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- Permian-Triassic detrital zircons were derived from a proximal magmatic source
- Early-Middle Triassic crustal uplift and thickening
- Late Triassic extensional collapse of orogen

Supporting Information:
- Readme
- Text S1
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Triassic sedimentation and postaccretionary crustal evolution along the Solonker suture zone in Inner Mongolia, China

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Abstract Detrital zircon U-Pb dating of the Xingfuzhilu Formation in southern Inner Mongolia yields a maximum depositional age of around 220 Ma. The predominantly Permian and Triassic zircons are characterized by oscillatory zoning and euhedral shapes, with mostly positive zircon $\varepsilon_{Hf}(t)$ values (+2.0 to +16.4), indicating that they were derived from a proximal magmatic source. Early-Middle Paleozoic zircons have variable zircon $\varepsilon_{Hf}(t)$ values from −6.2 to +11.2 and are characterized by weak oscillatory zoning and subhedral-subrounded shapes, suggesting that the sources are a proximal magmatic arc, possibly mixed with components of the Ondor Sum magmatic arc and the magmatic arc at the northern margin of the North China Craton. The remnants of Precambrian blocks in the southeastern Central Asian Orogenic Belt (CAOB), and the North China Craton may also have been a minor source region for the Xingfuzhilu succession. These results, combined with regional data, indicate that a closing remnant ocean basin or narrow seaway possibly existed in the Middle Permian (Guadalupian) immediately prior to final collision of the CAOB and closure of the Paleo-Asian Ocean. Subsequent collision resulted in the crustal uplift and thickening along the Solonker suture zone, accompanied by possible slab break-off and lithospheric delamination during the Latest Permian to Middle Triassic. The resultant orogen in the Late Triassic underwent exhumation and denudation of rocks in response to the postorogenic collapse and regional extension. Vertical crustal growth in the Triassic is documented by detrital zircons from the Xingfuzhilu Formation and appears to have been widespread across entire eastern CAOB.

1. Introduction

Study of sedimentary rocks can reveal information about their source regions and major continental tectonic events. The composition of siliciclastic sedimentary rocks is controlled predominantly by the original composition of the source rocks and their tectonic setting [e.g., *Dickinson and Suczek*, 1979; *Bhatia*, 1983, 1985; *Roser and Korsch*, 1986, 1988; *McLennan and Taylor*, 1991; *McLennan et al.*, 1993; *Cullers*, 2000]. In particular, detrital zircons can provide valuable information for the tectonic framework of the study area and its crustal evolution, because zircon grains may undergo multiple episodes of sedimentation, magmatism, and/or metamorphism while retaining their ages and geochemical information [e.g., *Bruguier et al.*, 1997; *Lee et al.*, 1997; *Košler and Sylvester*, 2003; *Andersen*, 2005; *Hawkesworth and Kemp*, 2006; *Cawood et al.*, 2007; *Condie et al.*, 2009; *Dickinson and Gehrels*, 2009; *Gehrels*, 2011; *Cawood et al.*, 2012; *Kooijman et al.*, 2012]. The age distribution of detrital zircons have been frequently used to constrain sedimentary provenance and maximum depositional age and can be used to reconstruct the tectonic evolution of the continental crust [e.g., *Nelson*, 2001; *Wilde et al.*, 2001; *Fedo et al.*, 2003; *Griffin et al.*, 2004; *Kemp et al.*, 2006, 2010; *Dickinson and Gehrels*, 2009; *Lancaster et al.*, 2011]. Furthermore, provenance and geodynamic development of siliciclastic sedimentary rocks can be better determined by a combined method including petrographic analyses, whole-rock geochemistry, zircon geochronology, and isotopic studies [e.g., *Dickinson et al.*, 1983; *Graham et al.*, 1993; *Yan et al.*, 2007, 2010].

The Central Asian Orogenic Belt (CAOB), or Altaids, located between the Siberia Craton to the north and Tarim and North China cratons to the south (Figure 1a), is one of the largest and most complex Phanerozoic accretionary orogenic belts on Earth, with considerable juvenile crustal growth [*Şengör et al.*, 1993; *Jahn et al.*, 2000a, 2000b, 2004; *Windley et al.*, 2002, 2007; *Kovalenko et al.*, 2004; *Xiao et al.*, 2009a; *Wilhem et al.*, 2012]. The orogenic belt is considered to have evolved from the early Neoproterozoic (ca. 1000 Ma) to the Permian,

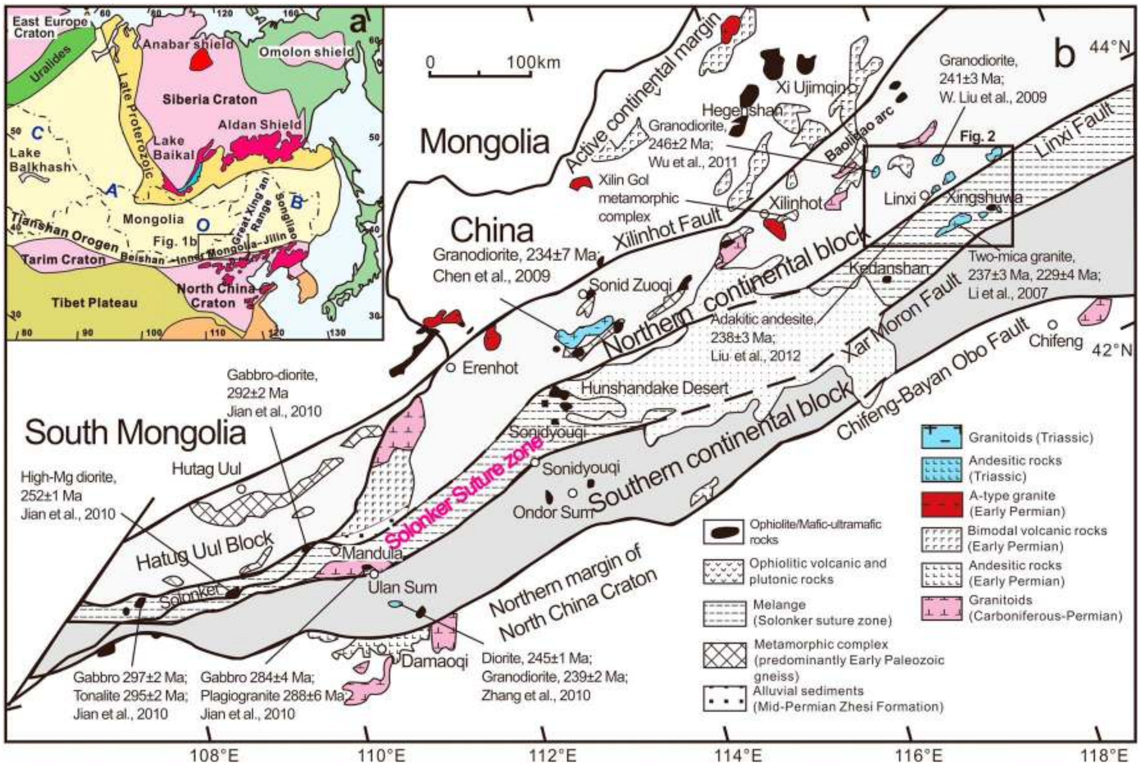

Figure 1. (a) Simplified sketch map of the Central Asian Orogenic Belt (CAOB) showing major tectonic divisions of Central Asia (modified after *Jahn et al.* [2000a, 2000b] and *Kröner et al.* [2008]). The approximate location of Figure 1b is indicated. (b) Simplified tectonic map of the southeastern CAOB showing the main tectonic subdivisions and the position of Figure 2 (modified after *Xiao et al.* [2003] and *Jian et al.* [2008, 2010]). Light gray area represents the northern Early-Middle Paleozoic orogen and the Hutag Uul Block [*Jian et al.*, 2008, 2010] or northern accretionary zone [*Xiao et al.*, 2003], whereas dark gray area represents the southern Early-Middle Paleozoic orogen [*Jian et al.*, 2008, 2010] or southern accretionary zone [*Xiao et al.*, 2003]. Published zircon U-Pb ages for Triassic magmatic rocks in the region are indicated and are from *Li et al.* [2007], *Chen et al.* [2009], *W. Liu et al.* [2009], *Y. S. Liu et al.* [2012], *Wu et al.* [2011], and *W. Zhang et al.* [2010].

through multiple accretion of arc/back-arc systems, ophiolites, and microcontinental fragments during the closure of the Paleo-Asian Ocean [*Khain et al.*, 2002; *Kovalenko et al.*, 2004; *Windley et al.*, 2007; *Xiao et al.*, 2008, 2009a; *Wilhem et al.*, 2012]. Paleozoic subduction-accretion complexes and arc-related igneous rocks associated with subduction of the Paleo-Asian Ocean are the two dominant rock assemblages in the CAOB and have been well-documented [*Şengör et al.*, 1993; *Badarch et al.*, 2002; *Kovalenko et al.*, 2004; *Helo et al.*, 2006; *Windley et al.*, 2007; *W. Liu et al.*, 2012]. However, associated clastic sediments and sedimentary rocks can also provide ideal samples for studying the formation and evolution of the CAOB [*Hendrix et al.*, 2001; *Badarch et al.*, 2002; *Khain et al.*, 2002; *Yakubchuk*, 2004; *Johnson et al.*, 2008; *Meng et al.*, 2010].

The Solonker suture zone lies in Inner Mongolia at the southernmost part of the CAOB. It trends ENE-WSW and records the final closure of the Paleo-Asian Ocean and the termination of accretionary events within the CAOB [*Xiao et al.*, 2003, 2009b; *Kovalenko et al.*, 2004; *Li*, 2006; *Jian et al.*, 2010; *Windley et al.*, 2010; *Li et al.*, 2013a] (Figure 1a). Although numerous studies have been undertaken on the Late Paleozoic subduction-accretion complexes and arc-related igneous rocks, and sedimentary rocks in the area [*Xiao et al.*, 2003; *Shen et al.*, 2006; *Miao et al.*, 2007a; *Jian et al.*, 2008, 2010; *Johnson et al.*, 2008; *Han et al.*, 2012a, 2012b; *B. Xu et al.*, 2013], the significance of Triassic sedimentary sequences, their tectonic setting, and postaccretionary history still remain to be determined because of their sparse outcrops [*He et al.*, 1997; *Chen et al.*, 2009; *J. Y. Li et al.*, 2009; *Li et al.*, 2010]. Young strata typically contain zircons with a wide range of ages, so they are likely to provide records that are more representative of the magmatic history of the crust than zircons in igneous rocks or in older strata [*Hawkesworth et al.*, 2010; *Dhuime et al.*, 2012]. The Triassic Xingfuzhilu clastic sedimentary sequence in Inner Mongolia [*Zhu and Zheng*, 1992; *He et al.*, 1997] records the sedimentary transition from

Late Paleozoic to Early Mesozoic; therefore, its depositional age and sedimentary provenance are of great importance in understanding the postaccretionary history of the southeastern CAOB. In terms of regional studies, the Xingfuzhilu Formation was originally assigned to the upper part of the Lower Permian (Cisuralian) Huanggangliang Formation. Later, some workers suggested that it was upper part of the Upper Permian (Lopinggian) Linxi Formation [*Gu and Hu*, 1982; *Bureau of Geology Mineral Resources of Inner Mongolia* (*BGMRIM*), 1991, 1996; *Liu et al*., 1999]. However, *Zhu and Zheng* [1992] first recognized that the Xingfuzhilu Formation was characterized by red-bed sedimentation, and discriminated it from the underlying Upper Permian Linxi Formation, as was the discovery of *Palaeanodonta-Palaeomutela* and *Cornia* fossils in the sequence. *He et al*. [1997] further demonstrated the existence of Triassic strata in the southern Great Xing'an Range by the discovery of Early Triassic ostracods, conchostracans, and bivalves in the Balinyouqi area of Inner Mongolia, although some of them are also characteristic of the Middle Triassic. However, because of the lack of systematic stratigraphic and geochronological studies, the exact depositional age, tectonic setting, and provenance of the Xingfuzhilu Formation are poorly understood and require reevaluation. In this study, we present modal analyses and a systematic detrital zircon U-Pb and Hf isotopic analysis of sandstones, with minor whole-rock geochemistry, from the clastic sedimentary sequence in order to evaluate the postaccretionary crustal evolution of the southeastern CAOB.

2. Geological Setting

The Beishan–Inner Mongolia–Jilin orogen is situated in the southernmost part of the CAOB along the Solonker suture zone and has also been referred to as the Early Mesozoic orogen [*Ren et al*., 1999, 2013; *Kovalenko et al*., 2004; *Li et al*., 2013a, 2013b, 2013c] (Figure 1a). The orogen was mainly constructed by convergent processes between the southern active margin marked by the South Mongolia terranes to the north of the Solonker suture zone and the northern margin of the North China Craton to the south [*Tang*, 1990; *Tang and Yan*, 1993; *Xiao et al*., 2003, 2009b; *Li*, 2006; *Jian et al*., 2008, 2010; *B. Xu et al*., 2013].

The study area is situated in southern Inner Mongolia and consists, from north to south, of the northern continental block, the Solonker suture zone, and the southern continental block [*Xiao et al*., 2003; *Jian et al*., 2008, 2010; *Li et al*., 2013b] (Figure 1b). The northern continental block, north of the Solonker suture zone, was an active Devonian-Carboniferous continental margin and consists mainly of the Early Paleozoic Hutag Uul Block in south Mongolia [*Badarch et al*., 2002] and a Late Cambrian to Late Silurian (ca. 498–420 Ma) [*Jian et al*., 2008] subduction-accretion complex associated with some accreted Precambrian blocks (e.g., Xilin Gol metamorphic complex) [*Xiao et al*., 2003; *Chen et al*., 2009; *Y. L. Li et al*., 2011; *B. Xu et al*., 2013]. The southern continental block between the North China Craton and the Solonker suture zone is characterized by an Early Ordovician to Early Silurian (ca. 488–438 Ma) subduction-accretion complex and arc-related igneous rocks [*Jian et al*., 2008; *Xiao et al*., 2008; *B. Xu et al*., 2013]. The final closure of the Paleo-Asian Ocean led to formation of the Solonker suture zone in the Permian [*Li*, 2006; *Chen et al*., 2009; *J. Y. Li et al*., 2009; *Jian et al*., 2010]. The suture zone is marked by the Solonker–Sonidyouqi-Kedanshan-Xingshuwa ophiolite belt [*Li*, 2006; *J. Y. Li et al*., 2009; *Jian et al*., 2010] (Figure 1b). This suture zone recorded the termination of activity in the southeastern CAOB, where a sequence of tectonomagmatic events occurred during the Permian to Triassic in response to block convergence, intracontinental shortening, and postorogenic collapse in Inner Mongolia [*Xiao et al*., 2003; *Li*, 2006; *Jian et al*., 2010; *Windley et al*., 2010; *Li et al*., 2012, 2013a].

In the Paleozoic, tectonic development of the southeastern CAOB was controlled by the Paleo-Asian Ocean between the Siberia and North China cratons [*Xiao et al*., 2003; *Kovalenko et al*., 2004; *Li*, 2006; *J. Y. Li et al*., 2009; *Windley et al*., 2010; *B. Xu et al*., 2013]. By the end of the Carboniferous, the CAOB was a vast accreted complex located at the southern margin of the Siberia Craton, as a result of northward subduction of the oceanic lithosphere [*Jahn et al*., 2000a; *Kovalenko et al*., 2004; *Li*, 2006; *Windley et al*., 2007; *Wilhem et al*., 2012]. In the Late Carboniferous to Early Permian, the Paleo-Asian Ocean (Solonker Ocean) still existed to the south of the active continental margin [*Xiao et al*., 2003, 2009b; *Li*, 2006; *J. Y. Li et al*., 2009; *Jian et al*., 2010; *Windley et al*., 2010]. The Tarim and North China cratons collided with the southern active margin (South Mongolia terranes) of Siberia in the Middle Permian, and this resulted in final closure of the Paleo-Asian Ocean and termination of accretionary orogenesis in the southeastern CAOB [*Johnson et al*., 2008; *Jian et al*., 2010; *Li et al*., 2013c]. Throughout the Mesozoic, the Paleo-Pacific Ocean events dominated this region [*Ren et al*., 1999, 2013; *Li*, 2006; *J. Y. Li et al*., 2009; *Wu et al*., 2011; *Li et al*., 2013a; *Zhou and Wilde*, 2013].

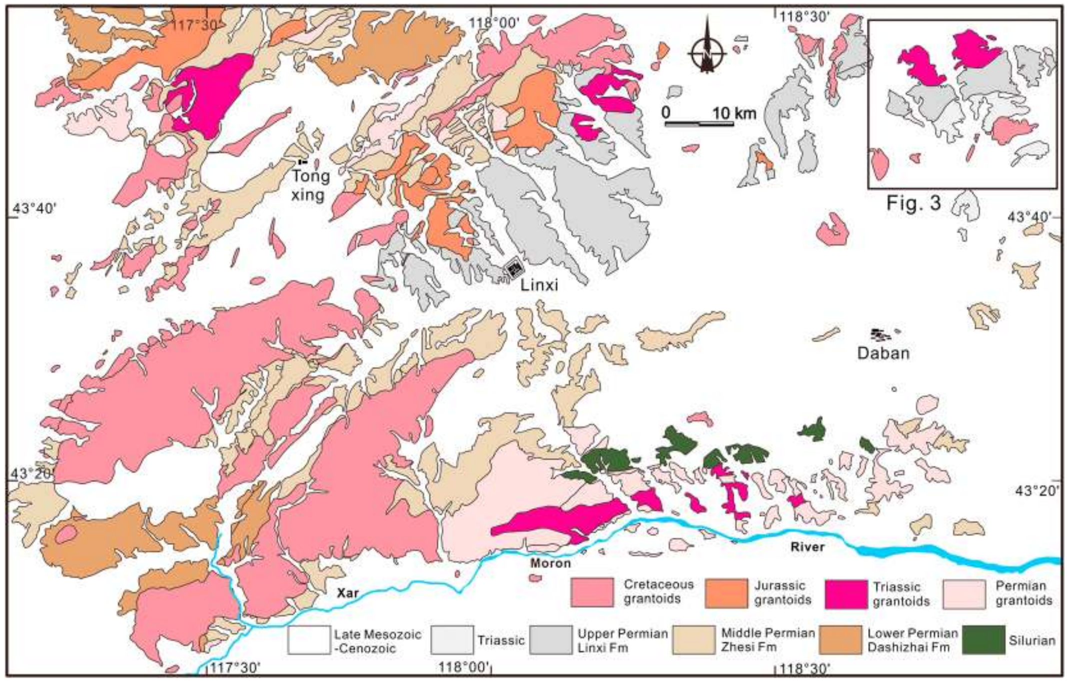

Figure 2. Simplified geological map of the Linxi area in Inner Mongolia, China, showing the Permian-Triassic strata and the location of Figure 3 (modified after *BGMRIM* [1991, 1996]).

The oldest rocks exposed in the Linxi area of southern Inner Mongolia are Proterozoic metamorphic rocks of the Baoyintu "Group" [*BGMRIM*, 1991, 1996; *B. Xu et al.*, 2013]. Paleozoic strata are dominated by volcanosedimentary sequences of the Lower Permian (Cisuralian) Dashizhai Formation, sedimentary sequences of the Middle Permian (Guadalupian) Zhesi Formation and the Upper Permian (Lopingian) Linxi Formation, all of which are covered or intruded by Mesozoic volcanic and granitoid rocks [*BGMRIM*, 1991, 1996; *Mueller et al.*, 1991; *Shen et al.*, 2006; *Li et al.*, 2013b] (Figure 2). The Dashizhai Formation consists mainly of lava, tuff, and volcanoclastic rocks, with the volcanic rocks showing a bimodal distribution [*X. H. Zhang et al.*, 2008]. The lower part of the Middle Permian Zhesi Formation is composed of dark gray marble, limestone, and calcareous sandstone, whereas the upper part is composed of grayish-green sandstone, conglomerate, and tuffaceous siltstone interbedded with slate [*BGMRIM*, 1991, 1996; *Shen et al.*, 2006; *Han et al.*, 2012a]. The Upper Permian Linxi Formation is mainly terrestrial and consists of conglomerate, sandstone, siltstone, and slate [*BGMRIM*, 1991, 1996; *He et al.*, 1997; *Shen et al.*, 2006]. Middle Permian and older strata are variably metamorphosed and structurally juxtaposed with ophiolitic fragments and plutonic bodies [*BGMRIM*, 1991, 1996; *Mueller et al.*, 1991; *Li*, 2006; *C. W. Wang et al.*, 2009; *Liu et al.*, 2011]. *Zhu and Zheng* [1992] first reassigned a red clastic sedimentary sequence as the Lower Triassic Xingfuzhilu Formation from the upper part of the original Linxi Formation, on the basis of fossils and regional lithological changes. It comprises conglomerate, sandstone, siltstone, mudstone, and shale.

Volcanism and granitoid plutonism occurred widely in the Linxi-Balinyouqi areas from the Late Paleozoic through to the Late Mesozoic (Figure 2). *Li et al.* [2007], *W. Liu et al.* [2009], and *Wu et al.* [2011] have recently shown that granitoid intrusions in this area are Permian, Triassic, and Late Jurassic in age. However, the most voluminous are the Early Cretaceous intrusions related to Early Cretaceous extension in NE Asia [*Wang et al.*, 2012; *Li et al.*, 2013b] (Figure 2).

3. The Xingfuzhilu Formation and Samples

The Xingfuzhilu Formation is mainly distributed in the Balinyouqi area of Inner Mongolia. Although, previous studies suggested that it unconformably overlies the Upper Permian Linxi Formation and is overlain by Jurassic volcanic rocks with an angular unconformity [*Zhu and Zheng*, 1992; *He et al.*, 1997], there is still too much uncertainty with respect to the stratigraphic relationships here because of poor outcrops. In light of

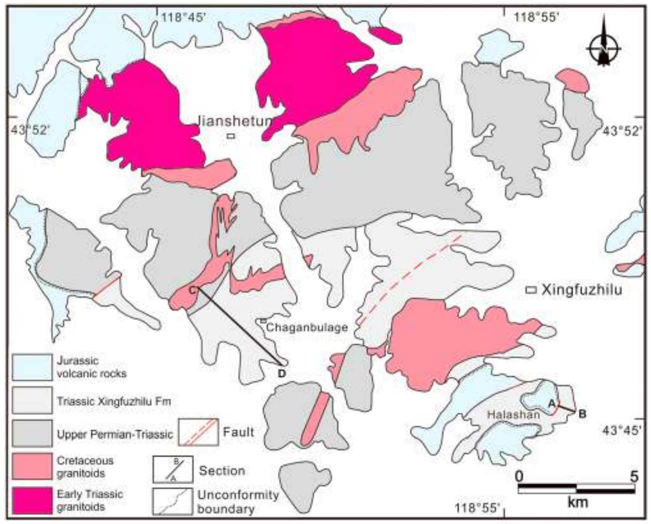

Figure 3. Simplified geological map of the Xingfuzhilu area in Inner Mongolia, China (modified after *BGMRIM* [1991, 1996] and *He et al.* [1997]).

previous studies [*BGMRIM*, 1991, 1996; *Zhu and Zheng*, 1992; *He et al*., 1997] and this study, the Chaganbulage section and the Halashan section are measured and revised (Figures 3 and 4). The Xingfuzhilu Formation has a thickness of up to 1654 m and is divided into three members [*Zhu and Zheng*, 1992; *He et al*., 1997]. The lower-middle sequence is widely distributed in the Chaganbulage area, whereas the intact upper part is present mainly in the Halashan area (Figures 3 and 4). The lower part is 173 m in thickness and is mainly composed of conglomerate with andesitic gravels and coarse-grained sandstone (Figure 5a). The middle part is 621 m in thickness and consists of purple sandstone and gray siltstone (Figures 5b and 5c), with parallel and cross bedding. The upper part is 860 m in thickness and comprises grayish-green mudstone and shale with limestone concretions and dark gray sandstone, and has parallel bedding [*Zhu and Zheng*, 1992; *He et al*., 1997] (Figure 5d). The lower-middle part of the Xingfuzhilu Formation shows red-bed features, indicating semiarid-arid terrestrial sedimentation. The detailed stratigraphy is presented in Figure 6. Cross bedding, reworking surfaces, ripple marks, and mud cracks occur in some outcrops. The Xingfuzhilu Formation is broadly divided into three sedimentary facies, from lower fluvial-alluvial fan facies to middle fluvial-lacustrine facies and upper lacustrine facies (Figure 6).

Eight Xingfuzhilu samples and 10 Linxi samples were collected for framework modal analyses (Table S1). Fourteen Xingfuzhilu samples were collected from the Chaganbulage and Halashan areas for whole-rock geochemical analyses (Table S2). Two samples were collected for zircon U-Pb dating and Hf isotopic analyses

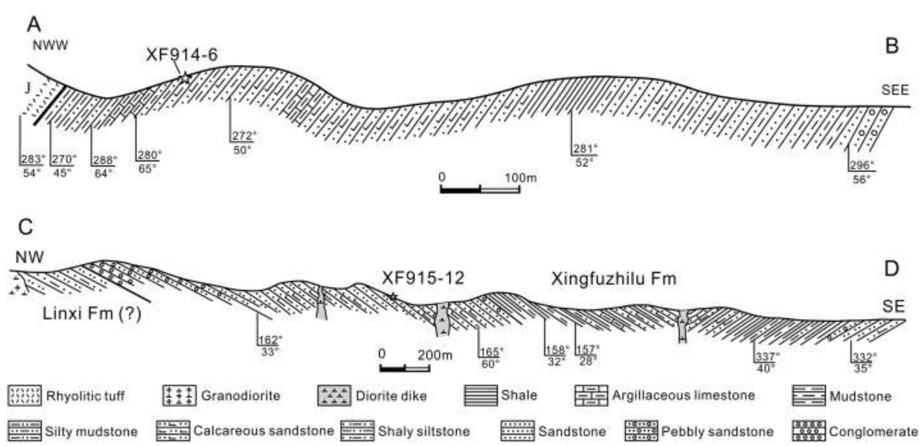

Figure 4. Cross sections of the Xingfuzhilu Formation. Locations of cross sections are marked on the Figure 3.

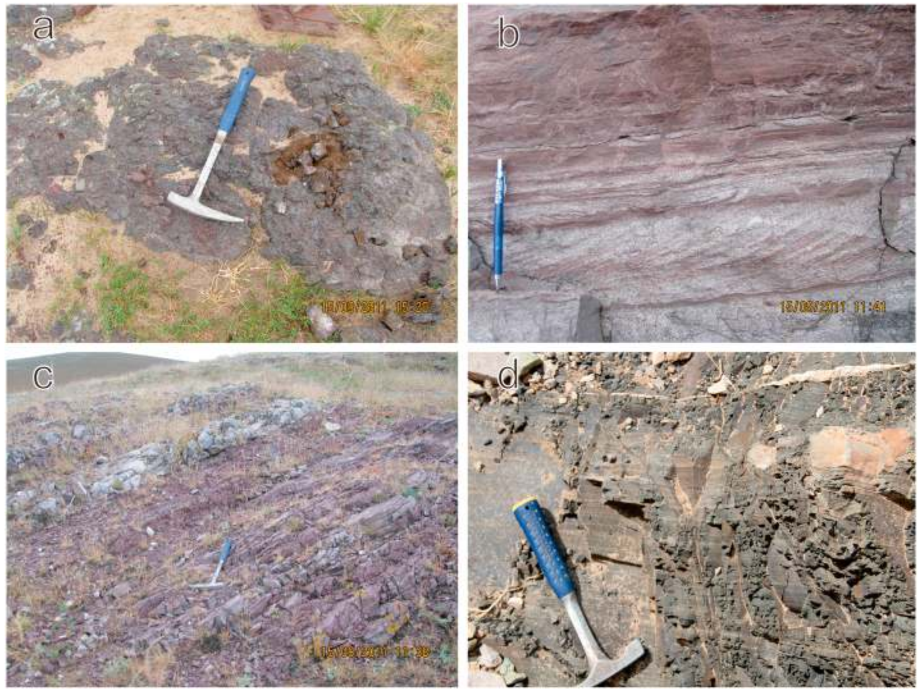

Figure 5. Field photographs of the Triassic Xingfuzhilu Formation in Inner Mongolia: (a) conglomerate with andesitic gravels and coarse-grained sandstone in the lower part, (b) purple and gray sandstone with cross bedding from the middle part of the formation, (c) purple siltstone and interbedded gray sandstone from the middle part of the formation, and (d) grayish-green bedding silty mudstone with limestone concretions in the upper part of the formation.

(Tables S3 and S4). Sample XF915-12 from the middle part of the Xingfuzhilu Formation in the Chaganbulage area is a gray, medium-grained sandstone and is subangular and moderately sorted with dominant plagioclase (Figure S1a). The sandstones contain many lithic fragments, which are mainly constituted by sedimentary and volcanic fragments (Figure S1a). Sample XF914-6 from the upper part of the Xingfuzhilu Formation in the Halashan area is a gray, fine- to medium-grained sandstone and is subround and well sorted (Figure S1b). The sandstones include abundant lithic fragments that are mainly comprised of sedimentary fragments (Figure S1b). Other sandstones from the Xingfuzhilu Formation are mainly composed of quartz, plagioclase, and lithic fragments.

Details of sandstone modal analyses, whole-rock geochemical analyses, and zircon U-Pb dating and Hf isotopic analyses are given in the supporting information. We use *Gradstein et al*. [2012] for the geological timescale.

4. Depositional Age

Recently, U-Pb dating of detrital zircons from the Upper Permian (Lopingian) Linxi Formation revealed the youngest zircon had ages of 256 ± 2 Ma [*Han et al*., 2011] and 258 ± 3 Ma [*Han et al*., 2012b], indicating the Late Permian maximum depositional age. Since the Xingfuzhilu Formation overlies the Linxi Formation [*Zhu and Zheng*, 1992; *He et al*., 1997], these data support a younger depositional age for the Xingfuzhilu Formation than previously estimated.

Our U-Pb results from detrital zircons from different lithological units of the Xingfuzhilu Formation place further constraints on the maximum depositional age. In this study, 210 detrital zircon grains from two sections of the Xingfuzhilu Formation were dated (Figure 4 and Table S3).

4.1. Sample XF915-12 (Middle Part of Xingfuzhilu Fm)

Zircon grains from sample XF915-12 in the middle part of the Xingfuzhilu Formation are colorless and/or pale yellow, transparent, and commonly euhedral. Their sizes range from 80 to 250 μm, with length to width ratios between 1.5:1 and 3:1. Most grains have oscillatory zoning (Figure S2a) and high Th/U ratios (0.30–1.72),

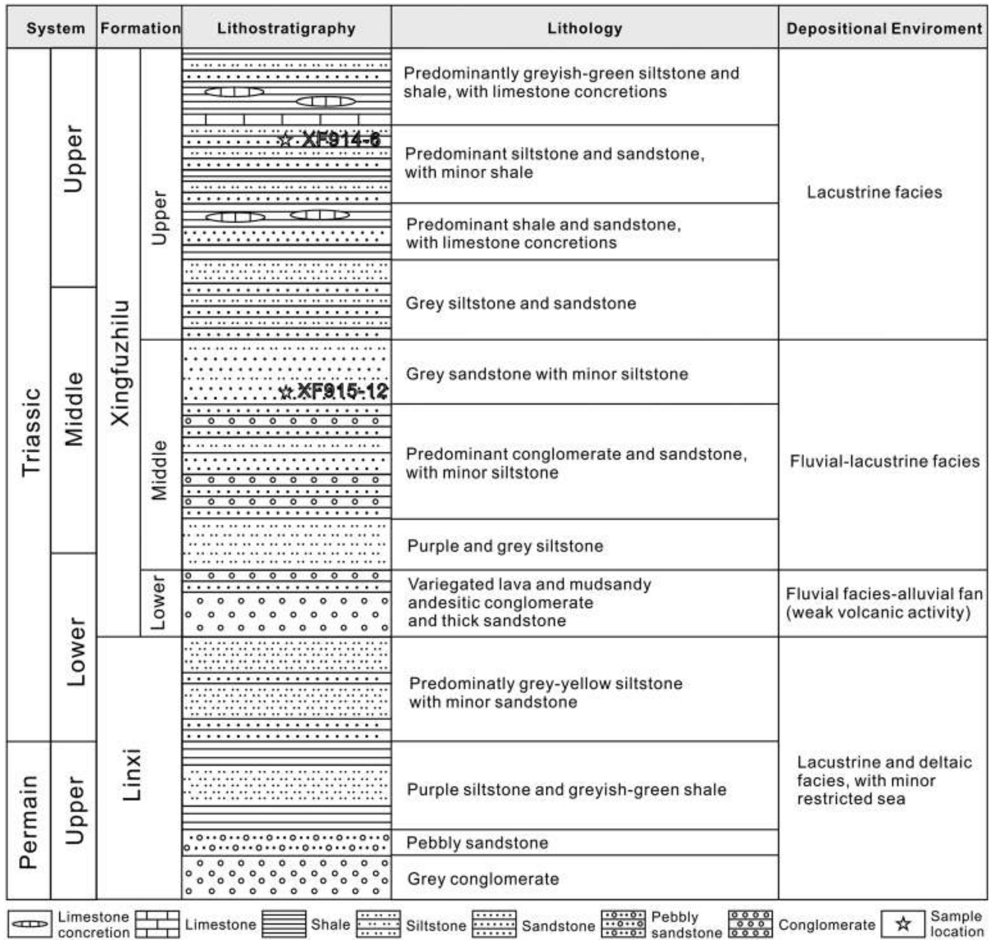

Figure 6. Lithostratigraphy and stratigraphic subdivision of the Xingfuzhilu Formation (modified after *BGMRIM* [1991, 1996] and *He et al*. [1997]).

suggesting a magmatic origin. Sixty-four spots were analyzed for zircon U-Pb isotopes, and the analyses are all concordant from 98% to 110% (Table S3). Their $^{206}Pb/^{238}U$ ages range from 283 Ma to 233 Ma (Figure 7a and Table S3), showing three age populations at 283–281 Ma, 274–252 Ma with a peak age at ~260 Ma and 250–233 Ma with a peak age at ~240 Ma (Figure 7b). The youngest zircon yields a concordant $^{206}Pb/^{238}U$ age of 233 ± 1 Ma (Figure 7a and Table S3).

4.2. Sample XF914-6 (Upper Part of Xingfuzhilu Fm)

Zircon grains from sample XF914-6 from the upper part of the Xingfuzhilu Formation are colorless to pale yellow and predominantly subhedral. They are 50–150 μm in length and have length to width ratios of 1:1 to 3:1. Most zircon grains have oscillatory zoning of magmatic origin (Figure S2b). One hundred and forty-six zircon grains were chosen for U-Pb isotopic dating, and 93 analyses yielded concordant age results (Figure 8a and Table S3). Fifty-three discordant analyses indicate strong lead loss. Even so, the distribution of the 93 concordant zircons is similar with those of discordant ages, although they were rejected from further calculations (Figure 8b). Most zircons show moderate to high Th/U ratios which range from 0.26 to 1.46, except for two zircon grains with low Th/U ratios of 0.08–0.10. Seven analyses record Archean $^{207}Pb/^{206}Pb$ ages (2625–2509 Ma). Sixteen analyses yield Proterozoic $^{207}Pb/^{206}Pb$ ages of 2409–604 Ma. Two main age peaks of 13 Early Paleozoic data (512–422 Ma) are at ~436 Ma and ~377 Ma, with one minor at ~460 Ma. Thirty-six Late Paleozoic $^{206}Pb/^{238}U$ ages (404–253 Ma) yield two main age peaks at ~253 Ma and ~271 Ma, with two minors at ~303 Ma and ~323 Ma. Twenty-one analyses record Triassic $^{206}Pb/^{238}U$ ages from 250 Ma to 219 Ma, and can be subdivided into two age groups, with $^{206}Pb/^{238}U$ ages of 250–231 Ma and 227–219 Ma. A relative age-probability diagram shows that ~225 Ma, ~253, ~271 Ma, and ~436 Ma are the dominant age

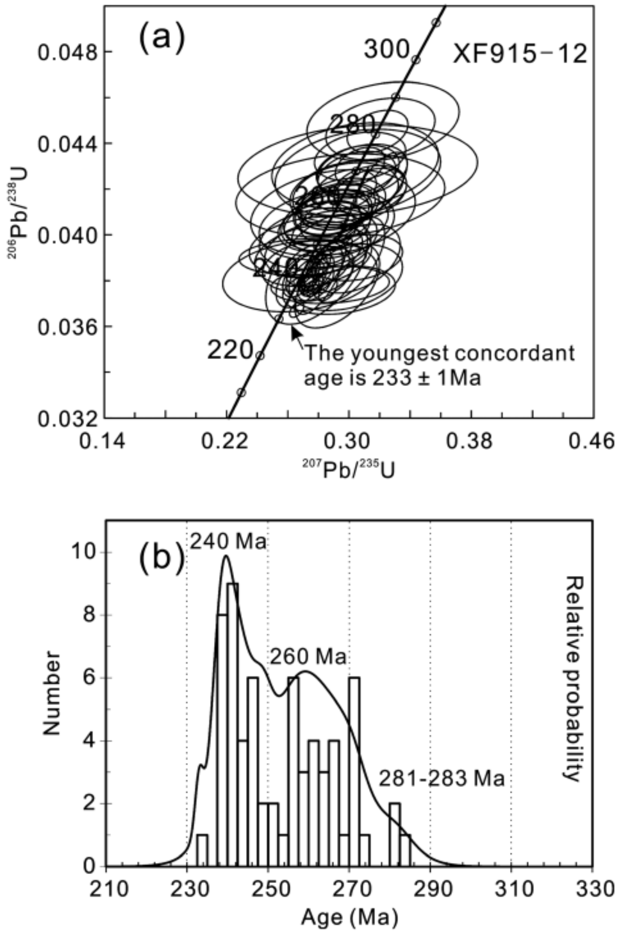

Figure 7. (a) U-Pb concordia diagram and (b) age histogram and relative probability diagram of detrital zircons from sample XF915-12 from the middle part of the Xingfuzhilu Formation.

peaks, with minor peaks at ~303 Ma, ~323 Ma, ~377 Ma, and ~460 Ma (Figure 8b). The distribution is similar to the age spectrum of the published Triassic andesite from this area (Figure 8c) [*Y. S. Liu et al.*, 2012].

The youngest zircon grain from the middle sandstone (Sample XF915-12) yielded a $^{206}Pb/^{238}U$ age of 233 ± 1 Ma (Figure 7a). Furthermore, the youngest zircon cluster with four grains (219–221 Ma) in sample XF914-6 from the upper succession of the Xingfuzhilu Formation define an average $^{206}Pb/^{238}U$ age of ~220 Ma (Figure 8a and Table S3). Therefore, we suggest the age of ~220 Ma as a more reliable constraint on the maximum depositional age of the Xingfuzhilu Formation, which is also in accord with the criterion that the youngest reliable zircon age must be composed of three or more grains [*Andersen*, 2005; *Dickinson and Gehrels*, 2009; *Gehrels*, 2011]. In light of evidence from the youngest zircon cluster, we suggest that the maximum depositional age of the upper Xingfuzhilu Formation should be Late Triassic (~220 Ma).

5. Sedimentary Provenance

Modal analyses from point-counting of the framework grains from the Xingfuzhilu Formation sandstones are listed in Table S1 in the supporting information. The framework grains (without matrix) of the eight sandstone samples from the Xingfuzhilu Formation are mainly composed of monocrystalline quartz (Qm = 1–53%), plagioclase (P = 4–59%), and lithic fragments (L = 13–36%, predominately clastic sedimentary fragments), with accessory heavy minerals including opaque minerals (2–25%; ilmenite, magnetite, and hematite) and some biotite and muscovite (Table S1). The Xingfuzhilu Formation sandstones can thus be classified as feldspathic litharenite, litharenite, and lithic arkose (Figure 9a), indicating mainly recycled orogenic and transitional arc provenances in the QtFL diagram (Figure 9b). However, the Upper Permian Linxi Formation sandstones mainly show recycled orogenic provenance (Figure 9b), whereas the Middle Permian Zhesi Formation sandstones mainly reveal recycled orogenic and dissected arc provenances (Figure 9b) [*Han et al.*, 2012b].

Predominately unstrained monocrystalline quartz grains in all the samples suggest a plutonic origin [*Basu et al.*, 1975; *Potter*, 1978; *Hendrix*, 2000]. The Xingfuzhilu Formation sandstones contain more plagioclase than K-feldspar and have high Na_2O/K_2O ratios (Table S2), reflecting derivation from mafic rocks rather than felsic rocks. The moderately high La/Th ratios and low Hf contents of the Xingfuzhilu Formation sandstones (Table S2) suggest derivation predominantly from a mixed felsic/mafic source [*Floyd and Leveridge*, 1987], whereas the Upper Permian Linxi Formation and Middle Permian Zhesi Formation were mainly derived from a felsic arc source together with some older components (Figure S3).

Furthermore, the sedimentary record is a valid representation of the magmatic record [*Condie et al.*, 2009; *Hawkesworth et al.*, 2010; *Cawood et al.*, 2012]. As shown in Figure 7b, the zircon ages from sample XF915-12 show two main age peaks at ~240 Ma and ~260 Ma. The obtained zircon ages from sample XF914-6

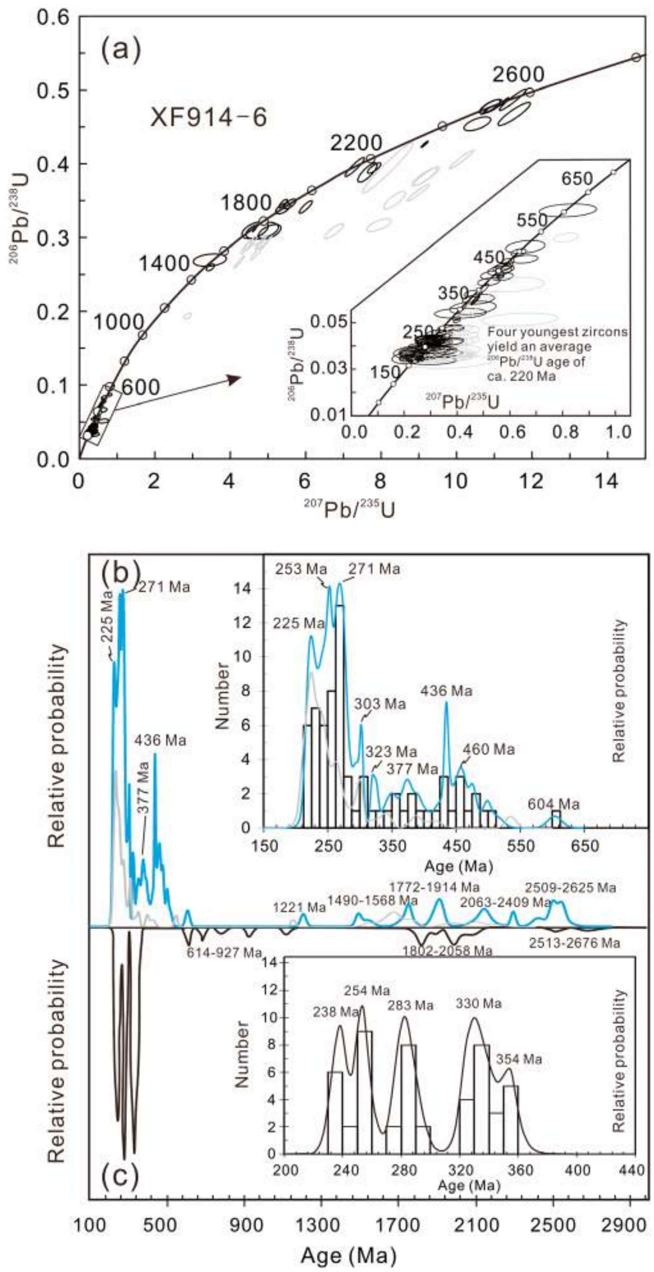

Figure 8. (a) U-Pb concordia diagram, (b) age histogram and relative probability diagram of detrital zircons from sample XF914-6 from the upper part of the Xingfuzhilu Formation, and (c) age histogram and relative probability diagram of zircons from Triassic andesite in the Linxi area [*Y. S. Liu et al.*, 2012]. Gray symbols in Figure 8a indicate discordant data due to lead loss. Blue line shows concordant data and gray line displays discordant analyses.

display a wide range from 2625 Ma to 219 Ma, with five dominant age peaks at ~225 Ma, ~253 Ma, ~271 Ma, ~303 Ma, and ~436 Ma, together with three Precambrian zircon populations at 1221–1568 Ma, 1772–2049 Ma, and 2509–2568 Ma (Figure 8b).

5.1. Triassic Magmatic Events

Triassic ages of the detrital zircons from the Xingfuzhilu Formation range from 252 Ma to 219 Ma, with two age peaks at ~240 Ma and ~225 Ma (Figures 7b, 8b, and 10a). Most zircon grains are characterized by euhedral shape and prominently oscillatory zoning of igneous origin (Figure S2), implying a near-source characteristic. They were the result of deposition after the weathering of nearby magmatic rocks.

Recently, many Triassic granitoids have been recognized in the area and are divided into two episodes for the Early-Middle Triassic (250–230 Ma) and the Late Triassic (230–200 Ma) [*Li et al.*, 2010, 2013a]. For example, a granodiorite from the Longtoushan pluton yielded a SHRIMP zircon U-Pb age of 241 ± 3 Ma [*W. Liu et al.*, 2009], while two-mica granites from the Shuangjingzi pluton in the Linxi area yielded two SHRIMP zircon U-Pb ages of 229 ± 4 Ma and 238 ± 3 Ma [*Li et al.*, 2007]. Two SHRIMP zircon U-Pb ages of 234 ± 7 Ma and 237 ± 6 Ma were determined for granodiorite from the Halatu pluton in the Sonid Zuoqi area [*Chen et al.*, 2009] and quartz diorite from the Qagan Obo pluton in the Dong Ujimqin area, respectively [*W. Y. Zhang et al.*, 2008]. SHRIMP zircon U-Pb ages of monzogranites from the Halatubei pluton and the Bao'erhan Lamamiao pluton in the Sonid Zuoqi area are 222 ± 4 Ma and 222 ± 6 Ma, respectively [*Y. R. Shi et al.*, 2004, 2007]. Some Early Mesozoic (250–214 Ma) volcanic rocks are also present in Inner Mongolia [*L. C. Zhang et al.*, 2008]. Recently, *Y. S. Liu et al.* [2012] reported a LA-ICPMS zircon U-Pb age of 238 ± 3 Ma for high-Mg adakitic andesite from the Linxi area, which also contain a similar Precambrian age spectrum to the sandstones from the Xingfuzhilu Formation (Figure 8c). Some quartzo-feldspathic gneisses in southern Mongolia also yield Triassic ages [*Webb et al.*, 2010; *Taylor et al.*, 2013].

Many studies also presented similar data for magmatic events along the northern margin of the North China Craton [*Ma et al.*, 2007; *Ren et al.*, 2009; *Yang and Wu*, 2009; *Zhang et al.*, 2009a; *X. H. Zhang et al.*, 2012; *Shao*

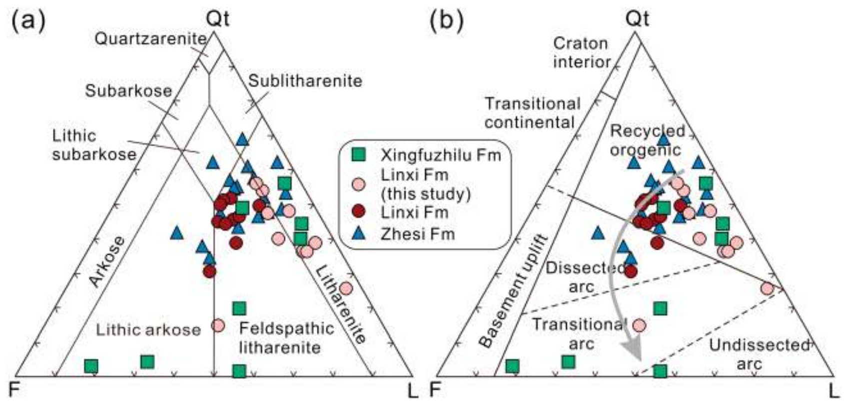

Figure 9. Qt-F-L diagrams showing Dickinson model components (after *Dickinson and Suczek* [1979] and *Dickinson et al.* [1983]) for the Xingfuzhilu Formation sandstones. Data for the Middle Permian Zhesi Formation and Upper Permian Linxi Formation are from *F. L. Li et al.* [2009] and *Han et al.* [2012b]. From the Middle Permian Zhesi Formation through Upper Permian Linxi Formation to Triassic Xingfuzhilu Formation, the sedimentary provenances are transitional from mainly recycled orogenic to dissected arc and transitional arc provenances.

and Yang, 2011]. For example, *Meng et al.* [2010] reported the Jurassic Xinglonggou Formation sandstones in the Chaoyang-Beipiao areas display an age peak at ~228 Ma, interpreted to be of igneous origin and derived from eastern CAOB. The ε_{Hf}(t) values of most Triassic zircons from the Xingfuzhilu Formation are +3.9 to +16.1, except for one grain with negative ε_{Hf}(t) values (−5.2) (Figure 11 and Table S4). These are similar to data reported from Triassic Longtoushan granitoids [*W. Liu et al.*, 2009] and Triassic Linxi andesites [*Y. S. Liu et al.*, 2012] in the area and for clastic sediments from the modern rivers [*Li*, 2010], as well as igneous rocks in the eastern CAOB [*Yang et al.*, 2006] (Figure 11). However, they are distinct from Triassic zircons from the North China Craton [e.g., *Yang et al.*, 2006, 2009; *Meng et al.*, 2010]. Therefore, Triassic zircons from the Xingfuzhilu Formation have been derived from near-source Triassic magmatic rocks in the southeastern CAOB.

5.2. Late Paleozoic Magmatic Events

The Late Paleozoic (253–354 Ma) detrital zircons from the Xingfuzhilu Formation sandstones display two dominant age populations with peaks at ~253 Ma and ~271 Ma and two minor peaks at ~303 Ma and ~323 Ma (Figure 8b). These age groups have been widely reported as magmatic events in the area, including from gabbro, diorite, granodiorite, monzogranite, syenogranite, A-type granite and syenite, and associated volcanic rocks, with zircon U-Pb ages from 325 Ma to 252 Ma [*Tong et al.*, 2010; *Wu et al.*, 2011]. These include the Baiyingaolao quartz diorite (323–313 Ma) [*Bao et al.*, 2007] and the Jinxing quartz diorite (322 ± 3 Ma) [*J. F. Liu et al.*, 2009] in the Xi Ujimqin area, the Qianjinchang granodiorite (275–274 Ma) and Yuanbaoshan monzogranite (273 ± 3 Ma) in the Linxi area [*Wu et al.*, 2011], the A-type granite (276 ± 2 Ma) in the Xilinhot area [*G. H. Shi et al.*, 2004], and the Shuangjing migmatite (270 ± 1 Ma) [*Li et al.*, 2008] and the Meilindaba quartz diorite (301 Ma) in southern Linxi area [*Wu et al.*, 2011]. The ages of 293–270 Ma are also similar to the age of bimodal volcanics from the Dashizhai Formation (279–289 Ma) [*X. H. Zhang et al.*, 2008, 2011a]. *Jian et al.* [2010] also presented some Carboniferous-Permian geochronological data (313–250 Ma) and detailed geochemistry for the mafic and felsic intrusions in the Mandula area along the Solonker suture zone and proposed that ca. 299–290 Ma, ca. 294–280 Ma, ca. 281–273 Ma, and 255–248 Ma intrusions were emplaced in the presubduction extension, subduction initiation, ridge-trench collision, and postcollisional slab break-off, respectively. The detrital zircons with Late Paleozoic ages from the Carboniferous to Permian Baoligaomiao Formation in the Hegenshan area show positive ε_{Hf}(t) values, indicating juvenile crustal accretion events [*D. P. Li et al.*, 2011]. Although many previous studies also presented similar data for magmatic events along the northern margin of the North China Craton [*Zhang et al.*, 2007a, 2009a, 2009b; *W. Zhang et al.*, 2010; *X. H. Zhang et al.*, 2010, 2011b; *Zhao et al.*, 2007; *Yang et al.*, 2012a] (Figure 10d), these Late Paleozoic zircons are characterized by negative ε_{Hf}(t) values [e.g., *Yang et al.*, 2006, 2009; *Meng et al.*, 2010] (Figure 11). The euhedral-subhedral crystal shapes for the Late Paleozoic zircons from the Xingfuzhilu Formation sandstones better support relatively fast sedimentation without abundant recycling. Therefore, these zircons with Late Paleozoic ages may be derived from the Late Paleozoic arc-related terranes in the northern continental block.

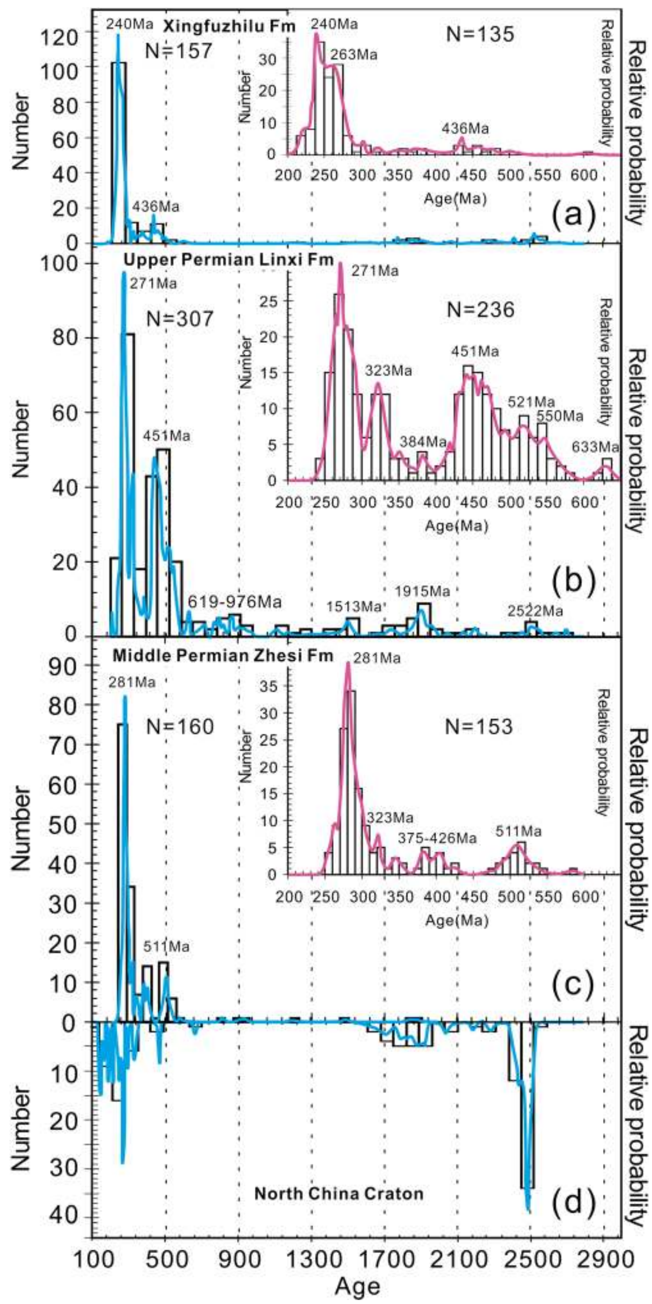

Figure 10. Age and relative probability diagrams for detrital zircons from (a) Xingfuzhilu Formation, (b) Upper Permian Linxi Formation, (c) Middle Permian Zhesi Formation, and (d) Major river sediments in North China Craton [*Yang et al.*, 2009]. Permian data are from *Han et al.* [2011]; *Han et al.* [2012a, 2012b].

The Late Paleozoic detrital zircons from the Xingfuzhilu sandstones mostly show positive ε_{Hf}(t) values (+2.0 to +16.4), which are similar to Late Paleozoic detrital zircons (with positive zircon ε_{Hf}(t) values of +3.5 to +10.4, *Han et al.*, 2012a) from the Upper Permian Linxi Formation sandstones (Figure 11 and Table S4), but they have slightly older peak age populations at ~271 Ma and ~323 Ma (Figure 10b). Therefore, from the Linxi Formation to the Xingfuzhilu Formation, the source is transitional from the older to younger magmatic arc, indicating the encroachment of an active arc system towards the Triassic depocenter. The Late Paleozoic zircons from the Upper Permian Linxi Formation were most likely derived from the ~271 Ma and ~323 Ma magmatic arcs in the Sonid Zuoqi–Xi Ujimqin magmatic belt in northern continental block [*Han et al.*, 2012a]. Therefore, these Late Paleozoic zircons from the Xingfuzhilu Formation were predominantly derived from proximal Permian magmatic rocks in the southeastern CAOB.

5.3. Early to Middle Paleozoic Magmatic Events

We also obtained a few Early to Middle Paleozoic (373–512 Ma) zircons with age peaks of ~377 Ma, ~436 Ma, and ~460 Ma were also obtained (Figure 8b). A likely provenance for these ages was identified, since some Early Paleozoic magmatic rocks (497–423 Ma) have been reported along the Sonid Zuoqi–Xi Ujimqin magmatic arc in the northern continental block [*Chen et al.*, 2000; *Y. R. Shi et al.*, 2004, 2005a, 2005b; *Jian et al.*, 2008; *Guo et al.*, 2009; *Y. L. Li et al.*, 2011; *B. Xu et al.*, 2013] and also in the Ondor Sum magmatic arc (490–411 Ma) in the southern continental block [*Liu et al.*, 2003; *Miao et al.*, 2007a; *Jian et al.*, 2008; *Zhang et al.*, 2013; *B. Xu et al.*, 2013]. The SHRIMP zircon U-Pb ages of the paragneiss and granitic gneiss from the Xilin Gol Complex are 406 ± 7 Ma and 382 ± 2 Ma, respectively [*Xue et al.*, 2009]. *Ge et al.* [2011] recently reported a SHRIMP zircon U-Pb age of 411 ± 6 Ma from volcanic rocks overlying Xilin Gol Complex. These data allow for the argument for a likely bidirectional subduction along the Solonker-Xar Moron suture zone during the Early-Middle Paleozoic. The range of Early-Middle Paleozoic ages of the detrital zircons obtained from Permian sandstones in the area display three main age populations at ~384 Ma, ~451 Ma, and ~511 Ma (Figures 10b and 10c), indicating derivation mainly from the Sonid Zuoqi–Xi Ujimqin magmatic arc [*Han et al.*, 2012a]. In addition, similar ages

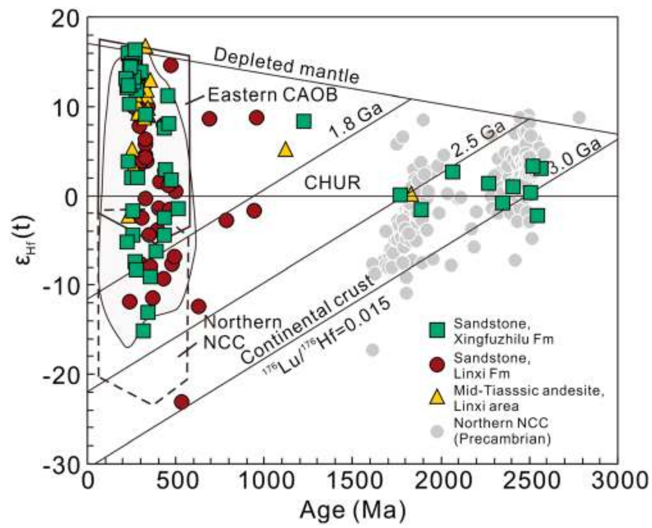

Figure 11. Plot of zircon ε_{Hf}(t) values versus U-Pb ages. Precambrian data for the northern North China Craton are from *Yang et al.* [2006, 2009] and *Meng et al.* [2010]; data for Middle Triassic andesite in the Linxi area are from *Y. S. Liu et al.* [2012]; data for Upper Permian Linxi Formation are from *Han et al.* [2012a]. Area marked by dashed line shows the distribution of zircon ε_{Hf}(t) values from Yanshan igneous rocks at the northern margin of the North China Craton. The continuous line marks the area of zircon ε_{Hf}(t) values from igneous rocks in the eastern CAOB (after *Yang et al.* [2006]). Gray area represents detrital zircons from modern rivers covering the entire area of northeastern China, which includes much of eastern CAOB (after *Li* [2010]).

were also reported along the northern margin of the North China Craton [*Zhang et al.*, 2007b; *Shi et al.*, 2010]. The Early-Middle Paleozoic detrital zircons from the Xingfuzhilu Formation sandstones show variable ε_{Hf}(t) values (−6.2 to +11.2), which are similar to the ε_{Hf}(t) values (−11.4 to +17.5) of the Early-Middle Paleozoic zircons from the Upper Permian Linxi Formation [*Han et al.*, 2012a] (Figure 11), indicating a mixed source from both juvenile crust and recycled older crust. The subhedral-subrounded zircons from these Early-Middle Paleozoic age groups may imply transportation from longer distances. Therefore, we suggest the provenance of these zircons was mainly from the Sonid Zuoqi–Xi Ujimqin Early-Middle Paleozoic magmatic arc in the northern continental block, possibly mixed with materials from the Ondor Sum Early-Middle Paleozoic magmatic arc in the southern continental block and from the magmatic arc at the northern margin of the North China Craton.

5.4. Implications of Precambrian Zircon Ages

Four very minor Precambrian zircon age groups of 1221–1568 Ma, 1762–1914 Ma, 2063–2409 Ma, and 2509–2625 Ma, with one zircon grain with an age of 604 Ma, are present in the samples (Figure 8b). However, such ages have not been reported from the basement rocks in NE China of the CAOB, except for some detrital or inherited zircons [*Wang et al.*, 2006; *Miao et al.*, 2007b; *Pei et al.*, 2007; *Chen et al.*, 2009; *Zhou et al.*, 2012; *Zhou and Wilde*, 2013]. Previously considered Proterozoic metamorphic rocks are now shown to be Paleozoic in age [*Miao et al.*, 2004; *Wu et al.*, 2011]. The Jiamusi Massif is a Precambrian microcontinental block whose metamorphic age has been precisely dated at 500 Ma by SHRIMP zircon analyses [*Wilde et al.*, 2000, 2003; *Zhou et al.*, 2011]. Previously mapped as Precambrian basement in southern Mongolia [*Wang et al.*, 2001; *Badarch et al.*, 2002; *Demoux et al.*, 2009; *Kröner et al.*, 2010; *Rojas-Agramonte et al.*, 2011] recently has also been documented as highly deformed metaigneous and metasedimentary rocks formed within the Devonian-Carboniferous South Mongolia arc and its subsequent Permian-Triassic collision with northern China by microstructural analyses and zircon U-Pb dating [*Taylor et al.*, 2013]. However, the basement of the Xing'an block (e.g., Xilin Gol Complex) was shown to be Mesoproterozoic to Neoproterozoic by zircons dating [*Chen et al.*, 2009; *Y. L. Li et al.*, 2011; *Zhou et al.*, 2011]. The protolith of the Xilin Gol Complex was probably sourced from subduction-related components and deposited along the southern Mongolian margin [*Chen et al.*, 2009; *Y. L. Li et al.*, 2011]. Precambrian zircons ranging from 614 Ma to 2676 Ma also present in the Triassic andesites in the Linxi area [*Y. S. Liu et al.*, 2012] (Figure 8c). One Mesoproterozoic zircon has an ε_{Hf}(t) value as high as +8.3 (Figure 11), indicating addition of some juvenile components. Therefore, the few zircons with ages younger than 1568 Ma probably originated from the Precambrian components of the Xing'an block (Xilin Gol Complex) in eastern CAOB, because magmatism in this period is rare in the northern North China Craton (Figure 10d). The 1784–2625 Ma age spectrum of the Xingfuzhilu Formation is consistent with major ages of the basement in the North China Craton (Figure 10d). Such a Precambrian zircon age spectrum was also found in the Jurassic sedimentary rocks in the Yixian-Beipiao Basin along the northern margin of the North China Craton [*Meng et al.*, 2010]. Furthermore, these Paleoproterozoic to Archean zircons show weakly negative to weakly positive ε_{Hf}(t) values (−2.2 to +3.3) (Figure 11 and Table S4), suggesting reworking of ancient crustal materials with some juvenile crustal additions. Similar zircon Hf isotopic compositions to those of the North China basement were determined in this study and indicate a common source [e.g., *Meng et al*., 2010; *Yang et al*., 2006, 2009] (Figure 11). Therefore, zircons with Paleoproterozoic to Archean ages (1772–2625 Ma) probably came from the northern margin of the North China Craton [*Zhao et al*., 2002, 2010; *Wilde and Zhao*, 2005; *Zhai et al*., 2005; *Zhai and Santosh*, 2011; *H. F. Zhang et al*., 2012; *Santosh et al*., 2013].

6. Tectonic Setting

In NW China and Southwest Mongolia, the youngest marine rocks are Upper Carboniferous–Lower Permian turbidites and shallow-marine sandstone, mudstone, and carbonate [*He et al*., 1994; *Carroll et al*., 1995, 2010; *Johnson et al*., 2008]. There is a transition during the Late Permian from organic-rich, wood- and coal-bearing fluvial and lacustrine rocks formed under relatively humid climates to braided-fluvial red beds with common desiccation features [*Wartes et al*., 2002; *Carroll et al*., 2010]. Arid conditions persisted from the Latest Permian to the Early Triassic, whereas coal-bearing and humid-climate sediments were once again widespread in the Middle to Late Triassic [*Hendrix et al*., 1992, 1996, 2001; *Greene et al*., 2001; *Carroll et al*., 2010].

In the eastern CAOB (e.g., NE China and Southeast Mongolia), the youngest marine rocks are predominantly Middle Permian (Guadalupian) turbidite and flysch, with shallow-marine sandstone, mudstone, and carbonate [*Mueller et al*., 1991; *Shen et al*., 2006; *Johnson et al*., 2008; *C. W. Wang et al*., 2008, 2009; *Liu et al*., 2011, *Tian et al*., 2012]. Middle Permian marine successions lie unconformably or in fault contact with Carboniferous and older metasedimentary, volcanic, and intrusive rocks, including ophiolites, and Precambrian metamorphic rocks [*BGMRIM*, 1991, 1996; *Mueller et al*., 1991; *Shen et al*., 2006; *Shi*, 2006; *C. W. Wang et al*., 2008, 2009; *Liu et al*., 2011]. Middle Permian marine successions formed at the southern margin of the Paleozoic Sonid Zuoqi–Xilinhot-Xi Ujimqin magmatic arc, marked by rapid subsidence and deposition of turbidite successions along the Solonker suture zone, may be the result of continental margin deposition [*C. W. Wang et al*., 2008, 2009; *Liu et al*., 2011]. Middle Permian marine clastic succession locally transformed into terrestrial facies in the top of the Middle Permian strata characterized by purple sandstone, conglomerate, tuffaceous siltstone interbedded with shale [*Wang et al*., 1999]. A climatic shift from the Carboniferous–Early Permian humid-environment, coal-bearing deposits to Late Permian arid-climate, red-bed deposition occurred in northeast China [*Mueller et al*., 1991; *Shen et al*., 2006; *Johnson et al*., 2008]. *Cope et al*. [2005] also suggested that the climatic shift represents a rain shadow effect created during uplift of the continental margin owing to collision and/or northward movement of northern China to arid subtropical latitudes during this time.

By the Late Permian, the sedimentary sequence is transitional from marine clastic rocks into mainly terrestrial sandstone, mudstone, and slate in the area [*Mueller et al*., 1991; *Shen et al*., 2006; *C. W. Wang et al*., 2008, 2009; *Liu et al*., 2011]. The terrestrial Late Permian (Lopingian) Linxi Formation unconformably overlies the Middle Permian Zhesi Formation and is considered to represent a molasse deposit with a mixed Boreal Angaran and palaeo-equatorial Cathaysian flora [*Gu and Hu*, 1982; *Wang and Liu*, 1986; *BGMRIM*, 1991, 1996; *Mueller et al*., 1991; *Y. G. Liu et al*., 1999, *Y. J. Liu et al*., 2011; *Wang et al*., 1999; *Shen et al*., 2006]. This formation contains the nonmarine bivalve *Palaeomutella–Palaeono-Donta* assemblage and the northern Angaran plants *Supaia*, *Iniopteris*, *Callipteris*, and *Noeggerathiopsis* [*BGMRIM*, 1991, 1996; *Liu et al*., 1999; *Shi*, 2006]. Recently, *Y. S. Zhang et al*. [2012] discovered the first conchostracan fossils in the upper part of the Linxi Formation, which are identified as *Huanghestheria linxiensis Niu* (*sp. nov*.), *Cyclotunguzites cf. gazimuri Novojilov*, and *Sphaerorthothemos cf. cellulatus*, providing reliable fossil evidence as the Upper Permian age for the Linxi Formation. The Late Permian sedimentary environment was mainly open freshwater lakes and deltas [*Y. G. Liu et al*., 1999; *Y. J. Liu et al*., 2011; *Wang et al*., 1999; *F. L. Li et al*., 2009]. There was a slightly salt water signature during the early stage of Linxi Formation deposition, which is close to the salinity values of marine limestone [*Keith and Weber*, 1964], indicating a brackish environment [*He et al*., 1997; *F. L. Li et al*., 2009].

The Latest Permian to Early Triassic volcanic eruption in the Linxi area indicates the seawater ultimately disappeared [*Tian et al*., 2012]. The salinity values (Z) of micriteic limestone from the Upper Triassic Xingfuzhilu Formation vary from 92.0 to 108.6, which are far less than the salinity values of marine limestone ($Z > 120$) [*Keith and Weber*, 1964], indicating a freshwater environment. The lower-middle part of the Xingfuzhilu Formation show red-bed features with cross bedding, ripple marks, and mud cracks, indicating semiarid-arid terrestrial sedimentation. Therefore, the Xingfuzhilu Formation formed predominantly in a fluvial-lacustrine sedimentary environment. Permian-Triassic successions in the area are also marked by a climatic shift from humid-environment deposits in the Middle-Late Permian to widespread arid-climate and red-bed deposition during Triassic time, corresponding to the global warming event at the Permian-Triassic boundary [*Johnson et al*., 2008; *Heumann et al*., 2012].

7. Postaccretionary Crustal Evolution of Southeastern CAOB

In the Late Carboniferous, the Paleo-Asian Ocean was partially closed owing to the amalgamation of the southern active margin of Siberia with the Tarim Craton in the western CAOB [*J. Y. Li et al*., 2009; *Wang et al*., 2010; *B. F. Han et al*., 2011]. However, in the Late Carboniferous to Early Permian, the Paleo-Asian Ocean was probably open along the Solonker suture zone in the southeastern CAOB [*Xiao et al*., 2003, 2009b; *Li*, 2006; *Jian et al*., 2010; *Windley et al*., 2010]. Therefore, suturing appears to have been diachronous from west to east [e.g., *Li*, 2006; *Johnson et al*., 2008; *Wu et al*., 2007; *J. Y. Li et al*., 2009; *Heumann et al*., 2012].

The ages of ~1800 Ma and ~2500 Ma, characteristic of the North China Craton, are rare in the Middle Permian sandstones from the Zhesi Formation, whereas they occur as a small population in the Late Permian sandstones from the Linxi Formation and the Late Triassic sandstones from the Xingfuzhilu Formation (Figures 8b and 10), indicating the final amalgamation occurred sometime in the Middle to Late Permian. The Middle Permian cessation of marine deposition [*Cope et al*., 2005; *Li*, 2006; *Shen et al*., 2006; *Johnson et al*., 2008; *C. W. Wang et al*., 2009; *Heumann et al*., 2012], together with the Middle Permian cessation of arc-related magmatism along the Solonker suture zone [*Chen et al*., 2000, 2009; *Jian et al*., 2010] and Late Permian mixing of polar-temperate, Siberian (Angaran) floral assemblages with tropical, north China (Cathaysian) floral assemblages [*Mueller et al*., 1991; *Li*, 2006; *Shi*, 2006], supports Middle-Late Permian final amalgamation between the southern Mongolia terranes and the northern margin of the North China Craton. Accordingly, a possible narrow seaway or remnant wedge-shaped ocean basin along the Solonker suture zone still existed from Beishan in NW China to Jilin in NE China during the Middle Permian to early Late Permian [*He et al*., 1997; *Li*, 2006; *Shi*, 2006; *Johnson et al*., 2008; *Jian et al*., 2010; *Heumann et al*., 2012; *Tian et al*., 2012] (Figure 12a).

The Upper Permian–Triassic strata in the area have been interpreted as a postcollisional/postorogenic cover sequence [*Wang and Liu*, 1986; *Mueller et al*., 1991], with a provenance component from the North China Craton (Figures 8b and 10). The Middle-Late Permian arc-continent collision resulted in the continental block being uplifted along the Solonker suture zone and undergoing exhumation and denudation, which led to the termination of the Middle Permian remnant ocean basin, onset of the Late Permian basin and the establishment of an orogen [*Cope et al*., 2005; *Johnson et al*., 2008; *Meng et al*., 2010; *Heumann et al*., 2012] (Figure 12b).

Nonmarine Triassic strata up to 4 km thick in southern Mongolia were related to intracontinental shortening of the amalgamated North China–Mongolia terranes during the Triassic orogeny [*Hendrix et al*., 1996, 2001; *Taylor et al*., 2013; *Guy et al*., 2014]. *Q. Zhang et al*. [2008], based on the relationship between the geochemistry of granitic rocks and estimated magma pressures, proposed an E-W-striking Early Mesozoic mountain belt. This belt, extending from Beishan to Jilin, started to uplift in the Early Triassic, accompanied by strong compression and rapid uplift along the Solonker suture zone (Figure 12b). *Davis et al*. [2004] have also documented metamorphic core complex formation in the Sonid Zuoqi area at ca. 224–208 Ma, which may indicate collapse of the Late Triassic collisional orogen and would support the presence of high topography prior to collapse. Uplift and significant crustal thickening in the area during the Latest Permian–Middle Triassic is further supported by the Latest Permian–Early Triassic (ca. 255–248 Ma) sanukitoid and adakitic rocks linked to slab break-off [*Jian et al*., 2010; *W. Zhang et al*., 2010] and the Middle Triassic (241–229 Ma) granitoids related to collisional events along the Solonker suture zone [*Chen et al*., 2000, 2009; *J. Y. Li et al*., 2009] and the Early-Middle Triassic compressional deformation at the northern margin of North China Craton [*Zhang et al*., 2014]. Furthermore, a youngest peak age (~240 Ma) of magmatic zircons from sandstones of the lower-middle part of the Xingfuzhilu Formation may indicate that abundant Middle Triassic rocks were exhumated and denudated, resulting from the uplifting and intracontinental shortening along the Solonker suture zone, accompanied by possible slab break-off and lithospheric delamination (Figure 12b). *Yang et al*. [2006] studied detrital zircons from Paleozoic to Late Mesozoic strata in the Xishan area near Beijing, which show a significant change in provenance from the Late Triassic to the Late Jurassic (205–158 Ma) sandstones containing Phanerozoic zircons with positive $\varepsilon_{Hf}(t)$ values, distinct from known

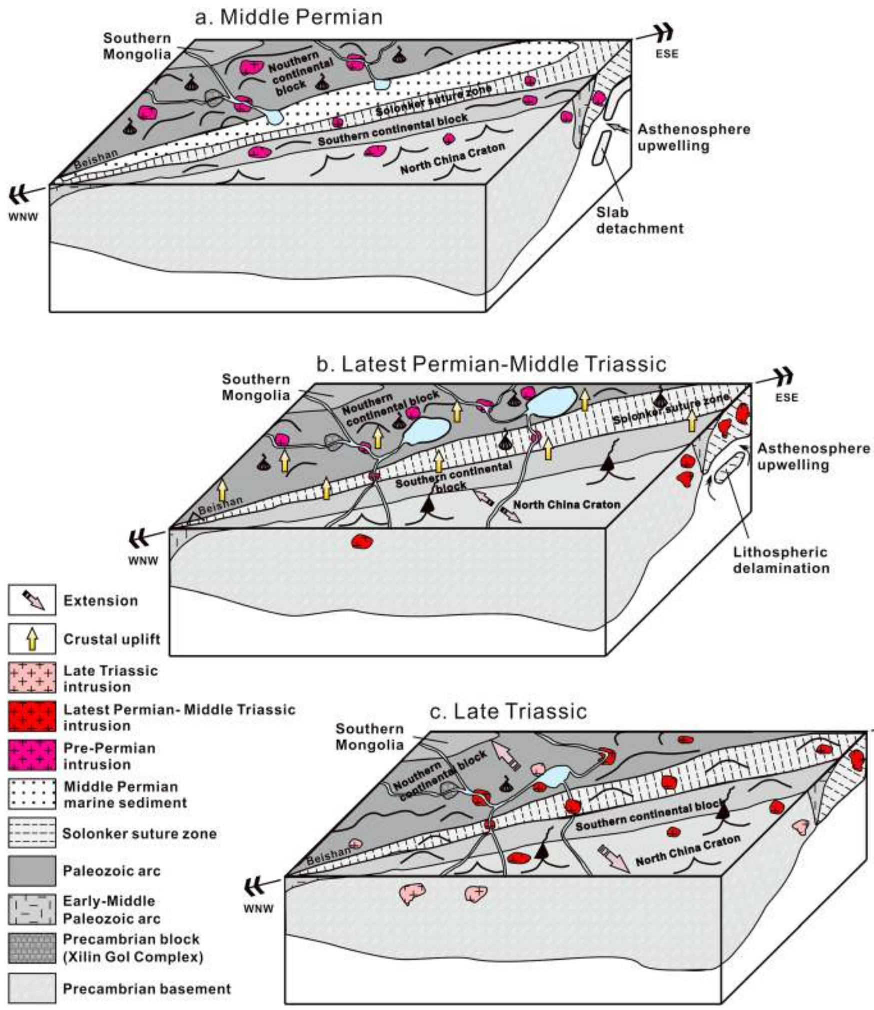

Figure 12. Paleogeographic diagrams for (a) Middle Permian, (b) Latest Permian–Middle Triassic, and (c) Late Triassic along the Solonker suture zone, summarizing magmatic, tectonic and stratigraphic characteristics, and the sedimentary provenance and tectonic evolution of the orogen discussed in this study (modified after *Johnson et al*. [2008]).

igneous zircons of North China Craton provenance. They further suggested a source from the eastern CAOB, resulting from the postorogenic exhumation and denudation of rocks due to uplift of the eastern CAOB in the Late Triassic. Therefore, the Late Triassic time possibly represented a phase of erosion and exhumation of magmatic arcs and unroofing of the collisional orogen due to postorogenic collapse along the Solonker suture zone in southeastern CAOB (Figure 12c). This scenario is also supported by postorogenic extension in the Late Triassic in eastern CAOB [*Wu et al*., 2002; *Davis et al*., 2009; *Li et al*., 2013a; *W. L. Xu et al*., 2013] and intraplate extension along northern margin of the North China Craton during the Late Triassic to Early Jurassic [*Yang et al*., 2006, 2012a, 2012b; *X. H. Zhang et al*., 2012; *Zhang et al*., 2014].

8. Implications for Triassic Crustal Growth

The CAOB is the largest Phanerozoic accretionary orogen on Earth, with evidence of considerable continental crustal growth. Its occurrence challenges the perception that growth of continental crust was mostly completed in the Precambrian [*Condie*, 2000, 2007; *Jahn et al*., 2000a, 2000b; *Cawood et al*., 2009]. Phanerozoic crustal growth has been established by the emplacement of voluminous granitoids with low initial $^{87}Sr/^{86}Sr$, generally positive $\varepsilon_{Nd}(t)$ values and young Nd model ages [*Jahn et al*., 2000a, 2000b; *Kovalenko et al*., 2004; *T. Wang et al*., 2009]. The present study was based on detrital zircons from the Xingfuzhilu

Formation, which was deposited after collision between the southern accretionary margin of the Siberia Craton and the northern margin of the North China Craton along the north of the Solonker suture zone to form the southeastern CAOB.

Two main pieces of evidence suggest that Triassic crustal growth documented by the Xingfuzhilu Formation detrital zircons was widespread and significant across the entire eastern CAOB [*Li et al*., 2013a]. Many Triassic detrital zircons from the eastern CAOB have positive zircon ε_{Hf}(t) values up to depleted mantle values, indicating juvenile magma was a major component [*Li*, 2010] (Figure 11). Also, Triassic granitic and volcanic rocks whose zircons display positive zircon ε_{Hf}(t) values at the time of magma crystallization are voluminous in the eastern CAOB [e.g., *Chen et al*., 2009; *W. Liu et al*., 2009; *Y. S. Liu et al*., 2012; *Li et al*., 2013a] (Figure 11).

Continental crust can grow by lateral accretion of arc complexes near subduction zones and by vertical addition of underplated magma at the crust-mantle interface [*Rudnick*, 1990; *Jahn et al*., 2004; *Condie*, 2007; *Cawood et al*., 2009; *Kröner et al*., 2014]. As described above, the eastern CAOB was formed by final closure of the Paleo-Asian Ocean in the Middle-Late Permian, leading to formation of the Solonker suture zone and collision between the North China Craton and the South Mongolia terranes. Triassic volcanic and intrusive rocks ranging in age from 248 Ma to 204 Ma in the southeastern CAOB can be classified into two main groups [*Li et al*., 2013a]: Early to Middle Triassic (248–233 Ma) and Late Triassic (230–204 Ma). Early to Middle Triassic granitoids in the area show large variations in ε_{Nd}(t) values from −5.3 to +5.8 and T_{DM} model ages from 0.99 Ga to 1.15 Ga, indicating derivation from a mixture of juvenile crust and old crust [*Li et al*., 2013a]. Late Triassic granitoids have ε_{Nd}(t) values from −2.3 to +1.0 and T_{DM} model ages from 0.82 Ga to 1.21 Ga, indicating derivation predominantly from juvenile crust sources with some contribution from old crust [*Li et al*., 2013a]. There is also evidence for the involvement of Precambrian crust in the source region. Therefore, Early to Middle Triassic crustal growth may also represent vertical addition of upwelling asthenosphere, possibly related to slab break-off and lithospheric delamination (Figure 12b). However, Late Triassic crustal growth may represent vertical addition of underplated magma in a postorogenic/nonorogenic extensional setting (Figure 12c) [*W. Liu et al*., 2009, 2012; *Jian et al*., 2010; *Wu et al*., 2011; *Li et al*., 2013a].

The Xingfuzhilu Formation in this study represents the clastic sedimentary response to regional extension after final collision of the South Mongolia terranes with the North China Craton. The closure of the Paleo-Asian Ocean led to a mixture of sources from both the North China Craton and the South Mongolia arc terranes for the Linxi and the Xingfuzhilu sediments. Therefore, the provenances of the Triassic Xingfuzhilu Formation can be interpreted as mixing of Triassic juvenile crustal additions with Precambrian crust of the North China Craton. Triassic zircons from the Xingfuzhilu Formation can be also divided into two groups with ages of 250–231 Ma and 227–219 Ma (Figure 8b), consistent with the ages of igneous intrusions in the area [*Li et al*., 2013a]. Therefore, collision-related uplift and slab-break off between 250 Ma and 231 Ma may have been responsible for vertical crustal growth, whereas postorogenic extension between 227 Ma and 219 Ma may be the result of mafic magmas underplating.

9. Conclusions

U-Pb detrital zircon dating of the Xingfuzhilu Formation in southern Inner Mongolia defines the youngest age cluster at ~220 Ma, indicating the maximum depositional age. The detrital zircons mainly yield Triassic and Paleozoic ages, with minor Precambrian ages. Two major zircon populations are in the Triassic (250–219 Ma with one major age peak at ~240 Ma) and the Carboniferous-Permian (354–253 Ma with one major peak at ~263 Ma), with two minor populations in the Early-Middle Paleozoic (512–373 Ma with one major peak at ~436 Ma) and the Precambrian (2625–604 Ma with predominantly Archean-Paleoproterozoic ages). The Triassic-Paleozoic zircons with mostly positive ε_{Hf}(t) values (+1.8 to +16.4) were predominantly derived from the weathering of nearby magmatic rocks in the northern continental block, possibly mixed with materials from Precambrian blocks in the southeast CAOB, as well as possibly from the southern continental block and the North China Craton. The distribution and provenance of Middle Permian strata recorded the final phase of marine deposition in a closing ocean basin or narrow seaway immediately prior to final collision during the Middle-Late Permian. The resultant collision resulted in the crustal uplift and thickening along the Solonker suture zone, accompanied by possible slab break-off and lithospheric delamination during the Latest Permian to Middle Triassic. Subsequently, Late Triassic time underwent exhumation and denudation of rocks in response to the postorogenic collapse and regional extension. Vertical Triassic crustal growth is recorded by Triassic detrital zircons with positive $\varepsilon_{Hf}(t)$ values in the region.

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