A rift system in southeastern Central Asian Orogenic Belt: constraint from sedimentological, geochronological and geochemical investigations of the Late Carboniferous-Early Permian strata in northern Inner Mongolia (China)

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11 Abstract:

12 The Late Carboniferous-Early Permian is the most controversial period for the
13 tectonic evolution of the southeastern Central Asian Orogenic Belt (CAOB). In this
14 study, we performed sedimentological and detrital zircon dating on the clastic
15 sediments, as well as zircon U-Pb age and geochemical analysis on the rhyolitic rocks
16 of the Late Carboniferous-Early Permian strata from northern Inner Mongolia (China).
17 The sedimentological analysis showed that the Late Carboniferous-Early Permian
18 sediments are composed of continental clastic and volcanic rocks with basal
19 conglomerate overlying the Devonian strata. The detrital zircon study revealed three
20 age peaks at ~300 Ma, ~440 Ma and ~530 Ma, indicating that the clastic rocks
21 derived from Paleozoic magmatic rocks and pre-Carboniferous sediments from
22 northern Inner Mongolia. The age data revealed that rhyolitic rocks from northern
23 Inner Mongolia extruded in two stages at Late Carboniferous and latest
24 Carboniferous-Early Permian. The Late Carboniferous rhyolites show I- to A-type
25 granitic affinities whereas the latest Carboniferous-Early Permian rhyolites have
26 A-type granitic characteristics. The difference suggests a transition of tectonic setting
27 from post-collisional extension to intraplate rift. The Late Carboniferous-Early
28 Permian strata from northern Inner Mongolia and South Mongolia show similar
29 sedimentary facies, detrital zircon age distribution and geochemistry features, hence
30 they were probably deposited in the same tectonic setting. A unified block was finally
31 proposed in northern Inner Mongolia and South Mongolia, where a rift system
32 provided an intra-continental sedimentary basin and induced intense syn-rift

magmatic activities. The intra-continental basin and syn-rift magmatism indicate that the Xing'an-Airgin Sum, Songliao-Hunshandake and South Mongolia Blocks in southeastern CAOB have been welded into a single continental block before the Late Carboniferous.

Key words: Paleo-Asian Ocean; Central Asian Orogenic Belt; northern Inner Mongolia; Late Carboniferous-Early Permian; rift; detrital zircon

1. Introduction

The Central Asian Orogenic Belt (CAOB), also referred as the Altaid Collage, represents the vast regions surrounded by the Siberian Craton, Tarim-North China Craton and the East European Craton (Sengör et al., 1993; Jahn et al., 2000; Safonova et al., 2011; Xiao et al., 2015). It was formed by successive accretion of magmatic arcs, accretionary prisms and microcontinents from Neoproterozoic to Late Paleozoic (Sengör et al., 1993; Kröner et al., 2007; 2014; Windley et al., 2007; Safonova, 2009; Safonova and Santosh, 2014; Xiao and Santosh, 2014; Xiao et al., 2015). During formation of the CAOB, significant amount of juvenile crust has been generated (Jahn et al., 2000; 2004; Kröner et al., 2014). The southeastern part of this gigantic belt, extending from South Mongolia, through Inner Mongolia to the northeastern China, recorded the Late Paleozoic closure of the Paleo-Asian Ocean related to the accretion of microcontinents to the northern margin of the North China Craton (NCC) (Fig. 1a) (Chen et al., 2000; Xiao et al., 2003; Yarmolyuk, et al., 2008; Kröner et al., 2010; Wu et al., 2011; Xu et al., 2013; 2015; Zhou and Wilde, 2013; Zhao et al., 2013; 2016;

55 Guy et al., 2014; Li et al., 2016). However, no consensus has been reached on the
 56 accretionary processes and the final closure of the Paleo-Asian Ocean. Broadly, two
 57 schools of thought have been proposed. The first considered that the final closure
 58 happened in the Late Permian-Early Triassic based on the geochemical studies of Late
 59 Carboniferous-Permian mafic-ultramafic intrusions and granitoids that were
 60 considered as ophiolite and magmatic arc, respectively (Chen et al., 2000; Song et al.,
 61 2015). The second proposed a Late Devonian closure on the basis of the Late
 62 Devonian unconformity and different deformation styles below and above the
 63 unconformity (Tang, 1990; Xu et al., 2013). Recent provenance studies from detrital
 64 zircon dating of Late Paleozoic sediments also led to these two thoughts (Eizenhöfer
 65 et al., 2014; Li et al., 2014b; Han et al., 2015; Luo et al., 2016; Chen et al., 2016).
 66 Meanwhile, the two viewpoints also result in different interpretation of
 67 Carboniferous-Permian tectonic evolution of south Mongolia and Inner Mongolia.
 68 Based on the abundant bimodal volcanic rocks, A-type granites and peralkaline
 69 granites in southern Mongolia and northern Inner Mongolia, a Late
 70 Carboniferous-Early Permian rift zone was proposed (Hong et al., 1994; Yarmolyuk et
 71 al., 2008; Tong et al., 2015). However, a northward subduction of the Paleo-Asian
 72 Ocean producing back-arc extension was also proposed to interpret these peralkaline
 73 granites and bimodal volcanic rocks (Zhang et al., 2011a; 2015). Therefore, whether
 74 an intraplate rift or back-arc related extension is still hotly debated for southern
 75 Mongolia-northern Inner Mongolia.

76 Previous studies in this region were mainly performed on the geochemistry of

magmatic rocks and structural analyses of accretionary complexes (Chen et al., 2000; Jian et al., 2008; Guy et al., 2014; Zhang et al., 2015). An integrated study of stratigraphy and the provenance of clastic sediments would help to reveal tectonic events (e.g., Hendrix et al., 1996; Henderson et al., 2010; DeCelles et al., 2014), and it has been well applied to understand the tectonic evolution of the CAO (e.g., Johnson et al., 2008; Safonova et al., 2010; Rojas-Agramonte et al., 2011; Heumann et al., 2012; Eizenhöfer et al., 2014; Li et al., 2014b; Chen et al., 2016). In order to resolve the controversial issue about the closure of the Paleo-Asian Ocean and to decipher the Late Paleozoic tectonic evolution of the southeastern CAO, we carried out stratigraphic analysis and detrital zircon dating on the clastic sequences, and geochemical study of volcanic rocks from the Late Carboniferous-Early Permian strata in northern Inner Mongolia (Fig. 1b) (IMBGMR, 1991; Zhao et al., 2014). Finally, a Late Carboniferous-Early Permian intra-continental rift system was proposed in southern Mongolia-northern Inner Mongolia after the final amalgamation of the CAO, which also indicate that the final closure of the Paleo-Asian Ocean occurred before the Late Carboniferous.

2. Geological Setting

Northern Inner Mongolia is located in northern China along the southeastern segment of the China-Mongolia border. It belongs to the western part of the Xing'an Block based on the new tectonic division by Xu et al. (2015) (Fig. 1a). To the north, the Cambrian Xinlin-Xiguitu suture zone separates the Xing'an Block from the

Erguna Block (Fig. 1a) (Xu et al., 2014). To the south, the Late Devonian-Early Carboniferous Xilinhote-Heihe suture zone separates the Xing'an Block from the Songliao Block (Fig. 1) (Zhang et al., 2011b; Xu et al., 2013). The basement of the Xing'an Block is composed of Meso- to Neoproterozoic metagabbro, gneiss, schist and carbonate (Ge et al., 2011; Sun et al., 2013; Xu et al., 2015). The Early Paleozoic units consist of Ordovician fine-grained clastic rocks and basaltic volcanic rocks, and Late Silurian *Tuvaella* brachiopod fauna-bearing carbonate-clastic sediments (IMBGMR, 1991; Wang et al., 2009).

The Devonian strata are widely distributed in the Xing'an Block, which are composed of sandstone and siltstone with intercalation of limestone. Both clastic and carbonate layers contain abundant shallow marine fossils, suggesting a shallow marine environment (IMBGMR, 1991). Note that plant fossils were discovered from the Late Devonian strata, indicating a transition of depositional facies from shallow marine to non-marine (IMBGR, 2008; Zhao et al., 2014).

After a ca. 40 Ma depositional hiatus, the ca. 3000 m-thick Late Carboniferous-Early Permian clastic-volcanic sequence, represented by the Baoligao and Gegenaobao Formations, unconformably cover the Devonian strata. Both formations consist of clastic rocks (e.g., conglomerate, coarse-grained sandstone and red beds) in the lower part and volcanic rocks in the upper part. The Angara flora identified from the clastic sediments reveals a continental depositional environment (Li et al., 1996). The upper volcanic units are composed of a bimodal sequence that consist of rhyolite, basaltic andesite and basalt, which has been considered as an

indicator of extensional tectonic setting (Zhang et al., 2011a; Li et al., 2014a). The bimodal sequence is coeval with the peralkaline-alkaline granites in northern Inner Mongolia and southern Mongolia (Zhang et al., 2015; Tong et al., 2015). Zircon dating from volcanic and alkaline granitic rocks revealed the emplacement time from 317 Ma to 276 Ma, and together they constitute a Late Carboniferous-Early Permian rift-related magmatic belt (Hong et al., 1994; 1996; Jahn et al., 2009; Xu et al., 2012; Li et al., 2014a; Tong et al., 2015).

Subsequent to the Early Mesozoic exhumation, the Late Jurassic volcanic rocks are widely distributed in northern Inner Mongolia (IMBGMR, 1991; Meng, 2003). From the Early Cretaceous, intraplate extension occurred in all of East Asia, producing NNE asymmetric grabens, metamorphic core complexes and extension-related magmatic rocks (Meng, 2003; Wang et al., 2011; Daoudene et al., 2012).

3. Stratigraphy and sedimentology

We carried out stratigraphic and sedimentological studies on the clastic sequence of the Baoligaomiao Formation in the Chaganaobao and Narenbaolige areas, and the coeval Gegenaobao Formation in the East-Ujimqin area. The location of each section is marked in Fig. 1b and the principal stratigraphic and sedimentological features are briefly described below:

3.1 The Chaganaobao area

The clastic sequence of the Baoligaomiao Formation in the Chaganaobao area is predominantly composed of purple conglomerate and coarse-grained sandstone, red

mudstone, with pyroclastic interlayers in the middle and upper stratigraphic levels
 (Fig. 2a). Purple conglomerate dominates the lower stratigraphic levels, which
 unconformably overlay the Devonian sandstone (IMBGR, 2007a). On the other hand,
 the laminated red siltstone dominates the middle part of this clastic sequence (Fig. 3a).
 Two layers of pyroclastics and tuffaceous siltstones were identified from the middle
 part of this sequence, indicating the existence of regional volcanism during their
 deposition (Fig. 2a). A ca. 160 m-thick conglomerate is situated on the top of this
 clastic sequence (Fig. 2a), the pebbles of which are rounded or sub-rounded, poorly
 sorted, with diameters of 0.5-10 cm (Fig. 3b). The clastic sequence is conformably
 covered by volcanic rocks (Fig. 2a). Abundant plant fossils that belong to the Angara
 flora in the age of Late Carboniferous were found within this formation, e.g.,
Noeggerathiopsis sp. and *Noe. Derzarinii Neuburg*, indicating a continental
 environment (IMBGR, 2007a).

3.2 The Narenbaolige area

The clastic sequence of the Baoligaomiao Formation in the Narenbaolige area
 consists predominantly of red conglomerate, purple and brown sandstone, with a few
 siltstone interlayers (Fig. 2b). Like in the Chaganaobao area, red conglomerate
 dominates the lower stratigraphic levels and unconformably covers the Devonian
 sandstone (Fig. 2b) (IMBGR, 2007b). The purple and brown sandstones and siltstones
 constitute the middle and upper stratigraphic levels (Fig. 2b), with pervasive
 horizontal beddings, indicating relatively stable depositional environment (Fig. 3c).

Limestone lenses and conglomerate blocks/interlayers can be observed within sandstone (Figs. 3d and 3e), indicating pulses of turbulence in a stable environment. A large number of plant fossils belonging to the Late Carboniferous Angara flora were identified from this formation, e.g., *Noeggerathiopsis* sp. and *Noe. Derzarinii*, suggesting a continental environment (IMBGR, 2007b).

3.3 The East-Ujimqin area

The clastic sequence of the Gegenaobao Formation in the East-Ujimqin area is ca. 1400 m-thick and unconformably overlies the Upper Devonian sandstone (Fig. 2). It consists of conglomerate at the bottom, conglomerate interbedded with siltstone and mudstone in the middle, and thin bedded sandstone in the upper part (Fig. 2c). The conglomerate is massive. The poorly sorted pebbles are rounded or subrounded with sizes from millimeters to decimeters (Fig. 3f). These features indicate an alluvial facies deposition. For the middle stratigraphic level, the pebbles within conglomerate layers are much smaller, showing upward fining graded bedding, and a sharp contact with black mudstone or siltstone (Figs. 3g and 3h). In the black mudstone and siltstone, the Angara flora in the age of Late Carboniferous was identified by previous studies, e.g., *Noeggerathiopsis* sp. (IMBGMR, 1991; IMBGR, 2008). The interbedded conglomerate with mudstone /siltstone represents a rapid change of depositional environment. This rock assemblage shows the same features with that of meandering fluvial facies deposition. The sandstones in the upper stratigraphic levels are thin bedded without obvious sedimentary structure, indicating a relatively stable

depositional environment. Meanwhile, shallow marine fossils, instead of the Angara flora, were identified from the upper part of the Gegenaobao Formation (IMBGR, 2008). This fossil-type variation indicates that the depositional environment changes from non-marine to shallow marine.

4. Detrital zircon geochronology of sedimentary strata

Sandstone samples were collected from the clastic sequence of the Baoligaomiao and Gegenaobao Formations in the Chaganaobao, Narenbaolige and East-Ujimqin areas (Figs. 1b and 2).

4.1 The Chaganaobao area

Two sandstone samples were collected from the bottom (#140531-40) and upper (#100717-05) part of the clastic sequence in the Chaganaobao area (Fig. 2).

The majority of zircon grains from sample 140531-40 are euhedral to subrounded, with width in the range from 60 to 150 μm and length from 90 to 250 μm (Fig. 4b). The Th/U ratios ranging from 0.11 to 1.19, combined with the oscillatory growth zoning (Fig. 4a), indicate a magmatic origin for the analyzed zircon grains (e.g., Rubatto, 2002; Corfu et al., 2003). All 75 analysed grains are concordant, with ages in the range of 314 ± 3 Ma to 3122 ± 13 Ma, and fall into a main age group at 314-569 Ma ($N = 70$), with peaks at 332 Ma and 500 Ma (Supplementary Table 1; Figs. 5a and 5b). Meanwhile, two grains yielded Neoproterozoic ages at 834 ± 9 Ma and 840 ± 10 Ma, and two grains yielded Paleoproterozoic ages at 1756 ± 18 Ma and 1833 ± 19 Ma, and one grain yielded an Archean age of 3122 ± 13 Ma

(Supplementary Table 1).

Most zircons from sample 100717-05 are euhedral to subrounded, with width of 40-60 μm and length from 60 to 90 μm (Fig. 4b). Most zircon grains show oscillatory zoning with Th/U ratios ranging from 0.14 to 1.08, revealing a magmatic origin. The 66 concordant grains from total 75 analyses yield ages ranging from 299 ± 7 Ma to 1473 ± 10 Ma and fall into a single age cluster at 299-565 Ma ($N = 61$) with peak ages at 328 Ma and 369 Ma, and a secondary peak at 307 Ma (Figs. 5c and 5d; Supplementary Table 1). In addition, four grains yielded Neoproterozoic ages from 787 ± 9 Ma to 936 ± 9 Ma, and one grain yielded a Mesoproterozoic age of 1473 ± 10 Ma (Supplementary Table 1).

4.2 The Narenbaolige area

The majority of zircon grains from sample 100721-08 are subhedral or subrounded, with width in the range from 40 to 80 μm and length of 60 - 150 μm (Fig. 4c). Most zircons show oscillatory zoning (Fig. 4c), with Th/U ratios from 0.13 to 1.79, suggesting their magmatic origin. 73 out of 76 analyses are concordant, yielding ages in the range of 275 ± 3 Ma to 3043 ± 13 Ma. The ages constitute a main age group at 275-542 Ma ($N = 66$), with three peaks at 447 Ma, 324 Ma and 279 Ma (Supplementary Table 1; Figs. 5e and 5f). Meanwhile, six grains yielded Proterozoic ages from 1117 ± 12 Ma to 1952 ± 15 Ma, and one grain yielded an Archean age of 3043 ± 13 Ma (Supplementary Table 1).

4.3 The East-Ujimqin area

For sample 100722-30, most zircons are euhedral to subhedral, ranging from

50-80 μm wide and 80 to 150 μm long (Fig. 4d). The clear oscillatory zoning combined with high Th/U ratios (0.35 - 1.10), indicate a magmatic origin. 74 out of 75 analyses are concordant (Supplementary Table 1). Except one grain giving an Early Paleozoic age of 432 ± 5 Ma, the other 73 grains fall into one main age populations ranging from 280 ± 3 Ma to 336 ± 3 Ma (Supplementary Table 1; Figs. 5g and 5h) with peak ages at 304 Ma and 314 Ma, and a secondary peak at 285 Ma (Fig. 5h).

5. Late Carboniferous-Early Permian volcanic rocks

Rhyolite samples were collected from the volcanic sequence of the Baoligaomiao Formation in the Chaganaobao, Baiyinwula and Alatanheli areas (Fig. 1b).

5.1 Zircon U-Pb dating results

5.1.1 Chaganaobao area

Zircon grains from two rhyolite samples (#140531-08 and #140531-45) are euhedral, with length/width ratios from 2 to 3. All grains show well developed oscillatory zoning (Figs. 4e and 4f). Nine inherited zircon grains from sample 130531-45 display ages from 434 ± 4 Ma to 1524 ± 15 Ma (Fig. 6a; Supplementary Table 2). After excluding a young age of 294 ± 5 Ma, other 13 grains fall in a cluster from 306 ± 4 Ma to 326 ± 4 Ma, that yield a weighted-mean $^{206}\text{Pb}/^{238}\text{U}$ age of 316 ± 4 Ma (MSWD = 2.3; Figs. 6a and 6b; Supplementary Table 2). For sample 130531-45, twenty-four out of 25 analyzed grains are concordant, falling in a cluster from 288 ± 7 Ma to 330 ± 3 Ma (Supplementary Table 2). After excluding an ungrouped young

grain with age of 288 ± 7 Ma and grains with ages over 310 Ma, ten concentrated grains fall in the age range from 307 ± 4 Ma to 298 ± 3 Ma and yield a weighted-mean $^{206}\text{Pb}/^{238}\text{U}$ age at 302 ± 3 Ma (MSWD = 0.63; Figs. 6c and 6d). This mean age is interpreted as the crystallization time of the rhyolite.

5.1.2 Baiyinwula area

Zircon grains from rhyolite sample (#100718-55) are euhedral, with length from 100 to 200 μm and width of 60-100 μm . The oscillatory zoning revealed by the CL images (Fig. 4g) and high Th/U ratios (0.56 to 2.06), suggest their magmatic origin. Twenty-two of the total 25 analyzed grains are concordant, falling in a cluster from 286 ± 4 Ma to 310 ± 4 Ma (Supplementary Table 2). A weighted-mean $^{206}\text{Pb}/^{238}\text{U}$ age of 298 ± 4 Ma was calculated (MSWD = 3.0; Figs. 6e and 6f), which represents the extrusive age for the rhyolite.

5.1.3 Alatanheli area

Zircon grains from rhyolite sample (#140530-19) are euhedral, with length from 100 to 250 μm and width of 60-100 μm . The CL images reveal oscillatory zoning for most grains (Fig. 4h) and their Th/U ratios are in the range of 0.34 to 0.72, suggesting the magmatic origin. All 25 analyzed grains are concordant. Except one Neoproterozoic grain (720 ± 7 Ma), 24 grains fall in a cluster from 302 ± 3 Ma to 324 ± 4 Ma (Supplementary Table 2). Eighteen concentrated grains give a weighted-mean $^{206}\text{Pb}/^{238}\text{U}$ age at 313 ± 2 Ma (MSWD = 1.0; Figs. 6g and 6h), representing the crystallization age of the rhyolite.

5.2 Geochemistry results

Whole rock major and trace elemental results of rhyolites from the Chaganaobao, Baiyinwula and Alatanheli areas are presented in Supplementary Table 3. Based on the age and geochemical differences, we divided these rhyolite samples into early stage rhyolite (with zircon ages at 313-315 Ma; #140531-04, 05 and #140530-17, 25, 26, 28) and late stage rhyolite (with zircon ages at 298-305 Ma; #140531-45 and #100718-47~51) (Supplementary Table 3).

Major elements for rhyolite samples of both stages show not clear differences. All rhyolite samples exhibit high SiO_2 content (72 - 78 wt.%), total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 5.3 - 9.0$ wt.%), and low CaO (0.07 - 1.27 wt.%) and MgO (0.02 - 1.10 wt.%) (Supplementary Table 3). In the SiO_2 versus Zr/TiO_2 diagram, all samples fall into the rhyolite field (Fig. 7a). In the K_2O vs SiO_2 diagram, all samples display high K_2O content and belong to the high-K and medium-K series (Fig. 7b), with $\text{K}_2\text{O/Na}_2\text{O}$ ratios of 0.76 - 1.67.

For trace elements, rhyolite samples of two stages display obvious differences. In the chondrite normalized rare earth elements (REE) diagrams, the early stage rhyolites show a slight enrichment of light REE, and flat high REE, with $(\text{La/Yb})_N$ ratios of 7.1 - 9.2 and slightly negative Eu anomalies ($\delta\text{Eu} = 0.51 - 0.76$) (Figs. 7c and 7G), whereas the late stage rhyolites have $(\text{La/Yb})_N$ ratios in the range of 1.8 to 6.8, and strong negative Eu anomalies ($\delta\text{Eu} = 0.09 - 0.36$) (Figs. 7c and 7e). In the Primitive Mantle (PM) normalized spidergram, the early stage rhyolites show enrichment in large ion lithophile elements (LILE), and obvious depletion of Ba, Sr, P and Ti, whereas the late stage rhyolites have much intensive enrichment of LILE and

depletion in Ba, Sr, P and Ti (Fig. 7).

In the $10000 \times \text{Ga}/\text{Al}$ versus $\text{Zr}+\text{Nb}+\text{Ce}+\text{Y}$ diagram, rhyolite samples of the early stage fall into both the I-type and A-type granites fields, whereas samples of the late stages fall into the A-type granites field (Fig. 8a) (Whalen et al., 1987). In the Nb-Y-Ce diagram (Eby, 1992), they all fall into the A2 field (Fig. 8b), indicating a post-orogenic extensional tectonic setting. In the Y+Nb versus Rb diagram and Y versus Nb diagram, rhyolite samples of the early stage fall into the post-orogenic granite or volcanic arc granite + syn-collisional granite fields, while samples of the late stages fall into the within-plate granite field (Figs. 8c and 8d) (Pearce et al., 1984). Meanwhile, the rhyolite of the late stage display nearly identical REE and trace element distributions (Figs. 7c~7f), and fall into the same field in the tectonic discrimination diagrams as that of the Early Permian A-type granite in Baiyinwula area (Fig. 8) (Zhang et al., 2015), indicating that they may evolved from the same magma chamber with the same petrogenesis. Note that the whole data set appear to suggest an approaching trend to A-type and within-plate granites from the early stage to the late stage rhyolites (Fig.s 8).

6. Discussion

6.1 Paleogeographic reconstruction of North Inner Mongolia and South Mongolia

From the aforementioned strata relationship, an unconformable contact between the basal conglomerates of the Late Carboniferous-Early Permian strata and underlying Devonian sandstone has been identified (Fig. 2). Meanwhile, Zhou et al.

(2015) identified that the Hegenshan ophiolite was unconformably overlain by the Geogenaobao Formation with pebbles of ultramafic rocks and cherts, postdating the emplacement of this ophiolite. Both the Baoligaomiao Formation and the lower part of Gegenaobao Formation present the same stratigraphic transition from basal conglomerate, through coarse-grained sandstone to red siltstone, with the abundant Angara flora that can be correlated. These features indicate that they were deposited in the similar continental environment. Furthermore, in the East-Ujimqin area, shallow marine fossils identified from upper layers of the Gegenaobao Formation suggest the transition of depositional environment from non-marine to marine. The Angara flora has been used to assign these strata as of the Late Carboniferous-Early Permian age (IMBGMR, 1991). However, the present detrital zircon dating yielded the youngest age of each sample at 299 ± 7 Ma, 275 ± 3 Ma and 280 ± 3 Ma (Figs. 4 and 5), indicating that both the Baoligaomiao and Gegenaobao Formations were deposited not earlier than Early Permian. Thus, we may assign these strata as an Early Permian sedimentary sequence. In addition, an intracontinental non-marine basin probably existed in northern Inner Mongolia (the western part of Xing'an Block) in the Early Permian, which was responsible for the Baoligaomiao and Gegenaobao Formations continental facies sediments.

Early Permian deposits are equally well exposed in the South Mongolia. They also comprise non-marine clastic and volcanic rocks (Lamb and Badarch, 2001; Johnson et al., 2008; Kröner et al., 2010), with abundant Angara flora (Hanžl and Aichler, 2007; Yarmolyuk et al., 2008). Johnson et al. (2008) divided the region of

South Mongolia into three sub-regions of Southwest Mongolia, South-Central Mongolia and Southeast Mongolia to show their distinct sedimentary features (Fig. 9). The Early Permian deposits in these three sub-regions display unconformable and fault contact with underlying strata (Johnson et al., 2008), which is similar to that of the northern Inner Mongolia (Fig. 9). In the Southwest Mongolia, the non-marine deposits are dominated by ~300 m-thick non-marine clastic rocks and felsic-intermediate volcanic rocks of the Ulaan Nur Formation (Fig. 9a) (Johnson et al., 2008). The South-Central Mongolia and Southeast Mongolia sub-regions display the same sedimentary features, with ~100 m-thick volcanic rocks and red beds of the Argalant Formation (Figs. 9b and 9c) (Johnson et al., 2008; Kröner et al., 2010; Heumann et al., 2012). These sedimentological features are identical with the Baoligaomiao Formation in northern Inner Mongolia, which displays non-marine conglomerate and red beds and volcanic rocks (Fig. 9d), with abundant Angara flora (IMBGMR, 1991). Note that, the Angara flora fossils found in these four sub-regions are comparable (Huang and Ding, 1998), indicating that these four sub-regions belong to a unified block or even the same sedimentary basin during the Early Permian. For the South-Central Mongolia and Southeast Mongolia sub-regions, shallow marine clastic and carbonate deposits evolved above the Argalant Formation non-marine deposits, showing the same transition from non-marine to shallow marine environment as the Gengaoaobao Formation in East-Ujimqin area (Fig. 9).

These sedimentological and paleontological similarities indicate that non-marine depositional environment prevailed in the South Mongolia and northern Inner

Mongolia during the Early Permian. Lamb and Badarch, (2001) proposed that a non-marine basin existed in the entire South Mongolia during the Early Permian following the Carboniferous arc system, postdating the closure of the oceanic basin between Mongolia and tectonic blocks of China. Based on the synthesized study of sedimentary and magmatic rocks in Southwest Mongolia, Kröner et al. (2010) concluded that the oceanic domain and continental domain of Southwest Mongolia (South Gobi Zone) were assembled into a single continental block prior to the Late Paleozoic, followed by the Early Permian extensional related magmatism and plant fossils bearing non-marine deposits. Taking the above arguments into considerations, we proposed that a single continental block (here we call it as South Mongolia Microcontinent) formed along the China-Mongolia border, including the entire South Mongolia and northern Inner Mongolia (Fig. 9). This microcontinent may extend eastward to the Erguna Block of Northeast China, which came into the intracontinental terrestrial evolution from the latest Carboniferous to the Permian (IMBGMR, 1991; Cui et al., 2013; Zhang et al., 2011b).

6.2 Provenance analysis and comparison of geochronological data

All four sandstone samples present consistent detrital zircon age histograms, which are characterized by dominant Late Carboniferous age peaks around 310-320 Ma and Early Paleozoic age peaks around 449 Ma and 500 Ma, with a few Proterozoic and Archean grains (Figs. 5 and 10a). It may indicate the same provenance for the Early Permian sediments in these three localities.

6.2.1 Late Carboniferous age peak

The most striking characteristic of detrital zircon age patterns for both northern Inner Mongolia and South Mongolia is the predominant age population of 360-280 Ma with an age peak at ~310 Ma (Figs. 10a and 10b). This significant age group has been well documented from both northern Inner Mongolia and South Mongolia by zircon U-Pb dating of granitic and volcanic rocks (Yarmolyuk et al., 2008; Blight et al., 2010a,b; Kröner et al., 2010; Wainwright et al., 2011; Economos et al., 2012; Zhang et al., 2011a, 2015; Tong et al., 2015). For northern Inner Mongolia, magmatic rocks of this age group were considered to be emplaced in an extensional environment (Zhang et al., 2011a; 2015; Li et al., 2014a; Tong et al., 2015). However, for South Mongolia, debates still exist, especially about the Carboniferous magmatic rocks. Yarmolyuk et al. (2008) proposed that the subduction-related arc magmatism ceased at 330 Ma, and followed by 320-280 Ma rift-related magmatic rocks. By contrast, other authors proposed that both the Early and Late Carboniferous magmatic rocks formed in arc setting, whereas the Early Permian rocks were produced as a result of regional extension and subsequent melting of the accreted crust (Kröner et al., 2010; Blight et al., 2010a,b; Wainwright et al., 2011; Economos et al., 2012). Despite the disagreement, the provenance for this age group is the Carboniferous-Permian granitoids and volcanic rocks from northern Inner Mongolia and South Mongolia. This age group has also been identified in igneous (Xu et al., 2014 and references therein) and sedimentary rocks from central Inner Mongolia (Fig. 9c) (Zhao et al., 2016). However, central Inner Mongolia experienced an extensive transgression

1 407 during the Late Carboniferous-Early Permian, which resulted in an intracontinental
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3 408 marine environment (Zhao et al., 2016). Hence, magmatic rocks from Central Inner
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6 409 Mongolia cannot be the source region for the terrestrial deposits in northern Inner
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11 411 6.2.2 Early Paleozoic age peaks

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14 412 The Early Paleozoic age groups around 449 Ma and 500 Ma are recognized from
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17 413 detrital zircon dating of the Late Paleozoic and Early Paleozoic strata along the
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20 414 China-Mongolia border (Fig. 10). The Early Paleozoic granitoids have been identified
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23 415 in South Mongolia (Helo et al., 2006; Kröner et al., 2010; 2011), Southeast Mongolia
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26 416 (Sorokin et al., 2011; Guo et al., 2013) and Northeast China (Wu et al., 2005; 2011;
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28 417 Ge et al., 2005; 2007). The amalgamation of the Erguna and Xing'an Blocks caused
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31 418 Cambrian arc magmatism and Ordovician-Silurian post-orogenic magmatism in
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34 419 Northeast China and Southeast Mongolia (Wu et al., 2005, 2012; Ge et al., 2007; Guo
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37 420 et al., 2013; Sorokin et al., 2011), corresponding to these two Early Paleozoic peaks.
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40 421 Cambrian granitoids were also identified in the Baga Bogd Massif of South Mongolia,
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42 422 Lake Zone and the Gobi-Altai zone of Southwest Mongolia (Demoux et al., 2009;
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45 423 Kröner et al., 2010, 2011; Hanžl and Aichler, 2007), suggesting a regional thermal
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48 424 event on the basement of South Mongolia. Subsequently, as the oceanic subduction
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51 425 occurred during the Ordovician-Early Devonian, arc-related magmatism dominated
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54 426 the entire South Mongolia (Helo et al., 2006; Kröner et al., 2010). Magmatic rocks
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57 427 from the two episodes can provide sources for these two Early Paleozoic age peaks.
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60 428 Meanwhile, these two Early Paleozoic age groups can also be revealed by detrital

zircon analyses of the Ordovician and Devonian strata from South Mongolia (Gibson et al., 2013) and northern Inner Mongolia (Fig. 10d) (Zhao et al., 2014). Considering the unconformity between the Permian strata and underlying Devonian clastic rocks, recycling of older clastic rocks can also provide source for these two age peaks. Therefore, these two Early Paleozoic age groups mostly derived from the Early Paleozoic magmatic rocks and recycling of pre-Carboniferous strata in northern Inner Mongolia and South Mongolia.

6.2.3 Precambrian ages

Precambrian zircon grains can be traced from two samples with predominant Meso- to Neo-proterozoic grains (Fig. 5). Similar Precambrian grains can also be identified from the Early Permian strata from South Mongolia (Fig. 10b). Precambrian gneisses and granitoids have been found from Southwest Mongolia (Kröner et al., 2010), Southeast Mongolia (Demoux et al., 2009) and northern Inner Mongolia (Wang et al., 2001; Sun et al., 2013; Xu et al., 2015). Their zircon U-Pb dating shows similar predominant Neoproterozoic and subordinate Mesoproterozoic ages. Although there is still no consensus about whether these Precambrian basements belong to a single microcontinent or separate blocks within the CAOB, they may provide sources for these Precambrian grains.

6.3 Tectonic setting of rhyolite and Late Carboniferous-Early Permian rift-related magmatic belt in Central Asia

The early stage (315-313 Ma; Late Carboniferous) rhyolites have I-type to A-type

granitic geochemical characteristics (Figs. 7 and 8), whereas the late stage (305-298 Ma; latest Carboniferous-Early Permian) rhyolites show the typical geochemical features of A-type granite (Whalen et al., 1987; Eby, 1990; Jahn et al., 2001; 2009; Wu et al., 2002). This type of transitional geochemistry can also be identified from the Transbaikalia magmatic belt, where early stage calc-alkaline granites were considered as post-collisional and the late stage alkaline granites were in within-plate setting (Litvinovsky et al., 2011). Meanwhile, Hong et al. (1994; 1996) first identified the Early Permian alkaline granites in northern Inner Mongolia, which belong to A-type granites and constitute a post-orogenic granitic belt (Fig. 11). In recent years, A-type granites, bimodal volcanic rocks and gabbros are increasingly recognized in this belt. In northern Inner Mongolia, U-Pb zircon dating revealed that they were emplaced in the Late Carboniferous-Early Permian (Fig. 11) (Xu et al., 2012; Zhang et al., 2011a; 2015; Li et al., 2014a; Tong et al., 2015), and geochemical studies support their generation in a regional extension environment. Meanwhile, basalt and gabbro reported from Baiyinwula and East-Ujimqin areas also show an intraplate geological setting (Cheng et al., 2014). For South Mongolia, Yarmolyuk et al. (2008) proposed a model of two-stage magmatic evolution: the 350-330 Ma magmatic rocks formed in a continental marginal arc, while the 320-280 Ma rocks in an extensional setting with two rift belts (Fig. 11). However, based on the arc affinity of the Late Carboniferous granitoids, some authors proposed that a Late Carboniferous subduction occurred in South Mongolia, followed by the latest Carboniferous-Early Permian post-collisional / post-orogenic thermal event, which led to the emplacement of bimodal volcanic rocks

and alkaline granites, and the formation of grabens and non-marine basins (Blight et al., 2010a; Kröner et al., 2010; Guy et al., 2014; 2015). Synthesizing these studies, the rift formation in South Mongolia might have started from the latest Carboniferous, and reached the climax during Early Permian with intense magmatism and continental facies sediments. The rift belt might extend eastwards and connect with the coeval alkaline magmatism and continental facies sediments in northern Inner Mongolia. However, the Carboniferous pre-rift evolution in South Mongolia and northern Inner Mongolia is different. In South Mongolia, the Devonian-Carboniferous oceanic subduction produced voluminous arc magmatic rocks, leading to the growth of continental crust and accretionary processes (Guy et al., 2014). The final amalgamation occurred in the latest Carboniferous and followed by post-orogenic extension, which means that the rift in South Mongolia developed in a post-orogenic geological setting (Kröner et al., 2010; Guy et al., 2014). While for northern Inner Mongolia, it experienced a long-term (ca. 40 Ma) exhumation from the Late Devonian to the Early Carboniferous (IMBGMR, 1991; Zhao et al., 2014). The regional extension began from the Late Carboniferous with magmatism and deposits, indicating that the rift in northern Inner Mongolia evolved in an intraplate setting.

Although the Early Permian extension model is accepted by most workers, the Early Permian magmatic arc model is still proposed for Southwest Mongolia based on the arc affinity of the Early Permian magmatic rocks, and this arc extends westward and connects with coeval magmatic arc in the Gobi-Tianshan region (Economos et al., 2012). This proposal is based on the interpretation of granodiorite, syenogranitic sheet,

andesite dike and rhyolite, which have the same U-Pb age of 290-295 Ma and positive $\epsilon_{\text{Nd}}(t)$, thus probable generation from the same magma chamber. However, the arc model cannot explain the association of bimodal volcanic rocks, A-type granites and peralkaline granites in this region (Yarmolyuk et al., 2008). Meanwhile the coexistence of mafic enclave-bearing granodiorite, syenogranite and dike swarms usually represents an extensional setting (Yang et al., 2006; Wong et al., 2009). In addition, from the structural geology study of olistostrome and geochemical analysis of bimodal volcanism in the Bogda Shan, Shu et al. (2011) proposed that an extension initiated from ca. 300 Ma in the Gobi-Tianshan, and reached the peak during the Early Permian. Hence, the model of Early Permian arc in Southwest Mongolia is probably debatable.

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6.4 Tectonic implications

Microblocks between the North China Craton and the Siberian Craton separate the Paleo-Asian Ocean into several branches. Successive collisions of these microblocks result in the gradual closure of each branch. The presented study confirms that a regional extension occurred in South Mongolia and northern Inner Mongolia during the latest Carboniferous-Early Permian, which led to several parallel rift belts (Fig. 11). The rift belts also indicate that the Paleo-Asian Ocean branch in this region has closed before the latest Carboniferous. The rift belts are thought to be caused by upwelling of voluminous magma and the scenario may be viewed as: (1) the beginning of magmatism (Late Carboniferous) is slightly older than the

sedimentary deposition (Early Permian), (2) the conglomerate at the bottom of the sedimentary strata contains abundant magmatic pebbles.

From multidisciplinary studies of two subparallel orogenic belts between North China Craton, Songliao Block and Xing'an Block (Fig. 1a), the final collision between the North China Craton and the Songliao Block was confined to Late Silurian-Early Devonian, while that of Songliao Block and Xing'an Block was confined to Late Devonian-Early Carboniferous (Xu et al., 2014; 2015). Meanwhile, the paleomagnetic results show the similar paleolatitudes of these three blocks during the Late Carboniferous and Early Permian, indicating that amalgamation of these three blocks occurred before the Late Carboniferous (Pruner, 1987; Chen et al., 1997; Li et al., 2012; Zhao et al., 2013). Moreover, mixture of Angara flora and Cathaysian flora was identified from the Late Carboniferous and Early-Middle Permian strata in western Xing'an Block, also indicating a pre-Late Carboniferous amalgamation (Zhou et al., 2010; Xin et al., 2011). After the amalgamation, the whole area came into an extensional setting, leading to intense magmatic events and non-marine basinal deposition in South Mongolia and northern Inner Mongolia (Fig. 9) (Lamb and Badarch, 2001; Johnson et al., 2008; Yarmolyuk et al., 2008; Kröner et al., 2010). The above evidence indicates that the Paleo-Asian Ocean between the North China Craton and South Mongolia has closed at least before the Late Carboniferous.

During Late Carboniferous-Early Permian, shallow marine clastic-carbonate deposits, represented by Benbatu and Amushan Formations, dominated the central Inner Mongolia. The deposits are considered as the inland sea deposits above the

welded continent (Fig. 12) (Zhao et al., 2016). These shallow marine sediments were related to post-orogenic extension and transgression, and can be considered as the first sedimentary cover after the orogenic events (Zhao et al., 2016). Further to the south, Late Carboniferous-Early Permian coal-bearing sediments dominated the northern margin of the North China Craton (Cope et al., 2005). These three sedimentary facies constitute the main paleogeographic features from Inner Mongolia to South Mongolia.

7. Conclusions

Based on the new sedimentological analysis, detrital zircon dating and geochemical study of the Late Carboniferous-Early Permian sedimentary-volcanic rocks in northern Inner Mongolia, and their comparison with coeval strata in South Mongolia, we come to the following conclusions:

(1) The Late Carboniferous-Early Permian deposits in northern Inner Mongolia are characterized by continental facies clastic and volcanic rocks of continental facies with basal conglomerate unconformably overlying the Devonian strata.

(2) The detrital zircon dating on sandstones from the lower part of the strata revealed three age peaks at ~300 Ma, ~440 Ma and ~530Ma. A comparison with the literature for the neighbouring regions indicates that the source of the sedimentary rocks came from Paleozoic magmatic rocks and recycling of pre-Carboniferous sediments in northern Inner Mongolia.

(3) Rhyolites from northern Inner Mongolia extruded at two stages: late Carboniferous and latest Carboniferous-Early Permian. The late Carboniferous

1 561 rhyolites show I- to A-type granitic affinities whereas the latest Carboniferous-Early
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3 562 Permian rhyolites have A-type granitic characteristics. They were generated in an
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6 563 extensional environment related to post-collisional and intraplate tectonic setting,
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11 565 (4) The Late Carboniferous-Early Permian strata from northern Inner Mongolia
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14 566 and South Mongolia show the same sedimentological features, detrital zircon age
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17 567 pattern and geochemical characteristics, indicating that they were deposited probably
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20 568 in the same tectonic setting. A rift system for the intra-continental basin sediments and
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23 569 extensive syn-rift magmatism was proposed in this region.

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48
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51
52 579 “Continental construction in Central Asia”.

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54 581 Appendix: Analytical procedures

55 582 A.1. LA-ICPMS zircon U-Pb dating

Zircon grains were separated using the conventional heavy liquid and magnetic techniques, followed by handpicking under a binocular microscope at the Langfang Regional Geological Survey, Hebei Province, China. Handpicked zircon grains were photographed with transmitted and reflected light under optical microscope. This was followed by cathodoluminescence (CL) imaging using a Quanta 200 FEG Scanning Electron Microscope at Peking University. The CL images revealed internal textures and helped us choose the best spots for U-Pb analyses. Zircon U-Pb dating was carried out using an Agilent 7500c ICP-MS coupled with a 193-nm ArFExcimer laser with an automatic positioning system at the Key Laboratory of Orogen and Crust Evolution, Peking University. Calibrations for zircon analyses were carried out using NIST 610 glass as an external standard and Si as internal standard. U-Pb isotope fractionation effects were corrected using zircon Plesovice (337 Ma) as external standard. Zircon standard 91500 was used as a secondary standard to monitor the deviation of age measurement/calculation. Isotopic ratios and element concentrations of zircon grains were calculated using software GLITTER (ver. 4.4.2, Macquarie University). Concordia ages and diagrams were obtained using Isoplot/Ex (3.0) (Ludwig, 2003). Common Pb correction was made following the method of Andersen (2002). The analytical data are presented on U-Pb concordia diagrams with 1σ errors. The mean ages are weighted means at 95% confidence levels (Ludwig, 2003).

A.2. Whole-rock major and trace element geochemistry

Major elemental compositions were analyzed using X-ray Fluorescence (XRF, Thermo Arl Advant XP+) at the Key Laboratory of Orogenic Belts and Crustal

Evolution, School of Earth and Space Sciences, Peking University. The precision is 0.5% for major element oxides. Loss on ignition (LOI) was measured by placing 1 g of sample in furnace at 1000 °C for several hours before being cooled in desiccators and reweighing. For trace element analyses, the chemical preparation and mass analysis were carried out at Insititute of Earth Science (IES), Academia Sinica, Taipei. About 200 mg of powdered sample was dissolved in amixture of HF and HNO₃ (2:1) in a screw-top Savillex Teflon beaker for 5–7 days at 100°C. This was followed by evaporation to dryness, refluxing in 6N HCl and drying twice, and finally redissolution in 1N HCl. The procedure was repeated until complete dissolution was achieved. Trace element analysis was performed using an Agilent 7500s at Department of geosciences, National Taiwan University. The standard reference materials used for trace element analyses are AGV-2, BCR-2, BHVO-2, BIR9-1 and DNC-1. Analytical errors are 0.5–3% for major elements and 1–10%for trace elements, depending on the concentrations.

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Figure captions:

Figure 1. (a) Tectonic sketch map of Northeastern China, modified after Wu et al. (2007) and Xu et al. (2015). (b) Geological map of North Inner Mongolia of the Xing'an-Airgin Sum Block from the Erenhot to East Ujimqin, after Zhao et al., 2014.

Figure 2. Measured stratigraphic sections of the Late Carboniferous-Early Permian Baoligaomiao Formation in the Chaganaobao and Narenbaolige areas, and Gegenaobao Formation in the East-Ujimqin area, showing lithology and sample sites.

Figure 3. Photographs of lithofacies from the Baoligaomiao Formation in the Chaganaobao (a-b) and Narenbaolige (c-e) areas, and the Gegenaobao Formation in the East-Ujimqin area (f-h). (a) Red beds; (b) Fluvial conglomerate; (c) Purple sandstone with horizontal beddings; (d) Conglomerate interbeds within sandstone; (e) Limestone lens within sandstone; (f) Rounded pebbles within the basal conglomerate; (g) Sharp contact between conglomerate and black mudstone; (h) Interbedded conglomerate and siltstone.

Figure 4. Cathodoluminescence (CL) images of selected zircon grains from each sample. The circles represent U-Pb analytical sites with ages presented below.

Figure 5. U-Pb concordia and probability diagrams of detrital zircon ages from each sandstone sample.

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1023 Figure 6. U-Pb concordia diagram and weighted mean age plot of four rhyolite
1024 samples.

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1026 Figure 7. Geochemical classification diagrams for the Late Carboniferous-Early

1027 Permian rhyolite. (a) Zr/TiO₂ vs. SiO₂ diagram (after Winchester and Floyd, 1976); (b)

1028 SiO₂-K₂O diagram (after Le Maitre, 1989); (c, e and g) Chondrite-normalized REE

1029 patterns; (d, f and h) Primitive mantle-normalized spider diagrams. Chondrite and

1030 primitive mantle normalizing values are from Sun and McDonough (1989).

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1032 Figure 8. (a) 10,000 Ga/Al vs. Zr+Nb+Ce+Y discrimination diagram of Whalen et al.

1033 (1987), I, S = I-, S-type granites. (b) Nb-Y-Ga ternary diagram of Eby (1992). A1 =

1034 within plate A-type granite, A2 = post-orogenic/post-collisional A-type granite. (c)

1035 Y+Nb vs. Rb and (d) Y vs. Nb tectonic discrimination diagram of Pearce et al. (1984).

1036 VAG = volcanic arc granites, WPG = within plate granites, COLG = collisional

1037 granites, ORG = oceanic ridge granites.

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1039 Figure 9. Distribution of Early Permian non-marine deposits in South Mongolia and

1040 northern Inner Mongolia. Early Permian depositional columns of Southwest Mongolia

1041 (a), South-Central Mongolia (b), Southeast Mongolia (c) and northern Inner Mongolia

1042 (d) are illustrated. Data of South Mongolia were from Johnson et al., 2008.

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Figure 10. Comparison of probability plots for the detrital zircon data of Late Carboniferous-Early Permian strata from the northern Inner Mongolia (a; this study), South Mongolia (b; Heumann et al., 2012), Central Inner Mongolia (c; Zhao et al., 2016) and Ordovician-Devonian strata from northern Inner Mongolia (d; Zhao et al., 2014).

Figure 11. Schematic distribution of Late Carboniferous-Early Permian intrusive and extrusive complexes in South Mongolia and northern Inner Mongolia. The peralkali-alkali granites and bimodal volcanic rocks constitute the rift system. References are as follows: (1) Yarmalyuk et al., 2008; (2) Blight et al., 2010a; (3) Xu et al., 2012; (4) Zhang et al., 2011a; (5) Nie et al., 2009; (6) Zhang et al., 2015; (7) Li et al., 2014a; (8) Shi et al., 2004; (9) Zhang et al., 2008; (10) Cheng et al., 2014; (11) Tong et al., 2015 ; (12) this study.

Figure 12 Simplified geodynamic and petrogenetic model to illustrate the tectonic evolution in northern Inner Mongolia-southern Mongolia and the generation of A-type granites, bimodal volcanic rocks and syn-rift sediments during the Late Carboniferous-Early Permian. The coeval inland sea existed in central Inner Mongolia, with shallow marine clastic-carbonate deposits.

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