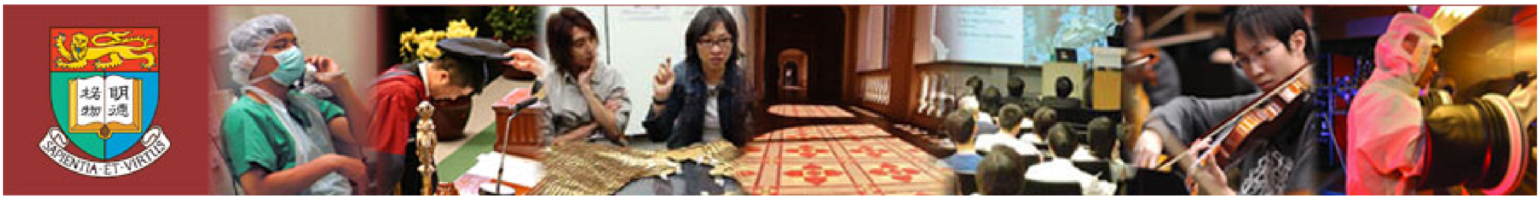

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U-Pb and Hf isotope study of detrital zircons from the Wulashan khondalites: Constraints on the evolution of the Ordos Terrene, Western Block of the North China Craton

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Abstract:

A major advancement of Precambrian geology in the North China Craton is its tectonic subdivision into the Eastern and Western Blocks separated by the Trans-North China Orogen. However, further understanding the history of the Western Block is hindered by the lack of data for the Ordos Terrane, which is covered by basin sediments in the southern part of the Western Block. The khondalites of the Wulashan Complex are high-grade metasedimentary rocks derived from the Ordos Terrane. Therefore, U-Pb and Hf isotope studies of detrital zircons from these khondalites will provide insights into the basement nature of the Ordos Terrane.

Detrital zircons from the Wulashan khondalites give U-Pb ages between 1.84 and 2.32 Ga, indicating Paleoproterozoic provenance(s) for the metasediments. These detrital zircons have concentric growth zoning, and possess ε_{Hf} values between -8 and +9, suggesting that they crystallised from magmas derived from underlying old crust and/or juvenile materials from the mantle. The lowest ε_{Hf} values with different ages define an evolutionary line that extrapolates to intersect the depleted mantle line at about 2.6 Ga in a ε_{Hf} vs. time diagram. This implies that the sedimentary procenance was

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underlain by a lower crust separated from the mantle at ~2.6 Ga. One sample has detrital zircons with ~2.0 Ga ages and positive ε_{Hf} from +1 to +9, clearly recording a significant crustal growth event at ~2.0 Ga in the region.

The above data indicate that the Ordos Terrane of the Western Block may have a ~2.6 Ga lower crust, with significant crustal growth at ~2.0 Ga, and 1.84 to 2.32 Ga Paleoprotozoic rocks were widely exposed during the deposition of these khondalites. This is in striking contrast with the Eastern Block that has basement ranging from the early Archean (up to ~3.8 Ga), through middle Archean (3.4 – 2.9 Ga), to late Archean (2.9 – 2.5 Ga). Our data clearly demonstrate that the Eastern and Western Blocks evolved separately before they collided to form the uniform North China Craton.

Keywords: Detrital zircons; LA-ICP-MS; U-Pb and Hf isotope; Khondalites; North China Craton

1 Introduction

Due to their high mechanical and chemical resistance, zircon minerals can survive erosion, transportation, diagenesis, metamorphism and even crustal melting. Hence detrital zircons from various sedimentary series have been studied for their U-Pb isotope compositions to reveal timing of major thermal events in their provenances. An early attempt was made by Ledent et al. [1] in early sixties of last century using large zircon fractions from the North American beaches and rivers, whereas more recently, spot analyses were conducted on small parts of single grains to avoid mixing of different generations, employing sensitive high resolution ion micro-probe (SHRIMP) or laser ablation-inductively coupled plasma mass spectrometer (LA-ICPMS) [2-4].

Zircons also contain high contents of Hf (0.5% to 2%) and have low Lu/Hf ratios, and thus are ideal for Hf isotopic study [5]. However, because of the low efficiency of thermal ionization, at least

100 to 200 mg of zircon is needed to obtain precise Hf isotopic measurement using thermal ionization mass spectrometry (TIMS) instruments. This means tens or hundreds of zircon grains are necessary for one analysis, which possibly include inherited or xenocrystic grains and may have been variably disturbed. This problem has been recently overcome with the development of multiple-collector ICPMS technology [6, 7]. Coupled with a laser ablation system, this technology allows precise analysis of Hf isotope composition on a small part of single grains [8-11]. Combined with U-Pb age determination and trace element measurement on the same grain (spot), zircon Hf isotope study paved a new avenue for petrogenetic researches [11, 12].

The North China Craton, one of the oldest crustal blocks in the world, has been recently subdivided into the Eastern and Western Blocks separated by a collisional orogenic belt, namely the Trans-North China Orogen [13-17] (Fig. 1). In the last decade, extensive investigations have been carried out on the North China Craton in term of lithology, structural style, metamorphic evolution, geochemistry and geochronology of the basement rocks and significant achievements have been made, e.g. recognition of numerous tonalitic- trondhjemitic- granodioritic (TTG) plutons [18-22] and fragments of ancient oceanic crust [23-25], finding of high-pressure granulites and retrograded eclogites [16, 26-28], defining crustal-scale ductile shear zones and domes [21, 29, 30], confining distribution of rocks with near-isobaric cooling anticlock-wise or near-isothermal decompression clockwise P-T paths [14, 17, 31-35], and dating of 3.8-3.9 Ga matasedimentary and granitoid rocks [36]. However, most of these data were obtained from the Eastern Block and the Trans-North China Orogen, with few data from the northern part of the Western Block, namely Yinshan Terrane. Data are lacking for the southern part of the Western Block, named the Ordos Terrane [37], which is covered by the Mesozoic to Cenozoic sediments of the Ordos Basin.

The khondalite series rocks in China are mainly exposed in the Western Block along an east- west-trending structural belt, named the Khondalite Belt. This belt is 600 km long and 100-200 km wide, separating the Ordos Terrane in the south from the Yinshan Terrane in the north and extends from Jining Complex in the east through the Daqingshan and Wulashan Complexes to the Qianlishan and Helanshan Complexes in the west (Fig. 1). It has long been accepted that the khondalite series rocks in the Western Block were deposited on the Archean basement, since in most cases they occur in close associations with the Archean TTG gneisses and mafic granulites. However, geochronological studies show that the khondalite series rocks are tectonically contact with the Archean TTG gneisses in the Western Block, and do not contain Archean zircons [30, 38-44]. This has led Zhao et al. [45] to suggest that the protoliths of the khondalite series rocks were not deposited directly on the Archean TTG gneiss basement, and these khondalite series rocks may be allochthonous to the associated Archean TTG gneisses. More recently, based on the fact that most khondalites occur surrounding the borderlands of the Ordos basin, Zhao et al. [37] proposed that the protoliths of the khondalite series rocks may represent stable continental margin deposits of the Ordos Terrane. This provides an alternative approach to study the nature and age of the Ordos basement, which is not directly accessible. In this study, U-Pb, Hf isotope and trace element compositions were analyzed on detrital zircons from the Wulashan khondalites, which enable us to examine age of sedimentary provenance, nature of the basement rocks and the crustal evolutionary history of the Western Block.

2 Geological backgrounds

As mentioned above, the North China Craton can be tectonically subdivided into the Eastern and Western Blocks separated by the Trans-North China Orogen. Detailed lithological, geochemical, structural, metamorphic and geochronological differences between the basement rocks of the Eastern and Western Blocks and their possible tectonic evolutions have been summarized by Zhao et al. [17] and are not repeated here. Most recently, this three-fold subdivision and tectonic model of the North China Craton have been further refined by new structural, petrological and geochronological data obtained over the past few years [37]. These new data indicate that the Western Block formed by amalgamation of the Ordos Terrane in the south and the Yinshan Terrane in the north along the east-west-trending Khondalite Belt at some time prior to the collision of the Western and Eastern Blocks [37].

As one of the largest granulite-facies metamorphic complexes in the Khondalite Belt, the Wulashan Complex is located in the central part of the belt and is dominated by the Paleoproterozoic graphite-bearing sillimanite-garnet gneiss, garnet quartzite, felsic paragneiss, calc-silicate rock and marble, which have previously been referred to as "khondalite series" in the Chinese literature [46-48]. Associated with these khondalite series rocks are Archean TTG gneisses, mafic granulites, and Paleoproterozoic syntectonic charnockites and S-type granites. The distribution of the Paleoproterozoic khondalite series and Archean TTG gneisses in the Wulashan Complex is controlled by the west-east extending composite synclinal structure. The Paleoproterozoic kondalite series is roughly at the centre of the syncline while the Archean TTG gneisses on the limbs although they are commonly intercalated. The khondalite series rocks in the Wulashan Complex preserve four distinct mineral assemblages (M_1-M_4). M_1 is represented by inclusions of plagioclase + biotite + quartz ± kyanite ± rutile within M_2 garnet porphyroblasts; M_2 represents the growth of garnet porphyroblasts and matrix plagioclase + biotite + quartz + sillimanite ± ilmenite; M_3 is represented by cordierite coronas and cordierite + orthopyroxene or cordierite + spinel symplectites, surrounding garnet porphyroblasts; and M_4

represents retrograde minerals biotite + chlorite replacing garnet, K-feldspar + sericite + chlorite replacing cordierite, and andalusite + muscovite dissecting the main foliation [45]. These mineral assemblages and their thermobarometric estimates define a clockwise P–T path involving near-isothermal decompression [45], which is considered to reflect a continental collisional setting in which the Yinshan Terrane in the north and the Ordos Terrane in the south collided to form the Western Block at 2.0-1.9 Ga [37, 45].

3. Analytical procedures

The samples were processed involving crushing and initial heavy liquid and subsequent magnetic separation. Zircons were hand- picked and mounted on adhesive tape, enclosed in epoxy resin and then polished to about half their sizes and photographed in reflected and transmitted light.

3.1. CL images

In order to investigate the structure and origin of zircons and choose potential target sites for later U-Pb and Hf analyses, cathodoluminescence (CL) imaging of zircon grains was taken using a CAMECA microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing.

3.2 Hf-isotope analysis

Hf-isotope analysis was carried out using an ArF excimer laser ablation system, attached to a Neptune Plasma multi-collector ICPMS, at the Institute of Geology and Geophysics, Chinese Academy of Science in Beijing. Most analyses were conducted with a beam diameter of ca. 63 μm, 10 Hz repetition rate, and energies density of 15J/cm^2, which yielded a signal intensity of ~10V at ^{180}Hf for the standard zircon 91500 in situ analysis. Typical ablation time was 27 s, resulting in pits 20–30 μm deep. Helium carrier gas was used to transport the ablated sample from the laser- ablation cell to the ICPMS torch after mixing with Ar gas in a mixing chamber. The Neptune Plasma MC-ICPMS was equipped with eight motorized Faraday cups and one fixed central channel where the ion beam can be switched between a Faraday detector and a SEM detector. Masses 172, 173, 175-180 and 182 were simultaneously measured in static-collection mode. Time-resolved mode was adopted to select stable portions of the ablation for calculating the final results. Background was collected for 45 s before ablation. More detailed instrumental settings and analytical procedures have been described by Xu et al. [49]. Data were normalized to $^{179}Hf/^{177}Hf$ = 0.7325, using exponential correction for mass bias. Interference of ^{176}Lu on ^{176}Hf was corrected by measuring the intensity of the interference-free ^{175}Lu isotope and using the recommended $^{176}Lu/^{175}Lu$ ratio of 0.02655 [50]. ^{176}Yb is another isobaric interference and was corrected by monitoring ^{172}Yb. However, this correction is not as straightforward as ^{176}Lu, because of a significant difference in the instrumental mass bias between Hf and Yb [50]. In this study, JMC14374 standard solution mixed with proportional amount of Yb (Yb/Hf = 0.0005, 0.01, 0.02, 0.05 and 0.3) was used to investigate the mass bias relationship between Yb and Hf. The newly determined $^{176}Yb/^{172}Yb$ ratio of 0.5886 [50] was adopted in this study and we found that the ^{176}Yb interference can be corrected properly using $\beta_{Yb} = 0.8725\beta_{Hf}$. The measured $^{176}Lu/^{177}Hf$ ratios and the ^{176}Lu decay constant of 1.865×10^{-11} year^{-1} reported by Scherer et al. [51] are used to calculate initial $^{176}Hf/^{177}Hf$ ratios. For the calculation of ε_{Hf} values, we have adopted the chondritic values of $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ reported by Blichert-Toft and Albarede [52]. The calculated model ages (T_{DM}) are based on the depleted mantle model described by Griffin et al. [9, 10], which used the measured $^{176}Lu/^{177}Hf$ ratio, referred to a model of depleted mantle with present-day $^{176}Hf/^{177}Hf$ = 0.28325 and $^{176}Lu/^{177}Hf$ = 0.0384.

3.3 U-Pb dating

The U-Pb isotope compositions of zircons were analyzed by using a VG PQ Excel ICP-MS equipped with New Wave Research LUV213 laser ablation system, installed in the Department of Earth Sciences, the University of Hong Kong. The laser system delivers a beam of 213 nm UV light from a frequency-quintupled Nd:YAG laser. Most analyses were carried out with a beam diameter of ca. 40μm, 10Hz repetition rate, and energy of 0.6–1.3 mJ per pulse. This gave ^{238}U signal of 3×10^4 to 100×10^4 counts, depending on U contents. Typical ablation time was 30 – 60 s, resulting in pits 20 – 40 μm deep. Helium carrier gas transported the ablated sample materials from the laser-ablation cell via a mixing chamber to the ICPMS torch after mixing with Ar gas. More detailed instrumental settings and analytical procedure have been described by Xia et al. [53]. U-Pb ages were calculated using the U decay constants recommended by Steiger and Jäger [54] and IsoplotEx 3 software [55]. Individual analyses are presented with 2 σ error in data tables and in concordia diagrams, and uncertainties in age results are quoted at 95% level (2σ). Considering that detrital zircons from the Wulashan khondalites may have more than one age population, we analyzed at least 50 zircon grains for each sample and $^{207}Pb/^{206}Pb$ age histograms were also plotted using IsoplotEx 3 to help discuss the age spectrum of the rocks exposed in the sedimentary provenance.

3.4 Trace element and source rock type classification

Hoskin and Ireland [56] suggested that REE patterns of zircons alone do not offer a good guide to the composition of their source rocks. However, using some other trace elements in addition to REE, an extensive study of the trace-elements in zircons has shown good correlations between trace element patterns and the composition of the magmatic source rocks [12]. U, Th, Y, Yb, Lu and Hf contents of zircons were used to construct a "trace element classification tree", which classifies any individual zircon grain in terms of its source rock type [12]. The following types of source rocks can be identified with a reliability of > 75%: kimberlite, carbonatite, mafic rocks, syenite, nepheline syenite and granitoids. Some difficulties exist, for example, the reliability is ≤ 50% for subdividing granitoids into SiO_2-rich (70-75%) or SiO_2-poor (< 65%) groups and zircons from large differentiated mafic sills tend to be classified as derived from either mafic rocks or syenites. Despite these ambiguities, trace element data for detrital zircons can provide useful information on the broad composition of the source rocks [11, 12]. This greatly enhances the use of detrital zircons in provenance studies. In this study, trace elements were determined by calibrating the observed ICPMS counts to the international standard 91500, which was also used as an external standard during U-Pb or Hf isotope analyses. Data are reported in Table 1.

4. CL imaging of zircons

The elemental, or structural, control on the cathodoluminescence (CL) emission is generally well understood for most minerals [57] and CL images have been widely used to distinguish igneous from metamorphic zircons. The CL images show that most zircons from khondalites in this study have concentric oscillatory zoning (Fig. 3a, c, d). Because oscillatory zonings and low to variable luminescence are characteristics for magmatic zircons [58-60], we interpret that these detrital zircons were igneous in origin. Some zircons are very low luminescent and nebulously-zoned (Fig. 3g), but their U-Th chemistry and U-Pb ages suggest a metamorphic origin (see below). A minor portion of zircons have discernable cores mantled by oscillatory zoning (Fig. 3b, h) or low luminescent, nebulously-zoned rims (Fig. 3e, f, i). The former cores are interpreted as xenocrytic or inherited because there are distinct differences in U, Th, Y and Yb contents and $^{207}Pb/^{206}Pb$ ages between the cores and rims (Table 1). The zircons with latter cores generally have similar U, Th, Y and Yb contents and $^{207}Pb/^{206}Pb$ ages between the cores and rims and thus are interpreted as sector zoned or metamict zircons with a single growth history [61]. Most of these detrital zircons have variable degree of rounding and surface abrasion, indicating long journey of the sedimentary transportation.

5 Results

The analytical data are given in Table 1 and Table 2. Because each detrital zircon grain may be derived from a different source rock, and thus represents part of the crustal history, more than 50 U-Pb and 25 Hf isotopic analyses have been conducted for each sample to satisfy the statistical requirement.

5.1 Sample WL007

This sample was collected from a graphite mine at Hadamengou area, about 15 km northwest of the Baotou city (N 40° 45.326'; E 109° 37. 529', Fig. 2). It is a garnet-bearing feldspar quartzite and garnet has been retrograded to chlorite. Most detrital zircons from this sample are euhedral or subeuhedral and have obviously concentric oscillatory zoning (Fig. 3a), with Th/U ratios ranging from 0.02 to 1.97 (Table 1), showing their igneous origin. Zircon U-Pb isotopic results are presented in Table 1 and in a concordant diagram (Fig. 4a). Fifty six out of sixty analytical results (indicated by open ellipse in Fig. 4a) define a wide range of $^{207}Pb/^{206}Pb$ ages between 1.84 and 2.32 Ga. It is worthy to note that this range is largely bracketed by the two nearly concordant data-points (discordance degree $\leq$ 3%; Table 1) at 1844 ± 22 Ma (WL007-8) and 2229 ± 18 Ma (WL007-23) respectively. There appear as multiple age peaks on the histogram and four age populations were calculated using Sambridge and Compston “mixture modeling” [62]: 1879 ± 7 Ma (35%), 1965 ± 7 Ma (21%), 2070 ± 7 Ma (25%) and 2185 ± 8 Ma (18%). Four analyses conducted on the xenocrytic or inherited cores yielded older $^{207}Pb/^{206}Pb$ ages of 2299 ± 21 Ma, 2363 ± 27 Ma, 2562 ± 33 Ma and 2319± 21 Ma respectively (solid ellipse in Fig. 4a).

According to the zircon trace element compositions, more than 80% zircons from this sample were derived from low-Si granitoids [12] (Fig. 5). These zircons have ε_{Hf} values from -8 to +3 (Fig. 6), suggesting some of them were crystallized in magma from old crust while some from juvenile materials derived from the depleted mantle source. The occurrence of 2.5 Ga xenocrytic or inherited cores supports this interpretation. The T_{DM} model ages show a bimodal distribution on the histogram, with peaks at 2.46 and 2.58 Ga (Fig. 9).

5.2 Sample WL011

This sillimanite-garnet gneiss sample was collected from south of the Taoerwan railway station, about 20 km north of Baotou city (N40° 47.942′; E109° 48.142′; Fig. 2). Most zircons from this sample are nearly equigranular and highly rounded, indicating their long distance of transportation. Although these zircons are low luminescent, the concentric oscillatory zonings are discernable (Fig. 3 c, d), their Th/U ratios range from 0.01 to 0.40, and U concentrations are up to 1566 ppm (Table 1). Therefore these zircons were also considered to come from an igneous provenance.

On the concordia diagram (Fig. 4b), the analytical points define a discordant line intercepting at age of 1913 ± 16 Ma (MSWD = 2.3). The $^{207}Pb/^{206}Pb$ age spectrum (Fig. 4b) has a major peak at 1880 ± 6 Ma (60%), a shoulder at 1927 ± 11 Ma (22%), and a minor peak at 1980 ± 8 Ma (18%). Two discordant grains give $^{207}Pb/^{206}Pb$ age of 2068 and 2097 Ma. Trace element data suggest that these zircons were derived largely from low-Si granitoid (Fig 5). All Hf-isotope data are scattered below the CHUR reference line (Fig. 6), with narrow ε_{Hf} values ranging from - 8 to - 3. The T_{DM} model ages show a unimodal distribution on histogram, with peak at 2.49 Ga (Fig. 5).

5.3 Sample WL016

This quartzite sample was collected from Houdian village, about 30 km south of Guyang city (N

40° 45.990'; E 110° 05. 060', Fig. 2). Zircons from this sample are mostly subhedral to euhedral, low luminescent, and have discernable concentric oscillatory zoning (Fig. 3 f), with Th/U ratios ranging from 0.07 to 0.94, indicating derivation from an igneous provenance. Some zircon grains have distinct luminescent core (Fig. 3e), but their U, Th, Y, Yb, Hf concentrations and $^{207}Pb/^{206}Pb$ age are similar (Wl016-32, 33, 34 and WL016-40, 41, Table 1), possibly suggesting they were crystallized from a fractionating magma.

The 56 U-Pb analyses give a narrow range of $^{207}Pb/^{206}Pb$ ages between 1930 and 2095 Ma. It is also worthy to note that this range is actually defined by the two nearly concordant data-points WL016-41 and WL016-15 (discordance degree $\leq$ 3%; Table 1). The data mostly plot on or near the Concordia with an intercept age of 2008 ± 14 Ma (MSWD=1.2) and appear as a unimodal age at 1993 Ma on the histogram (Fig. 6). All Hf-isotope analyses lie between the CHUR and DM reference lines (Fig. 9), with ε_{Hf} values ranging from + 1 to + 9, mostly at + 5 (Fig. 8). The T_{DM} model ages range from 2.08 to 2.36 Ga, close to their crystallization ages, indicating their derivation from a juvenile source. The trace element data suggest that syenite may be the predominant source (Fig. 8).

5.4 Sample WL020

This sample is a garnet-bearing feldspar quartzite, collected from Yaowanzi Village, about 20 km southeast of Guyang city (N 40° 51174'; E 110° 06. 213', Fig. 2). Zircon grains from this sample are also mostly subhedral to euhedral, low luminescent, and have discernable concentric oscillatory zoning (Fig. 3g, i). Their Th/U ratios range from 0.06 to 1.0, indicating an igneous origin. Few zircon grains have obvious xenocrytic or inherited cores (Fig. 3h), which have lower U, Th, Y and Yb concentrations and $^{207}Pb/^{206}$ Pb ages distinctive from the zircon rims (Table 1).

Fifty six out of 67 U-Pb analyses define a good discordant line with an intercept age at 1954 ± 16

Ma (MSWD = 3.1, Fig. 4c, open ellipse). Two analyses on the xenocrytic or inherited cores give nearly concordant $^{207}Pb/^{206}Pb$ ages of 2200 ± 24 Ma and 2502 ± 33 Ma. On the histogram, there is a striking peak at about 1944 ± 2, well matches the intercept age. The other analyses, as indicated with solid ellipse on the concordia diagram (Fig. 4c), constitute two minor peaks on the age spectrum: 2050 ± 5 and 2159 ± 5 Ma. Hf-isotope analyses yield a wide range of ε_{Hf} values from -7 to +6. T_{DM} model ages range from 2.22 to 2.69 Ga, with a peak at 2.37 Ga, suggesting zircons crystallized in magmas from old crust and/or juvenile materials from depleted mantle. Trace element data imply that most zircon grains were derived from mafic or doleritic rocks (Fig. 5). However, this could represent a misclassification of granitoid-derived zircons with unusually low Lu, Hf and Y concentration [11, 63].

6 Discussions

Since Lu and Hf are strongly fractionated during melt extraction from the mantle, the crust evolves with average $^{176}Lu/^{177}Hf$ ratio of 0.015, which is very different from that of the mantle (0.038). Consequently, magmas derived from old crust have Hf isotopic compositions distinct from those from juvenile materials derived from the depleted mantle. Therefore, U-Pb and Hf isotope data for the detrital zircons can be used to study the age and nature of the provenance rocks, and further to decipher the time-integrated history of continental crust in the region.

6.1 Time framework of the Ordos Terrane

The North China Craton, including both the Eastern and the Western Blocks, has been conventionally considered to be composed of Archean to Paleoproterozoic basement formed during four distinct tectonic cycles, named the Qianxi (>3.0 Ga), Fuping (3.0 -2.5 Ga), Wutai (2.5 -2.4 Ga) and Lüliang (2.4 -1.8 Ga) cycles [39, 64-67]. Although recent studies have abandoned the polycyclic model and its main assumption that the North China Craton has a single basement [23, 30, 41, 66, 68], and the three-fold tectonic subdivision has been widely accepted [17. 41, 69, 70], the basement of the Western Block is still considered to be dominated by late Archean rocks, just like its eastern counterpart.

The protoliths of the khondalites are mainly pelitic or arenaceous sediments. The major and trace elements indicate that the sediments experienced long journey of transportation and have been well mixed [48]. In addition, the khondalites are widely distributed around the borderlands of the Ordos Terrane. Therefore, we can assume that the khondalites cover a large area of sampling and represent the average composition of the Ordos Terrane. Thus, U-Pb zircon ages of this study can reflect the age of rocks exposed on the Ordos Terrane during the deposition of the protoliths of the khondalites. Data of this study indicate that the Ordos Terrane was covered by 1.84 to 2.32 Ga Paleoproterozoic, not Archean, rocks. Detrital zircons from khondalites in Jining [42, 44] and Lüliang Complexes [43] also yielded this age range.

6.2 The crustal growth history of the Ordos Terrane

The distributions of U/Pb zircon ages and Nd isotope data from the world-wide continental crust have been used to support the hypothesis of episodic growth of continents [71-73]. Previous Nd isotopic data from the Eastern Block, Trans-North China Orogen and Yinshan Terrane show a culmination of crustal growth from 3.8 to 2.6 Ga, and 2.8 Ga was considered as the best estimate of the major mantle extraction age for the North China Craton [74]. Our new U-Pb and Hf isotope data clearly indicate that this estimate can not apply to the Ordos Terrane. We have not found any U-Pb age older than 2.6 Ga from detrtal zircons (including the inherited or xenocrystal core) of the khondalites. In the composite plot of ε_{Hf} values versus

U-Pb age for all the analyzed zircons in this study (Fig. 6), the lowest ε_{Hf} values (except one) with different ages define an evolutionary line that extrapolates to intersect the depleted mantle line at about 2.6 Ga. This line represents the most felsic materials in the terrane, which are free of later interaction with juvenile materials from the depleted mantle. It may imply that the sedimentary provenance was underlain by a lower crust separated from the mantle at 2.6 Ga. This is consistent with previous Nd isotopic data for khondalites from the Helanshan [43], Jining and Lüliang Complexes [42], which have Nd isotope model age (T_{DM}) ranging from 2.5 to 2.8 Ga with a peak at 2.6 Ga. Hence, we suggest here that 2.6 Ga is the best estimate of the major mantle extraction age for the Ordos Terrane. The inherited or xenocrystal cores of the detrital zircons in this study give U-Pb ages up to 2.56 Ga, which is also consistent with this interpretation.

This study also reveals that ~2.0Ga was a major magmatic event for the Ordos Terrane. Almost all the detrital zircons from samples WL016 and WL020 formed during this important event. Zircon population of this age also exists in other samples. All zircons from sample WL016 have positive ε_{Hf}, and two grains plot near the depleted mantle line (Fig. 6), clearly indicating that their precursor magmas came from juvenile materials derived from the depleted mantle. The sample WL020 has ε_{Hf} values from -7 to +6, 30% zircon grains have positive ε_{Hf} values and the other 70% are negative, this large range in ε_{Hf} values may indicate mixing between magmas from old crust and from juvenile materials at about 2.0 Ga. Therefore we consider that 2.0 Ga was a major crustal growth time for the Ordos Terrane. Large amount of magmas from the mantle underplated or/and intruded the Ordos Terrane, and caused the partial melting of the lower crust at that time. A subordinate amount of detrital zircons have ages ~1.9 Ga. This may be a late stage of the same tectonic event, or alternatively a consequent event in the Western Block. We notice that ~1.9 Ga zircons mostly have negative ε_{Hf} values, suggesting juvenile materials were not significantly involved in the magma activity at ~1.9Ga.

Based on the results of this study, we proposed that the basement of the Ordos Terrane was largely extracted from the mantle at about 2.6 Ga, a significant crustal growth event happened at ~2.0 Ga, and this terrane was tectonically active during the period of 2.0 to 1.9 Ga. This is in strong contrast with the Eatern Block of the North China Craton, which has an early Archeaen (up to 3.8 Ga) and middle Archean (2.9 to 3.4 Ga) nuclei, late Archean (2.5 to 2.7 Ga) rocks are widespread, and 2.8 Ga is the best estimate of the major mantle extraction time. This clearly demonstrates that the Eastern and Western Blocks evolved separately before they collided to form the uniform North China Craton, thus, supporting the recently proposed three fold subdivision model for this Craton [13, 16, 17, 75].

6.3 Maximum depositional age of the khondalites

One of the key issues regarding the tectonic history of the North China Craton concerns the depositional age of the khondalites in the Western Block. Qian et al. [76] first proposed that these khondalites possibly represent a late Archean cover sequence unconformably overlying the middle Archean orthogneissic basement. Many other researchers also considered these khondalite suites are of late Archean age in their regional geological modeling [22, 39, 48, 77, 78]. However, this consideration is not consistent with isotopic geochronologocal data presented here.

Zircon CL images was used to investigate the internal structure of detrital zircons in this study and metamorphic overgrowth and xenocrytic or inherited cores were clearly identified. Therefore the spot isotope analyses can be conducted on well-defined detrital zircon grains and consequently the youngest age of detrital zircons can be used as a constraint on the maximum age of the deposition. The youngest nearly concordant age for the detrital zircon is 1844 ± 22 Ma (WL007-8), which is almost identical to that obtained from the Jining khondalites (1842 ± 16 Ma) [44]. Therefore, our results constrain 1.84Ga to be the maximum depositional age for the khondalites.

7. Conclusions

U-Pb and Hf isotopic data for detrital zircons show that the Wulashan khondalites came from a Paleoproterozoic sedimentary provenance, not an Archean source as previously considered. The minimum age of the detrital zircons indicates that the protoliths of the khondalites deposited not prior to 1.84 Ga. The Hf isotope data imply that the sedimentary provenance was underlain by a lower crust extracted from the mantle at 2.6 Ga. Our results also suggest a significant crustal growth event in the Ordos Terrane at about 2.0 Ga. This is in strong contrast with the Eastern Block of the North China Craton that has an early Archean (up to 3.8 Ga) and middle Archean (2.9 to 3.4 Ga) nuclei and late Archean (2.5 to 2.9 Ga) rocks are widespread. This suggests that the Eastern and Western blocks evolved separately before they collided to form the uniform North China Craton.

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Figure Captions

Fig.1. Tectonic subdivision of the North China Craton and spatial distribution of the khnodalites (followed Zhao et al. [37]).

Fig. 2. Distribution of basement rocks in the Wulashan area (after Lu et al. [48]).

Fig.3. Representative cathodoluminescence images for zircons from the Wulashan khondalites. Descriptions of zircons are included in the text.

Fig. 4. Concordia diagram of U-Pb zircon analytical results. The insets are histograms for the distribution of $^{207}Pb/^{206}Pb$ ages. Also shown are sum curves modeled by the Gauss distribution for all individual ages.

Fig. 5. Left: relative abundance of source rock types according to zircon compositions for each sample. Granitoid[1] represents granitoid with < 65% SiO_2, Granitoid[2] represents granitoid with 70~ 75% SiO_2, and Granitoid[3] represents granitoid with > 75% SiO_2. Centre: probability plots of ε_{Hf} values for each sample, with vertical dotted line indicating CHUR composition. Right: probability plots of T_{DM} data for each sample.

Fig. 6. Composite plots of ε_{Hf} values vs. $^{207}Pb/^{206}Pb$ age for the analyzed zircons from all the samples. The dotted line (with $^{176}Lu/^{177}Hf$ of 0.003) shows ε_{Hf} evolution of the lower crust in the Ordos Terrane