

A total of 165 zircons within the northern Ordos Basin dated between 350 Ma and 268 Ma (peaking at 300–323 Ma). Among them, 35 zircons were used for our test data, and 130 zircons were collected. All 35 tested zircons have Th/U ratios > 0.4, confirming their magmatic origin. Among these, 20 grains provided $\varepsilon_{\text{Hf}}(t)$ values ranging from −13.35 to 6.2 (average −4.2); 30% of the $\varepsilon_{\text{Hf}}(t)$ values were < −3, with the majority falling between −9 and −3 (Table 1). The T_{DM2} ages range from 918 to 2146 Ma (with an average of 1614 Ma, 30% of the T_{DM2} ages are <1.5 Ga, with the majority falling between 1.5 and 1.9 Ga, Table 1). Lu–Hf isotopes indicate that these zircons predominantly originated from the Neoproterozoic–Paleoproterozoic crust.

The ~350–268 Ma detrital zircons peak at 327 Ma, 308 Ma, and 291 Ma (Figure 11g). Among these, 91 zircon grains account for 14.1% of all concordant detrital zircons (645). Most zircons have Th/U ratios above 0.4 (Table S2 and Figure 7), indicating that they are mainly magmatic zircons. Some grains display fan zoning structures, indicating metamorphic origin. Hf isotope data analysis is from [34]. These findings suggest that a Paleo–Mesoproterozoic crustal source was involved in minor Neoproterozoic crustal components.

Strong magmatism occurred in the YB from 350–230 Ma as a result of orogenesis within the Central Asia Orogenic Belt [163,324,325]. Contemporaneous magmatism has also been observed in adjacent regions around the Ordos Basin (Figures 8l–o and 11m,n). Luo et al. (2010) argued that detrital zircons aged 350–260 Ma originated from the YB [195].

From 350–230 Ma, strong magmatism occurred in the AB. In this study, we collected 298 magmatic zircons from the AB (Figure 11m), showing a primary age peak at 271 Ma and secondary peaks at 304 Ma, 327 Ma, and 436 Ma. Seventeen metamorphic zircons were collected, displaying a primary age peak at 275 Ma and a secondary peak at 471 Ma.

In terms of heavy mineral analysis, paleocurrent analysis, zircon age, and Lu–Hf isotopes were used. In terms of heavy mineral analysis, paleocurrent analysis, zircon ages, and Lu–Hf isotopes, we infer that detrital zircons aged 350–260 Ma in the northern Ordos Basin may have originated from the YB and AB. The reason for this is that the zircon age spectra, hafnium isotopes, and two-stage model age characteristics of the northern Ordos Basin, 350–260 Ma, are similar to those of the YB and AB. Second, both the paleocurrent and heavy mineral results indicate that the 350–230 Ma source in the northern Ordos Basin may have been from YB and AB.

We also infer that the sources of 350–260 Ma detrital zircons show distinct variations among the YB, AB, and He 8 Members in the southern Ordos Basin (Figures 10 and 11). Initially, strong magmatism in the YB and the AB occurred predominantly from ~340–320 Ma and ~285–260 Ma (Figure 11n,m). Conversely, the 350–260 Ma age populations in the southern Ordos Basin are primarily concentrated from ~320–285 Ma (Table 1 and Figure 11g). Furthermore, by integrating paleocurrent analysis and heavy mineral studies, we infer that the YB and AB contributed sedimentary materials to the northern Ordos Basin. In contrast, the sources of the southern Ordos Basin were primarily NQinOB, NQiOB, and TNCO. Additionally, at the YB, all $\varepsilon_{\text{Hf}}(t)$ values > −10. In comparison, 35.7% of the southern Ordos Basin, has $\varepsilon_{\text{Hf}}(t)$ < −10 (Table 1). Similarly, at the YB, all T_{DM2} values < 2.0 Ga. In contrast, in the southern Ordos Basin, some T_{DM2} > 2.0 Ga and mostly < 1.55 Ga or >1.85 Ga (Table 1). Unlike the YB, the AB, and the northern Ordos Basin, there are notable occurrences of $\varepsilon_{\text{Hf}}(t)$ < −10 and T_{DM2} > 2.0 Ga at 350–320 Ma in the southern Ordos Basin. Moreover, the majority of $\varepsilon_{\text{Hf}}(t)$ values in the 320–285 Ma zircons in the southern Ordos Basin are either >−3.9 or <−9, whereas those in the YB, AB, and northern Ordos Basin show different patterns.

We propose that the origin of the ~350–260 Ma zircons in the southern Ordos Basin can be traced to NQinOB, and the first reason is detailed in reference [34]. Additionally, several studies document metamorphic ages ranging from 350 Ma to 260 Ma (Figure 11k).

Examples include titanite U–Pb isotope ratios yielding an age of 324 Ma [74], LA–ICP–MS zircon dating indicating ages of 335–345 Ma [97], 341.7 ± 3 Ma [97], and 330–348 Ma [86], and SHRIMP zircon dating revealing an age of 347 ± 6 Ma [84]. Zircons from the Jiangligou and Zhongchuan granitic bodies in West Qinling yield a U–Pb-weighted age of 264 Ma. Furthermore, Zhang et al. (1994) obtained two ages in the NQinOB amphibolite via mineral Rb–Sr dating contour determination [111]. These findings suggest significant magmatic and/or metamorphic events occurred in the NQinOB during the period from 350 to 260 Ma, with a particular emphasis on the interval around ~320–260 Ma.

Therefore, NQinOB might have had some record of ~320–260 Ma tectonothermal events, due to severe denudation in the later uplift, even though few event records of this period have been found.

6.1.3. Comprehensive Provenance Analysis of the He 8 Member

In summary, the provenances of the 2600–1600 Ma, 520–386 Ma, and 350–268 Ma age populations in the southern Ordos Basin were the TNCO, the NQinOB–NQiOB, and the NQiOB, respectively. In terms of geological methods, we suggest that the TNCO, the NQinOB, and the NQiOB are the source areas of the southern Ordos Basin.

First, previous studies have shown that the source directions of the southern Ordos Basin are SE, SW, and S [4–7,9–12]. In addition, the distributions of zircon crystallization ages, Lu–Hf isotopic compositions, and Hf model ages from the 2600–1600 Ma age group are like those of the TNCO (Figures 8 and 9). Therefore, we conclude that the main source of the He 8 Member in the southern Ordos Basin of 2600–1600 Ma zircons most likely came from the TNCO and recycled sedimentary materials. The ~2.5 Ga magmatism corresponds to juvenile crustal reworking in the TNCO. Magmatism at ~2.25–2.0 Ga was associated with continental marginal activity, whereas metamorphism at ~1.95–1.80 Ga resulted from collisions between the East and West Blocks during the TNCO. The distributions of zircon crystallization ages, Lu–Hf isotopic compositions, and Hf model ages from the 520–386 Ma age group are like those of the NQinOB and the NQiOB. The distributions of zircon crystallization ages, Lu–Hf isotopic compositions, and Hf model ages from the 350 to 268 Ma age group are wholly similar to those of the NQinOB, indicating significant magmatic and/or metamorphic events in that region from 350–268 Ma.

For the northern Ordos Basin, we consider that the provenances of the 2600–1600 Ma, 520–386 Ma, and 350–268 Ma age populations were the TNCO, AB, KB, and YB. At ~2500 Ma, a large-scale magmatic metamorphic event dominated by TTG gneisses and mantle-sourced granites occurred, forming the North China Craton. The peak at 2439 Ma in the north basin samples corresponds to the formation of the North China Craton. Moreover, the age peak at ~2.4 Ga in the northern Ordos Basin is related to magmatic and metamorphic events in the YB and the KB. Two important metamorphic thermal events occurred in the KB and the TNCO at ~1950 Ma and ~1850 Ma. The peak at approximately 1800–2000 Ma in the northern Ordos Basin corresponds to these two magmatic metamorphic events. The Carboniferous–Permian medium-acid magmatism is widely exposed in Daqing Shan Mountain–Wula Shan Mountain and Yinshan Mountain on the north margin of the basin, with an east–west belt direction. The tectonic setting ages of 300–320 Ma in the northern Ordos Basin are indicative of this subduction event in which the Andean-type active continental margin was associated with the subduction of the Paleo-Asian Ocean into the North China Block. High paleozoic magmatism occurred in the AB, in which 222–420 Ma granite and 424–421 Ma diabase were exposed in the late Ordovician–Devonian period of Longshoushan Mountain. The peak at 439 Ma in the north basin samples may record and reflect the frequent late Ordovician–Devonian magmatism in the middle Paleoproterozoic of the AB, whose formation was related to the subduction closure of the Paleo-Asian Ocean. Based on zircon U–Pb dating methods, we suggest that the YB, AB, TNCO, and KB are the source areas of the He 8 Member in the northern Ordos Basin.

In the southern Ordos Basin, the results of paleocurrent, heavy mineral, zircon chronostratigraphy, and hafnium isotope methods suggest that the sources are NQinOB, NQiOB, and TNCO, and the sources in the northern Ordos Basin are YB, AB, KB, and TNCO.

First, paleocurrent studies have shown that the provenances of the He 8 Member in the northern Ordos Basin are S and SE and that those in the southern Ordos Basin are NE and NW. In addition, analyses of the heavy minerals of the He 8 Member suggest that the heavy mineral assemblage in the northern Ordos Basin is similar to those in the western Alashan, Wulashan, and eastern Jining regions [23,338]. The heavy mineral assemblages in northeastern Ordos Basin have affinities with those in the Yinshan area [16], suggesting that the sediment source of the He 8 member in the northern Ordos Basin is mainly from the YB, KB, TNCO, and AB [24]. The heavy mineral assemblage in the southern Ordos Basin is dominated by zircon + rutile + leucoxene + tourmaline, and the lithology of the parent rocks in its source area is dominated by sedimentary rocks and acidic magmatism, followed by mesobasic intrusive rocks and metamorphic rocks. Based on zircon age spectra and Hf isotope methods, it is possible to analyze the age peaks of the three areas in the southern Ordos Basin, Zones I, II, and III, with peaks at 310 Ma, 1850 Ma, 2350–2500 Ma, and 440–600 Ma, which are similar to the age peaks of the NQiOB and the NinOB. The age peaks at 1850 Ma and 2350–2500 Ma correspond to the two-phase events of the TNCO. The age peaks of 315–420 Ma from Zones IV, V, and VI in the northern Ordos Basin correspond to magmatic events in the YB, and the age peaks of 1830–2000 Ma and approximately 2400 Ma correspond to metamorphic events in the KB and the TNCO. The secondary age peaks at 420 Ma in Zone V and 433 Ma in Zone VI correspond to the 430 Ma magmatic event in the AB.

In summary, according to many methods, we conclude that the provenance in the southern Ordos Basin is from the NQiOB, NQinOB, and TNCO, whereas the provenance in the northern Ordos Basin is from the YB, KB, AB, and TNCO. Thus, the provenances in the northern Ordos Basin and the southern Ordos Basin are different.

6.2. Tectonic Implications

The NQinOB and North China Craton amalgamated along the Erlangping back-arc basin before 460 Ma [2,94,339]. After that, NQinOB began to provide sediments to the Ordos Basin [2]. First, the occurrence of 520–386 Ma zircons in the southern Ordos Basin is representative of the NQinOB–NQiOB source contribution, implying that NQinOB–NQiOB experienced uplift before the sedimentation of the He 8 Members in the early Middle Permian and subduction–convergent evolution related to arc–continent collision during the early Paleozoic. In addition, the zircons in the 350–268 Ma age group are likely sourced from the NQinOB. Many ca. 350–260 Ma detrital zircons are present in the upper Permian clastic rocks in the four azimuthal basins of the North Qinling Liyuhe Basin (east, Figure 11k), the West Qinling Lintan area (west, Figure 11j), the South Qinling Zhen'an Basin (south, Figure 11i), and the southern Ordos Basin of the periphery (north), e.g., the zircons from the granitic bodies of West Qinling Jiangligou and Zhongchuan have a U–Pb-weighted age of 264 Ma. Some scholars have obtained dozens of ca. 350–260 Ma magmatic/metamorphic age records in magmatic/metamorphic rocks in the QiOB via using the Ar–Ar method, K–Ar method, Sm–Nd method, Rb–Sr method, and the age of the intersection point of the U–Pb inconsistency line, which suggests that detrital zircons in this period came from the NQinOB and that strong regional metamorphism took place during this period. Our study suggests that the detrital zircons from this period originated from the NQinOB [196,340,341] and that strong regional metamorphism occurred in the NQinOB during this period. In addition, although there are few reports of magmatic and/or metamorphic events in the NQinOB during the ~320–260 Ma period and tectonic activity was not strong, our study indicates that many ~320–260 Ma detrital zircons were supplied to the southern Ordos Basin by the NQinOB, suggesting that the NQinOB might have experienced magmatic and/or metamorphic events that remained underexplained during the ~320–260 Ma period.

From ~320–260 Ma, the NQinOB might have experienced significant tectonic activity that has not been fully revealed thus far.

7. Conclusions

- (1) The basin can be divided into six zones in the Ordos Basin based on the paleoflow characteristics, heavy mineral distribution characteristics, ZTR index, ATi, and ZGi.
- (2) According to the cathodoluminescence (CL) image features and Th/U features of the zircons, most of the zircons in the southern Ordos Basin and northern Ordos Basin are of magmatic origin, and a few are of metamorphic origin. The $\epsilon_{\text{Hf}}(t)$ and T_{DM2} values of the zircons indicate that their sources were dominated by the Paleoproterozoic and early Paleoproterozoic, with a few Neoproterozoic and Neopaleozoic zircons also present.
- (3) Zircon U–Pb dating and Lu–Hf isotope compositions reveal the origin of the He 8 Member sediments: the AB, the YB, the KB, and the TNCO provided the materials to the northern Ordos Basin, while the NQinOB, the NQiOB, and the TNCO provided the materials to the southern Ordos Basin.
- (4) From ~320–260 Ma, the NQinOB may have experienced magmatic and/or metamorphic events that remain underexplained, even though there are few zircon-related reports of ~320–260 Ma tectonothermal events in the NQinOB.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min14111076/s1> Supplementary Table S1: The longitude, latitude, and lithological descriptions of the samples; Supplementary Table S2: Zircon LA–ICP–MS U–Pb isotope data from the He 8 Member of the Shihezi Formation sandstones in northern Ordos Basin; Supplementary Table S3: Lu–Hf isotope data from the He 8 Member of the Shihezi Formation in Ordos Basin.

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References

1. Xie, X.Y.; Heller, P.L. U–Pb detrital zircon geochronology and its implications: The early Late Triassic Yanchang Formation, south Ordos Basin, China. *J. Asian Earth Sci.* **2013**, *64*, 86–98. [\[CrossRef\]](#)
2. Bao, C.; Chen, Y.; Li, D.; Wang, S. Provenances of the Mesozoic sediments in the Ordos Basin and implications for collision between the North China Craton (NCC) and the South China Craton (SCC). *J. Asian Earth Sci.* **2014**, *96*, 296–307. [\[CrossRef\]](#)
3. Cui, L.; Peng, N.; Liu, Y.; Qiao, D.; Liu, Y. Detrital Zircon Geochronology and Tectonic Evolution Implication of the Middle Jurassic Zhiluo Formation, Southern Ordos Basin, China. *Minerals* **2023**, *13*, 45. [\[CrossRef\]](#)
4. Chen, Q.H.; Li, W.H.; Liu, H.W.; Li, K.Y.; Pang, J.G.; Guo, Y.Q.; Yuan, Z. Provenance analysis of sandstone of the Upper Carboniferous to Middle Permian in Ordos Basin. *J. Palaeogeogr.* **2009**, *11*, 629–640. (In Chinese with English Abstract)

5. Li, Y.; Yu, X.; Shan, X.; Du, Y.; Zhou, J.; Han, X. Provenance and sedimentary facies of He 8 member of Xiashihezi formation in southeastern Ordos basin. *J. Northeast. Pet. Univ.* **2016**, *40*, 4+51–60. (In Chinese)
6. Wang, R.; Luo, S.; Wang, X.; Lv, Q.; Wang, H.; Liu, B.; Liu, J. Analysis and identification of provenance of 8th Member of Shihezi Formation in the Southwestern Ordos Basin. *J. Oil Gas Technol.* **2014**, *36*, 26–29. (In Chinese with English Abstract)
7. Yang, R.; Peng, D.; Pan, R.; Shi, S.; Zhang, L. Sediment provenance analysis of the 8th Member of the Upper Paleozoic Xiashihezi Formation in the southwest area of Ordos basin. *J. Pet. Geosci. Eng.* **2012**, *26*, 1–5+136. (In Chinese with English Abstract)
8. Chen, A.Q.; Chen, H. Provenance and sandy accumulation regularity of Neopaleozoic in North Ordos Basin. *J. Petrol. (Ed. Nat. Sci.)* **2011**, *35*, 1–7. (In Chinese with English Abstract)
9. Cui, K. Provenance of the Upper Paleozoic Shan1-He 8 Formation in Southern Ordos Basin and Its Influence on the Sedimentary Filling Pattern. Master's Thesis, Northwest University, Xi'an, China, 2019. (In Chinese with English Abstract)
10. Yang, J.P. Sedimentary-Tectonic Evolution and Gas-Potential Exploration of Late Paleozoic in Southern Ordos Basin. Ph.D. Thesis, Northwest University, Xi'an, China, 2011. (In Chinese with English Abstract)
11. Li, T.T. Prototype and Evolution of Shihezi Formation, Yanchang Formation Basin in Southern Ordos and Its Adjacent Region. Master's Thesis, Northwest University, Xi'an, China, 2011. (In Chinese with English Abstract)
12. Qu, H.; Ma, Q.; Gao, S.; Mei, Z.; Miao, J. On provenance of the Permian in the southeastern Ordos Basin. *Acta Geol. Sin.* **2011**, *85*, 979–986. (In Chinese with English Abstract)
13. Wang, F.; Tian, J.C.; Rong, C. Sedimentary characteristics and provenance analysis of the 8th member of Xiashihezi formation in the northern Ordos basin. *Comput. Tech. Geophys. Geochem. Explor.* **2010**, *32*, 41–47+118–119. [[CrossRef](#)]
14. Li, K.Y.; Wenhou, L. Spatial-temporal coupling sand control mechanism of Permian source-to-sink system in Ordos Basin. *J. Northeast Petrol. Univ.* **2020**, *50*, 183–192. (In Chinese with English Abstract)
15. Wang, G.R. The Study of Sources and Sequence-Lithofacies Palaeogeography of Upper Palaeozoic, Northern Ordos. Ph.D. Thesis, Chengdu University of Technology, Sichuan, China, 2011. (In Chinese with English Abstract)
16. Li, J.W.; Chen, J.; Zhao, K.Q.; Mei, H.P.; Liu, W.P. Analysis of the provenance of the 8th member in Ordos Basin. *J. Xi'an Univ. Sci. Tech.* **2016**, *36*, 40–46. (In Chinese with English Abstract)
17. Chen, Y.L. Study on Depositional Systems and Lithofacies Paleogeography of He-8 Period, Erdos Prototype Basin. Master's Thesis, Chang'an University, Xi'an, China, 2015. (In Chinese with English Abstract)
18. Chen, Q.H.; Wenhou, L. Tectonic Setting and Provenance Analysis of Late Paleozoic Sedimentary Rocks in the Ordos Basin. *Acta Geol. Sin.* **2012**, *86*, 1150–1162. (In Chinese with English Abstract)
19. Wang, F.; Liu, X.S.; Zhang, L.; Hu, J.L.; Tian, J.C.; Chen, R.; Wang, J.; Wu, J.Y.; Xiao, Y.X. Detrital Zircon U–Pb Geochronology Characteristics of Permian Sandstone and Its Constraints on the Tectonic Evolution of the Southern Ordos Basin. *J. Sediment.* **2023**, *41*, 1396–1413. (In Chinese with English Abstract)
20. Jiang, Z.W. The Study of Provenance and Basin Mountain Coupling of Shan1-H8 Member, Upper Palaeozoic, Southern Ordos Basin. Ph.D. Thesis, Northwest University, Xi'an, China, 2020. (In Chinese with English Abstract)
21. Gong, W.Q. Provenance Analysis and Detrital Zircon U–Pb Dating of Chang 6 Chang 4+5 of Yanchang Formation in Dingbian and Xiasiwan Area, Ordos Basin. Master's Thesis, Northwest University, Xi'an, China, 2023. (In Chinese with English Abstract)
22. Qu, H.J.; Han, X.; Chen, S.; Yang, B.; Du, M.L.; Dong, Y.Y.; Zhao, C. U–Pb Dating of Detrital Zircon from the Upper Paleozoic Clastic Rocks and Basin-mountain Coupling of the Northeastern Ordos Basin. *Geotect. Metallog.* **2020**, *44*, 501–527. (In Chinese with English Abstract)
23. Liu, K.; Wang, R.; Shi, W.Z.; Zhang, W.; Tan, S.; Qi, R.; Xu, L.T. Multiple Provenance System of Lower Shihezi Formation in Hangjinqi Area, Northern Ordos Basin: Evidence from Mineralogy and Detrital Zircon U–Pb Chronology. *Earth Sci.* **2021**, *46*, 540–554. (In Chinese with English Abstract)
24. Wang, D. Late Paleozoic Tectonic Relationship between Alxa and North China Blocks: Constraints from Sedimentology and Provenance. Master's Thesis, Northwest University, Xi'an, China, 2019. (In Chinese with English Abstract)
25. Zhang, J.; Li, J.Y.; Liu, J.F.; Feng, Q.W. Detrital zircon U–Pb ages of Middle Ordovician flysch sandstones in the western ordos margin: New constraints on their provenances, and tectonic implications. *J. Asian Earth Sci.* **2011**, *42*, 1030–1047. [[CrossRef](#)]
26. Najman, Y. The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins. *Earth Sci. Rev.* **2006**, *74*, 1–72. [[CrossRef](#)]
27. Long, X.; Yuan, C.; Sun, M.; Xiao, W.; Zhao, G.; Wang, Y.; Cai, K.; Xia, X.; Xie, L. Detrital zircon ages and Hf isotopes of the early Paleozoic flysch sequence in the Chinese Altai, NW China: New constraints on depositional age, provenance and tectonic evolution. *Tectonophysics* **2010**, *480*, 213–231. [[CrossRef](#)]
28. Dickinson, W.R.; Gehrels, G.E. U–Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment. *GSA Bull.* **2015**, *121*, 408–433. [[CrossRef](#)]
29. Zhang, K.-J.; Ji, C.; Zhou, Y.-Z.; Zhang, Y.-J. Tracing oceanic plateau relics in the basement of mainland China: A synthesis of aeromagnetic and seismic refraction data. *Earth-Sci. Rev.* **2024**, *255*, 104849. [[CrossRef](#)]
30. Zhang, K. North and South China collision along the eastern and southern North China margins. *Tectonophysics* **1997**, *270*, 145–156. [[CrossRef](#)]
31. Zhang, K.J. Escape hypothesis for the North and South China collision and the tectonic evolution of the Qinling orogen, eastern Asia. *Eclogae Geol. Helv.* **2002**, *95*, 237–247.

32. Zhang, K. Destruction of the North China Craton: Lithosphere folding-induced removal of lithospheric mantle? *J. Geodyn.* **2011**, *53*, 8–17. [\[CrossRef\]](#)
33. Zhang, C.; Diwu, C.; Kröner, A.; Sun, Y.; Luo, J.; Li, Q.; Gou, L.; Lin, H.; Wei, X.; Zhao, J. Archean–Paleoproterozoic crustal evolution of the Ordos Block in the North China Craton: Constraints from zircon U–Pb geochronology and Hf isotopes for gneissic granitoids of the basement. *Precambrian Res.* **2015**, *267*, 121–136. [\[CrossRef\]](#)
34. Jiang, Z.; Luo, J.; Liu, X.; Hu, X.; Ma, S.; Hou, Y.; Fan, L.; Hu, Y. Provenance and Implication of Carboniferous–Permian Detrital Zircons from the Upper Paleozoic, Southern Ordos Basin, China: Evidence from U–Pb Geochronology and Hf Isotopes. *Minerals* **2020**, *10*, 265. [\[CrossRef\]](#)
35. Wang, C.Y.; Chen, M.J.; Wang, Z.C.; Guo, Y.H. Sedimentary facies of the Shanxi Formation and Member 8 of Xiashihezi Formation of Permian in southern Ordos Basin. *J. Palaeogeogr.* **2007**, *9*, 369–378. (In Chinese with English Abstract)
36. Fossum, K.; Morton, A.C.; Dypvik, H.; Hudson, W.E. Integrated heavy mineral study of Jurassic to Paleogene sandstones in the Mandawa Basin, Tanzania: Sediment provenance and source-to-sink relations. *J. Afr. Earth Sci.* **2019**, *150*, 546–565. [\[CrossRef\]](#)
37. Morton, A.C.; Hallsworth, C. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sediment. Geol.* **1994**, *90*, 241–256. [\[CrossRef\]](#)
38. Liu, C.H.; Li, Z.H.; He, F.; Zhang, Y.L.; Li, Z.C. Quantitative analysis of provenance in the Lower Cretaceous of the northwestern Ordos Basin. *Earth Sci. Front.* **2024**, *31*, 80–99. [\[CrossRef\]](#)
39. Cui, K. Paleocurrent analysis of the Upper Palaeozoic Shan 1 and He 8 Member in the southwestern Ordos Basin. *Groundwater* **2019**, *41*, 142–192. (In Chinese)
40. Yuan, H.-L.; Gao, S.; Dai, M.-N.; Zong, C.-L.; Günther, D.; Fontaine, G.H.; Liu, X.-M.; Diwu, C. Simultaneous determinations of U–Pb age, Hf isotopes and trace element compositions of zircon by excimer laser–ablation quadrupole and multiple–collector ICP–MS. *Chem. Geol.* **2008**, *247*, 100–118. [\[CrossRef\]](#)
41. Wu, F.Y.; Li, X.H.; Zheng, Y.F.; Gao, S. Lu–Hf isotopic systematics and their applications in petrology. *Acta Petrol. Sin.* **2007**, *23*, 185–220. (In Chinese with English Abstract)
42. Hanchara, J.M.; Millerb, C.F. Zircon zonation patterns as revealed by cathodoluminescence and backscattered electron images: Implications for interpretation of complex crustal histories. *Chem. Geol.* **1993**, *110*, 1–13. [\[CrossRef\]](#)
43. El-Naby, H.H.A.; Dawood, Y.H. Testing the validity of detrital zircon chemistry as a provenance indicator. *Arab. J. Geosci.* **2014**, *7*, 341–353. [\[CrossRef\]](#)
44. Hoskin, P.W.O.; Schaltegger, U. The Composition of Zircon and Igneous and Metamorphic Petrogenesis. *Rev. Mineral. Geochem.* **2003**, *53*, 27–62. (In Chinese) [\[CrossRef\]](#)
45. Hoskin, P.W.O. Patterns of chaos: Fractal statistics and the oscillatory chemistry of zircon. *Geochim. Cosmochim. Acta* **2000**, *64*, 1905–1923. [\[CrossRef\]](#)
46. Pidgeon, R.T. Recrystallisation of oscillatory zoned zircon: Some geochronological and petrological implications. *Contrib. Mineral. Petrol.* **1992**, *110*, 463–472. [\[CrossRef\]](#)
47. Corfu, F.; Hanchar, J.M.; Hoskin, P.W.O.; Kinny, P. Atlas of zircon textures. *Rev. Mineral. Geochem.* **2003**, *53*, 469–500. [\[CrossRef\]](#)
48. Belousova, E.A.; Griffin, W.L.; Reilly, S.Y.O.; Fisher, N.I. Igneous zircon: Trace element composition as an indicator of source rock type. *Contrib. Mineral. Petrol.* **2002**, *143*, 602–622. [\[CrossRef\]](#)
49. Rubatto, D. Zircon trace element geochemistry: Partitioning with garnet and the link between U–Pb ages and metamorphism. *Chem. Geol.* **2002**, *184*, 123–138. [\[CrossRef\]](#)
50. Chen, B.; Liu, S.; Geng, Y.; Liu, C. Zircon U–Pb, Hf isotopes and significance of the late Archean–Paleoproterozoic granitoids from the Wutai–Lvliang terrain, North China. *Acta Petrol. Sin.* **2006**, *22*, 296–304. (In Chinese with English Abstract)
51. Du, L.L.; Yang, C.H.; Wang, W.; Ren, L.; Wan, Y.; Wu, J.; Zhao, L.; Song, H.; Geng, Y.; Hou, K. Paleoproterozoic rifting of the North China Craton: Geochemical and zircon Hf isotopic evidence from the 2137Ma Huangjinshan A-type granite porphyry in the Wutai area. *J. Asian Earth Sci.* **2013**, *72*, 190–202. [\[CrossRef\]](#)
52. Guo, L.; Liu, S.; Liu, Y.; Tian, W.; Yu, S.; Li, Q.; Lv, Y. Zircon Hf isotopic features of TTG gneisses and formation environment of Precambrian Sushui complex in Zhongtiao mountains. *Acta Petrol. Sin.* **2008**, *24*, 139–148. (In Chinese with English Abstract)
53. Jiang, N.; Guo, J.; Zhai, M.; Zhang, S. ~2.7Ga crust growth in the North China craton. *Precambrian Res.* **2010**, *179*, 37–49. [\[CrossRef\]](#)
54. Liu, C.; Zhao, G.; Liu, F.; Shi, J. Zircon U–Pb and Lu–Hf isotopic and whole-rock geochemical constraints on the provenance and age of the Shuangshanzi and Qinglonghe Groups in Eastern Hebei: Implications for the tectonic evolution of the Eastern Block. *Precambrian Res.* **2014**, *255*, 699–715. [\[CrossRef\]](#)
55. Liu, F.; Guo, J.; Lu, X.; Diwu, C. Crustal growth at ~2.5 Ga in the North China Craton: Evidence from whole-rock Nd and zircon Hf isotopes in the Huai’an gneiss terrane. *Sci. Bull.* **2009**, *54*, 4704–4713. [\[CrossRef\]](#)
56. Santosh, M.; Yang, Q.; Teng, X.; Tang, L. Paleoproterozoic crustal growth in the North China Craton: Evidence from the Lüliang Complex. *Precambrian Res.* **2015**, *263*, 197–231. [\[CrossRef\]](#)
57. Wang, X.; Zhu, W.; Ge, R.; Luo, M.; Zhu, X.; Zhang, Q.; Wang, L.; Ren, X. Two episodes of Paleoproterozoic metamorphosed mafic dykes in the Lvliang Complex: Implications for the evolution of the Trans-North China Orogen. *Precambrian Res.* **2014**, *243*, 133–148. [\[CrossRef\]](#)
58. Zhang, R.Y.; Zhang, C.L.; Diwu, R.C.; Sun, Y. Zircon U–Pb geochronology, geochemistry and its geological implications for the Precambrian granitoids in Zhongtiao Mountain, Shanxi Province. *Acta Petrol. Sin.* **2012**, *28*, 3559–3573. (In Chinese with English Abstract)

59. Zhao, G.; Wilde, S.A.; Guo, J.; Cawood, P.A.; Sun, M.; Li, X. Single zircon grains record two Paleoproterozoic collisional events in the North China Craton. *Precambrian Res.* **2010**, *177*, 266–276. [\[CrossRef\]](#)
60. Chen, H.; Wang, J.; Wang, H.; Wang, G.; Peng, T.; Shi, Y.; Zhang, Q.; Wu, C. Metamorphism and geochronology of the Luoning metamorphic terrane, southern terminal of the Palaeoproterozoic Trans-North China Orogen, North China Craton. *Precambrian Res.* **2015**, *264*, 156–178. [\[CrossRef\]](#)
61. Guan, H.; Sun, M.; Wilde, S.A.; Zhou, X.; Zhai, M. SHRIMP U–Pb zircon geochronology of the Fuping Complex: Implications for formation and assembly of the North China Craton. *Precambrian Res.* **2002**, *113*, 1–18. [\[CrossRef\]](#)
62. Kröner, A.; Wilde, S.A.; Zhao, G.C.; O'Brien, P.J.; Sun, M.; Liu, D.Y.; Wan, Y.S.; Liu, S.W.; Guo, J.H. Zircon geochronology and metamorphic evolution of mafic dykes in the Hengshan Complex of northern China: Evidence for late Palaeoproterozoic extension and subsequent high-pressure metamorphism in the North China Craton. *Precambrian Res.* **2006**, *146*, 45–67. [\[CrossRef\]](#)
63. Liu, S.; Zhao, G.; Wilde, S.A.; Shu, G.; Sun, M.; Li, Q.; Tian, W.; Zhang, J. Th–U–Pb monazite geochronology of the Lüliang and Wutai Complexes: Constraints on the tectonothermal evolution of the Trans-North China Orogen. *Precambrian Res.* **2006**, *148*, 205–224. [\[CrossRef\]](#)
64. Lu, J.; Wang, G.; Wang, H.; Chen, H.; Wu, C. Metamorphic P–T–t paths retrieved from the amphibolites, Lushan terrane, Henan Province and reappraisal of the Paleoproterozoic tectonic evolution of the Trans-North China Orogen. *Precambrian Res.* **2013**, *238*, 61–77. [\[CrossRef\]](#)
65. Trap, P.; Faure, M.; Lin, W.; Bruguier, O.; Monié, P. Contrasted tectonic styles for the Paleoproterozoic evolution of the North China Craton. Evidence for a ~2.1 Ga thermal and tectonic event in the Fuping Massif. *J. Struct. Geol.* **2008**, *30*, 1109–1125. [\[CrossRef\]](#)
66. Trap, P.; Faure, M.; Lin, W.; Monié, P. Late Paleoproterozoic (1900–1800 Ma) nappe stacking and polyphase deformation in the Hengshan–Wutaishan area: Implications for the understanding of the Trans-North-China Belt, North China Craton. *Precambrian Res.* **2007**, *156*, 85–106. [\[CrossRef\]](#)
67. Trap, P.; Faure, M.; Lin, W.; Monié, P.; Meffre, S.; Melleton, J. The Zhanhuang Massif, the second and eastern suture zone of the Paleoproterozoic Trans-North China Orogen. *Precambrian Res.* **2009**, *172*, 80–98. [\[CrossRef\]](#)
68. Wan, Y.; Song, B.; Liu, D.; Wilde, S.A.; Wu, J.; Shi, Y.; Yin, X.; Zhou, H. SHRIMP U–Pb zircon geochronology of Palaeoproterozoic metasedimentary rocks in the North China Craton: Evidence for a major Late Palaeoproterozoic tectonothermal event. *Precambrian Res.* **2006**, *149*, 249–271. [\[CrossRef\]](#)
69. Wan, Y.; Wilde, S.A.; Liu, D.; Yang, C.; Song, B.; Yin, X. Further evidence for ~1.85 Ga metamorphism in the Central Zone of the North China Craton: SHRIMP U–Pb dating of zircon from metamorphic rocks in the Lushan area, Henan Province. *Gondwana Res.* **2006**, *9*, 189–197. [\[CrossRef\]](#)
70. Wang, G.; Wang, H.; Chen, H.; Lu, J.; Wu, C. Metamorphic evolution and zircon U–Pb geochronology of the Mts. Huashan amphibolites: Insights into the Palaeoproterozoic amalgamation of the North China Craton. *Precambrian Res.* **2014**, *245*, 100–114. [\[CrossRef\]](#)
71. 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. [\[CrossRef\]](#)
72. Zhang, H.; Wang, H.; Santosh, M.; Zhai, M. Zircon U–Pb ages of Paleoproterozoic mafic granulites from the Huai'an terrane, North China Craton (NCC): Implications for timing of cratonization and crustal evolution history. *Precambrian Res.* **2016**, *272*, 244–263. [\[CrossRef\]](#)
73. Zhao, G.; Wilde, S.A.; Sun, M.; Li, S.; Li, X.; Zhang, J. SHRIMP U–Pb zircon ages of granitoid rocks in the Lüliang Complex: Implications for the accretion and evolution of the Trans-North China Orogen. *Precambrian Res.* **2008**, *160*, 213–226. [\[CrossRef\]](#)
74. Bader, T.; Franz, L.; Ratschbacher, L.; de Capitani, C.; Webb, A.A.G.; Yang, Z.; Pfänder, J.A.; Hofmann, M.; Linnemann, U. The Heart of China revisited: II Early Paleozoic (ultra)high-pressure and (ultra)high-temperature metamorphic Qinling orogenic collage. *Tectonics* **2013**, *32*, 922–947. [\[CrossRef\]](#)
75. Diwu, C.; Sun, Y.; Zhao, Y.; Liu, B.; Lai, S. Geochronological, geochemical, and Nd–Hf isotopic studies of the Qinling Complex, central China: Implications for the evolutionary history of the North Qinling Orogenic Belt. *Geos. Front.* **2014**, *5*, 499–513. [\[CrossRef\]](#)
76. Li, N.; Sun, Y.; Li, J.; Xue, L.; Li, W. Molybdenite Re–Os isotope age of the Dahu Au–Mo deposit, Xiaoqinling and the Indosinian mineralization. *Acta Petrol. Sin.* **2008**, *24*, 810–816. (In Chinese with English Abstract)
77. Liang, X.; Sun, S.; Dong, Y.; Yang, Z.; Liu, X.; He, D. Fabrics and geochronology of the Wushan ductile shear zone: Tectonic implications for the Shangdan suture zone in the Qinling orogen, Central China. *J. Asian Earth Sci.* **2016**, *139*, 71–82. [\[CrossRef\]](#)
78. Qin, Z.; Wu, Y.; Siebel, W.; Gao, S.; Wang, H.; Abdallsamed, M.I.M.; Zhang, W.; Yang, S. Genesis of adakitic granitoids by partial melting of thickened lower crust and its implications for early crustal growth: A case study from the Huichizi pluton, Qinling orogen, central China. *Lithos* **2015**, *238*, 1–12. [\[CrossRef\]](#)
79. Qin, Z.; Wu, Y.; Wang, H.; Gao, S.; Zhu, L.; Zhou, L.; Yang, S. Geochronology, geochemistry, and isotope compositions of Piaoichi S-type granitic intrusion in the Qinling orogen, central China: Petrogenesis and tectonic significance. *Lithos* **2014**, *202–203*, 347–362. [\[CrossRef\]](#)
80. Shi, Y.; Yu, J.; Santosh, M. Tectonic evolution of the Qinling orogenic belt, Central China: New evidence from geochemical, zircon U–Pb geochronology and Hf isotopes. *Precambrian Res.* **2013**, *231*, 19–60. [\[CrossRef\]](#)

81. Su, W.; Liu, J.; Chen, N.; Guo, S.; Ba, J.; Zhang, L.; Liu, X.; Shi, Y. Geochronology and tectonic background of magmatic and metamorphic events in the East Qinling-Dabie mountains. *Acta Petrol. Sin.* **2013**, *29*, 1573–1593+1847. (In Chinese with English Abstract)
82. Wang, H.; Wu, Y.; Gao, S.; Liu, X.; Liu, Q.; Qin, Z.; Xie, S.; Zhou, L.; Yang, S. Continental origin of eclogites in the North Qinling terrane and its tectonic implications. *Precambrian Res.* **2013**, *230*, 13–30. [\[CrossRef\]](#)
83. Wen, Z.; Xu, X.; Zhao, R.; Wang, F.; Hu, W. Geologic and geochemical features of Devonian granites in Dangchuan area, western Qinling, and its tectonic significance. *Geol. Rev.* **2008**, *54*, 827–836. [\[CrossRef\]](#)
84. Yan, Z.; Wang, Z.; Chen, J.; Yan, Q.; Wang, T.; Zhang, Y. Geochemistry and SHRIMP zircon U–Pb dating of amphibolites from the Danfeng Group in the Wuguan area, North Qinling terrane and their tectonic significance. *Acta Geol. Sin.* **2009**, *83*, 1633–1646. (In Chinese)
85. Zhang, C.; Liu, L.; Wang, T.; Wang, X.; Li, L.; Gong, Q.; Li, X. Granitic magmatism related to early Paleozoic continental collision in North Qinling. *Chin. Sci. Bull.* **2013**, *58*, 4405–4410. [\[CrossRef\]](#)
86. Zhang, H.; Yu, H.; Zhou, D.; Zhang, J.; Dong, Y.; Zhang, G. The meta-gabbroic complex of Fushui in north Qinling orogen: A case of syn-subduction mafic magmatism. *Gondwana Res.* **2015**, *28*, 262–275. [\[CrossRef\]](#)
87. Zhang, Z.; Zhang, G.; Liu, D.; Wang, Z.; Tang, S.; Wang, J. *Isotopic Chronology and Geochemistry of Ophiolite, Granite and Clastic Sedimentary Rocks in Qinling Orogenic Belt*; Geological Publishing House: Beijing, China, 2006; pp. 1–340.
88. Min, L. Petrogenesis of Granites and Their Relation to Tectonic Evolution of Orogen in the East Part of Qinling Orogenic Belt. Ph.D. Thesis, Chinese Academy of Geological Sciences, Beijing, China, 2011. (In Chinese with English Abstract)
89. Liu, B. Magmatism and Crustal Evolution in the Eastern North Qinling Terrain. Ph.D. Thesis, University of Science and Technology of China, Beijing, China, 2014. (In Chinese with English Abstract)
90. Chen, D.; Ren, Y.; Gong, X.; Liu, L.; Gao, S. Identification and Its Geological Significance of Eclogite in Songshugou, the North Qinling. *Acta Petrol. Sin.* **2015**, *31*, 1841–1854. (In Chinese with English Abstract)
91. Chen, D.; Liu, L. New data on the chronology of eclogite and associated rock from Guanpo Area, North Qinling orogeny and its constraint on nature of North Qinling HP-UHP eclogite terrane. *Earth Sci. Front.* **2011**, *18*, 158–169. (In Chinese with English Abstract)
92. Chen, D.; Liu, L.; Sun, Y.; Zhang, A.; Liu, X.; Luo, J. LA–ICP–MS U–Pb dating of zircon from Songshugou high pressure basic granulite in the northern Qinling Mountains and its geological significance. *Chin. Sci. Bull.* **2004**, *49*, 2296–2304. [\[CrossRef\]](#)
93. Dong, Y.; Zhang, G.; Hauzenberger, C.; Neubauer, F.; Yang, Z.; Liu, X. Palaeozoic tectonics and evolutionary history of the Qinling orogen: Evidence from geochemistry and geochronology of ophiolite and related volcanic rocks. *Lithos* **2011**, *122*, 39–56. [\[CrossRef\]](#)
94. Faure, M.; Lin, W.; Monié, P.; Meffre, S. Palaeozoic collision between the North and South China blocks, Triassic intracontinental tectonics, and the problem of the ultrahigh-pressure metamorphism. *Comptes Rendus Geosci.* **2008**, *340*, 139–150. [\[CrossRef\]](#)
95. Gong, X.; Chen, D.; Ren, Y.; Liu, L.; Gao, S.; Yang, S. Identification of coesite-bearing amphibolite in the North Qinling and its geological significance. *Chin. Sci. Bull.* **2016**, *61*, 1365–1381. (In Chinese)
96. He, S.; Wang, H.; Chen, J.; Xu, X.; Zhang, H.; Ren, G.; Yu, J. Zircon U–Pb Chronology of Kuanping Rock Group By LA–ICP–MS and its Geological Significance. *Acta Geol. Sin.* **2007**, *81*, 79–87. [\[CrossRef\]](#)
97. Li, P.; Chen, J.; Xu, X.; Wang, H.; Li, T.; Gao, T. Petrogenesis and LA–ICPMS zircon U–Pb dating of the Wuguan intrusive body in North Qinling. *Acta Petrol. Mineral.* **2011**, *30*, 610–624. [\[CrossRef\]](#)
98. Li, T.; Santosh, M.; Dong, Y. Tectonic evolution of a complex orogenic system: Evidence from the northern Qinling belt, Central China. *J. Asian Earth Sci.* **2015**, *113*, 544–559. [\[CrossRef\]](#)
99. Li, Y.; Zhou, H.; Li, Q.; Xiang, H.; Zhong, Z.; Brouwer, F.M. Palaeozoic polymetamorphism in the North Qinling orogenic belt, Central China: Insights from petrology and in situ titanite and zircon U–Pb geochronology. *J. Asian Earth Sci.* **2014**, *92*, 77–91. [\[CrossRef\]](#)
100. Liao, X.; Liu, L.; Wang, Y.; Cao, Y.; Chen, D.; Dong, Y. Multi-stage metamorphic evolution of retrograde eclogite with a granulite-facies overprint in the Zhaigen area of the North Qinling Belt, China. *Gondwana Res.* **2016**, *30*, 79–96. [\[CrossRef\]](#)
101. Liu, J.; Sun, Y.; Tong, L.; Sun, W. Emplacement age of the Songshugou ultramafic massif in the Qinling orogenic belt, and geologic implications. *Int. Geol. Rev.* **2009**, *51*, 58–76. [\[CrossRef\]](#)
102. Liu, L.; Liao, X.; Zhang, C.; Chen, D.; Gong, X.; Kang, L. Multi-metamorphic timings of HP-UHP rocks in the North Qinling and their geological implications. *Acta Petrol. Sin.* **2013**, *29*, 1634–1656. [\[CrossRef\]](#)
103. Liu, Q.; Wu, Y.B.; Wang, H.; Gao, S.; Qin, Z.W.; Liu, X.C.; Yang, S.H.; Gong, H.J. Zircon U–Pb ages and Hf isotope compositions of migmatites from the North Qinling terrane and their geological implications. *J. Metamorph. Geol.* **2014**, *32*, 177–193. [\[CrossRef\]](#)
104. Liu, X.C.; Jahn, B.M.; Hu, J.; Li, S.Z.; Liu, X.; Song, B. Metamorphic patterns and SHRIMP zircon ages of medium-to-high grade rocks from the Tongbai orogen, central China: Implications for multiple accretion/collision processes prior to terminal continental collision. *J. Metamorph. Geol.* **2011**, *29*, 979–1002. [\[CrossRef\]](#)
105. Song, C.; Zhang, G.; Wang, Y.; Cai, Z. The constraints of strain partitioning and geochronology in Luonan–Luanchuan tectonic belts on Qinling orogenic belt. *Earth Sci.* **2009**, *52*, 300–312. [\[CrossRef\]](#)
106. Yang, J.; Liu, F.; Wu, C.; Xu, Z.; Shi, R.; Chen, S. Two Ultrahigh-Pressure Metamorphic Events Recognized in the Central Orogenic Belt of China: Evidence from the U–Pb Dating of Coesite-Bearing Zircons. *Int. Geol. Rev.* **2005**, *47*, 463–477. (In Chinese) [\[CrossRef\]](#)

107. Yang, J.; Xu, Z.; Pei, X.; Shi, R.; Wu, C.; Zhang, J.; Li, H.; Meng, F.; Rong, H. Discovery of Diamond in North Qinling: Evidence for a Giant UHPM Belt across Central China and Recognition of Paleozoic and Mesozoic Dual Deep Subduction between North China and Yangtze Plates. *Acta Geol. Sin.* **2002**, *76*, 484–495. (In Chinese)
108. Yu, H.; Zhang, H.; Li, X.; Zhang, J.; Santosh, M.; Yang, Y.; Zhou, D. Tectonic evolution of the North Qinling Orogen from subduction to collision and exhumation: Evidence from zircons in metamorphic rocks of the Qinling Group. *Gondwana Res.* **2016**, *30*, 65–78. [\[CrossRef\]](#)
109. Liu, L.; Liao, X.; Wang, Y.; Wang, C.; Santosh, M.; Yang, M.; Zhang, C.; Chen, D. Early Paleozoic tectonic evolution of the North Qinling Orogenic Belt in Central China: Insights on continental deep subduction and multiphase exhumation. *Earth Sci. Rev.* **2016**, *159*, 58–81. [\[CrossRef\]](#)
110. Hao, W. Neoproterozoic-Early Paleozoic Metamorphism and Magmatism During the Multistage Evolution of the Eastern Qinling-Tongbai Orogenic Belt. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2014. (In Chinese with English Abstract)
111. Wang, Y.W. Multi-Metamorphism of Amphibolites in Qinling Complex and Its Tectonic Implications. Master's Thesis, Northwest University, Xi'an, China, 2015. (In Chinese with English Abstract)
112. Hua, X. Early Paleozoic Ploy-Metamorphism and Tectonic Evolution of the Northern Qinling-Tongbai Orogenic Belt. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2012. (In Chinese with English Abstract)
113. Bader, T.; Ratschbacher, L.; Franz, L.; Yang, Z.; Hofmann, M.; Linnemann, U.; Yuan, H. The heart of China revisited, I. Proterozoic tectonics of the Qin mountains in the core of supercontinent Rodinia. *Tectonics* **2013**, *32*, 661–687. [\[CrossRef\]](#)
114. Chen, Y.; Song, S.; Niu, Y.; Wei, C. Melting of continental crust during subduction initiation: A case study from the Chaidanuo peraluminous granite in the North Qilian suture zone. *Geochim. Cosmochim. Acta* **2014**, *132*, 311–336. [\[CrossRef\]](#)
115. He, S.; Wang, H.; Xu, X.; Zhang, H.; Ren, G. A LA-ICP-MS U-Pb chronological study of zircons from Hongtubu basic volcanic rocks and its geological significance in the east segment of North Qilian orogenic belt. *Adv. Earth Sci.* **2007**, *22*, 143–151. (In Chinese)
116. Lin, Y.; Zhang, L.; Ji, J.; Wang, Q.; Song, S. Lawsonite blueschist 40Ar-39Ar age and geological significance of Jiugequan in North Qilian Mountains. *Chin. Sci. Bull.* **2010**, *55*, 1710–1716. (In Chinese) [\[CrossRef\]](#)
117. Mao, J.; Zhang, Z.; Jian, P.; Wang, Z.; Yang, J.; Zhang, Z. U-Pb zircon dating of the Yeniutan granitic intrusion in the western part of the North Qilian Mountains. *Geol. Rev.* **2000**, *46*, 616–620. [\[CrossRef\]](#)
118. Pan, G.; Xiao, Q.; Lu, S.; Deng, J.; Feng, Y.; Zhang, K.; Zhang, Z.; Wang, F.; Xing, G.; Hao, G.; et al. Subdivision of tectonic units in China. *Geol. China* **2009**, *36*, 1–28+255. (In Chinese)
119. Pei, X.; Sun, R.; Ding, S.; Liu, H.; Li, Z.; Liu, Z.; Meng, Y. LA-ICP-MS zircon U-Pb dating of the Yanjiadian diorite in the eastern Qilian Mountains and its geological significance. *Geol. China* **2007**, *34*, 8–16. (In Chinese with English Abstract)
120. Shi, R.; Yang, J.; Wu, L.; Wooden, J. First SHRIMP dating for the formation of the Late Sinian Yushigou ophiolite, North Qilian mountains. *Acta Geol. Sin.* **2004**, *78*, 649–657. (In Chinese)
121. Song, Z.; Ren, Y.; Li, Z.; Yang, J.; Li, Y.; Wang, W. A preliminary study of the petrogenic age of granodiorite in Baishanzhi, North Qilian Mountains. *Acta Geos. Sin.* **2005**, *26*, 92–94. (In Chinese)
122. Su, J.; Hu, N.; Zhang, H.; Fu, G. Single-zircon U-Pb dating and geological significance of the Diaodaban granitic gneiss in the western segment of North Qilian mountains. *Geol. Sci.* **2004**, *23*, 11–14. (In Chinese)
123. Tseng, C.; Yang, H.; Wan, Y.; Liu, D.; Wen, D.; Lin, T.; Tung, K. Finding of Neoproterozoic (~775 Ma) magmatism recorded in metamorphic complexes from the North Qilian orogen: Evidence from SHRIMP zircon U-Pb dating. *Chin. Sci. Bull.* **2006**, *51*, 963–970. (In Chinese with English Abstract) [\[CrossRef\]](#)
124. Tung, K.; Yang, H.; Yang, H.; Liu, D.; Zhang, J.; Wan, Y.; Tseng, C. SHRIMP U-Pb geochronology of the zircons from the Precambrian basement of the Qilian Block and its geological significances. *Chin. Sci. Bull.* **2007**, *52*, 2687–2701. [\[CrossRef\]](#)
125. Wan, Y.; Yang, J.; Xu, Z.; Wu, C. Geochemical characteristics of the Maxianshan Complex and Xinglongshan Group in the eastern segment of the Qilian orogenic belt. *J. Geol.* **2000**, *43*, 52–68. (In Chinese)
126. Wu, C.; Xu, X.; Gao, Q.; Li, X.; Lei, M.; Gao, Y.; Ronald, B.F.; Joseph, L.W. Early Palaeozoic ggranitoid magmatism and tectonic evolution in North Qilian, NW China. *Acta Petrol. Sin.* **2010**, *26*, 1027–1044. (In Chinese with English Abstract)
127. Wu, C.; Yang, J.; Yang, H.; Zheng, Q.; Shi, D.; Chen, S.; Joe, W.; Trevor, L. The zircon SHRIMP dating and geological significance of the two I-type granites in the eastern Qilian. *Acta Geol. Sin.* **2005**, *20*, 286. (In Chinese)
128. Xia, L.; Xia, Z.; Xu, X. *Tectonic-Volcanic Magmatic-Mineralization Dynamics of the Northern Qilian Mountains*; China Land Press: Beijing, China, 2001; pp. 1–105.
129. Xia, X.; Song, S. Age of formation and tectonic environment of Jiugequan ophiolite, southern Gansu province, north Qilian mountains. *Chin. Sci. Bull.* **2010**, *55*, 1465–1473. (In Chinese) [\[CrossRef\]](#)
130. Xiang, Z.; Lu, S.; Li, H.; Li, H.; Song, B.; Zheng, J. SHRIMP U-Pb zircon age of gabbro in Aoyougou in the western segment of the North Qilian mountains, China and its geological implications. *Geol. Bull.* **2007**, *26*, 1686–1691. (In Chinese with English Abstract)
131. Xu, X.; He, S.; Wang, H.; Zhang, E.; Chen, J.; Sun, J. Tectonic framework of North Qinling mountain and North Qilian mountain conjunction area in Early Paleozoic: A study of the evidences from strata and tectonic-magmatic events. *Northwest. Geol.* **2008**, *41*, 1–21. (In Chinese)
132. Yan, Z.; Aitchison, J.; Fu, C.; Guo, X.; Niu, M.; Xia, W.; Li, J. Hualong Complex, South Qilian terrane: U-Pb and Lu-Hf constraints on Neoproterozoic micro-continental fragments accreted to the northern Proto-Tethyan margin. *Precambrian Res.* **2015**, *266*, 65–85. [\[CrossRef\]](#)

133. Yang, H.; Zhang, H.; Luo, B.; Zhang, J.; Xiong, Z.; Guo, L.; Pan, F. Early Paleozoic intrusive rocks from the eastern Qilian orogen, NE Tibetan Plateau: Petrogenesis and tectonic significance. *Lithos* **2015**, *224*–225, 13–31. [\[CrossRef\]](#)
134. Yu, J.; Li, X.; Ma, Z.; Sun, J.; Wang, J. Chronological study of meta-acidic volcanics in Qingshuigou-Bailiugou orefield, Qilian county of Qinghai province. *Adv. Earth Sci.* **2010**, *25*, 55–60. (In Chinese with English Abstract)
135. Zhang, L.Y.; Qu, X.M.; Xin, H.B. Geochemical characteristics, zircon U–Pb LA–ICP–MS ages of medium-acid dykes in the Huashugou iron-copper deposit, Jingtieshan orefield, and their geological significances. *Geol. Rev.* **2008**, *54*, 253–262. [\[CrossRef\]](#)
136. He, Y.; Chen, L.; Sun, Y.; Li, H. Zircon chronology of Xinjie complex in Longxian county and its geological significance. *J. NEPU* **2005**, *35*, 135–137+142. (In Chinese)
137. Song, S.; Zhang, L.; Niu, Y.; Song, B.; Zhang, G.; Wang, Q. SHRIMP eclogite zircon dating and its tectonic significance in North Qilian mountains. *Chin. Sci. Bull.* **2004**, *49*, 848–852. [\[CrossRef\]](#)
138. Yu, S. Composition, Metamorphism and Deformation of Subduction-Accretionary Complex in the North Qilian Mountain. Master's Thesis, Chinese Academy of Geological Science, Beijing, China, 2008. (In Chinese with English Abstract)
139. Dan, W.; Li, X.; Guo, J.; Liu, Y.; Wang, X. Integrated in situ zircon U–Pb age and Hf–O isotopes for the Helanshan khondalites in North China Craton: Juvenile crustal materials deposited in active or passive continental margin? *Precambrian Res.* **2012**, *222*–223, 143–158. [\[CrossRef\]](#)
140. Dong, C.Y.; Liu, D.; Wan, Y.; Xu, Z.; Wang, W.; Xie, H. Hf Isotope Composition and REE Pattern of Zircons from Early Precambrian Metamorphic Rocks in the Daqing Mountains, Inner Mongolia. *Geol. Rev.* **2009**, *55*, 509–520. [\[CrossRef\]](#)
141. Gong, W.; Hu, J.; Wu, S.; Chen, H.; Qu, H.; Li, Z.; Liu, Y.; Wang, L. Possible southwestward extrusion of the Ordos Block in the Late Paleoproterozoic: Constraints from kinematic and geochronologic analysis of peripheral ductile shear zones. *Precambrian Res.* **2014**, *255*, 716–733. [\[CrossRef\]](#)
142. He, X.; Yin, C.; Long, X.; Qian, J.; Wang, L.; Qiao, H. Archean to Paleoproterozoic continental crust growth in the Western Block of North China: Constraints from zircon Hf isotopic and whole-rock Nd isotopic data. *Precambrian Res.* **2017**, *303*, 105–116. [\[CrossRef\]](#)
143. Liu, J.; Liu, F.; Ding, Z.; Liu, P.; Chen, J.; Liu, C.; Wang, F.; Yang, H.; Cai, J.; Shi, J. Late Neoproterozoic–Paleoproterozoic arc-continent accretion along the Khondalite Belt, Western Block, North China Craton: Insights from granitoid rocks of the Daqingshan–Wulashan area. *Precambrian Res.* **2017**, *303*, 494–519. [\[CrossRef\]](#)
144. Wang, L.; Guo, J.; Yin, C.; Peng, P. Petrogenesis of ca. 1.95 Ga meta-leucogranites from the Jining Complex in the Khondalite Belt, North China Craton: Water-fluxed melting of metasedimentary rocks. *Precambrian Res.* **2017**, *303*, 355–371. [\[CrossRef\]](#)
145. Xu, Z.; Wan, Y.; Dong, C.; Ma, M.; Liu, D. Late Neoproterozoic magmatism identified in Daqingshan, Inner Mongolia: SHRIMP zircon U–Pb dating. *Acta Petrol. Sin.* **2015**, *31*, 1509–1517. (In Chinese with English Abstract)
146. Yang, Q.; Santosh, M. Paleoproterozoic arc magmatism in the North China Craton: No Siderian global plate tectonic shutdown. *Gondwana Res.* **2015**, *28*, 82–105. [\[CrossRef\]](#)
147. Yin, C.; Zhao, G.; Guo, J.; Sun, M.; Xia, X.; Zhou, X.; Liu, C. U–Pb and Hf isotopic study of zircons of the Helanshan Complex: Constraints on the evolution of the Khondalite Belt in the Western Block of the North China Craton. *Lithos* **2011**, *122*, 25–38. [\[CrossRef\]](#)
148. Zhang, D.; Wei, J.; Fu, L.; Schmitt, A.K.; Wang, D.; Tan, J.; Liu, J. Petrogenesis and thermal overprint of S-type granites in Helanshan region, North China Craton: Constraints on the 1.90 Ga khondalites decompression melting and 1.32 Ga tectono-thermal event. *Precambrian Res.* **2017**, *303*, 660–672. [\[CrossRef\]](#)
149. Zhang, X.; Yuan, L.; Xue, F.; Zhai, M. Neoproterozoic metagabbro and charnockite in the Yinshan block, western North China Craton: Petrogenesis and tectonic implications. *Precambrian Res.* **2014**, *255*, 563–582. [\[CrossRef\]](#)
150. Zhong, C.; Deng, J.; Wan, Y.; Tu, W. Paleoproterozoic granitoids in the Daqingshan Mountain area, Inner Mongolia: Geochemistry, SHRIMP zircon dating and geological significance. *Acta Petrol. Sin.* **2014**, *30*, 3172–3188. (In Chinese with English Abstract)
151. Cai, J.; Liu, F.; Liu, P.; Wang, F.; Shi, J. Geochronology of the Paleoproterozoic khondalite rocks from the Wulashan–Daqingshan area, the Khondalite Belt. *Acta Petrol. Sin.* **2015**, *31*, 3081–3106. (In Chinese with English Abstract)
152. Dong, C.; Wan, Y.; Wilde, S.A.; Xu, Z.; Ma, M.; Xie, H.; Liu, D. Earliest Paleoproterozoic supracrustal rocks in the North China Craton recognized from the Daqingshan area of the Khondalite Belt: Constraints on craton evolution. *Gondwana Res.* **2014**, *25*, 1535–1553. [\[CrossRef\]](#)
153. Huang, G.; Jiao, S.; Guo, J.; Peng, P.; Wang, D.; Liu, P. P–T–t constraints of the Barrovian-type metamorphic series in the Khondalite belt of the North China Craton: Evidence from phase equilibria modeling and zircon U–Pb geochronology. *Precambrian Res.* **2016**, *283*, 125–143. [\[CrossRef\]](#)
154. Jiao, S.; Guo, J.; Harley, S.L.; Peng, P. Geochronology and trace element geochemistry of zircon, monazite and garnet from the garnetite and/or associated other high-grade rocks: Implications for Palaeoproterozoic tectonothermal evolution of the Khondalite Belt, North China Craton. *Precambrian Res.* **2013**, *237*, 78–100. [\[CrossRef\]](#)
155. Liu, P.; Liu, F.; Liu, C.; Liu, J.; Wang, F.; Xiao, L.; Cai, J.; Shi, J. Multiple mafic magmatic and high-grade metamorphic events revealed by zircons from meta-mafic rocks in the Daqingshan–Wulashan Complex of the Khondalite Belt, North China Craton. *Precambrian Res.* **2014**, *246*, 334–357. [\[CrossRef\]](#)
156. Ma, M.; Wan, Y.; Santosh, M.; Xu, Z.; Xie, H.; Dong, C.; Liu, D.; Guo, C. Decoding multiple tectonothermal events in zircons from single rock samples: SHRIMP zircon U–Pb data from the late Neoproterozoic rocks of Daqingshan, North China Craton. *Gondwana Res.* **2012**, *22*, 810–827. [\[CrossRef\]](#)

157. Peng, P.; Guo, J.; Zhai, M.; Bleeker, W. Paleoproterozoic gabbro-noritic and granitic magmatism in the northern margin of the North China craton: Evidence of crust-mantle interaction. *Precambrian Res.* **2010**, *183*, 635–659. [\[CrossRef\]](#)
158. Peng, P.; Wang, X.; Windley, B.F.; Guo, J.; Zhai, M.; Li, Y. Spatial distribution of ~1950–1800 Ma metamorphic events in the North China Craton: Implications for tectonic subdivision of the craton. *Lithos* **2014**, *202–203*, 250–266. [\[CrossRef\]](#)
159. Santosh, M.; Liu, D.; Shi, Y.; Liu, S.J. Paleoproterozoic accretionary orogenesis in the North China Craton: A SHRIMP zircon study. *Precambrian Res.* **2013**, *227*, 29–54. [\[CrossRef\]](#)
160. Santosh, M.; Wan, Y.; Liu, D.; Chunyan, D.; Li, J. Anatomy of Zircons from an Ultrahot Orogen: The Amalgamation of the North China Craton within the Supercontinent Columbia. *J. Palaeogr.* **2009**, *117*, 429–443. [\[CrossRef\]](#)
161. Santosh, M.; Wilde, S.; Li, J. Timing of Paleoproterozoic ultrahigh-temperature metamorphism in the North China Craton: Evidence from SHRIMP U–Pb zircon geochronology. *Precambrian Res.* **2007**, *159*, 178–196. [\[CrossRef\]](#)
162. Wan, Y.; Liu, D.; Dong, C.; Xu, Z.; Wang, Z.; Wilde, S.A.; Yang, Y.; Liu, Z.; Zhou, H. The Precambrian Khondalite Belt in the Daqingshan area, North China Craton: Evidence for multiple metamorphic events in the Palaeoproterozoic era. *Geol. Soc. Spec. Publ.* **2009**, *323*, 73–97. [\[CrossRef\]](#)
163. Yin, C.; Zhao, G.; Sun, M.; Xia, X.; Wei, C.; Zhou, X.; Leung, W. LA–ICP–MS U–Pb zircon ages of the Qianlishan Complex: Constraints on the evolution of the Khondalite Belt in the Western Block of the North China Craton. *Precambrian Res.* **2009**, *174*, 78–94. [\[CrossRef\]](#)
164. Zhou, X.; Geng, Y. Metamorphic age of the khondalites in the Helanshan region: Constraints on the evolution of the Western block in the North China Craton. *Acta Petrol. Sin.* **2009**, *25*, 1843–1852. (In Chinese with English Abstract)
165. Arkin, A.; Xie, G.; Zhang, J.; Qu, J.; Tian, R.; Zhao, H.; Li, F.; Li, T. Geochemistry, zircon U–Pb age and tectonic settings of pillow basalts in the Langshan area on the northern margin of the Alxa block, Inner Mongolia. *Geol. Bull. China* **2019**, *38*, 810–823. (In Chinese with English Abstract)
166. Bai, X.; Xu, Z.; Liu, Z.; Xin, H.; Wanqiong, W.; WANG, X.; Lei, C. Zircon U–Pb dating, geochemistry and geological significance of the Early Silurian plutons from the southeastern margin of the Central Asian Orogenic Belt. *Acta Petrol. Sin.* **2015**, *31*, 67–79. (In Chinese with English Abstract)
167. Chen, L.; Guo, J.; Chen, F.; Zhang, L. Discovery of Nb-rich volcanic rocks in Guyang greenstone terrane, Inner Mongolia. In Proceedings of the 2004 National Symposium on Petrology and Geodynamics, Haikou, China, 11–24 November 2004; p. 345. (In Chinese).
168. Chen, N.H.; Zhao, G.; Jahn, B.; Sun, M.; Zhou, H. U–Pb zircon ages and Hf isotopes of ~2.5 Ga granitoids from the Yinshan Block, North China Craton: Implications for crustal growth. *Precambrian Res.* **2017**, *303*, 171–182. [\[CrossRef\]](#)
169. Dong, X.; Xu, Z.; Liu, Z.; Sha, Q. Zircon U–Pb geochronology of Archean high-grade metamorphic rocks from Xi Ulanbulang area, central Inner Mongolia. *China Earth Sci.* **2012**, *55*, 204–212. [\[CrossRef\]](#)
170. Jian, P.; Kröner, A.; Windley, B.F.; Zhang, Q.; Zhang, W.; Zhang, L. Episodic mantle melting–crustal reworking in the late Neoproterozoic of the northwestern North China Craton: Zircon ages of magmatic and metamorphic rocks from the Yinshan Block. *Precambrian Res.* **2012**, *222–223*, 230–254. [\[CrossRef\]](#)
171. Jian, P.; Zhang, Q.; Liu, D.; Jin, W.; Jia, X.; Qian, Q. SHRIMP dating and geological significance of Late-Achaean high-Mgdiorite (sanukite) and hornblende-granite at Guyang of Inner Mongolia. *Acta Petrol. Sin.* **2005**, *21*, 151–157. (In Chinese with English Abstract)
172. Liu, C.; Sun, L.; Wu, Q.; Zeng, F. Discovery of the Early Carboniferous Granite in Guyang, Inner Mongolia: Evidence from Zircon SHRIMP U–Pb Dating. *Geol. J. China Univ.* **2015**, *21*, 519–528. [\[CrossRef\]](#)
173. Liu, M.; Zhang, D.; Xiong, G.; Zhao, H.; Di, Y.; Wang, Z.; Zhou, Z. Zircon U–Pb age, Hf isotope and geochemistry of Carboniferous intrusions from the Langshan area, Inner Mongolia: Petrogenesis and tectonic implications. *J. Asian Earth Sci.* **2016**, *120*, 139–158. [\[CrossRef\]](#)
174. Liu, P.; Zou, L.; Tian, Z.; Ji, L.; Shi, J. Determination of Late Paleozoic metamorphic event in the Langshan area, western Inner Mongolia: New evidence from LA–ICP–MS zircon U–Pb dating of the Wulashan Group. *Geol. Bull. China* **2019**, *38*, 1691–1710. (In Chinese with English Abstract)
175. Liu, Y.; Wang, W.; Teng, X.; Guo, S.; Reng, F.; He, P.; Tian, J.; Duan, X. Geochemistry and Hf isotopes characteristics and geological significance of latest early Permian granodiorite of Langshan area, Inner Mongolia. *Adv. Earth Sci.* **2019**, *34*, 366–381. (In Chinese)
176. Ma, M.; Xu, Z.; Zhang, L.; Dong, C.; Dong, X.; Liu, S.; Liu, D.; Wan, Y. SHRIMP dating and Hf isotope analysis of zircons from the Early Precambrian basement in the Xi Ulanbulang area, Wuchuan, Inner Mongolia. *Acta Petrol. Sin.* **2013**, *29*, 501–516. (In Chinese with English Abstract)
177. Ma, X.; Fan, H.; Santosh, M.; Guo, J. Geochemistry and zircon U–Pb chronology of charnockites in the Yinshan Block, North China Craton: Tectonic evolution involving Neoproterozoic ridge subduction. *Int. Geol. Rev.* **2013**, *55*, 1688–1704. [\[CrossRef\]](#)
178. Ma, X.; Guo, J.; Liu, F.; Qian, Q.; Fan, H. Zircon U–Pb ages, trace elements and Nd–Hf isotopic geochemistry of Guyang sanukitoids and related rocks: Implications for the Archean crustal evolution of the Yinshan Block, North China Craton. *Precambrian Res.* **2013**, *230*, 61–78. [\[CrossRef\]](#)
179. Tian, J.; Teng, X.; Liu, Y.; Teng, F.; He, P.; Guo, S.; Wang, W. Petrogenesis and tectonic significance of the Early Carboniferous hornblende-gabbro and granodiorite in Langshan area, Inner Mongolia. *Acta Petrol. Mineral.* **2018**, *37*, 754–770. (In Chinese with English Abstract)

180. Tian, J.; Xin, H.; Teng, X.; Liu, Y.; Guo, S.; Teng, F.; He, P.; Wang, W. Tectonic Significance of Carboniferous-Triassic Magmatism in Langshan Area, Inner Mongolia. *Earth Sci.* **2019**, *44*, 206–219. (In Chinese with English Abstract)
181. Zhang, Q.; Yuhong, L.; Chen, G.; Han, W.; Wang, J. Geochronology, Geochemistry, and Hf isotopic Compositions of the Late-Carboniferous Volcanic Rocks in Tongshengmao of Daqinshan Area, Inner Mongolia and Their Geological Implications. *Geol. J. China Univ.* **2018**, *24*, 160–171. [[CrossRef](#)]
182. Zhang, W.; Jian, P. SHRIMP dating of the Permian Guyang diorite-quartz diorite-tonalite suite in the northern margin of the North China Craton. *Geol. China* **2012**, *39*, 1593–1603. (In Chinese with English Abstract)
183. Zhang, Y.; Zhang, Y.; Zheng, B.; Xu, G.; Han, J.; Mu, J.; Zhang, L. Geological character and significance of Adakite and TTG in Xiaonangou-Mingxinggou district in central of Inner Mongolia. *Acta Petrol. Sin.* **2006**, *22*, 2762–2768. (In Chinese with English Abstract)
184. Zheng, R.; Zhang, J.; Xiao, W. Association of Permian gabbro and granite in the Langshan, southern Central Asian Orogenic Belt: Age, origin, and tectonic implications. *Lithos* **2019**, *348–349*, 105174. [[CrossRef](#)]
185. Zhou, H.; Zhao, G.; Han, Y.; Wang, B. Geochemistry and zircon U–Pb–Hf isotopes of Paleozoic intrusive rocks in the Damao area in Inner Mongolia, northern China: Implications for the tectonic evolution of the Bainaimiao arc. *Lithos* **2018**, *314–315*, 119–139. [[CrossRef](#)]
186. Zhang, J. Magma Mixing Origin of Yamatu Granite in Nuergong-Langshan Area, Western Margin of North China Craton: In-Situ Zircon U–Pb, Hafnium Isotopic, Petrology and Geochemistry Evidences. Master’s Thesis, China University of Geosciences, Beijing, China, 2012. (In Chinese with English Abstract)
187. Zhao, Q. Origin and Tectonic Setting of Late Paleozoic-Early Mesozoic Granites in Daqingshan District, Inner Mongolia. Ph.D. Thesis, Jilin University, Changchun, China, 2010. (In Chinese with English Abstract)
188. Ren, Y. The Study of Granite-Greenstone Belt in Xihongshan Area. Master’s Thesis, Jilin University, Changchun, China, 2010. (In Chinese with English Abstract)
189. Mo, N. Geochronology, Hf Isotope of Phanerozoic Granitoids in Baotou-Erenhot Area and Its Tectonic Implications. Master’s Thesis, China University of Geosciences Beijing, Beijing, China, 2016. (In Chinese with English Abstract)
190. Zheng, J. Late Paleozoic-Mesozoic Granites Origin and Its Tectonic Settings Analysis of Inner Mongolia Wula Mountain. Master’s Thesis, East China Institute of Technology, Nanchang, China, 2016. (In Chinese with English Abstract)
191. Mi, G. Determination and Geological Significance of Late Paleozoic Alkali-Rich Intrusions Belt at the Northern Foot of Yinshan-Yanshan. Master’s Thesis, China University of Geosciences, Beijing, China, 2020. (In Chinese with English Abstract)
192. Dong, X. The Metamorphism, Times and Tectonic Significance of High-Grade Metamorphic Rocks in Xiwulangbulang Area Inner Mongolia. Master’s Thesis, Jilin University, Changchun, China, 2009. (In Chinese with English Abstract)
193. Wang, D.; Guo, J.H.; Huang, G.Y.; Mark, S. The Neoproterozoic ultramafic–mafic complex in the Yinshan Block, North China Craton: Magmatic monitor of development of Archean lithospheric mantle. *Precambrian Res.* **2015**, *270*, 80–99. [[CrossRef](#)]
194. Wang, D.; Guo, J.H.; Liu, F. *Geochemistry, Zircon U–Pb Chronology and Hf Isotope Characteristics of Late Archean Metamorphic Volcanic Rocks in Wulan-Bulang Area, West Sichuan, Inner Mongolia: Indicators for the Formation and Evolution of Yinshan Block in North China Craton*, China Geosciences Joint Academic Annual Meeting, Beijing, 2014; China Geophysical Society: Beijing, China, 2014; pp. 2273–2274.
195. Luo, J.L.; Wei, X.S.; Yao, J.L.; Liu, X.S.; Liu, X.H. Provenance and depositional facies controlling on the Upper Paleozoic excellent natural gas-reservoir in northern Ordos basin, China. *Geol. Bull. China* **2010**, *29*, 811–820. (In Chinese with English Abstract)
196. Gao, C.; Guo, A.; Li, K. LA-ICP-MS U–Pb of detrital zircon from Liuyehe basin in North Qinling Mountains. *Geol. Bull. China* **2015**, *34*, 1689–1698. (In Chinese with English Abstract)
197. Liang, G. Geological Characteristics and Source Analysis of the Triassic Strata in the Lintan Area, Western Qinling. Master’s Thesis, Chang’an University, Xi’an, China, 2020. (In Chinese with English Abstract)
198. Li, K.; Guo, A.; Gao, C. A tentative discussion on the source area of the Late Triassic Liuyehe basin in North Qinling Mountains and its relationship with the Ordos basin: Evidence from LA-ICP-MS U–Pb dating of detrital zircons. *Lithos* **2015**, *34*, 1426–1437. (In Chinese with English Abstract)
199. Chen, C. The Evolution of Permian SEDIMENTARY Sequences in Zhen’an, Shaanxi, China, and Its Response to the Changes of Permian Paleoclimate, PALEOENVIRONMENT and Paleogeography. Master’s Thesis, Hefei University, Hefei, China, 2018. (In Chinese with English Abstract)
200. Bao, C.; Chen, Y.; Li, D. LA-MC-ICP-MS zircons U–Pb dating and Hf isotopic compositions of the Paleoproterozoic amphibolite in Bayan UI area, Inner Mongolia. *Geol. Bull. China* **2013**, *32*, 1513–1524. (In Chinese with English Abstract)
201. Dong, C.Y.; Li, D.Y.; Li, J.J.; Wan, Y.S.; Zhou, Y.H.; Li, C.D.; Yang, Y.H.; Xie, L.W. New Evidence of the Formation of the Konzi Rock Belt in the West Craton of North China: Zircon SHRIMP dating and Hf isotopic composition in the Bayan-Ula Helan Mountain area. *Chin. Sci. Bull.* **2007**, *52*, 1913–1922. (In Chinese) [[CrossRef](#)]
202. Dan, W.; Li, X.; Guo, J.; Liu, Y.; Wang, X. Paleoproterozoic evolution of the eastern Alxa Block, westernmost North China: Evidence from in situ zircon U–Pb dating and Hf–O isotopes. *Gondwana Res.* **2012**, *21*, 838–864. [[CrossRef](#)]
203. Gong, J.H.; Zhang, J.; Wang, Z.; Yu, S.; Li, H.; Li, Y. Origin of the Alxa Block, western China: New evidence from zircon U–Pb geochronology and Hf isotopes of the Longshoushan Complex. *Gondwana Res.* **2016**, *36*, 359–375. [[CrossRef](#)]

204. Zhou, Y.H.; Mo, X.X.; Li, J.J.; Li, H.M. The U–Pb Isotope Dating Age of Single Zircon from Biotite Plagioclase Gneiss in the Qinggele Area, Alashan, Western Inner Mongolia. *Bull. Mineral. Petrol. Geochem.* **2007**, *26*, 221–223. (In Chinese with English Abstract)
205. Gong, J.H. Compositions, Characteristics, Chronological Framework and Origin of Early-Precambrian Metamorphic Basement in Western Alxa Block. Ph.D. Thesis, Chinese Academy of Geological Sciences, Beijing, China, 2013. (In Chinese with English Abstract)
206. Gong, J.H.; Zhang, J.X.; Yu, S.Y.; Li, H.K.; He, H.J. The 2.5Ga TTG in the western Alxa Block and its geological significance. *Chin. Sci. Bull.* **2012**, *57*, 2715–2728. (In Chinese)
207. Zhang, J.; Li, J.Y.; Liu, J.F.; Li, Y.F.; Qu, J.F.; Zhang, Y.P. LA–ICP–MS U–Pb ages of pillow lava basalts in southwestern Langshan, Inner Mongolia and their implication. *Geol. Bull. China* **2013**, *32*, 287–296. (In Chinese)
208. Li, J.J.; Shen, B.F.; Li, H.M.; Zhou, H.Y.; Guo, L.J.; Li, C.Y. Single-grained zircon U–Pb age of granodiorite gneiss in the Bayan-Ula Mountains area of western Inner Mongolia. *Geol. Bull. China* **2004**, *23*, 1243–1245. (In Chinese)
209. Liu, K.X. Tectonic Evolution of Alxa Block from the Proterozoic to Early Paleozoic. Master’s Thesis, Lanzhou University, Lanzhou, China, 2014. (In Chinese with English Abstract)
210. Liu, K.X.; Wang, J.R.; Zhao, B.B.; Zhai, X.W.; Dai, J.F. Chronology and tectonic significance of gneiss granite in Alxa Right Banner Waist Spring. *J. Lanzhou Univ. (Nat. Sci.)* **2014**, *50*, 907–908. [\[CrossRef\]](#)
211. Wang, M.M. Zircon Geochronology and Hf Isotopic Compositions for the Haisen Chulu, Aergelintai Granite in Alxa, Inner Mongolia and Their Geological Significances. Master’s Thesis, China University of Geosciences, Beijing, China, 2019. (In Chinese with English Abstract)
212. Shen, Q.H.; Geng, Y.S.; Wang, X.S.; Wu, C.M. Petrology, geochemistry, formation environment and ages of Precambrian amphibolites in Alxa region. *Acta Petrol. Mineral.* **2005**, *24*, 21–31. (In Chinese with English Abstract)
213. Dan, W.; Li, X.; Wang, Q.; Wang, X.; Liu, Y. Neoproterozoic S-type granites in the Alxa Block, westernmost North China and tectonic implications: In situ zircon U–Pb–Hf–O isotopic and geochemical constraints. *Am. J. Sci.* **2014**, *314*, 110–153. [\[CrossRef\]](#)
214. Wu, S.; Hu, J.; Ren, M.; Gong, W.; Liu, Y.; Yan, J. Petrography and zircon U–Pb isotopic study of the Bayanwulashan Complex: Constraints on the Paleoproterozoic evolution of the Alxa Block, westernmost North China Craton. *J. Asian Earth Sci.* **2014**, *94*, 226–239. [\[CrossRef\]](#)
215. Liu, Y. Characteristics and Geological Significance of Paleoproterozoic Granite in Jinchuan, Gansu Province. Master’s Thesis, China University of Geosciences, Beijing, China, 2008. (In Chinese with English Abstract)
216. Geng, Y.S.; Wang, X.S.; Wu, C.M.; Zhou, X.W. Late-Paleoproterozoic tectonothermal events of the metamorphic basement in Alxa area: Evidence from geochronology. *Acta Petrol. Sin.* **2010**, *26*, 1159–1170. (In Chinese with English Abstract)
217. Dan, W.; Li, X.; Wang, Q.; Tang, G.; Liu, Y. An Early Permian (ca. 280 Ma) silicic igneous province in the Alxa Block, NW China: A magmatic flare-up triggered by a mantle-plume? *Lithos* **2014**, *204*, 144–158. [\[CrossRef\]](#)
218. Dan, W.; Li, X.; Wang, Q.; Wang, X.; Wyman, D.A.; Liu, Y. Phanerozoic amalgamation of the Alxa Block and North China Craton: Evidence from Paleozoic granitoid, U–Pb geochronology and Sr–Nd–Pb–Hf–O isotope geochemistry. *Gondwana Res.* **2016**, *32*, 105–121. [\[CrossRef\]](#)
219. Bao, C.; Chen, Y.; Li, D. Discovery of the Late Permian volcanics in the Zhulazhagamaodao, northern margin of the Alxa Block. *Earth Sci. Front.* **2012**, *19*, 156–163. (In Chinese with English Abstract)
220. Song, B.; Zhang, H.Y.; Wei, D.T.; Li, W.; Zhao, F.; Li, W.M. Revelation of the Meso-Neoproterozoic Crust on the Southern Margin of the Central Asian Orogenic Belt: Chronology and Hf Isotope Tracer from Drilling-intersected Alkaline Granites, Northern Beishan-Alxa. *Acta Geos. Sin.* **2021**, *42*, 9–20. (In Chinese with English Abstract)
221. Dan, W.; Wang, Q.; Wang, X.; Liu, Y.; Wyman, D.A.; Liu, Y. Overlapping Sr–Nd–Hf–O isotopic compositions in Permian mafic enclaves and host granitoids in Alxa Block, NW China: Evidence for crust–mantle interaction and implications for the generation of silicic igneous provinces. *Lithos* **2015**, *230*, 133–145. [\[CrossRef\]](#)
222. Feng, J.; Xiao, W.; Windley, B.; Han, C.; Wan, B.; Zhang, J.E.; Ao, S.; Zhang, Z.; Lin, L. Field geology, geochronology and geochemistry of mafic–ultramafic rocks from Alxa: Implications for Late Permian accretionary tectonics in the southern Altai. *J. Asian Earth Sci.* **2013**, *78*, 114–142. [\[CrossRef\]](#)
223. Li, F.W. Characteristics and Tectonic Significance of Carboniferous Intrusive Rocks in Engelwusu, Alashan, Inner Mongolia. Master’s Thesis, China University of Geosciences, Beijing, China, 2018. (In Chinese with English Abstract)
224. Li, C. Characteristics of Early Permian Intrusive Rocks in Sangejing Area of Alashan Zuoqi, Inner Mongolia. Master’s Thesis, China University of Geosciences, Beijing, China, 2018. (In Chinese with English Abstract)
225. Liu, C.T. Characteristics and Geological Significance of Silurian Intrusions in Nurgai Area, Inner Mongolia. Master’s Thesis, China University of Geosciences, Beijing, China, 2019. (In Chinese with English Abstract)
226. Xie, F.Q. Study of Granites Rock Mass of Zongnai, Sha Laza and Bayinnuoergong. Master’s Thesis, China University of Geosciences, Beijing, China, 2014. (In Chinese with English Abstract)
227. Xie, F.Q.; Wang, L.D.; Li, Q.; Shi, C.X.; Chen, X.B. Zircon LA–ICP–MS Dating of Granites from the Southeastern Zongnai Mountain Alxa and Its Geochemical Characteristics. *Rock Mineral. Anal.* **2015**, *3*, 375–382. [\[CrossRef\]](#)
228. Chen, G.C.; Shi, J.Z.; Jiang, T.; Zhang, H.Y.; Li, W.; Wang, B.W. LA–ICP–MS zircon U–Pb dating and geochemistry of granitoids in Tamusu, Alxa Right Banner, Inner Mongolia. *Geol. Bull. China* **2015**, *34*, 1884–1896. (In Chinese with English Abstract)

229. Yin, H.Q. Late Paleozoic Sedimentary Characteristics and Its Tectonic Evolution in Northern Alxa Area, Inner Mongolia. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2016. (In Chinese with English Abstract)
230. Ran, H.; Zhang, W.J.; Liu, Z.B. Geochemical characteristics and LA-ICP-MS zircon U-Pb dating of the Late Permian monzogranite in Hanggale, Alxa Right Banner, Inner Mongolia. *Geol. Bull. China* **2012**, *31*, 1565–1575. (In Chinese with English Abstract)
231. Gong, J.H.; Zhang, J.X.; Wang, Z.Q.; Yu, S.Y.; Wang, D.S. Zircon U-Pb Dating, Hf Isotopic and Geochemical Characteristics of Two Suites of Gabbros in the Beidashan Region, Western Alxa Block: Its Implications for Evolution of the Central Asian Orogenic Belt. *Acta Geol. Sin.* **2018**, *92*, 1369–1388. (In Chinese)
232. Gong, J.H.; Zhang, J.X.; Wang, Z.Q.; Yu, S.Y.; Wang, D.S. Late Ordovician-Carboniferous tectonic evolutionary history of the Alxa Block: Constrained by the multistage magmatic-metamorphic-deformation events in Beidashan area. *Acta Petrol. Mineral.* **2018**, *37*, 771–798. (In Chinese with English Abstract)
233. Zhang, J.J. Petrogenesis of the Permian Granitoids from the Northern Alxa Block and THEIR Geodynamic Implications. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2015. (In Chinese with English Abstract)
234. Zhang, J.J.; Wang, T.; Castro, A.; Zhang, L.; Shi, X.J.; Tong, Y.; Zhang, Z.C.; Guo, L.; Yang, Q.D.; Iaccheri, L.M. Multiple Mixing and Hybridization from Magma Source to Final Emplacement in the Permian Yamatu Pluton, the Northern Alxa Block, China. *J. Palaeogr.* **2016**, *57*, 933–980. [[CrossRef](#)]
235. Jiao, J.; Zemin, M.; Hao, L. Zircon U-Pb age and geological significance of the YejiLi mafic-ultramafic rock mass in the southern margin of the Alxa massif. *Geotecton. Metallog.* **2017**, *41*, 950–959. [[CrossRef](#)]
236. Zhang, J.X.; Wang, K.L. Zircon U-Pb dating and geochemical characteristics of gabbro in Yabulai, northern margin of Alxa block. *J. Palaeogr.* **2021**, *45*, 13–20. (In Chinese)
237. Li, J. Characteristics and Tectonic Significance of Late Paleozoic Intrusive Rocks Along the YabraiBayan Noel of Alxa, Inner Mongolia. Master's Thesis, China University of Geosciences, Beijing, China, 2012. (In Chinese with English Abstract)
238. Jin, X.; Ping, S.; Lin, X. LA-ICP-MS Zircon U-Pb age, geochemical characteristics and genesis of the Early Permian gabbro in the Norgong area of northern Alxa. *Western Res.* **2016**, *31*, 55–60. (In Chinese)
239. Lu, J.C.; Wei, X.X.; Li, Y.H.; Wei, J.S. Geochemical characteristics of Carboniferous-Permian hydrocarbon source rocks of Xiangtan 9 well in Ejin Banner, western Inner Mongolia. *Geol. Bull. China* **2012**, *31*, 1628–1638. (In Chinese with English Abstract)
240. Ma, J.; Lei, C.C.; Wang, W.B.; Li, W.X. A Study on Geochemistry, Zircon U-Pb Dating and Tectonic Setting of the Zhuxiaobuhe Mylonitized Granite in the Yagan Area of Northern Margin of the Alxa Terrain. *Bull. Mineral. Petrol. Geochem.* **2021**, *40*, 1357–1368. [[CrossRef](#)]
241. Li, J.J.; Zhai, Y.S.; Song, H.Q.; Li, H.M.; Zhang, Y.S. Metallogenic Epoch of the Oubulage Copper-Gold Deposit in the Alashan Area, Inner Mongolia Autonomous Region. *Bull. Mineral. Petrol. Geochem.* **2010**, *29*, 323–327. (In Chinese with English Abstract)
242. Li, J.J.; Zhai, Y.S.; Yang, Y.Q.; Wang, Y.B.; Li, C.D. Re-discussion on the metallogenic age of Zhulazaga gold deposit in Alashan Area, Inner Mongolia: Evidence from zircon U-Pb SHRIMP age. *Earth Sci. Front.* **2010**, *17*, 178–184. (In Chinese with English Abstract)
243. Li, J.J. Regional Metallogenic System of Alashan Block in Inner Mongolia Autonomous Region. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2006. (In Chinese with English Abstract)
244. Wang, K.L.; Li, H.K.; Zhang, X.M.; Tian, Z.B.; Zhang, J.X.W. Geochemistry, Geochronology and Sr-Nd Isotope of Mafic Dykes in the Yabulai Area, Northern Margin of the Alxa Massif. *Geol. Explor.* **2021**, *57*, 1017–1027. (In Chinese)
245. Wang, K.L.; Zhang, J.X.; Zhang, X.M.; Li, H.K.; Zheng, L. Magma mixing origin of the mafic microgranular enclaves from the Yabulai pluton in the western part of northern Alxa Block. *Geol. Rev.* **2020**, *66*, 13–34. [[CrossRef](#)]
246. Wang, K.L.; Zhang, X.M.; Li, H.K.; Zheng, L.; Zhang, J.X.; Xing, D.X.; Chen, T.; Hou, Z.Y. Zircon U-Pb age, petrogenesis and tectonic setting of the Yabulai adakite, north Alxa Block, Inner Mongolia. *Geol. Bull. China* **2021**, *40*, 1443–1458. (In Chinese with English Abstract)
247. Wang, K.L. Geochemical Characteristics and Tectonic Setting of Late Varisian Period in Alashan Block. Master's Thesis, Chang'an University, Xi'an, China, 2011. (In Chinese with English Abstract)
248. Ye, K.; Zhang, L.; Wang, T.; Shi, X.J.; Zhang, J.J. Geochronology, geochemistry and zircon Hf isotope of the Permian intermediate acid igneous rocks from the Yabulai Mountain in western Alxa, Inner Mongolia, and their tectonic implications. *Acta Petrol. Mineral.* **2016**, *35*, 901–928. (In Chinese with English Abstract)
249. Zou, L.; Shi, X.J.; Zhang, J.J. LA-ICP-MS zircon U-Pb age geochemical characteristics of the Taohaotuoxiquan gabbro in northern Alxa, Inner Mongolia. *Geol. Bull. China* **2013**, *32*, 1536–1547. (In Chinese with English Abstract)
250. Zou, L.; Liu, P.H.; Liu, L.S.; Wang, W.; Tian, Z.H. Diagenetic and Metamorphic Timing of the Diebusige Complex, the Eastern Alxa Block: New Evidence from Zircon LA-ICP-MS U-Pb Dating of BiotitePlagioclase Gneiss. *Earth Sci.* **2020**, *45*, 3313–3329. (In Chinese with English Abstract)
251. Xu, L.; Xie, Q.X. LA-ICP-MS Zircon U-Pb Age and Geochemical Characteristics of the Bayannuoergong Quartz Diorite in Alxa, Inner Mongolia. *Xinjiang Geol.* **2015**, *33*, 529–536. (In Chinese)
252. An, L.K. Feature and Tectonic Significance of the Engerwusu Ophiolitic Melange of Alaxa, Inner Mongolia. Master's Thesis, China University of Geosciences, Beijing, China, 2013. (In Chinese with English Abstract)
253. Zhang, L.Q. Post-Collisional Magmatism and Geodynamic Process from the North Qilian Orogen to Southern Margin of the Alxa Block, NW China. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2019. (In Chinese with English Abstract)

254. Gan, L.S.; Wu, T.R.; Chen, Y.; Zhang, W.; Zhang, Z.Y. Geochronology and geochemical characteristics of the Shangdan pluton in the northern margin of the Alxa Block, Inner Mongolia and its tectonic implications. *Acta Petrol. Sin.* **2018**, *34*, 3359–3374. (In Chinese with English Abstract)
255. Liu, Q.; Zhao, G.; Han, Y.; Eizenhöfer, P.R.; Zhu, Y.; Hou, W.; Zhang, X. Timing of the final closure of the Paleo-Asian Ocean in the Alxa Terrane: Constraints from geochronology and geochemistry of Late Carboniferous to Permian gabbros and diorites. *Lithos* **2017**, *274–275*, 19–30. [\[CrossRef\]](#)
256. Liu, Q.; Zhao, G.; Sun, M.; Han, Y.; Eizenhöfer, P.R.; Hou, W.; Zhang, X.; Zhu, Y.; Wang, B.; Liu, D. Early Paleozoic subduction processes of the Paleo-Asian Ocean: Insights from geochronology and geochemistry of Paleozoic plutons in the Alxa Terrane. *Lithos* **2016**, *262*, 546–560. [\[CrossRef\]](#)
257. Qiang, S. Geochemical Characteristics and Tectonic Significance of Late Paleozoic Igneous Rocks in the Yagan Region of Alxa. Master's Thesis, Lanzhou University, Lanzhou, China, 2020. (In Chinese with English Abstract)
258. Pi, Q.H.; Liu, C.Z.; Chen, Y.L.; Li, Y.Q.; Li, D.P. Formation epoch and genesis of intrusive rocks in Huogeqi orefield of Inner Mongolia and their relationship with copper mineralization. *Mineral Depos.* **2010**, *29*, 437–451. [\[CrossRef\]](#)
259. Yang, Q.D.; Zhang, L.; Wang, T.; Shi, X.J.; Zhang, J.J. Geochemistry and LA-ICP-MS zircon U–Pb age of Late Carboniferous Shalazhashan pluton on the northern margin of the Alxa Block, Inner Mongolia and their implications. *Geol. Bull. China* **2014**, *33*, 776–787. (In Chinese with English Abstract)
260. Zheng, R.G.; Li, J.Y.; Zhang, J.; Xiao, W.; Li, Y. Early Carboniferous High Ba–Sr Granitoid in Southern Langshan of Northeastern Alxa: Implications for Accretionary Tectonics along the Southern Central Asian Orogenic Belt. *Acta Geol. Sin.* **2019**, *93*, 820–844. [\[CrossRef\]](#)
261. Zheng, R.G.; Li, J.Y.; Liu, J.F. The age of volcanic rocks of Amushan Formation on the northern margin of Alxa block: Evidence from zircon U–Pb data. *Geol. China* **2017**, *44*, 612–613. (In Chinese)
262. Zheng, R.G.; Wu, T.R.; Zhang, W. Geochronology and geochemistry of the Yagan granite in the northern margin of the Alxa block: Constraints on the tectonic evolution of the southern Altaids. *Acta Petrol. Sin.* **2013**, *29*, 2665–2675. (In Chinese with English Abstract)
263. Tian, R.S. Late Paleozoic Tectonic Evolution in the Northern Margin of the Alxa Block. Ph.D. Thesis, Nanjing University, Nanjing, China, 2022. (In Chinese with English Abstract)
264. Li, R.W. Geochemistry and Tectonic Implications of Gabbros and Granites in the Northern Alxa, NW China. Master's Thesis, Lanzhou University, Lanzhou, China, 2020. (In Chinese with English Abstract)
265. Zhang, S.M.; He, Z.Y.; Zhao, P.B.; Hu, E.H.; Wang, Y.N.; Zhou, Y.B. Zircon U–Pb Chronology and Geochemistry of the Wuliji Intrusions in the Northern Alxa Block: Constraints on the Tectonic Evolution of the Southern Altaids. *Earth Sci.* **2021**, *46*, 101–121. (In Chinese with English Abstract)
266. Shi, X.; Wang, T.; Zhang, L.; Castro, A.; Xiao, X.; Tong, Y.; Zhang, J.; Guo, L.; Yang, Q. Timing, petrogenesis and tectonic setting of the Late Paleozoic gabbro–granodiorite–granite intrusions in the Shalazhashan of northern Alxa: Constraints on the southernmost boundary of the Central Asian Orogenic Belt. *Lithos* **2014**, *208–209*, 158–177. [\[CrossRef\]](#)
267. Wu, S. Metamorphism and Deformation History of the Basement Rocks from the Northeastern Alxa Block and Their Tectonic Implications. Ph.D. Thesis, Chinese Academy of Geological Sciences, Beijing, China, 2014. (In Chinese with English Abstract)
268. Wang, Z.; Han, B.; Feng, L.; Liu, B.; Zheng, B.; Kong, L. Tectonic attribution of the Langshan area in Western Inner Mongolia and implications for the Neoproterozoic–Paleoproterozoic evolution of the Western North China Craton: Evidence from LA-ICP-MS zircon U–Pb dating of the Langshan basement. *Lithos* **2016**, *261*, 278–295. [\[CrossRef\]](#)
269. Chen, W.; Zhou, W.P.; Chen, K.X.; Liu, M.W.; Wang, T.; Fang, M.; He, H.Y.; Fang, B. Early Permian granodiorite zircon U–Pb chronology and geochemical characteristics of Jinchangshan, Alashan Right Banner, Inner Mongolia. *Mineral. Petrol.* **2013**, *33*, 53–60. (In Chinese)
270. Zhang, W.; Wang, J.R.; Chen, W.F.; Zhai, X.W.; Ma, J.L. The Discovery of the Carboniferous Adakite and its Tectonic Implications in Alxa Youqi. *Geol. J. China Univ.* **2014**, *20*, 378–387. (In Chinese with English Abstract)
271. Wen, Z.; Tairan, W.; Jicheng, F. Temporal constraints of paleoceanic closure on the northern margin of the Alxa massif: Evidence from the Uliji granite massif. *Sci. Sin.* **2013**, *43*, 1299–1311. (In Chinese with English Abstract)
272. Liu, W.H.; Pan, J.Y.; Liu, X.D.; Wang, K.X.; Wang, G. Petrogenesis and Tectonic Implication of Qingshanbao Pluton in Longshou Mountains, Gansu: Constraints from Elemental Geochemistry, Zircon U–Pb age and Sr–Nd isotopes. *Mineral. Petrol.* **2019**, *39*, 26–40. (In Chinese)
273. Xiao, C. Structural Deformation Characteristics and Its Significance in HuobuHaer of Ejinaqi, Inner Mongolia. Ph.D. Thesis, China University of Geosciences, Beijing, China, 2020. (In Chinese with English Abstract)
274. Cui, X.; Wang, G.H.; Wang, Z.Y.; Liu, D.W.; Lei, C.C. Discovery of Structural Schist Belt in Huobuhaer area of Ejinaqi, Inner Mongolia: Implication for Its Tectonic Significance. *Mineral. Petrol.* **2019**, *39*, 81–89. [\[CrossRef\]](#)
275. Shi, X.J.; Zhang, L.; Zhang, C.G.; Zhang, J.J.; Ding, Z.Y. Zircon Geochronology and Geochemistry of the Granitoids in Yagan Area, Northern Alxa and their Tectonic Implications. *Earth Sci.* **2020**, *45*, 2469–2484. (In Chinese with English Abstract)
276. Shi, X.J.; Zhang, L.; Wang, T. Geochronology and geochemistry of the intermediate-acid intrusive rocks from Zongnaishan area in northern Alxa, Inner Mongolia, and their tectonic implications. *Acta Petrol. Mineral.* **2014**, *33*, 989–1007. (In Chinese with English Abstract)

277. Shi, X.J.; Tong, Y.; Wang, T.; Zhang, J.J.; Zhang, Z.C. LA-ICP-MS zircon U-Pb age and geochemistry of the Early Permian Halinudeng Granite in northern Alxa area, western Inner Mongolia. *Geol. Bull. China* **2012**, *31*, 662–670. (In Chinese with English Abstract)
278. Yang, X.; Li, Y.K.; Wang, A.J. Closure time limit of the back-arc basin in the southwest of the Mongolian Ocean: Constraints from geochemistry and zircon dating of rocks in the southern Alxa block. *Acta Geol. Sin.* **2019**, *93*, 1639–1654. [[CrossRef](#)]
279. Pan, X. Petrogenesis of Tebai Basic-Ultrabasic Pluton in the Beidashan Area in the Southern Margin of the Alxa Block and Its Tectonic Significance. Master's Thesis, Chang'an University, Xi'an, China, 2019. (In Chinese with English Abstract)
280. Teng, X.J.; Tian, J.; Liu, Y.; Zhang, Y.; Teng, F. Definition and Geological Significance of Early Silurian Quartz Diorite Pluton in Langshan Area, Inner Mongolia. *Earth Sci.* **2019**, *44*, 1236–1252. (In Chinese with English Abstract)
281. Geng, Y.S.; Zhou, X.W. Early Permian magmatic events in the Alxa metamorphic basement: Evidence from geochronology. *Acta Petrol. Sin.* **2012**, *28*, 2667–2685. (In Chinese with English Abstract)
282. Niu, Y. Geological and Geochemical Characteristics and Petrogenesis of Qingshanbao Pluton in Longshou Mountains, Gansu. Master's Thesis, East China University of Technology, Fuzhou, China, 2019. (In Chinese with English Abstract)
283. Huo, Y.J.; Zhang, L.; Wang, M.M. Geochemistry, age and zircon Hf isotope characteristics for the Late Paleozoic intrusive rocks in Ubud area of Beidashan, Alxa and their significances. *Chin. J. Geol. (Sci. Geol. Sin.)* **2021**, *56*, 182–209. (In Chinese)
284. Li, Y. Geochemistry of Volcanic Rocks in the Jinta Formation of North to Alxa Block and Its Tectonic Implications. Master's Thesis, Lanzhou University, Lanzhou, China, 2019. (In Chinese with English Abstract)
285. Ma, Z. Study on Petrogenesis of Xiayantan Intrusion in Beidashan Area, Southern Margin of Alxa Block, and Its Geological Significance. Master's Thesis, Chang'an University, Xi'an, China, 2019. (In Chinese with English Abstract)
286. Wang, Z.Z.; Chen, X.H.; Shao, Z.G.; Li, B.; Ding, W.C. Petrogenesis of the Late Silurian-Early Devonian granites in the Longshoushan-Helishan area, Gansu Province, and its tectonic implications for the Early Paleozoic evolution of the south-western Alxa Block. *Acta Geol. Sin.* **2020**, *94*, 2243–2261. [[CrossRef](#)]
287. Zheng, R.G.; Wu, T.; Zhang, W.; Xu, C.; Meng, Q.P. Late Paleozoic subduction system in the northern margin of the Alxa block, Altaids: Geochronological and geochemical evidences from ophiolites. *Gondwana Res.* **2014**, *25*, 842–858. [[CrossRef](#)]
288. Zhang, Z.P.; Liu, G.; Xu, C.; Meng, Q.T.; Guo, C. Geochemical Characteristics and LA-ICP-MS Zircon U-Pb Dating of the Late Permian Granites in the Tamusu Area of Alxa Right Banner, Inner Mongolia and Their Implications. *Geol. Explor.* **2016**, *52*, 893–909. [[CrossRef](#)]
289. Liu, Z.B.; Zhang, W.J. Geochemical characteristics and LA-ICP-MS zircon U-Pb dating of the Late Permian granodiorite in Hanggale, Alxa Right Banner, Inner Mongolia. *Geol. Rev.* **2014**, *60*, 409–426. [[CrossRef](#)]
290. Dang, Z.C.; Li, J.J.; Zhao, Z.L.; Fu, C.; Tang, W.L. TIMS zircon U-Pb age of Bayinnuoergong granite pluton of Alxa Block, Inner Mongolia. *Geol. Bull. China* **2016**, *35*, 593–598. (In Chinese with English Abstract)
291. Zhou, X.C.; Zhang, H.F.; Luo, B.J.; Pan, F.B.; Zhang, S.S. Origin of high Sr/Y-type granitic magmatism in the southwestern of the Alxa Block, Northwest China. *Lithos* **2016**, *256–257*, 211–227. [[CrossRef](#)]
292. Zhang, Z.Q. Geological Characteristics and Tectonic Significance of Early Permian Gabbro in Alax You Qi, Inner Mongolia. Master's Thesis, China University of Geosciences, Beijing, China, 2017. (In Chinese with English Abstract)
293. Shi, X.J.; Zhang, L.; Wang, T.; Zhang, J.J.; Liu, M.H. Zircon geochronology and Hf isotopic compositions for the Mesoproterozoic gneisses in Zongnaishan area, northern Alxa and its tectonic affinity. *Acta Petrol.* **2016**, *32*, 3518–3536. (In Chinese with English Abstract)
294. Liu, P.H.; Zou, L.; Tian, Z.H.; Jin, L.; Shi, J.R. Discovery and Geological Significance of an Early Paleozoic (Ca.420 Ma) Metamorphic Event from the Eastern Alxa Block: New Evidence from Monazite and Zircon LA-ICP-MS U-Pb Dating. *Earth Sci.* **2019**, *44*, 2441–2470. (In Chinese with English Abstract)
295. Xiao, Z.B.; Kang, J.L.; Wang, H.C.; Gao, Z.R.; Xiang, Z.Q. Formation Age of Alxa Group-Complex (Special) in Alxa Area, Inner Mongolia. *N. China Geol.* **2015**, *38*, 182–191. (In Chinese)
296. Gong, J.H.; Zhang, J.X.; Yu, S.Y. The origin of Longshoushan Group and associated rocks in the southern part of the Alxa block: Constraint from LA-ICP-MS U-Pb zircon dating. *Acta Petrol. Mineral.* **2011**, *30*, 795–818. (In Chinese with English Abstract)
297. Zhang, J.X.; Gong, J. Revisiting the nature and affinity of the Alxa Block. *Acta Petrol. Sin.* **2018**, *34*, 940–962. (In Chinese with English Abstract)
298. Geng, Y.S.; Zhou, X.W. Early Neoproterozoic granite events in Alax area of Inner Mongolia and their geological significance: Evidence from geochronology. *Acta Petrol. Mineral.* **2010**, *29*, 779–795. (In Chinese with English Abstract)
299. Zou, L.; Liu, P.H.; Tian, Z.H.; Jin, L.; Shi, J.R. Late Paleozoic Metamorphic Complex of Precambrian Metamorphic Basement from Eastern Alxa Block: New Evidence from Zircon LA-ICP-MS U-Pb Dating of Boluositanmiao Complex. *Earth Sci.* **2019**, *44*, 1406–1436. (In Chinese with English Abstract)
300. Luo, J.; Yun, J.B.; He, Z.L.; Li, T.Y.; Song, H.M. The discovery of Mesoproterozoic gneiss from Mao 11 well in Cha'gan Sag, Inner Mongolia: Evidence from zircon U-Pb geochronology. *Geol. China* **2018**, *45*, 632–633. (In Chinese)
301. Niu, P.F.; Qu, J.F.; Zhang, J.; Zhang, B.H.; Zhao, H. Zircon U-Pb age and Hf isotopic characteristics of the Diebusige Complex in Langshan area, Inner Mongolia, and its constraints on the tectonic evolution of the Alxa Block. *Geol. Bull. China* **2022**, *41*, 754–773. (In Chinese with English Abstract)

302. Zhou, Y.Z.; Han, B.F.; Xu, Z.; Ren, R.; Su, L. The age of the Proterozoic rocks in Yingba area in western Inner Mongolia: Constraints on the distribution of the South Gobi micro-continent in the Central Asian orogenic belt. *Geol. Bull. China* **2013**, *32*, 318–326. (In Chinese with English Abstract)
303. Geng, Y.S.; Wang, X.S.; Shen, Q.H.; Wu, C.M. Redefinition of the Alxa Group-complex (Precambrian metamorphic basement) in the Alxa area, Inner Mongolia. *Geol. China* **2006**, *33*, 138–145. (In Chinese)
304. Qing, Y. Study on Metamorphic Substrate in Tamusin Area of Alashan Right Banner in Inner Mongolia. Master's Thesis, China University of Geosciences, Beijing, China, 2010. (In Chinese with English Abstract)
305. Griffin, W.L.; Person, N.J.; Belousova, E.; Jackson, S.E.; Achterbergh, E.V.; Reilly, S.Y.O.; Shree, S.R. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochim. Cosmochim. Acta* **2000**, *64*, 133–147. [[CrossRef](#)]
306. Yu, S.; Zhang, J.; Del Real, P.G.; Zhao, X.; Hou, K.; Gong, J.; Li, Y. The Grenvillian orogeny in the Altun–Qilian–North Qaidam mountain belts of northern Tibet Plateau: Constraints from geochemical and zircon U–Pb age and Hf isotopic study of magmatic rocks. *J. Asian Earth Sci.* **2013**, *73*, 372–395. [[CrossRef](#)]
307. Huo, Y. Geochemical Characteristics and Geological Significance of Late Paleozoic Intrusive Rocks in Ubud, Beidashan, Alxa. Master's Thesis, China University of Geosciences, Beijing, China, 2020. (In Chinese with English Abstract)
308. Zhang, J.J.; Zhang, L.; Wang, T.; Shi, X.J. Geochemical, age and Hf-in-zircon isotopic characteristics and geological significance of granite and MME from the Mandelinqwula pluton, northern Alxa block, Inner Mongolia. *Geol. Bull. China* **2019**, *38*, 1675–1690. (In Chinese with English Abstract)
309. Geng, Y.S.; Zhou, X.W. Characteristics of geochemistry and zircon Hf isotope of the Early Neoproterozoic granite in Alxa area, Inner Mongolia. *Acta Petrol. Sin.* **2011**, *27*, 897–908. (In Chinese)
310. Liu, Q.; Zhao, G.; Han, Y.; Eizenhöfer, P.R.; Zhu, Y.; Hou, W.; Zhang, X.; Wang, B. Geochronology and geochemistry of Permian to Early Triassic granitoids in the Alxa Terrane: Constraints on the final closure of the Paleo-Asian Ocean. *Lithosphere* **2017**, *9*, L646.1. [[CrossRef](#)]
311. Dong, Y.P.; Santosh, M. Tectonic architecture and multiple orogeny of the Qinling Orogenic Belt, Central China. *Gondwana Res.* **2016**, *29*, 1–40. [[CrossRef](#)]
312. Guo, P.; Liu, C.Y.; Wang, J.Q.; Deng, Y.; Mao, G.Z. Detrital-zircon geochronology of the Jurassic coal-bearing strata in the western Ordos Basin, North China: Evidences for multi-cycle sedimentation. *Geos. Front.* **2018**, *9*, 1725–1743. [[CrossRef](#)]
313. Lu, S.N.; Chen, Z.H.; Li, H.K.; Hao, G.J.; Zhou, H.Y.; Xiang, Z.Q. Late Mesoproterozoic-early Neoproterozoic evolution of Qinling orogeny. *Geol. Bull. China* **2004**, *23*, 107–112. (In Chinese)
314. Zhang, C.L.; Gou, L.L.; Diwu, C.R.; Liu, X.Y.; Zhao, J.; Hu, Y.H. Early Precambrian geological events of the basement in Western Block of North China Craton and their properties and geological significance. *Acta Petrol. Sin.* **2018**, *34*, 981–998. (In Chinese with English Abstract)
315. Wang, X.; Wang, T.; Zhang, C. Granitoid magmatism in the Qinling orogen, central China and its bearing on orogenic evolution. *Sci. China Earth Sci.* **2015**, *45*, 1109–1125. [[CrossRef](#)]
316. Song, S.; Niu, Y.; Su, L.; Zhang, C.; Zhang, L. Continental orogenesis from ocean subduction, continent collision/subduction, to orogen collapse, and orogen recycling: The example of the North Qaidam UHPM belt, NW China. *Earth Sci. Rev.* **2014**, *129*, 59–84. [[CrossRef](#)]
317. Mazumder, R. Correlations between the Eastern Block of the North China Craton and the South Indian Block of the Indian Shield: An Archaean to Palaeoproterozoic link. *Precambrian Res.* **2003**, *127*, 379–380. [[CrossRef](#)]
318. Zhao, G.; Sun, M.; Wilde, S.A.; Sanzhong, L. Late Archean to Paleoproterozoic evolution of the North China Craton: Key issues revisited. *Precambrian Res.* **2005**, *136*, 177–202. [[CrossRef](#)]
319. Zhao, G.; Cawood, P.A. Precambrian geology of China. *Precambrian Res.* **2012**, *222–223*, 13–54. [[CrossRef](#)]
320. Davis, G.A.; Wang, C.; Zheng, Y.; Zhang, J.; Zheng, C.; Gehrels, G.E. The enigmatic Yinshan fold-and-thrust belt of northern China: New views on its intraplate contractional styles. *Geology* **1998**, *26*, 43–46. [[CrossRef](#)]
321. Yang, Z.Y.; Yuan, W.; Tong, Y.B.; Liu, J.; Wang, Y. Tectonic Affinity Reconnaissance of the Alxa Block in the Pre-Mesozoic. *Acta Geos. Sin.* **2014**, *35*, 673–681. (In Chinese with English Abstract)
322. Dong, X.; Xu, Z.; Liu, Z.; Sha, Q. 2.7 Ga Granitic Gneiss in the Northern Foot of Daqingshan Mountain, Central Inner Mongolia, and Its Geological Implications. *Earth Sci.* **2012**, *31*, 20–27. (In Chinese with English Abstract)
323. Duan, R. Paleoproterozoic Tectono-Thermal Events in the Southern Margin of the Yinshan Block of the North China Craton. Master's Thesis, Chinese Academy of Geological Sciences, Beijing, China, 2022. (In Chinese with English Abstract)
324. Zhang, S.; Zhao, Y.; Song, B.; Hu, J.; Liu, S.; Yang, Y.; Chen, F.; Liu, X.; 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. *GSA Bull.* **2006**, *121*, 181–200. [[CrossRef](#)]
325. Zhang, S.; Zhao, Y.; Song, B.; Yang, Z.; Hu, J.; Wu, H. Carboniferous granitic plutons from the northern margin of the North China block: Implications for a late Palaeozoic active continental margin. *J. Geol.* **2007**, *164*, 451–463. [[CrossRef](#)]
326. Hui, J.; Zhang, K.J.; Zhang, J.; Qu, J.; Zhang, B.; Zhao, H.; Niu, P. Middle-late Permian high-K adakitic granitoids in the NE Alxa block, northern China: Orogenic record following the closure of a Paleo-Asian oceanic branch? *Lithos* **2021**, *400–401*, 106379. [[CrossRef](#)]

327. Lei, C.C.; Li, W.X.; Zhang, C.; Wang, W.B.; Ma, J. Zircon U–Pb ages, whole-rock geochemical characteristics and their tectonic significances of the Dalunwusu intermediate-acidic intrusive rocks in the northern margin of the Alxa Block. *Bull. Mineral. Petrol. Geochim.* **2023**, *42*, 860–872. (In Chinese with English Abstract)
328. Duan, J.; Li, C.; Qian, Z.; Jiao, J. Geochronological and geochemical constraints on the petrogenesis and tectonic significance of Paleozoic dolerite dykes in the southern margin of Alxa Block, North China Craton. *J. Asian Earth Sci.* **2015**, *111*, 244–253. [\[CrossRef\]](#)
329. Zhang, L.; Zhang, H.; Zhang, S.; Xiong, Z.; Luo, B.; Yang, H.; Pan, F.; Zhou, X.; Xu, W.; Guo, L. Lithospheric delamination in post-collisional setting: Evidence from intrusive magmatism from the North Qilian orogen to southern margin of the Alxa block, NW China. *Lithos* **2017**, *288–289*, 20–34. [\[CrossRef\]](#)
330. Liu, R.E.; Huang, Y.M.; Wei, X.F.; Sun, F.J.; Lin, J. Analysis of provenance of Late Paleozoic in the Northern Ordos Basin and its Geological significance. *J. Mineral. Petrol.* **2003**, *23*, 82–86. [\[CrossRef\]](#)
331. Cawood, P.A.; Hawkesworth, C.J.; Dhuime, B. Detrital zircon record and tectonic setting. *Geology* **2012**, *40*, 875–878. [\[CrossRef\]](#)
332. Dong, C.Y.; Wan, Y.S.; Xu, Z.Y.; Liu, D.Y.; Yang, Z.H. Late Paleoproterozoic Kongzi Rock System in Daqingshan Area of North China Craton: Zircon SHRIMP U–Pb dating. *Sci. Sin.* **2012**, *42*, 1851–1862. (In Chinese)
333. Song, D.F.; Xiao, W.J.; Windley, B.F.; Han, C.M. Provenance and tectonic setting of late Paleozoic sedimentary rocks from the Alxa Tectonic Belt (NW China): Implications for accretionary tectonics of the southern Central Asian Orogenic Belt. *GSA Bull.* **2021**, *133*, 253–276. [\[CrossRef\]](#)
334. Mo, N.; Guo, L.; Tong, Y.; Wang, T.; Liu, J.; Li, J. Geochronology, Geochemistry, Hf Isotope of Xiaojinggou Pluton in the Northern Margin of North China Craton and Its Tectonic Implications Geochronology, Geochemistry, Hf Isotope of Xiaojinggou Pluton in the Northern Margin of North China Craton and Its Tectonic Implications. *Acta Sci. Nat. Univ. Pekin.* **2014**, *50*, 1021–1034. [\[CrossRef\]](#)
335. Liu, Y.; Neubauer, F.; Genser, J.; Takasu, A.; Ge, X.; Handler, R. 40Ar/39Ar ages of blueschist facies pelitic schists from Qingshuigou in the Northern Qilian Mountains, western China. *Isl. Arc* **2006**, *15*, 187–198. [\[CrossRef\]](#)
336. Song, S.; Zhang, L.; Niu, Y.; Su, L.; Song, B.; Liu, D. Evolution from Oceanic Subduction to Continental Collision: A Case Study from the Northern Tibetan Plateau Based on Geochemical and Geochronological Data. *J. Petrol.* **2006**, *47*, 435–455. [\[CrossRef\]](#)
337. Zhang, J.X.; Meng, F.C.; Wan, Y.S. A cold Early Palaeozoic subduction zone in the North Qilian Mountains, NW China: Petrological and U–Pb geochronological constraints. *J. Metamorph. Geol.* **2007**, *25*, 285–304. [\[CrossRef\]](#)
338. Zhang, Z.; Liu, D.; Fu, G. *Isotopic Dating of Metamorphic Strata in the North Qinling Orogenic Belt*; Geological Press: Beijing, China, 1994; p. 191.
339. Dou, W.T.; Hou, M.C.; Dong, G.Y. Provenance analysis of the Upper Paleozoic Shanxi to Lower Shihezi formations in north Ordos basin. *Nat. Gas Ind.* **2009**, *29*, 25–28+132. (In Chinese)
340. Mattauer, M.; Matte, P.; Malacelle, J.; Tapponnier, P.; Maluski, H.; Xu, Z.; Lu, Y.; Tang, Y. Tectonics of the Qinling Belt: Build-up and evolution of eastern Asia. *Nature* **1985**, *317*, 496–500. [\[CrossRef\]](#)
341. Cheng, C.; Li, S.Y.; Xie, X.Y.; Manger, W.L.; Busbey, A.B. U–Pb detrital zircon geochronology and Hf isotopic composition of Permian clastic rocks, Zhen’an basin, South Qinling belt: Implications for the Paleozoic tectonic evolution of the Qinling orogenic belt. *Int. Geol. Rev.* **2018**, *61*, 1462–1478. [\[CrossRef\]](#)

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