Detrital-Zircon Age Spectra of Neoproterozoic-Paleozoic Sedimentary Rocks from the Ereendavaa Terrane in NE Mongolia: Implications for the Early-Stage Evolution of the Ereendavaa Terrane and the Mongol-Okhotsk Ocean

Laicheng Miao 1,2,*, Mingshuai Zhu 1,2, Chenghao Liu 1,3, Munkhtsengel Baatar 4, Chimidtseren Anaad 4, Shunhu Yang 1,2 and Xingbo Li 1,3

1 Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; zhumingshuai@mail.iggcas.ac.cn (M.Z.); liuchenghao@mail.iggcas.ac.cn (C.L.); yangshunhu@mail.iggcas.ac.cn (S.Y.); lixingboaries@163.com (X.L.)
2 Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China
3 College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
4 School of Geology and Mining, Mongolian University of Science and Technology, Ulaanbaatar 120646, Mongolia; tsengel@must.edu.mn (M.B.); chimidtseren@must.edu.mn (C.A.)

* Correspondence: miaolc@mail.iggcas.ac.cn; Tel.: +86-10-82998561

Received: 29 June 2020; Accepted: 17 August 2020; Published: 22 August 2020

Abstract: The Mongol-Okhotsk orogenic belt (MOB) is considered to be the youngest division of the huge Central Asian Orogenic Belt, but its origin and evolution are still enigmatic. To better understand the history of the MOB, we conducted U-Pb geochronological analyses of detrital-zircon grains from Neoproterozoic-Paleozoic sedimentary sequences as well as a volcanic suite in the Ereendavaa terrane, the southern framing unit of the MOB, in NE Mongolia. Our results show that the protoliths of the quartzite assemblage of the Ereendavaa terrane basement (or proto-Ereendavaa terrane) was deposited after ca. 1.15 Ga on a passive continental margin. The detrital-zircon age spectra of the Silurian and Devonian sedimentary sequences of the terrane demonstrate that the source areas were dominated by proximal Cambrian-Ordovician arc rocks, likely resulting from the northward subduction of the Kherlen Ocean lithosphere beneath the Ereendavaa terrane. Based on a combination of our new data with those published, we show that the Mongol-Okhotsk Ocean split from an early Paleozoic domain during, or after, the early Silurian by a mantle plume, and developed an Andean-type margin along its northern rim possibly at Middle Devonian times, and a bidirectional subduction system in mid-Carboniferous at approximately 325 Ma. This bipolar subduction of the Mongol-Okhotsk Ocean might have lasted until the Triassic.

Keywords: detrital-zircon age spectrum; Ereendavaa terrane; Mongol-Okhotsk orogenic belt; opening of the Mongol-Okhotsk ocean; northeastern Mongolia

1 Introduction

The Mongol-Okhotsk Belt (MOB), extending over 3000 km from central Mongolia in the southwest to the Uda Gulf of the Sea of Okhotsk in the northeast (Figure 1), was formed by the closing of the Mongol-Okhotsk Ocean (MOO) between the Northern Asian (Siberia) continent and the Amur Superterrane [1–4]. The MOO is considered to be the youngest domain within the Central Asian Orogenic Belt (CAOB), a vast region that resulted from the evolution of the Paleo Asian Ocean (PAO) and is bounded by the Siberia and Baltica cratons to the north and by the Sino-Korean and Tarim...
cratons to the south [5–8]. However, this is inconsistent with the recognition that the final closure of the PAO, with a long-lasting evolution at least from the Neoproterozoic until the Permian, took place along the Solonker-Linxi suture in northern Inner Mongolia, China, in the southern CAOB [2,6,8–10]. Therefore, the MOB is essential for understanding the geotectonic history of the Central Asian Orogenic Belt and also entire NE Asia.

Figure 1. Sketch map showing the major tectonic units along the Mongol-Okhotsk belt (after [11]).

The evolution of the MOB is enigmatic, with contrasting models proposed concerning its development [6,11–13]. It appears that there is a general consensus regarding the timing of the final closure of the MOO despite the contrasting tectonic models. It is widely accepted that the closing of the MOO occurred in a scissor manner, with a progressive Jurassic to Early Cretaceous closing of the ocean and associated collisional orogenesis from the west towards the east [1,4,6,14–16]. Nevertheless, the time of opening is still a matter of controversy. Some authors have suggested that MOO has existed since Vendian (610–570 Ma) to Cambrian [5,6], whereas others have proposed that the ocean formed later in the Silurian [8,11,13,17] or even later [4,18].

Detrital zircon geochronology of sedimentary rocks is a powerful tool to study the history of sedimentary basins and it has been used worldwide [19–21]. Previous detrital-zircon geochronological studies for the sedimentary sequences within the MOB suggest that the MOO was opened during the early Paleozoic [11,22] or late Paleozoic [16,23]. These studies were mainly focused on the sedimentary sequences of the accretionary complexes inside the MOB, with little attention paid to those on the continental blocks fringing the MOO basin [11,22]. Although these studies do provide important constraints for the evolution of the MOO, some key information regarding the early-stage development of the ocean might have been undisclosed. This is because the accretionary complexes inside the MOB may not preserve the early-stage sedimentation records of the MOO due to the subduction consumption of the ocean lithosphere. In this regard, studies of the sedimentary sequences on the rifted margins of the MOO will be very useful, since the rifted margins witness the whole history of the ocean development. Despite some deformation of the rifted margins of the MOO, chiefly because of their involvement in continental collision following the closure of the ocean, the detrital zircon U-Pb geochronology for the sedimentary rocks deposited on the rifted margins is still capable of providing direct information of provenance of detritus and the ocean evolution, owing to the considerably high closure temperature of the zircon U-Pb isotope system, greater than 900 °C [24].
On the other hand, the age uncertainty of the basement on which an ocean opened will hamper the interpretation of provenance of detrital zircon in sedimentary sequences. This is particularly true for the Ereendavaa terrane that fringes the MOB to the south. Though it has long been interpreted as a cratonic terrane with basement rocks as old as the Neoarchean-Paleoproterozoic [13], there is no robust evidence so far to support the interpretation. Instead, recent reliable dating demonstrates that the metamorphic rocks of the terrane were mainly formed during the Paleozoic [25,26]. In other words, to ascertain whether early Precambrian basement rocks exist in the Ereendavaa terrane is also an issue to explore.

We assume if early Precambrian basement rocks exist in the Ereendavaa terrane, they would contribute much detritus to the Neoproterozoic-Paleozoic sedimentary sequences of the terrane, and thus generate detrital-zircon age spectra comprising major peaks of that age. In addition, it is also assumed that syn-sedimentary detrital zircon grains in the sedimentary rocks deposited at rifted margins depict the magmatic activity in subduction-related arcs at the framing margins of the MOO, and, therefore, provide key information concerning the subduction history of the ocean lithosphere. In this context, this paper presents results of zircon U-Pb geochronology of Neoproterozoic-Paleozoic (meta-) sedimentary rocks and andesitic-rhyolitic volcanic formations developed on the Ereendavaa terrane, which constitutes the southern margin of the Mongolian segment of the MOO, with aims to (1) verify whether early Precambrian rocks are present in the Ereendavaa terrane, and (2) constrain the early-stage evolution of both the MOO and the Ereendavaa terrane. Our results provide, for the first time, robust constraints not only for the depositional ages of the Neoproterozoic-Paleozoic sedimentary sequences but also for the development of magmatic arcs on the Ereendavaa terrane, and indicate that the MOO was opened after the early Silurian.

2. Geological Setting

The MOB, extending over 3000 km from central Mongolia in the southwest to the Uda Gulf of the Sea of Okhotsk in the northeast (Figure 1), formed by closing of the MOO between the Northern Asian (Siberia) continent and the Amur Superterrane [1–4]. Structurally, the MOB is sandwiched by the Northern Asian Caton (Siberia) to the north and the Amur Superterrane to the south, with an abrupt termination in the southwest (Figures 1 and 2). The core of the MOB is represented by a ribbon-like ophiolite-bearing suture zone and accretionary wedges [1,15,27]. The suture zone, which is termed the Aga terrane [2], is composed mainly of ophiolites and minor turbiditic series and is subdivided into the Onon, Tukuringra, Galam, and Nilanskiy terranes (Figure 1). Of these, the Onon terrane consists of the intra-oceanic Onon arc of assumed Devonian–Early Carboniferous age [4], which would be the oldest arc identified so far that was related to the southward subduction of the MOO lithosphere beneath the Amur Superterrane. The accretionary wedges are characterized by containing thick turbiditic sequences and minor ophiolitic assemblages, which include the Hangai, Kentei-Daurian, Unya-Bom, and Ulban terranes [2,28]. Spatially, the accretionary wedge terranes are mainly distributed on the northern side of the suture zone, although some also occur inside the suture zone at the eastern end of the MOB (Figure 1). Alternatively, some authors have considered all of these suture zone terranes and accretionary wedges together as one large accretionary complex resulting from subduction of the MOO lithosphere [6,22,23].

The territory of Mongolia has traditionally been divided into two tectonic domains separated by the Main Mongolian Lineament (MML), namely an early Paleozoic domain to the north and a late Paleozoic domain to the south [13,15]. The Mongolian segment of the MOB is located within the early Paleozoic domain (Figure 2) and here the MOO suture zone is represented by the Adaatsag and Dochgol terranes [11,13,15], corresponding to the Onon terrane in the northeastern prolongation in Russia [2,4]. The suture is bounded by the Hangay-Hentey turbiditic terrane to the north, by the Baydrag terrane to the southwest, and by the Ereendavaa terranes to the south (Figure 2).
Figure 2. Sketch map showing tectonostratigraphic terranes of Mongolia and the approximate location of the study area of this paper (adapted from [13]). Terrane and belt names: I—Ereendavaa, II—Kherlen, III—Idermeg, IV—Adaatsag (Onon); V—Hangay-Hentey; VI—Haraa; A—Middle Gobi, B—Selenge; MOSZ—Mongol-Okhotsk suture zone.

The Hangay-Hentey terrane contains mainly Devonian-Carboniferous turbidites and Silurian-Devonian radiolarian cherts [11,13,17]. The authors of [13] interpreted the entire Hangay-Hentey sediment series to unconformably overlie an older basement of an unknown age. However, the authors of [17] and [11] suggested that the main body of the Hangay-Hentey belt, which is tectonically located between the early Paleozoic Haraa terrane in the northwest and the Mongol-Okhotsk suture zone (MOSZ) in the southeast, was formed in a trench-accretionary wedge environment. Previous detrital zircon geochronological studies show that the sedimentary rocks of the Hangay-Hentey terrane were mainly formed after the early Carboniferous [11,22,23] although the strata were previously believed to be Silurian, Devonian, or Carboniferous in age. In contrast, the sedimentary rocks of the Haraa terrane, which was considered Cambrian/Ordovician-Silurian in age, at the northern margin of the Hangay-Hentey basin display distinct detrital zircon age spectra, with the youngest age peaks (514–437 Ma) [11,23] being older than those of the Hangay-Hentey rocks, implying that the Haraa terrane formed earlier than the Hangay-Hentey terrane.

The Mongolia segment of the MOSZ, i.e., the Adaatsag and Dochgol terranes of [13], is a narrow belt of highly deformed rocks that were metamorphosed under greenschist and amphibolite facies conditions. It is interpreted as an accretionary wedge complex composed of schist, quartzite, metasandstone, phyllite, chert, metavolcanic rocks, coral limestone, and mélangé containing fragments of ophiolite [13,15,28]. The MOSZ contains the 325-Ma Adaatsag ophiolite [15] at its western end and the 321-Ma Khuhu Davaa ophiolite [29] in its central part, and it is intruded by Triassic-Early-Jurassic granitic plutons [13,15]. These ophiolites have geochemical signatures of supra-subduction zone (SSZ)-type ophiolites and are interpreted to form during the subduction initiation of the MOO lithosphere [29]. In the central portion, the accretionary wedge complex of the suture was locally thrust southward over the Silurian-Devonian sedimentary sequence intruded by swarms of dolerite sills/dikes or gabbroic intrusions at the northern margin of the Ereendavaa terrane (Figures 2 and 3; [26]). In northeastern-most Mongolia and Russia, the Dochgol terrane consists predominately of late Permian-Triassic accretionary complexes containing ophiolite blocks of unknown age, metavolcanics with geochemical signatures of both MORBs and OIBs [30], and fossiliferous marine sediments [31]. Generally, the suture zone complexes form a fold-and-thrust belt with the top-to-SE structural polarity [15], in accordance with observations from the Ereendavaa terrane [26].
The area to the south of the MOSZ belongs to the eastern part of the early Paleozoic domain, which is composed, from north to south, of the Ereendavaa, Kherlen, and Idermeg terranes (Figures 2 and 3). The Ereendavaa terrane is considered as a cratonic massif and consists of Proterozoic gneiss, amphibolite, schist and marble, overlain by black schist, metasandstone, siltstone, limestone and minor conglomerate and volcanic rocks and intruded by granites of different age [13]. However, recent work seems to suggest that it predominately formed during the Paleozoic since the gneiss, amphibolite, and schist of the Ereendavaa terrane mainly have Paleozoic protolith ages, although some Precambrian zircon inheritance does exist in these rocks [26]. On the other hand, granitic rocks/gneisses with Proterozoic ages have been reported from the northeastern extension of the Ereendavaa terrane both in Russia and NE China. On the Russian side, biotite granite and leucogranite were dated at ca. 740 Ma by zircon U–Pb method and the Chinese portion of the terrane (also known as “Erguna” massif or block [32]) contains Paleoproterozoic granitic gneiss with ages of ca. 1840 Ma [33] and is intruded by Neoproterozoic mafic plutons with ages between 850 and 740 Ma [34]. Studies have shown that the Ereendavaa terrane, which constitutes the Ereendavaa Mountain Range, was exhumed during the Early Cretaceous at ca. 140 Ma [35].

![Figure 3. Simplified geological map of the Ondorkhan-Onon region in NE Mongolia (modified from [36]). Terranes: I—Ereendavaa, II—Kherlen, III—Idermeg, IV—Adaatsag (Onon), V—Hangay-Hentey.](image)

The Idermeg terrane is located on the northern side of the MML and is mainly composed of marble, quartzite, conglomerate, sandstone, and limestone containing archeacyathes and stromatolites that are believed to be Neoproterozoic to Cambrian in age [13]. These rocks are assumed to overlie a crystalline basement composed of gneiss, amphibolite, schist, and phyllite [2,13]. The Idermeg terrane is classified by [13] as a passive continental margin terrane and is assumed to form in a Neoproterozoic–Cambrian continental shelf environment and represent the early Paleozoic southern margin of the Siberian amalgamated complex [8,37].

The Kherlen terrane was previously classified as an island arc terrane [13] but it is actually a Cambrian ophiolitic complex that was tectonically emplaced during the Silurian, and thus representing the suture between the Ereendavaa and Idermeg terranes [25]. This timing is in line with that of the amalgamation of the early Paleozoic domain of Mongolia [8,11,13].
The Ereendavaa terrane, possibly with the Idermeg and Kherlen ones, is considered to be the eastern prolongation of the Tuva-Mongolian Massif or the Central Mongolian Block (CMB) that frames the MOB in the northwest, west, and southwest. The CMB is considered either as an isolated microcontinent in the PAO during the late Proterozoic and Cambrian [4,38], a Precambrian continental ribbon connecting the Siberian craton [6,15,39], or a composite tectonic unit consisting of several smaller Precambrian blocks with uncertain tectonic relationships between each other [13]. Presently, the CMB forms a tight “V” or “horseshoe” in map view, opening towards the east [6,23]; the inside part of the “V” is considered to be the MOO realm and the outside part is the PAO one. Therefore, the Ereendavaa terrane, as well as the whole CMB, is the junction between the two orogenic systems.

3. Sample Descriptions

Samples of this study were collected from the southwestern segment of the Ereendavaa terrane, as well as the Kherlen terrane, which was likely an allochthonous unit thrust over the autochthonous Ereendavaa terrane in the Ondorkhan region. The sampling locations are shown in Figure 4, and the GPS coordinates and basic lithological features of the samples analyzed are listed in Table 1.

![Geological map of the Ondorkhan area in northeastern Mongolia (modified from [36]). Terranes: I—Ereendavaa, II—Kherlen, III—Idermeg. Stars denote the localities where the dated samples were collected, and the numbers beside the stars are the last digitals of corresponding sample numbers, which have same prefix of “MOE-“.](image)

Figure 4. Geological map of the Ondorkhan area in northeastern Mongolia (modified from [36]). Terranes: I—Ereendavaa, II—Kherlen, III—Idermeg. Stars denote the localities where the dated samples were collected, and the numbers beside the stars are the last digitals of corresponding sample numbers, which have same prefix of “MOE-“.

| Sample No. | GPS Coordinate | Lithology | Structure/Texture | Major Components | Stratum Age | Maximum Age 1 (Ma) |
|------------|----------------|-----------|-------------------|------------------|-------------|-------------------|
| MOE-152    | 47.348° N 110.571° E | Quartzite | Massive to weakly foliated structure, coarse-grained, foliated structure, coarse- to medium-grained texture | Mainly quartz with minor muscovite and/or Fe-oxide minerals | Vendian-Cambrian [36] | 1150 |
| MOE-216    | 47.479° N 111.227° E | Quartzite | Magma flow structure, porphyritic and aphanitic or microcrystalline texture | Mainly quartz with minor muscovite and Fe-oxide minerals | Riphean [36] or Vendian-Cambrian [40] | 1200 |
| MOE-147    | 47.389° N 109.376° E | Rhyolite | Foliated, bedding, kink and ripple fold structures porphyroclastic and medium-grained textures | Mainly quartz with minor muscovite and K-feldspar; aphanitic or tiny felsic minerals in matrix | Vendian-Cambrian [36,40] | 450 2 |
| MOE-41     | 47.443° N 109.462° E | Sandstone | Plagioclase, K-feldspar, quartz, and muscovite or sericite | | Silurian [36,40] | 447 |

Table 1. Summary of basic petrographic features of analyzed samples from NE Mongolia.
### Table 1. Cont.

| Sample No. | GPS Coordinate | Lithology | Structure/Texture | Major Components | Stratum Age | Maximum Age ¹ (Ma) |
|------------|----------------|-----------|-------------------|------------------|-------------|-------------------|
| MOE-42     | 47.426° N, 109.479° E | Siltstone | Foliated, kinking and ripple folding structures, fine-grained texture | Plagioclase, K-feldspar, quartz, and muscovite or sericite | Cambrian [36,40] | 452 |
| MOE-44     | 47.213° N, 109.449° E | Arkose   | Bedding structure, coarse-grained texture | Plagioclase, K-feldspar, quartz, debris, and/or sercite | Devonian [36,40] | 428 |
| MOE-51     | 47.178° N, 109.460° E | Sandstone| Bedding structure, coarse-grained texture | Plagioclase, K-feldspar, quartz, debris, muscovite or sericite, and/or epidote | Devonian [36,40] | 434 |
| MOE-104    | 47.460° N, 109.795° E | Sandstone| Foliated and mylonitic structures, porphyroclastic texture | Plagioclase, K-feldspar, quartz, debris, sericite, and/or epidote | Devonian [36,40] | 436 |

¹ Maximum depositional ages inferred from the detrital zircon data of this study; ² Crystallization age of rhyolite from an intermediate-felsic volcanic suite in the study area.

Sample MOE-152 is a quartzite sampled from an outcrop of the Precambrian basement rocks at approximately 8 km northwest of the Ondorkhan city (Figure 4). The geological setting of the quartzite is uncertain because of thick coverage of Cenozoic sediments. The quartzite is composed predominantly of quartz (>95 modal), with minor amounts of muscovite. Subcrystalline structure was locally observed (Figure 5A). This quartzite does not show clear effects of deformation, but the presence of muscovite suggests that it has experienced at least the upper greenschist facies metamorphism.

Sample MOE-216 was collected at approximately 55 km northeast of the Ondorkhan city, where Precambrian basement rocks crop out along both the northern and southern banks of the Kherlen River (Figure 4). These basement rocks were previously assigned to the Early-Middle Riphean [36] or Vendian-Early-Cambrian age [40] (note: Riphean and Vendian are two geological periods of the Geological Time Scale of Russia. The Riphean generally refers to the Mesoproterozoic-Early-Neoproterozoic period, i.e., from ca. 1800 to 680 Ma, and the Vendian to the Late Neoproterozoic from ca. 680 to 570 Ma; according this time scale, 1800 Ma and 570 Ma are the lower limit of the Mesoproterozoic and the upper limit of the Cambrian, respectively). This sample is a quartzite and has petrographic features similar to sample MOE-152 described above, except for the presence of a strong foliation defined by parallel bands of quartz, muscovite and Fe-oxide minerals (Figure 5B).

Sample MOE-147 is a rhyolite taken from a thick volcanic-volcanoclastic suite exposed to the northeast of the Murun town (Figure 4). This volcanic suite was previously considered to be Vendian-Early-Cambrian in age [36,40] and consists of mainly andesite, dacite, rhyolite, and corresponding volcanoclastic rocks. The sampled rhyolite shows magmatic foliation structure and porphyritic texture, with phenocrysts of quartz and K-feldspar in an aphanitic or microcrystalline matrix of similar compositions (Figure 5C). The purpose for selecting this rhyolite sample is to date the time of magmatic emplacement of the volcanic suite, which is crucial for understanding the evolution of both the Ereendavaa terrane and the MOO.

Samples MOE-41 and MOE-42 were taken from a metasedimentary sequence cropping out approximately 7 km south of the Jargalt Sum (town). This sequence has been strongly deformed and metamorphosed to some extent; it strikes in the northeast direction dipping to NNW (340°∠50°). Kink bands and folds were observed within this sequence in the field. This sequence overlies the Precambrian (Riphean) basement gneisses of the Ereendavaa terrane and was mapped as containing Cambrian and Silurian strata, but they are in a fault contact. Samples MOE-41 and MOE-42 show similar petrographic features, such as elongation of mineral grains, and a mineral assemblage of plagioclase, quartz, K-feldspar, and muscovite/sercite (Table 1), except for some difference in grain size, of which the latter sample is finer than the former one (Figure 5D,E). It is noted that the mineral
grains in these two samples likely occur as porphyroclasts and that the debris clasts in the rocks are indiscernible due to modification by deformation and metamorphism.

Figure 5. Microphotographs (crossed polarizers) showing textures and constitutions of the dated rocks from the Ondorkhan area in NE Mongolia. Panels (A–H) are for samples MOE-152, -216, -147, -41, -42, -44, -51, and -104, respectively. Please refer to main text and Table 1 for their petrographic details. Abbreviation: Db—debris; Ep—epidote; Kfs—potassic feldspar; Mus—muscovite; Pl—plagioclase; Q—quartz; Ser—sericite.
Samples MOE-44, MOE-51, and MOE-104 were sampled from a thick Devonian sequence cropping out approximately 35 km south of the Jargalt town and also extending in a northeasterly direction (Figure 4). The first two samples are coarse-grained arkose or sandstone (Figure 5F,G). Horizontal bedding and cross bedding structures were observed within the strata, which generally dip NNW, with relatively flat dip angles of 25–30°. Judging from the graded bedding, sample MOE-44 is stratigraphically higher than sample MOE-51. The last sample (MOE-104) was collected from the NE segment of the Devonian sequence, approximately 30 km east of the Jargalt town. This sample is a fine-grained sandstone and has experienced some extent of deformation as illustrated by slight elongation and orientation of the mineral grains (Figure 5H).

4. Analytical Results

Detrital or magmatic zircon grains from the above-described eight samples were analyzed using the LA-ICP-MS zircon U-Pb dating technique (Supplementary Material 1) [41–46]. The analytical data are presented in Table S1.

**Sample MOE-152**: This is a quartzite sampled from the basement rocks exposed at ca. 8 km northwest of the Ondorkhan city. Zircon grains from this sample are rounded or stubby in morphology, with or without oscillatory zoning (Figure 6A1–A6). Some zircon grains show a core-overgrowth internal structure, and the zircon cores mostly display oscillatory zoning whereas the overgrowths do not. These zircon grains have very smooth outlines that cut the magmatic oscillatory zoning, if there is any, or cut both the zircon cores and overgrowths at high angles, indicating that the detrital zircon grains have been subjected to long-distance transportation and/or long-time ablation. A total of 78 zircon grains were analyzed for U-Pb age determination and yielded apparent ages ranging from ca. 1021 to 2850 Ma (Table S1), with the most evident age peak at ca. 1426 Ma, two subordinate peaks at ca. 1115 and 1600 Ma, respectively, and three minor peaks at ca. 2090, 2660 and 2850 Ma (Figure 7A,B), respectively.

**Sample MOE-216**: This is a quartzite sample collected from the basement rocks exposed at ca. 55 km east of Ondorkhan city. Zircon grains of this sample display similar, if not identical, morphological and internal textural features to those from sample MOE-152 described above (Figure 6B1–B6). A total of 70 zircon grains of this sample were analyzed for U-Pb dating and gave an apparent age range from 1146 to 3043 Ma (Table S1) and generated an age spectrum also resembling that of sample MOE-152, except for slight differences in age range and peak age. This sample has the most predominant peak at ca. 1482 Ma, two subordinate peaks at ca. 1200 and 1722 Ma, respectively, and three minor peaks at ca. 2288, 2578 and 3040 Ma (Figure 7C; the 3040-Ma one is not shown in Figure 7C,D), respectively.

**Sample MOE-147**: Zircon grains from this rhyolite sample are mostly stubby prisms with well-developed oscillatory zoning (Figure 6C1–C5); rounded zircon grains with internal cracks were occasionally observed (Figure 6C6). In total, 26 analyses on 26 zircon grains were selected to analyze for U-Pb age determination and gave apparent ages ranging from ca. 432 to 1452 Ma (Table S1). Of these, 24 analyses giving an age range of ca. 432–465 Ma formed a coherent group and yielded a weighted mean age of 450 ± 3 Ma (n = 24, mean square of weighted deviates (MSWD) = 1.9; Figure 8A,B). The remaining two analyses on two zircon grains that respectively have cracks inside and rounded morphology gave apparent ages of ca. 532 and 1452 Ma, respectively.
4. Analytical Results

Detrital or magmatic zircon grains from the above-described eight samples were analyzed using the LA-ICP-MS zircon U-Pb dating technique (Supplementary Material 1) [41–46]. The analytical data are presented in Table S1.

Sample MOE-152: This is a quartzite sampled from the basement rocks exposed at ca. 8 km northwest of the Ondorkhan city. Zircon grains from this sample are rounded or stubby in morphology, with or without oscillatory zoning (Figure 6A1–A6). Some zircon grains show a core-overgrowth internal structure, and the zircon cores mostly display oscillatory zoning whereas the overgrowths do not. These zircon grains have very smooth outlines that cut the magmatic oscillatory zoning, if there is any, or cut both the zircon cores and overgrowths at high angles, indicating that the detrital zircon grains have been subjected to long-distance transportation and/or long-time ablation. A total of 78 zircon grains were analyzed for U-Pb age determination and yielded apparent ages ranging from ca. 1021 to 2850 Ma (Table S1), with the most evident age peak at ca. 1426 Ma, two subordinate peaks at ca. 1115 and 1600 Ma, respectively, and three minor peaks at 2090, 2660 and 2850 Ma (Figure 7A,B), respectively.

Figure 6. Representative cathode luminescence (CL) images of zircon grains of the dated samples from the Ereendavaa terrane in NE Mongolia. Also shown are approximate positions, numbers and apparent ages of the analytical spots (open circles of dashed line). Each raw image is for representative zircon grains from one sample; (A–H) are for samples MOE-152, MOE-216, MOE-147, MOE-41, MOE-42, MOE-44, MOE-51, and MOE-104, respectively. The analytical spot names are the same as those in Table S1. All scale bars are 50 μm long (please note that the scale bar for each panel in one raw image is the same and so it is just shown in the leftmost panel of each raw image).

Sample MOE-41: Zircon grains from this sandstone are mostly elongated to stubby prisms displaying well-developed oscillatory zoning despite their variable degrees of luminescence in the CL image, with several grains showing rounded morphology and core-overgrowth structures (Figure 6D1–D6). It is noteworthy that the rounded grains are essentially analogical in morphology and internal texture with those from quartzites MOE-152 and MOE-216. A total of 82 zircon grains or fragments were analyzed for U-Pb age determination and yielded apparent ages ranging from ∼436 to 2924 Ma (Table S1), with the main peak at ca. 519 Ma and several minor peaks at ca. 447, 814 and 918 Ma (Figure 9A,B). In addition, this sample also contains Mesoproterozoic (ca. 1500 Ma) and Archean (ca. 2924 Ma) zircon grains. The youngest peak of ca. 447 Ma, composed of the nine youngest analyses, is identical to the weighted mean $^{206}$Pb/$^{238}$U age of 447 ± 4 Ma (mean square of weighted deviates (MSWD) = 1.6; Figure 9B) of these 9 analyses.
Sample MOE-41: Zircon grains of this sandstone are mostly characterized by elongated to stubby prisms, with small amounts of grains showing rounded morphology (Figure 6F1–F6). In CL images, the former group of zircon grains displays well-developed oscillatory zoning (Figure 6F1–F3) whereas rounded zircon grains with internal cracks were occasionally observed (Figure 6C6). In total, 26 analyses on 26 zircon grains were selected to analyze internal texture with those from quartzites MOE-152 described above (Figure 6B1–B6). A total of 82 zircon grains of this sample were analyzed for U-Pb dating and gave apparent ages ranging from ca. 432 to 1452 Ma (Table S1). Of these, 24 analyses giving an age range of ca. 432–465 Ma formed a coherent group and yielded a weighted mean age of 450 ± 3 Ma (n = 24, mean square of weighted deviates (MSWD) = 1.9; Figure 8B). The remaining two analyses on two zircon grains that respectively have cracks inside and outside deviates (MSWD) = 1.6; Figure 9D) if the analytical errors are considered. Similarly, analyses of two zircon grains from this Cambrian siltstone are generally similar in morphology, grain size, and CL feature to those from sample MOE-41 described above (Figure 6E5–E6). In total, 68 zircon grains were analyzed for U-Pb age determination and yielded an age range from ~413 to 2504 Ma (Table S1), with the main peak at ca. 497 Ma (Figure 9C). Of these, there are seven zircon grains yielding a subordinate age peak at ca. 451 Ma, identical to their weighted mean 206Pb/238U age of 447 ± 4 Ma (mean square of weighted deviates (MSWD) = 1.6; Figure 9B) of these 9 analyses.

Sample MOE-44: Zircon grains from this rhyolite sample are mostly stubby prisms with well-developed oscillatory zoning despite their variable degrees of luminescence in the CL image, with several grains showing rounded morphology and core-overgrowth structures (Figure 6G5). A total of 70 zircon grains of this sample were analyzed for U-Pb age determination and yielded an age range from 1146 to 3043 Ma (Table S1), with the main peak at ca. 497 Ma (Figure 9C). Of these, there are seven zircon grains of this sample displaying similar, if not identical, morphological features to those from sample MOE-41 described above (Figure 6E1–E6). A total of 2504 Ma (Table S1), with the main peak at ca. 497 Ma (Figure 9C). Of these, there are seven zircon grains yielding a subordinate age peak at ca. 451 Ma, identical to their weighted mean 206Pb/238U age of 447 ± 4 Ma (mean square of weighted deviates (MSWD) = 1.6; Figure 9D) if the analytical errors are considered. Similarly, this sample also contains Precambrian zircon grains with several small peaks of age at ca. 664, 893 and 1770 Ma (Figure 9C). This sample has the most predominant peak at ∼68 zircon grains were analyzed for U-Pb age determination and yielded an age range from 1482 Ma, two subordinate peaks at ca. 1200 and 1722 Ma, respectively, and three minor peaks at ca. 2288, 2578 and 3040 Ma (Figure 7C; the 3040-Ma one is not shown in Figure 7C,D), respectively. In CL images, with several grains showing rounded morphology (Figure 6F). In addition, this sample also contains Mesoproterozoic (ca. 1500 Ma) and Archean (ca. 2924 Ma) zircon grains. The youngest peak of ca. 447 Ma, composed of the nine youngest analyses, is identical to the weighted mean 206Pb/238U age of 447 ± 4 Ma (mean square of weighted deviates (MSWD) = 1.6; Figure 8A) and concordia plots (right) for two quartzite samples MOE-152 (A,B) and MOE-216 (C,D) from the Ereendavaa terrane in NE Mongolia. (A) Concordia plot and (B) Bar chart showing individual apparent ages and the weighted average (thick green line). Error ellipses in (A) and the error bars in (B) are at 1σ level.

Figure 7. Detrital zircon age-relative probability curves (left) and concordia plots (right) for two quartzite samples MOE-152 (A,B) and MOE-216 (C,D) from the Ereendavaa terrane in NE Mongolia. (A) Concordia plot and (B) Bar chart showing individual apparent ages and the weighted average (thick green line). Error ellipses in (A) and the error bars in (B) are at 1σ level.

Figure 8. Zircon U-Pb data of a rhyolite sample MOE-147 from a ‘Vendian-early Cambrian’ volcanic suite on the Ereendavaa terrane in NE Mongolia. (A) Concordia plot and (B) Bar chart showing individual apparent ages and the weighted average (thick green line). Error ellipses in (A) and the error bars in (B) are at 1σ level.
the rounded grains show relatively strong luminescence, likely a result of low concentrations of Th and U, with or without oscillatory zoning (Figure 6F). A total of 69 zircon grains were analyzed for U-Pb dating and yielded apparent ages ranging from ca. 412 to 2851 Ma (Table S1), with the most obvious age peak at ca. 496 Ma and several subordinate peaks at ca. 428, 591, 793, 960 and 1785 Ma (Figure 10A). Moreover, this sample also contains one Mesoproterozoic (ca. 1451 Ma) and one Archean (ca. 2851 Ma) zircon grains. The youngest peak age of ca. 428 Ma, which contains 15 youngest analyses, is consistent with the weighted mean $^{206}$Pb/$^{238}$U age of 425 ± 5 Ma ($n = 13$, MSWD = 1.9; Figure 10B) of the 13 youngest analyses if the analytical errors are considered.

Figure 9. Detrital zircon age-relative probability diagrams (left) and concordia diagrams (right) for samples MOE-41 (A,B) and MOE-42 (C,D) from the Paleozoic sedimentary rocks on the Ereendavaa terrane in NE Mongolia.

Sample MOE-51: The sandstone contains zircon grains that are mostly characterized by elongated to stubby prisms with magmatic oscillatory zoning, and minor zircon grains are rounded in morphology without or with weak oscillatory zoning (Figure 6G). A total of 72 analyses were carried out on 72 zircons of this sample and generated an apparent age range from 408 to 2447 Ma (Table S1). They form an age spectrum resembling that of sample MOE-44, with the most evident peak at ca. 500 Ma and subordinate peaks at ca. 434, 830, 969 and 1825 Ma (Figure 10C). The youngest 12 analyses that constitute the youngest peak at ca. 434 Ma yielded a weighted mean $^{206}$Pb/$^{238}$U age of 428 ± 6 Ma ($n = 12$, MSWD = 2.4; Figure 10D); these two ages, within analytical errors, overlap each other.

Sample MOE-104: Zircon grains from the sandstone are similar in morphology to those from samples MOE-44 and MOE-51 although the quantity of rounded zircon grains in this sample seem to be greater than in the other two samples (Figure 6I–H). A total of 76 analyses were done on 76 zircon grains and gave apparent ages ranging from 423 to 2415 Ma (Table S1), with the main age peak at ca. 510 Ma and subordinate peaks at ca. 436, 816, 897, 943, 1236 and 1830 Ma (Figure 10E). Apart from these, another three Neoproterozoic (588, 654 and 724 Ma) and three Paleoproterozoic (2087, 2107 and 2415 Ma) zircon grains were detected in this sample. The three analyses on the three youngest zircon grains of this sample gave a weighted mean $^{206}$Pb/$^{238}$U age of 435±6 Ma (MSWD = 3.6; Figure 10F), in line with the youngest peak age of ca. 436 Ma.
analyses that constitute the youngest peak at ca. 434 Ma yielded a weighted mean 206Pb/238U age of 428 ± 6 Ma (n = 12, MSWD = 2.4; Figure 10D); these two ages, within analytical errors, overlap each other. Sample MOE-104: Zircon grains from the sandstone are similar in morphology to those from samples MOE-44 and MOE-51 although the quantity of rounded zircon grains in this sample seem to be greater than in the other two samples (Figure 6H1–H6). A total of 76 analyses were done on 76 zircon grains and gave apparent ages ranging from 423 to 2415 Ma (Table S1), with the main age peak at ca. 510 Ma and subordinate peaks at ca. 436, 816, 897, 943, 1236 and 1830 Ma (Figure 10E). Apart from these, another three Neoproterozoic (588, 654 and 724 Ma) and three Paleoproterozoic (2087, 2107 and 2415 Ma) zircon grains were detected in this sample. The three analyses on the three youngest zircon grains of this sample gave a weighted mean 206Pb/238U age of 435±6 Ma (MSWD = 3.6; Figure 10F), in line with the youngest peak age of ca. 436 Ma.

Figure 10. Detrital zircon age-relative probability curves (left) and concordia diagrams (right) for samples MOE-44 (A,B), MOE-51 (C,D), and MOE-104 (E,F) from Devonian sedimentary sequence on the Ereendavaa terrane in NE Mongolia.

5. Discussion

5.1. Deposition/Formation Time of the Dated Strata

The two quartzite samples (MOE-152 and -216) were collected from metamorphic strata in the Ereendavaa terrane exposed at two different places. Due to the lack of reliable paleontological and isotopic dating data, these metamorphic strata/rocks were previously assigned to a wide range of the protolith ages from the Early Riphean to the Middle Riphean [36], or from the Vendian to the early Cambrian [40], with the metamorphic age(s) unknown. According to our results, these two quartzite samples show similar age data of ca. 1021–2850 Ma and 1146–3043 Ma, with the youngest peak ages of ca. 1115 and 1200 Ma, respectively. From the CL images, it is certain that these ages represent the crystallization or metamorphic ages of the zircon grains or zircon domains themselves, rather than the metamorphic ages of the dated rocks. This is because, on the one hand, that the zircon grains or zircon domains giving these youngest ages mostly display very fine oscillatory zoning (Figure 6A1,A2), clearly suggesting a magmatic, not metamorphic, origin of the zircon grains. On the other hand, even if few analyzed zircon domains occur as metamorphic overgrowths without distinct zoning (Figure 6A3), the smooth outline boundaries of the zircon grains cut the overgrowths and/or the zircon cores at high angles, indicating that the metamorphic overgrowths had already formed before the protolith sedimentation of the quartzites. Therefore, we conclude that the youngest peak ages of ca. 1115 and 1200 Ma of the two quartzite samples represent the maximum deposition ages of the protoliths of the sedimentary sequences from which the two samples came.
Though these two samples were taken from two localities, they are not far from each other, approximately 60 km along the strike of regional tectonic units (Figures 3 and 4). Considering the similarities of the lithology and detrital zircon age spectra, we suggest that the two quartzites belong to a single sedimentary sequence that was deposited after ca. 1200–1115 Ma. In this case, it is rational to deduce that the sequence was deposited during the latest Middle Riphean to early Late Riphean, rather than during the Vendian to early Cambrian as suggested by [40]. The reason for this is that the samples would contain some early Neoproterozoic (1000–680 Ma) detrital zircon grains if the sequence was formed during the Vendian to early Cambrian. Instead, zircon grains with early Neoproterozoic ages are relatively abundant in the samples from the Paleozoic sedimentary sequences (Figures 9 and 10).

Sample MOE-147 was taken from a thick volcanic sequence cropping approximately 20 km north of the Ondorkhan city (Figure 4), which is composed of basaltic andesites, andesites, dacites, rhyolites, and their volcanic agglomerates, breccias and pyroclastic rocks. This volcanic sequence was previously designated a Vendian to early Cambrian age [36,40]. However, the rhyolite sample yielded a zircon U-Pb age of 450 ± 3 Ma (Figure 8). This age is interpreted to date the magmatic emplacement of the volcanic rocks because it was obtained from zircon crystals that show typical magmatic oscillatory zoning (Figure 6C1–C5). This demonstrates that the volcanic sequence was formed in the Late Ordovician.

The two samples of MOE-41 and MOE-42 were collected from an early Paleozoic sedimentary sequence. The former sample (MOE-41), taken from the Silurian stratum, gave the youngest age peak at ca. 447, consistent with the weighted mean age of 447 ± 4 Ma of the youngest analyses (Figure 9B). These ages were obtained from the elongated zircon crystals with the well-developed oscillatory zoning (Figure 6D1,D2), and therefore the 447-Ma age constrains the maximum depositional age of the sedimentary strata from which this sample was collected. Consequently, deposition of the sampled rocks must be later than the Ordovician. The latter sample (MOE-42), from the Cambrian strata, contains 7 zircon grains that yielded the youngest age peak of ca. 451 Ma and a weighted mean age of 452 ± 3 Ma (Figure 9D), suggesting that this rock was formed after ca. 451 Ma. This proves that the sedimentary protolith is not Cambrian, but must be younger than the Late Ordovician. The age of 452 ± 3 of sample MOE-42 overlaps, within the analytical errors, with the age 447 ± 4 Ma of sample MOE-41, and thus this whole early Paleozoic sedimentary sequence was probably deposited after the Ordovician, most likely during the Silurian.

The three sandstone samples (MOE-44, -51 and -104), which were all collected from the Devonian sequence, gave the three youngest age peaks of ca. 428, 434, and 436 Ma and three weighted mean 206Pb/238U ages of 425 ± 5, 428 ± 6, and 435 ± 6 Ma (Figure 10), respectively. These ages overlap each other if the analytical errors are considered. Similarly, these youngest zircon grains are all euhedral prisms showing well-developed oscillatory zoning (Figure 6F1–F3, G1–G3 and H1–H3), and, therefore, we interpret them to represent the maximum ages of the sandstones. Although a maximum depositional age of late Silurian could be inferred from the dating data (e.g., the youngest age peak of ca. 437 Ma), we are inclined to interpret the youngest age of ca. 425 Ma as the lower limit of sedimentation time, which means that the deposition of the sequence occurred after the Gorstian, because this interpretation is in line with the fossil data of the sequence that suggests an Early–Middle Devonian stratigraphic age [36,40].

In summary, our new dating data provide direct evidence for the deposition/formation ages of Neoproterozoic metasedimentary rocks and Paleozoic sedimentary and volcanic successions overlying the Ereendavaa terrane in NE Mongolia. This provides robust constraints on the evolution of both the Ereendavaa itself and the MOO.

5.2. Constraints on the Evolution of the Ereendavaa Terrane

The Ereendavaa terrane, which forms the southern foreland of the MOB, witnessed the whole evolution of the MOO. This terrane was considered a cratonic block with basement rocks as old as the Paleoproterozoic or even the Archean [13,36,40]. However, recent SHRIMP zircon U-Pb dating
showed that the so-called oldest basement rocks, such as orthogneisses, amphibolites, and schists, are actually Paleozoic and/or even Early Mesozoic in age [26]. The quartzite assemblage, the protolith deposition of which is constrained by this study to occur after 1200–1115 Ma, most likely during the latest Mesoproterozoic to early Neoproterozoic period, seems to be the oldest rock identified so far by radiogenic isotope dating. Importantly, the lithology of quartzite, derived from a quartz sandstone, suggests deposition in a passive continental margin setting. This corollary is supported by the morphology and internal texture of detrital zircon grains from the quartzites, which indicate a long-distance transport and long-term sorting of detritus. The main age peaks of ca. 1426 and 1482 Ma, within an age range of ca. 1.1–1.8 Ga, of the two quartzite samples suggest that the source area is mainly Mesoproterozoic in age. Several Paleoproterozoic and even Archean zircon grains detected in the quartzite indicate that either rocks with these ages also exist in the source area or that these zircon grains are recycled during the sedimentation. In terms of the paleogeography, the (proto) Ereendavaa terrane was probably located at a passive margin of Rodinia during the early Neoproterozoic.

All five samples from the Paleozoic sedimentary rocks have similar age spectra that show predominant age peaks between ca. 496 Ma and 520 Ma, with each exhibiting several subordinate Neoproterozoic age peaks between ca. 591 Ma and 970 Ma. This illustrates that these sedimentary rocks have similar provenance from a source area that supplied detritus of the middle Cambrian and Neoproterozoic age. The zircon grains contributing to the main peaks are euhedral prisms with well-developed oscillatory zoning (Figure 6), suggesting a proximal provenance. Cambrian intrusive rocks ranging in composition from gabbro to granite are widespread within the Ereendavaa terrane, which most likely represent products of Cambrian arc magmatism [13,25,26]. Consequently, it is possible that the zircon grains with ages belonging to the main peaks in the age spectrum were derived from the Cambrian magmatic arc. Similarly, the zircon grains making up several minor Neoproterozoic age peaks might have been derived from older igneous rocks although no such arc rocks have been proven so far. The volcanic sequence that was previously assigned to the Vendian–early-Cambrian was actually emplaced during the Ordovician, as evidenced by the crystallization ages of ca. 450 Ma (Figure 8) and 460–455 Ma [47] of the rhyolites, suggesting the presence of Ordovician magmatism on the Ereendavaa terrane. The lithological assemblage of andesite–dacite–rhyolite as well as their equivalent volcanoclastic rocks, the geochemical features, and zircon εHf(t) values (+0.1 to +4.07) [47] demonstrate that the Ordovician igneous rocks formed at an Andean-type margin at that time. Therefore, we suggest that the Ereendavaa terrane became an active continental margin during the Cambrian-Ordovician. There are some occurrences of early Silurian intrusions (ca. 430–440 Ma [25] and our unpublished data) within the Ereendavaa terrane, which are characterized by the presence of K-rich granites and by rounded shapes in map view. These features and the observation that these early Silurian granites intrude the Cambrian Kherlen ophiolite jointly indicate a postcollisional origin for these early Silurian granites, related to the collision between the Ereendavaa and Idermeg terranes [25]. Consequently, arc magmatism might have been active within the Ereendavaa terrane at least from the Cambrian to Late Ordovician and the postcollisional magmatism mainly occurred during the early Silurian. The zircon grains belonging to the youngest age peaks of the three Devonian samples (ca. 428, 434 and 436 Ma; Figure 10) were probably derived from the early Silurian postcollisional granites.

It is evident from the detrital-zircon age spectra of the Paleozoic sedimentary rocks (Figures 9 and 10) that a gap exists between ca. 600 Ma and 780 Ma, despite the subordinate Neoproterozoic age peaks dispersed between ca. 591 Ma and 970 Ma. The scarcity of zircon grains with ages of ca. 600–780 Ma in the source of detritus demonstrates that the middle to early late-Neoproterozoic magmatism was inactive, in contrast to the latest Neoproterozoic (ca. 600–540 Ma) and early Neoproterozoic (780–970 Ma). We interpret the ca. 600–540 Ma magmatism as an early phase of a Neoproterozoic-Cambrian-Ordovician magmatic arc. There are two possible explanations for the ca. 780–970 Ma magmatism. One possibility is a supra-subduction setting and the alternative scenario assumes a rifted continental margin. We tentatively prefer the second explanation because of the possible relationship to the separation of the Idermeg terrane from the Ereendavaa one. Summing up, our data suggest that the Ereendavaa terrane...
evolved into an active continental margin at least since the latest Neoproterozoic (ca. 600 Ma) until the Late Ordovician (ca. 450 Ma), and a collision to postcollisional tectonic setting was established during the Late Ordovician-early Silurian.

If the Ereendavaa terrane alone or together with the Idermeg terrane was part of the ribbon CMB, a question arises concerning the polarity of the Neoproterozoic-Ordovician subduction beneath the Ereendavaa terrane. Based on available data, we believe that the solution is northward subduction of the PAO lithosphere at the southern side of the Ereendavaa terrane (present coordinates). The justification for this is two-fold. On the one hand, the Cambrian Kherlen ophiolite, which was previously regarded as a volcanic arc terrane \[13,15\], occurs to the south of the Ereendavaa terrane and is interpreted to represent the suture between the Ereendavaa and Idermeg terranes [25]. The suturing time was constrained before ca. 442 Ma [25], slightly younger than the early Paleozoic arc magmatism. On the other hand, the Adaatsag-Doqgol terrane, the suture zone of the MOO, occurs to the north of the Ereendavaa terrane but the oldest ophiolite identified so far in this suture is Upper Mississippian in age, ca. 325 Ma [15,29], i.e., considerably younger than the early Paleozoic arc magmatism. Previous studies have documented that SSZ-type ophiolites in the Neo-Tethys belts normally formed during the subduction initiation [48–52]. The ca. 325-Ma ophiolites in the MOO suture zone display geochemical features of SSZ-type ophiolites, and thus the southward subduction of the MOO lithosphere probably started at ca. 325 Ma [29]. The Onon arc within the Russian segment of the suture zone, which was considered as an intra-ocean arc related to the southward subduction of the MOO, was proposed to be the oldest arc within the MOO and was presumed to be Late Devonian to Early Carboniferous in age [13]. Therefore, we propose that the Neoproterozoic to early Paleozoic arc magmatism was generated by the northward subduction of the PAO lithosphere beneath the Ereendavaa terrane.

The event that was associated with the tectonic emplacement of the Kherlen ophiolite at the end of the Ordovician (ca. 450–442 Ma) is likely a record of the amalgamation of the Siberian southern margin, resulting in the early Paleozoic domain of northern Mongolia.

5.3. Implications for the Evolution of the MOO

With respect to the evolution of the MOO, two contrasting models have been suggested. One model is that the MOO was a long-lived feature between \(\sim 620 \text{ Ma and} 200 \text{ Ma, as a new ocean basin [6,53]}\) or one evolving into a remnant ocean basin in the late Early-Paleozoic [4]. The other scenario is that the MOO opened later as a back-arc basin during the Silurian [11,13,54] or the Carboniferous [23], or as a new basin related to a mantle plume/hot-spot [22]. According to our new data and those previously published, we favor the second possibility, that is, the MOO was opened through break-up of the early Paleozoic basement. Supporting evidence for this is summarized below.

First, the detrital zircon age spectra of our samples from the Silurian-Devonian sequences (some were erroneously assigned to be Cambrian in age as evidenced by sample MOE-42) at the southern margin of the MOO, namely the Ereendavaa terrane, resemble those of the second group of samples of [23], which were taken from the “Cambrian-Silurian” sequences of the Haraa terrane at the northern margin of the MOO. That is, they all comprise Cambrian main age peaks centered at ca. 510 Ma, except for one sample of [23] with the main age peak at ca. 605 Ma, and several subordinate Neoproterozoic age peaks as well as early Paleoproterozoic and even Archean ones. This similarity implies that these sedimentary sequences located on the opposite margins might have been connected prior to the MOO opening. This corollary is in line with the observation that the source areas of the overlying Devonian-Carboniferous sequence and the underlying “Cambrian-Silurian” one at the northern margin were two different terranes, rather than one single terrane, the age distribution of which changed with time [23].

Second, the Silurian-Devonian samples from the Ereendavaa terrane contain no detrital-zircon grains of similar stratigraphic age, which is contrasting to the previously dated post-Devonian sedimentary samples that show youngest age peaks corresponding to their stratigraphic ages [11,22]. This is because of occurrence of contemporaneous volcanic arcs on both margins during the
Carboniferous and Triassic periods \[13,15\]. The dominance of the Cambrian-Ordovician zircon grains in the Silurian-Devonian samples suggests that their age spectra are inherited from reworked, older Neoproterozoic to early Paleozoic magmatic arc complexes \[13,47\]. It is noted that the authors of \[11,22,55\] reported a dominance of slightly negative $\varepsilon$Hf(t) values for Cambrian-Ordovician detrital zircons from the late Paleozoic and younger sedimentary rocks on the Ereendavaa terrane, which are different from the slightly positive $\varepsilon$Hf(t) values (+0.1–+4.07) of zircons from the Ordovician arc rhyolites \[47\]. This discrepancy could be explained in terms of different extents of mixing by crust- and mantle-derived melts for the magmas that formed the source rock of the detrital zircons and the arc rhyolites, respectively. This means that the magma forming the source rock of the detrital zircons contains more ancient crustal material than that of the rhyolites. Anyway, the age spectra of the Silurian-Devonian sedimentary rocks indicate no contemporaneous volcanic input during the Silurian-Devonian deposition on the southern margin of the MOO. This implies that extension and basement erosion likely prevailed at the southern margin of the MOO at that time. This is corroborated by the fact that swarms of doleritic sills intruding the Devonian sedimentary sequence in the Ereendavaa terrane (Figures 3 and 4) are indicative of an extensional regime. We presume that the extensional event was linked to the opening of the MOO, probably occurring at its rifted passive margin.

Third, the MOO suture physically dissects the Paleozoic domain that was amalgamated during the early Silurian \[8,26,56\] in central-NE Mongolia, as well as the Russian Transbaikal and northern Chinese Greater Xing’an regions (Figure 1). The Ereendavaa and Idermeg terrane basement blocks are welded by the early Paleozoic Kherlen suture in the southeast and the Precambrian continental blocks and orogenic collage comprising Neoproterozoic-early Paleozoic island arcs, ophiolites, and accretionary complexes extending in the northwest (Figure 2) \[13\]. These features demonstrate that the MOO developed later on the amalgamated early Paleozoic domain, which is further supported by the observation that the MOO lithosphere subduction-related igneous rocks penetrate and/or cover the adjacent blocks in both the north and south of the MOO suture \[4,11,13,15\]. These igneous rocks, respectively represented by the Selenge and Middle Gobi volcanic–plutonic belts in the north and south of the suture (Figure 2), are predominantly Permian-Triassic age \[13,57,58\]. Additionally, porphyry-type Cu-Mo mineralization related to the subduction of the MOO lithosphere was mainly formed during Permian-Triassic times \[2,31,59–61\].

Finally, no ophiolite that is older than the Carboniferous has been identified so far in the MOO suture zone (the Adaatsag and Dochgol terranes), with the oldest one having an age of ca. 325 Ma \[15,29\], similarly implying that the MOO opened relatively late. The authors of \[17\] reported deep-water radiolarian cherts of upper Silurian-Devonian age at the southeastern edge of the Hangay-Hentey belt, but the meta-sandstones from the same sequence at nearly the same location as that of the radiolarian chert samples have the maximum deposition age of ca. 437–340 Ma \[11,22,23\]. We interpret the cherts to be coeval with the ocean formation and later to be integrated into an accretionary complex.

Regarding the geodynamic setting of the MOO opening, we prefer the mantle plume origin \[22\] to the back-arc extensional one \[11,13\]. This is mainly owing to the recent recognition by \[22\] of rock packages characteristic of a drowned seamount within the accretionary complex of the MOB, which is robust evidence for the MOO opening above a mantle plume or hot-spot.

Based on the above discussion, we synthesize the tectonic evolution of the Ereendavaa terrane and the MOO as follows (Figure 11):
During the late Mesoproterozoic, mostly likely between ca. 1.2–1.0 Ga, the protolith of the quartzite sequence, belonging to the Ereendavaa basement (proto Ereendavaa terrane (PET) in Figure 11) was deposited on a passive continental margin, with a detritus source of mainly Mesoproterozoic age, though minor contributions from Paleoproterozoic and Archean rocks were also possible. We presume that the passive continental margin corresponded to the southern margin (present coordinates) of the early Precambrian Siberian block, one of the outer blocks of the Rodinian supercontinent at that time. The proto-Idermeg terrane (PIT in Figure 11), which has a passive continental margin...
origin [13], is presumed to form simultaneously, and link, with the PET (Figure 11A). During the early Neoproterozoic period (ca. 978–780 Ma), the passive continental margin seemed to experience extension and rifting, with the PIT drifting away from the margin of the PET, leading to the formation of the Kherlen Ocean (KO), and then during the late Neoproterozoic-Ordovician period (ca. 600–450 Ma) the northward subduction of the KO lithosphere generated the Andean-type continental margin on the PET (Figure 11B). At the same time, the northward subduction the PAO lithosphere beneath the Idermeg terrane (IT) was likely ongoing.

During the Late Ordovician to early Silurian (ca. 450–440 Ma), the KO was closed, leading to the collision of the IT with the PET, with the Kherlen suture between them (Figure 11C). This collisional event likely recorded the final amalgamation of the early Paleozoic domain of Mongolia, which was later split by the MOO. Postcollisional extension and magmatism dominated the Ereendavaa terrane during the early Silurian (ca. 440–430 Ma). Meanwhile, extension and rifting triggered by a mantle plume were likely ongoing during this period [22] (Figure 11C).

During the late Silurian to Early Devonian time (ca. 430–400 Ma), the amalgamated early Paleozoic domain was rifted, and break-up of the MOO occurred. Accompanying the extension and the MOO opening, the Silurian-Devonian sedimentary sequences formed on both the southern and northern margins of the MOO (Figure 11D). They presently exist on the northern edge of the Ereendavaa terrane and the southern edge of the Haraa terrane.

During the Middle Devonian-early Carboniferous (ca. 400–325 Ma), the northern margin of the MOO evolved from the rifted passive margin into an active one, whereas the southern margin remained passive (Figure 11E). This is based on the fact that the Devonian-Carboniferous sedimentary rocks to the north of the MOO suture zone contain numerous detrital zircon grains of Middle Devonian age [11,22,23] but contemporaneous sedimentary rocks within and to the south of the suture zone do not [11], indicating Devonian arc volcanism occurring only at the northern margin of the MOO.

At approximately the end of the early Carboniferous (ca. 325 Ma), southward subduction of the MOO lithosphere was initiated, forming the Adaatsag and Huhu Davaa ophiolites [15,29], and the MOO had evolved into a bidirectional convergent system since then (Figure 11F). Two subduction zones might have existed at the southern margin of the MOO during the early stage of this period, which correspondingly generated two arcs: one intra-ocean arc (the Onon arc) [4,13] and one continental arc. This bidirectional convergent system might had continued until the end of the Triassic or even the Early Jurassic, resulting in the Selenge and Middle Gobi volcano–plutonic belts of mainly the Permian-Triassic age, which occur to the north and south of the Mongol-Okhotsk belt, respectively.

6. Conclusions

Based on our detrital zircon U-Pb results combined with published data, the following conclusions can be reached:

1. Protoliths of the quartzite assemblage as part of the basement of the Ereendavaa terrane was deposited after ca. 1.2–1.15 Ga, most likely during the Late Mesoproterozoic (1.2–1.0 Ga), in a passive continental margin setting.

2. The thick intermediate-felsic volcanic sequence to the north of the Ondorkhan was formed during the Late Ordovician (ca. 450 Ma), rather than during the Vendian-early Cambrian as previously suggested. This volcanic sequence is interpreted as part of a Late-Neoproterozoic-Ordovician arc formation resulting from the northward (present coordinates) subduction of the Kherlen Ocean lithosphere beneath the proto Ereendavaa terrane.

3. The so-called Cambrian strata dated by this study, which yielded the youngest detrital zircon age peak at ca. 451 Ma that is similar to that of the nearby Silurian sequence, was deposited during the Silurian. All these strata and the nearby Devonian sedimentary sequence have a similar detrital zircon age spectrum with a maximum ca. 497–519 Ma, suggesting early Paleozoic arc provenance.

4. The Mongol-Okhotsk Ocean split the amalgamated early Paleozoic domain above a mantle plume after the early Silurian and developed an Andean-type continental margin along its
northern margin during the Devonian and a bidirectional subduction system at ca. 325 Ma. This bidirectional subduction system might have lasted at least until the Triassic.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-163X/10/9/742/s1, Table S1: U-Pb analytical results of detrital zircon from the Neoproterozoic-Paleozoic sedimentary sequences in the Ereendavaa terrane in NE Mongolia, and Supplementary Material 1: LA-ICP-MS zircon U-Pb dating method.

Author Contributions: Conceptualization, M.B.; Data curation, C.L.; Formal analysis, X.L.; Investigation, M.Z., C.A. and S.Y.; Writing—original draft, L.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 41772230), the Chinese Academy of Sciences (grant number GJHZ1805), and the National Key R&D Program of China (grant number 2017YFC0601306).

Acknowledgments: We thank Sanchir Dorjgochoo at the Institute of Geology, Mongolian Academy of Sciences, for providing some new geological material concerning the work area in Mongolia. K. Togtokh is thanked for her logistic assistance and sample treatment during the field expedition in Mongolia. The Gaonianlinghang company is acknowledged for the quick and high-quality preparation of zircon mounts analyzed. Help and technical support from Bei Xu and Yanjie Zhang during the LA-ICP-MS zircon U-Pb analyses at the Key Laboratory of Regional Geology and Mineralization, Hebei GEO University is highly appreciated. We give our special thanks to the two reviewers, and Wilfried Winkler, the Academic Editor, for their constructive suggestions and valuable comments.

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

References
1. Natal’ in, B. History and modes of mesozoic accretion in southeastern russia. Isl. Arc 1993, 2, 15–34. [CrossRef]
2. Parfenov, L.M.; Popeko, L.I.; Tomurtogoo, O. Problems of tectonics of the Mongol–Okhotsk orogenic belt. Geol. Pac. Ocean 2001, 16, 797–830.
3. Zonenshain, L.P.; Kuzmin, M.I.; Natapov, L.M. Geology of the USSR: A plate tectonic synthesis. Geodynamics 1990, 21, 97–120.
4. Zorin, Y.A. Geodynamics of the western part of the Mongol–Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia. Tectonophysics 1999, 306, 33–56. [CrossRef]
5. Sengör, A.M.C.; Natal’in, B.A.; Burtman, V.S. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature 1993, 364, 299–306. [CrossRef]
6. Sengör, A.M.C.; Natal’in, B.A. Paleotectonics of Asia: Fragments of synthesis. In The Tectonic Evolution of Asia; Yin, A., Harrison, T.M., Eds.; Cambridge University Press: New York, NY, USA, 1996; pp. 486–640.
7. Jahn, B.-M.; Wu, F.; Chen, B. Granitoids of the central Asian orogen and continental growth in the phanerozoic. Trans. R. Soc. Edinb. Earth Sci. 2000, 91, 181–193.
8. Windley, B.F.; Alexeiev, D.; Xiao, W.; Kröner, A.; Badarch, G. Tectonic models for accretion of the central Asian orogenic belt. J. Geol. Soc. Lond. 2007, 164, 31–47. [CrossRef]
9. Khain, E.V.; Bibikova, E.V.; Kröner, A.; Zhuravlev, D.Z.; Sklyarov, E.V.; Fedotova, A.A.; Kravchenko-Bereznoy, I.R. The most ancient ophiolites of the central Asian fold belt: U–Pb, and Pb–Pb zircon ages for the dunzhugur complex, Eastern Sayan, Siberia, and geodynamic implications. Earth Planet. Sci. Lett. 2002, 199, 311–325. [CrossRef]
10. Xiao, W.; Windley, B.F.; Hao, J.; Zhai, M. Accretion leading to collision and the Permian suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. J. Geol. Soc. Lond. 2003, 160, 1069. [CrossRef]
11. Bussien, D.; Gongbojav, N.; Winkler, W.; Quadt, A. The Mongol–Okhotsk belt in Mongolia—An appraisal of the geodynamic development by the study of sandstone provenance and detrital zircons. Tectonophysics 2011, 510, 132–150. [CrossRef]
12. Zorin, Y.A.; Belichenko, V.G.; Turutanyov, E.K.; Kozhevnikov, V.M.; Ruzhentsev, S.V.; Dergunov, A.B.; Filippova, I.B.; Tomurtogoo, O.; Arvisbaatar, N.; Bayasgalan, T.; et al. The South Siberia–Central Mongolian transect. Tectonophysics 1993, 225, 361–378. [CrossRef]
13. Badarch, G.; Cunningham, W.D.; Windley, B.F. A new terrane subdivision for Mongolia: Implications for the Phanerozoic crustal growth of central Asia. J. Asian Earth Sci. 2002, 21, 87–110. [CrossRef]
14. Kravchinsky, V.A.; Cogné, J.P.; Harbert, W.P.; Kuzmin, M.I. Evolution of the Mongol-Okhotsk ocean as constrained by new paleomagnetic data from the Mongol-Okhotsk suture zone, Siberia. Geophys. J. Int. 2002, 148, 34–57. [CrossRef]

15. Tomurtogoo, O.; Windley, B.F.; Kröner, A.; Badarch, G.; Liu, D.Y. Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: Constraints on the evolution of the Mongol–Okhotsk ocean, suture and orogen. J. Geol. Soc. Lond. 2005, 162, 125–134. [CrossRef]

16. Sorokin, A.A.; Zaika, V.A.; Kovach, V.P.; Kotov, A.B.; Xu, E.; Yang, H. Timing of closure of the eastern Mongol–Okhotsk Ocean: Constraints from U–Pb and Hf isotopic data of detrital zircons from metasediments along the Dzhagdy Transect. Gondwana Res. 2020, 81, 58–78. [CrossRef]

17. Kurihara, T.; Tsukada, K.; Otoh, S.; Kashiwagi, K.; Chuluun, M.; Byambadash, D.; Boijir, B.; Gonchigdorj, S.; Nuramkhan, M.; Niwa, M.; et al. Upper Silurian and Devonian pelagic deep-water radiolarian chert from the Khangai–Khentei belt of central Mongolia: Evidence for middle Paleozoic subduction accretion activity in the central Asian orogenic belt. J. Asian Earth Sci. 2008, 34, 209–225. [CrossRef]

18. Zhao, X.; Cee, R.S.; Zhou, Y.; Wu, H.; Wang, J. New palaeomagnetic results from northern China: Collision and suturing with Siberia and Kazakhstan. Tectonophysics 1990, 14, 43–81.

19. Carrapa, B. Resolving tectonic problems by dating detrital minerals. Geology 2010, 38, 191–192. [CrossRef]

20. Lawton, T.F.; Hunt, G.J.; Gehrels, G.E. Detrital zircon record of thrust belt unroofing in Lower Cretaceous synorogenic conglomerates, central Utah. Geology 2010, 38, 463–466. [CrossRef]

21. Gehrels, G. Detrital zircon U-Pb geochronology applied to tectonics. Annu. Rev. Earth Planet. Sci. 2014, 42, 127–149. [CrossRef]

22. Ruppen, D.; Knaf, A.; Bussien, D.; Winkler, W.; Chimedtseren, A.; von Quadt, A. Restoring the Tectonics of Asia; Kovalenko, V., Yarmolyuk, V., Eds.; Cambridge University Press: New York, NY, USA, 1996; pp. 374–420.

23. Parfenov, L.M.; Bulgatov, A.N.; Gordienko, I.V. Terranes and accretionary history of the Transbaikal orogenic belts. Int. Geol. Rev. 1995, 37, 736–751. [CrossRef]

24. Gusev, G.S.; Peskov, A.I. Geochemistry and conditions of ophiolite formations of eastern Transbaikalia. Geochim. 1996, 8, 723–737.

25. Kravchinsky, V.A.; Yarmolyuk, V.; Bogatikov, O. Magmatism, Geodynamics, and Metallogeny of Central Asia; MIKO—Commercial Herald Publishers: Moscow, Russia, 1995.

26. Wu, Y.F.; Sun, D.Y.; Ge, W.C.; Zhang, Y.B.; Grant, M.L.; Wilde, S.A.; Jahn, B.-M. Geochronology of the Panerozoic granitoids in northeastern China. J. Asian Earth Sci. 2011, 41, 1–30. [CrossRef]

27. Sun, L.X.; Ren, B.F.; Zhao, F.Q.; Ji, S.P.; Geng, J.Z. Late Paleoproterozoic magmatic records in Eerguna massif: Evidence from the zircon U-Pb dating of granitic gneisses (in Chinese with English abstract). Geol. Bull. China 2013, 32, 341–352.

28. Tang, J.; Xu, W.; Wang, F.; Wang, W.; Xu, M.; Zhang, Y. Geochronology of Neoproterozoic magmatism in the Erguna Massif, NE China: Petrogenesis and implications for the breakup of the Rodinia supercontinent. Precambrian Res. 2013, 224, 597–611. [CrossRef]
35. Daoudene, Y.; Ruffet, G.; Cocherie, A.; Ledru, P. Timing of exhumation of the Ereendavaa metamorphic core complex (north-eastern Mongolia)—U-Pb and $^{40}$Ar/$^{39}$Ar constraints. *J. Asian Earth Sci.* 2011, 62, 98–116. [CrossRef]

36. Jamyandorj, U.; Tungalag, F.; Boishenko, A.F. *Geological Map of the Central and Eastern Mongolia, Scale 1: 500,000;* Institute of Geological Research Regional Geological Sector, Ministry of Heavy Industries: Ulaanbaatar, Mongolia, 1990.

37. Kröner, A.; Windley, B.F.; Badarch, G.; Tomurtogoo, O.; Hegner, E.; Jahn, B.M.; Gruschkha, S.; Khain, E.V.; Demoux, A.; Wingate, M.T.D. Accretionary growth and crust-formation in the central Asian orogenic belt and comparison with the Arabian–Nubian shield. *Geol. Soc. Am. Mem.* 2007, 200, 181–209.

38. Mossakovskiy, A.A.; Ruzhentsev, S.V.; Samygin, S.G.; Kheraskova, T.N. Central Asian fold belt: Geodynamic evolution and formation history. *Geotektonika* 1994, 27, 445–474.

39. Xiao, W.; Windley, B.F.; Han, H.; Liu, W.; Wan, B.; Zhang, J.; Ao, S.; Zhang, Z.; Song, D. Late Paleozoic to early Triassic multiple roll-back and oroclinal bending of the Mongolia collage in central Asia. *Earth Sci. Rev.* 2018, 186, 94–128. [CrossRef]

40. Tomurtogoo, O.; Badarch, G.; Makhbadar, T.S.; Orlomaa, D.; Khosbayar, P. *Geological Map of Mongolia, Scale 1: 1,000,000;* General Directorate of Mineral Research & Exploration of Turkey: Ankara, Turkey, 1999.

41. Jacobsen, Y.N.; Scherer, E.E.; Munker, C.; Mezger, K. Separation of U, Pb, Lu, and Hf from single zircons for combined U-Pb dating and Hf isotope measurements by TIMS and MC-ICPMS. *Chem. Geol.* 2005, 220, 105–120. [CrossRef]

42. Gerdes, A.; Zen, A. Combined U-Pb and Hf isotope LA-(MC-)ICP-MS analyses of detrital zircons: Comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in central Germany. *Earth Planet. Sci. Lett.* 2006, 249, 47–61. [CrossRef]

43. Liu, Y.S.; Hu, Z.C.; Zong, K.Q.; Gao, C.G.; Gao, S.; Xu, J.; Chen, H.H. Reappraisement and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS. *Chinese Sci. Bull.* 2010, 55, 1535–1546. [CrossRef]

44. Andersen, T. Correction of common lead in U-Pb analyses that do not report Ar constraints. *Earth Planet. Sci. Lett.* 2014, 383, 359–362. [CrossRef]

45. Steiger, R.H.; Jäger, E. Subcommission on geochronology: Convention on the use of decay constant in geo-and cosmochronology. *Earth Planet. Sci. Lett.* 1977, 36, 359–362. [CrossRef]

46. Ludwig, K.R. *User’s Manual for Isoplot 3.00: A Geochronological Toolkit for Microsoft Excel;* Berkeley Geochronology Center: Berkeley, CA, USA, 2003; Volume 4, pp. 1–71.

47. Narantsetseg, T.; Orolmaa, D.; Yuan, C.; Wang, T.; Guo, L.; Xu, J.; Chen, H.H. Reappraisement and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS. *Chinese Sci. Bull.* 2010, 55, 1535–1546. [CrossRef]

48. Whattam, S.A.; Stern, R.J. The 'subduction initiation rule': A key for linking ophiolites, intra-oceanic forearcs, and subduction initiation. *Contrib. Miner. Petr.* 2011, 162, 1031–1045. [CrossRef]

49. Stern, R.J.; Reagan, M.; Ishizuka, O.; Ohara, Y.; Whattam, S. To understand subduction initiation, study forearc crust; to understand forearc crust, study ophiolites. *Lithosphere* 2012, 4, 469–483. [CrossRef]

50. Reagan, M.K.; Pearce, J.A.; Petronotis, K.; Almeev, R.R.; Avery, A.J.; Carvallo, C.; Chapman, T.; Christeson, G.L.; Ferré, E.C.; Godard, M.; et al. Subduction initiation and ophiolite crust: New insights from IODP drilling. *Int. Geol. Rev.* 2017, 59, 1439–1450. [CrossRef]

51. Stern, R.J.; Gerya, T. Subduction initiation in nature and models: A review. *Tectonophysics* 2018, 746, 173–198. [CrossRef]

52. Whattam, S.A.; Montes, C.; Stern, R.J. Early central American forearc follows the subduction initiation rule. *Gondwana Res.* 2020, 79, 283–300. [CrossRef]

53. Khain, E.V.; Bibikova, E.V.; Salnikova, E.E.; Kröner, A.; Gibsher, A.S.; Didenko, A.N.; Degtyarev, K.E.; Fedotova, A.A. The Palaeo-Asian Ocean in the Neoproterozoic and early Palaeozoic: New geochronologic data and palaeotectonic reconstructions. *Precambrian Res.* 2003, 122, 329–358. [CrossRef]

54. Gordienko, I.V. Paleozoic geodynamic evolution of the Mongol-Olkhotsk fold belt. *J. Southeast Asian Earth Sci.* 1994, 9, 429–433. [CrossRef]

55. Winkler, W.; Bussien, D.; Baatar, M.; Anaad, C.; von Quadt, A. Detrital zircon provenance analysis in the central Asian orogenic belt of central and southeastern Mongolia—A Palaeotectonic model for the Mongolian Collage. *Minerals* 2020, accepted.
56. Miao, L.; Zhang, F.; Jiao, S. Age, protoliths and tectonic implications of the Toudaoqiao blueschist, Inner Mongolia, China. J. Asian Earth Sci. 2015, 105, 360–373. [CrossRef]

57. Zhao, P.; Xu, B.; Jahn, B. The Mongol-Okhotsk Ocean subduction-related Permian peraluminous granites in northeastern Mongolia: Constraints from zircon U-Pb ages, whole-rock elemental and Sr-Nd-Hf isotopic compositions. J. Asian Earth Sci. 2017, 144, 225–242. [CrossRef]

58. Koval, P.V.; Grebenshchikova, V.I.; Lustenberg, E.E.; Henney, P.J. Database of granites in the Mongol-Okhotsk zone, Mongolia-Siberia, and its use in mineral exploration. J. Geochem. Explor. 1999, 66, 199–210. [CrossRef]

59. Berzina, A.P.; Sotnikov, V.I. Character of formation of the Erdenet-Ovoo porphyry Cu-Mo magmatic center (northern Mongolia) in the zone of influence of a Permo-Triassic plume. Russ. Geol. Geophys. 2007, 48, 141–156. [CrossRef]

60. Kang, Y.; She, H.; Lai, Y.; Wang, Z.; Li, J.; Zhang, Z.; Xiang, A.; Jiang, Z. Evolution of middle-late Triassic granitic intrusions from the Badaguan Cu-Mo deposit, Inner Mongolia: Constraints from zircon U-Pb dating, geochemistry and Hf isotopes. Ore Geol. Rev. 2018, 95, 195–215. [CrossRef]

61. Mi, K.; Liu, Z.; Li, C.; Liu, R.; Wang, J.; Peng, R. Origin of the badaguan porphyry Cu-Mo deposit, Inner Mongolia, northeast China: Constraints from geology, isotope geochemistry and geochronology. Ore Geol. Rev. 2017, 81, 154–172. [CrossRef]