Huge sedimentary hiatus in the southern margin of the North China Craton from mid-Mesoproterozoic to Neoproterozoic

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**ABSTRACT**

The Mesoproterozoic to Neoproterozoic Eras were characterized by environmental, evolutionary, and lithospheric stability in the North China Craton (NCC). It is controversial that huge uplift(s) occurred in the North China Craton during this period. The southern NCC developed early terrestrial deposition in the latePaleoproterozoic and glacial sequence in the late Neoproterozoic record integrated geological history of the NCC in the intervening interval. Geochemistry compositions of mid-Mesoproterozoic carbonaceous slates (ca. 1330 Ma) show similar provenances to the underlying Mesoproterozoic sedimentary rocks in the southern NCC. Detrital zircons from the mid-Mesoproterozoic strata yield U–Pb ages from ca. 2450 to 1850 Ma with minor ages of 2950 and 2750 Ma. U–Pb ages of detrital zircons from the Neoproterozoic strata yield from ca. 1700 to 1000 Ma besides peak ages of 2600, 2400, and 1950 Ma. The early Paleozoic sedimentary rocks also display peak ages between ca. 1850 and 1000 Ma along with peaks at ca. 2500 and 2300 Ma. These detrital zircon ages are quite different from those of the Mesoproterozoic sedimentary rocks in the NCC. According to paleogeography study, the late-Paleoproterozoic to the early Mesoproterozoic clastic sequences are controlled by Xiong'er volcanic event in the southern NCC and carbonate platform developed later. The Mesoproterozoic sequences are overlain disconformably by the Neoproterozoic strata. In combination with compiled magmatic and detrital zircon ages, a sedimentary gap spanned at least 300 Ma from mid-Mesoproterozoic to Neoproterozoic in the southern NCC. Thus, the disconformity between the Mesoproterozoic and Neoproterozoic sedimentary sequences in the southern NCC should represent a huge sedimentary hiatus. Both the variable provenances and huge sedimentary hiatus between the Mesoproterozoic and Neoproterozoic sedimentary sequences support that the NCC might not split from relict landmass of Columbia Supercontinent before Neoproterozoic. The relict landmass was involved in aggregation of the Rodinia supercontinent.

**1. Introduction**

Cratonic and rift sedimentary assemblages developed in the Paleoproterozoic after the emergence of protocratons are caused by accretions of Archean greenstone terranes (Kroner et al. 1988; Zhao et al. 2004, 2011; Zhai and Santosh 2011; Wang et al. 2020a). The cratons stabilized afterwards and then the earth stepped into ‘Middle Age’, which was characterized by environmental,
evolutionary, and lithospheric stability (Holland 2006; Young 2013; Cawood and Hawkesworth 2014; Zhai and Peng 2020; Brown et al. 2020). Huge sedimentary hiatus (more than 300 Ma) occurred in North American, Australia, Amazon, and Baltica continental blocks, which constituted the core of Rodinia Supercontinent, and led to parallel or lower angle unconformities between Neoproterozoic and Paleoproterozoic strata (Marmont 1987; Daziel 1997; Torsvik 2003; Jefferson et al. 2007; Li et al. 2008; Davidson 2008; Pirajno et al. 2009; Jarrett et al. 2018). Both Siberia and North China cratons are supposed to be away from the supercontinent (Li et al. 2008, 2019) or the Grenville orogenic belts (Zhai et al. 2015). Nevertheless, great uplift(s) could last for at least 300 Ma in Siberia (Gladkochub et al. 2010). It is controversial that huge uplift(s) occurred in the North China Craton (NCC) (Qu et al. 2014; Hu et al. 2016; Su et al. 2016; Li et al. 2018; 2019; Zhong et al. 2019; Liu et al. 2020). Whether the huge sedimentary hiatus occurred in the North China Craton (NCC) could be a key to get a better insight of the evolution of the supercontinent.

The southern NCC developed early terrestrial deposits in the Mesoproterozoic and glacial sequence in the late Neoproterozoic record integrated geological history of the NCC in the intervening interval. We provide new detrital zircon ages from the mid-Mesoproterozoic to the early Paleozoic strata and geochemistry of the mid-Mesoproterozoic sedimentary rocks in the southern NCC. With the addition of published detrital zircon ages and geochemistry data, this study presents a huge sedimentary hiatus from mid-Mesoproterozoic to Neoproterozoic in the southern NCC.

2. Geological settings

The NCC is bounded by the Central Asian Orogen to the north and separated from the South China Block to the south by the Qin Qi Kun and Danbi-Sulu orogens (Figures 1a and 1b). The oldest units in the NCC are Archean metamorphosed greenstone belts and Archean to Paleoproterozoic orthogneiss, which are angular unconformably overlain by Mesoproterozoic volcanic–sedimentary successions and Phanerozoic cover (Jahn et al. 1987; Zhao et al. 2001; Nutman et al. 2011; Zhai and Santosh 2011; Wan et al. 2011, 2012; Zhao and Zhai 2013; Zhai et al. 2015). Xiong’er volcanics (1800 to 1750 Ma) is the largest magmatism after the formation of the crystalline basement of the North China Craton (Zhao et al. 2015, 2019). Paleoproterozoic Guanxian Group, Xiaogoubei Formation, and Bingmagou Formation overlie the Xiong’er volcanic-sedimentary successions (Figure 2) (Guan et al. 1988; BGMRH, 1989; Jahn and Ernst 1990; Wang et al. 2016a; Yue et al. 2020). Based on the tectonic framework and basin-fill history in the late Paleoproterozoic to Neoproterozoic, the sedimentary sequences are divided into three lithostratigraphic areas, i.e. Songshan-Jishan, Mianchi-Queshan, and Lushi-Luanchuan areas (Figure 1c) (Guan et al. 1988; BGMRH, 1989). Paleo- to Mesoproterozoic Bingmagou Formation, Xiaogoubei Formation, and Gaoshanhe Group nonconformably overlie the Xiong’er volcanic-sedimentary successions (Figure 2) (Guan et al. 1988; BGMRH, 1989; Jahn and Ernst 1990; Wang et al. 2016a; Yue et al. 2020).

In Songshan-Jishan area, Paleo- to Mesoproterozoic Bingmagou Formation and Ma’anshan or Puyu formations are separated by a low angular unconformity. A disconformity occurs between the Ma’anshan Formation and the Neoproterozoic Luoquan or Luotuopan formations (Figures 2 and 3a). The Xiaogoubei formation in Mianchi-Queshan area is disconformity overlain by Ruyang Group, which consists of Yunmengshan, Biaocaping, and Beidajian formations. Late-Paleoproterozoic Luoyu Group, comprising Cuizhuang, Sanjiangtang, and Luoyukou formations, contacts with the Ruyang Group, and Huanglianduo formation disconformably (Figure 2). In the meanwhile, Neoproterozoic Luoquan or Dongjia formations disconformably overlies the Luoyukou or Huanglianduo formations, respectively (Figures 2, 3b and 3c). The Gaoshanhe Group in Lushi-Luanchuan area is covered disconformably by Mesoproterozoic Guandaokou Group (Figure 2). Weather crust disconformably overlies carbonates of the Guandaokou Group (Figure 3d), which is consists of Longjiayan, Xunjiansi, Duguan, Fengjiawan and Baishigou formations (Figure 2, 3e and 3f). In addition, Neoproterozoic Luoquan Formation or Luanchuan Group restdisconformably upon the Guandaokou Group (Figure 2, 3g and 3h). nean Provincial Natural Science Foundation of ChinaThe Neoproterozoic Luanchuan Group is comprised of Sanchuan, Nan’iniu, Meyeaoogou, Dahongkou, and Yuku formations (Figure 2). In Songshan-Jishan and Mianchi-Queshan areas, the early Cambrian strata consist of Xinji, Zhushadong, and Mantou Formations (Figure 2). The early Paleozoic Taowan Group occurs in Lushi-Luanchuan area. Phanerozoic strata disconformably that overlie the Precambrian sedimentary sequences are supposed to represent the Great Unconformity in the southern NCC (Li et al. 2020a).

Mafic dike swarms (1750 Ma) and anorthosite-rapakivi granites (ca. 1700 Ma) in the southern NCC have genetic link to the volcanic rocks of the Xiong’er Group (Zhao et al. 2015). Paleo- to Mesoproterozoic (ca. 1800 to 1500 Ma) alkaline granitoids are
interpreted as within-plate granites and could be related to the breakup of Columbia Supercontinent (Lu et al. 2002; Bao et al. 2011; Cui et al. 2013; Deng et al. 2016; Zhao and Deng 2016; Wang et al. 2020b). Neoproterozoic magmatism (840–860 Ma) in the southern NCC occurred mainly in Lushi-Luanchua area, including trachytes, syenites, and mafic dike swarms and could be related to the break-up of the Rodinia (Liu et al. 2005; Gao et al. 2009; Wang et al. 2011; Hu et al. 2019).

3. Sampling and analytical methods

Five samples for detrital zircon study were collected from Meso-Neoproterozoic to Cambrian sequences, i.e. Baishugou Formation, Sanchuan Formation, Xinji Formation, Mantou Formation, and Taowan Group (Figure 2). Eighteen carbonaceous slate samples (MT) were collected from the Neoproterozoic Guandaokou Group (Baishugou Formation) in Lushi-Luanchuan area for geochemistry study (Figure 1c).

Major, trace, and rare earth elements (REE) of all samples were analyzed. Whole-rock chemical compositions were analyzed at the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences. Major elements in whole rocks (except FeO and loss on ignition) were determined by standard X-ray fluorescence (XRF) using a Philips Model 1480 spectrometer equipped with a Rh tube. Trace element abundances (Y, Zr, Nb, Hf, Rb, Cs, Ba, Sr, Th, U, V, Cr, Co, Ni, Cu, Sc, and REE) were analyzed by using a combination of emission spectrography (ES) and inductively coupled plasma mass spectrometry (ICP-MS). Detection limits were ≤0.1 wt. % for major elements.

Figure 1. Geological maps showing: (a) the location of the study area within China (modified from Zhao et al. 2001); (b) the distribution of the main Late Paleo- to Neoproterozoic strata in different sedimentary basins (modified from Dong et al. 2014; Hu et al. 2014a, 2016; Peng 2015a); and (c) locations of the samples in this study (modified from HNIGS, 2009; SXIGS, 2009).
and ≤ 2 ppm for most trace elements. The detection limits for Ba, Cr, Rb, Sr, and V are 5 ppm. Correlation coefficients were calculated from the data set composed of the geochemical analyses of all the samples, with the significance level (α) < 0.01.

Mineralogical and textural studies of selected samples were carried out using optical microscopy, X-ray diffraction (XRD), and electron probe X-ray microanalysis (EPMA). XRD and EPMA analyses were carried out using at the laboratory of the China University of Geosciences, Beijing (CUGB). The analysis conditions were described by Zuo et al. (2021).

Zircon grains were mounted on adhesive tape, enclosed in a resin mount, and polished to approximately half their thickness with grinding fluid (1 μm). Images of these zircon grains were captured using an optical microscope in transmitted and reflected light. High resolution cathodoluminescence (CL) imaging was performed using a field emission scanning electron microscope (TESCAN, MIRA 3LMH) at the Nanjing Hongchuang Geological Exploration Technology Service Co., Ltd. Both these imaging approaches were utilized to identify internal structures and to select target sites for further U–Pb analysis.

Figure 2. Stratigraphic chart presenting nomenclature used in the Yanliao and Xiong’er basins as well as the collected ages from sedimentary and magmatic rocks. Data sources of Yanliao Basin: Jing’eryu Formation from Gao et al. (2011); Xiamaling Formation from Gao et al. (2008) and Su et al. (2010); Tieying Formation from Li et al. (2014); Wumishan Formation from Li et al. (2014); Gaoyuzhuang Formation from Li et al. (2010); Dahongyu Formation from Zhang et al. (2015); Chuanlinggou Formation from Gao et al. (2009). Data sources of Xiong’er Basin: Bingmagou and Xinji formations from Zuo et al. (2019a); Ma’anshan Group from Meng et al. (2018), Hu et al. (2012a) and Zhang et al. (2016); Hejiazhai Formation from Jia (2018); Ruyang Group from Lan et al. (2014), Li et al. (2013), Hu et al. (2014b) and Li et al. (2020b); Xiaogoubei Group from Meng et al. (2018) and Zuo et al. (2019a); Luoyu Group from Lan et al. (2014), Su et al. (2012), Li et al. (2017) and Li et al. (2020b); Dongjia and Huanglianduo formations from Zuo et al. (2019b); Luquan Formation from Li et al. (2020a); Yuku, Meiyougou and Sanchuan formations from Jia (2018) and Li et al. (2020c); Dahongkou Formation from Yan et al. (2010) and Hu et al. (2019); Fengjiawan Formation from Li et al. (2018); Gaoshanhe Group from Zhu et al. (2011).
Figure 3. Outcrop photos and photomicrographs of Meso- to Neoproterozoic and Paleozoic depositional sequences in the southern NCC. (a) Hejiazhai Formation disconformably overlie Ma’anshan Formation; (b) Luoquan Formation disconformably contact with Xinji, Sanjiaotang, and Luoyukou formations (c); (d) weather crust disconformably overlying Mesoproterozoic carbonates; (e) and (f) contacts among Duguan, Xunjiansi and Fengjiawan formations; (g) disconformity contact between Neoproterozoic Luanchuan and Guandaokou groups. (h) pebbled sandstones in Sanchuan Formation of the Luanchuan Group (g).
Detrital zircon U–Pb dating of the samples from Neoproterozoic and early Paleozoic strata was accomplished by LA-ICP-MS (Agilent 7900 ICP-MS), with a laser beam (RESOlution M-50-LR Coherent COMPexPro® 102) repetition rate of 6 Hz and a 26 μm diameter analytical point size, at the State Key Laboratory of Marine Geology (Tongji University). Detailed operating parameters and procedures for the laser ablation system, ICP-MS instrument, and data reduction are as described in Liu et al. (2010). The mid-Mesoproterozoic sample was analyzed at the Wuhan SampleSolution Analytical Technology Co., Ltd., Wuhan, China. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are the same as description by Zong et al. (2017). Laser sampling was performed using a GeolasPro laser ablation system that consists of a COMPexPro 102 ArF excimer laser. The spot size and frequency of the laser were set to 32 μm and 5 Hz, respectively, in this study.

Zircon standard 91,500 was used as the external standard and analyzed twice every six or ten analyses. Offline selection and integration of the background and analysis signals, time drift corrections, and quantitative calibration were carried out using the ICPMS DataCal software package for zircon (Liu et al. 2010; Spencer et al. 2016). We use 1500 Ma (206Pb/238U) as the cutoff in selecting 207Pb/206Pb or 206Pb/238U ages in the relative age probability diagrams (Spencer et al. 2016). All of the uncertainties have been reported at 2 sigma. The assessment of concordant is conducted using the covariance of uncertainties of Ludwig (2003) within Isoplot. In this study, we define that the concordant ages are within the range of ±10% in the plot of 206Pb/238U versus 207Pb/206Pb ages (206Pb/238U age of >1500 Ma) or 206Pb/238U versus 207Pb/235U ages (206Pb/238U age of <1500 Ma). Concordance is defined as 100% x abs [1 − (206Pb/238U age)/(207Pb/235U age)] for the <1500 Ma zircon and 100% x abs [1 − (206Pb/238U age)/(207Pb/206Pb age)] for the >1500 Ma zircon. Multi-Dimensional Scaling (MDS) analysis are followed Vermeesch (2013) and Spencer and Kirkland (2016) by R with a package (Provenance, Vermeesch et al. 2016).

4. Analytical results

4.1 Mineralogy and geochemistry of mid-esoproterozoic sedimentary rocks

The XRD results show that carbonaceous slates consist mainly of quartz, illite, and K-feldspar (Figure S1). Minor apatite, phosphosiderite, illite, and limonite were also observed by EPMA (Figure 4) (Table S1). Illite generally is enriched vanadium in this study and mainly occur as fine flakes or aggregates (Figure 4d) (Table S1). There is no clear boundaries between apatite and quartz (Figure 4e). Both apatite and phosphosiderite occur as pillared particles and coexist with quartz, denoting an epigenetic origin (Figures 4e and g). Limonite occurs as debris particles and veins in the matrix and crack, and in some case, occurs as colloidal, suggesting occurrence of pyrite.

Analyzed samples for geochemistry study have been reported in Tables S2. All weight percent oxides were recalculated to 100% on a volatile-free and reduced iron basis in Tables S3. Average data of Post-Archean Australian shales (PAAS) (Taylor and McLennan 1985), which are considered as representative of the composition of upper continental crust, are included as a reference. Carbonaceous slates have higher SiO2 and P2O5 and lower Al2O3 than that of PAAS. There are strong correlations between K2O and Al2O3 suggesting occurrence of clays and feldspar, which is also supported by XRD analyses (Figures S1 and S2). Positive correlation between P2O5 and CaO indicates calcium phosphate, such as apatite, rhabdophane or cordillarite group (Figure S2). Since geochemical data are closed or constant-sum data, when one component of a compositional data set increases or decreases in relative abundance, the other components are forced to change as well. Al2O3 is likely to be immobile during weathering, diagenesis, and metamorphism (Cardenas et al. 1996; Bauluz et al., 2000; Meinhold et al. 2007; Qiu et al. 2016). Therefore, the Al2O3 abundances are used as normalization factor to make possible the comparison between different lithologies. If major oxides of analyzed samples are normalized to Al2O3, the only significant difference in the samples is the SiO2/Al2O3 ratio which indicates the variable contents of clay minerals and feldspar (Table S3).

Except Ba and U, all the analyzed samples are depleted in large ion lithophile elements (Rb, Cs, Sr, and Th) (Figure 5). Rb, Cs, Th, and Sc have significant correlations with Al2O3 and K2O (Figure S2) (Table S4), implying that their distributions are controlled by illitic phases (Bauluz et al., 2000). However, there is no clear correlation between Sr, U, Ba, and other major elements due to their high mobility during chemical weathering. The high field strength elements (HFSEs) (Ta, Zr, Nb, and Hf) are preferentially partitioned into melts during crystallization and anatexis, felsic rocks display HFSE enrichment in comparison to mafic rocks (Feng and Kerrich 1990). Carbonaceous slates are enriched in Nb than that of the PAAS (Table S2). HFSEs are also positively correlated with Al2O3 and K2O (Table S4).
The distributions of transition trace elements (Ni, Cu, Co, and Cr) are depleted in all samples (Table S2). Ni, Cu, and Co correlate with SiO$_2$ negatively and with FeO positively (Table S4). V enriched in carbonaceous slates, despite without evident correlation with major elements in this study, can be associated with clay minerals (Breit and Wanty 1991; Tribovillard et al. 2006). Positive correlations among Al$_2$O$_3$/SiO$_2$, CaO, and REE have been observed (Figures S2). The value of correlation coefficient between REEs and P$_2$O$_5$ is 0.23, which could be caused by the occurrence of phosphosiderite. As element concentrations could be affected by quartz dilution, higher contents of SiO$_2$ in all rocks analyzed in this study have less REE content than that of PAAS (Table. S2).

Fractionated chondrite-normalized REE patterns, negative Eu anomalies, and LREE fractionated (Figure 6a) suggest that source rocks have undergone near-surface crystal fractionation with feldspar involved. PAAS-normalized REE patterns show slight enrichment in HREE, but depleted in LREE (Figure 6b). Apatite shows a relatively wide range of chemical variations depending on the environment in which it was formed (Frietsch and Perdahl 1995; Kon et al. 2014). REEs can be released from detrital minerals (apatite and silicate) as REE$^{3+}$ ions and adsorbed by secondary phosphate minerals, clay minerals, and Fe–Mn oxides (Köhler et al. 2005; Stille et al. 2009) and therefore apatite has an important role in controlling REE contents and fractionations in the sedimentary rocks. The close affinity of REEs for apatite could account for the slight enrichment in HREE in the samples.

### 4.2 Detrital zircon U–Pb geochronology

CL images show that most grains have preserved magmatic oscillatory zonation. The majority of the zircons also have oscillatory zoning and high Th/U ratios.
both of which are indicative of a magmatic origin (Rubatto 2002; Hoskin and Schaltegger 2003; Wu and Zheng 2004; Kirkland et al. 2015). Figure 7 shows U–Pb concordia age plots and relative age probability diagrams for detrital zircons in this study. Sandstone (21YT-2) and quartzite (BSG0301) were collected in Baishugou Village (Figures 1c and 2). Zircon grains from the sandstone are euhedral to moderate degrees of rounding, mainly colorless, and measures 120–300 μm in size (Figure S1). Age distributions show dominant populations at 2450, 2050, and 1850 Ma, with two grains at 2950 and 2750 Ma (Figures 7a and b) (Table S5).

Zircon grains from the quartzite are euhedral to well-rounded, ranging from dark purple to light pink in color, and measures 30–130 μm in size (Figure S3). Age distributions show two dominant populations between 1700 and 1000 Ma, with subordinate peaks at 2600, 2400, and 1950 Ma (Figures 7c and d) (Tables S6).

Carbonaceous phyllite (SCK-4) was collected in Lushi-Luanchun area (Figures 1c and 2). Detrital zircon grains are mainly colorless with moderate degrees of rounding and sphericity ranging from 110 to 220 μm (Figure S3). Two main populations at 1850 and 1200 Ma with subordinate populations of 2500, 2300, 2100, 1500, and 1000 Ma are shown in Figures 7e and f (Table S7).
Figure 7. U–Pb concordia age plots and relative age probability diagrams for detrital zircons from the Xiong’er Basin. All analyses are used regardless of discordance in the U–Pb concordia diagrams. Gray lines in probability diagrams represent: concordant ages (≥1000 Ma), of which uncertainties (2σ) less than 10% of $^{206}$Pb/$^{238}$U versus $^{207}$Pb/$^{235}$U and $^{206}$Pb/$^{238}$U versus $^{207}$Pb/$^{206}$Pb ages; uncertainties (2σ) of concordant ages (<1000 Ma), fall in the range of ±2% of $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$Pb.
Sandstone (17X02) was collected in Mianchi-Queshan area (Figures 1c and 2). Zircon grains are moderate degrees of rounding and sphericity ranging from 90 to 260 μm (Figure S3) and yield an age distribution with two main populations at 2500 and 1850 Ma with minor populations of 2100 and 1650 Ma (Figures 7g and h) (Table S8). Siltstone from the Mantou Formation (MD01) was collected from Songshan-Jishan area (Figures 1c and 2). Zircons are moderate degrees of rounding and sphericity with wide ranges from 50 to 200 μm (Figure S3). Unlike the zircons above, these grains yield an age distribution with two main populations at 1100 and 550 Ma, and subordinate populations of 2600, 2000, 1850, 1300 and 850 Ma (Figures 7i and k) (Table S9). However, there are detrital zircon ages (less than 1000 Ma) with uncertainties (2σ) bigger than 2% of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$. These ages should be left out in provenance analysis.

5. Discussion

5.1 Variable provenances between Neoproterozoic and Nesoproterozoic sequences

Based on the trace elements and REEs distributions, the mid-Neoproterozoic sedimentary rocks show the similar provenances of the underlying early-Mesoproterozoic sandstones and mudrocks (Figures 5 and 6).

Detrital zircon study shows typical cluster ages of 2500 and 1850 Ma (Figure 7), which broadly coincide with amalgamation of micro-continents and finalized cratonization of the NCC, respectively (Zhao et al. 1999; Zhai and Liu 2003; Zhai and Santosh 2011; Zhai and Peng 2020). The NCC underwent Mesoproterozoic extension in its interior, and rifting along its northern, eastern, and southern margin (Zhao 2014; Peng 2015a; Zhang et al. 2017; Li et al. 2019). Alkali granitoids (ca. 1800 to 1500 Ma) and mafic dikes (1360–1200 Ma and 925–800 Ma) occurred in the NCC (Lu et al. 2003; Bao et al. 2011; Peng 2015b; Wang et al. 2016b, 2020b; Zhang et al. 2017). As baddeleyite cannot be retained in sediments during sedimentary cycles, detrital zircon grains aged from mid-Mesoproterozoic to the early-Neoproterozoic may not be derived from weathering of the mafic dikes/sills from the NCC. It is reasonable to infer that these zircon grains would be derived from other continents involved in the Grenville-Sveconorwegian-Sunsas Orogeny. Detrital zircons from the Xinji Formation in this study show no Neoproterozoic aged spectra, which have been identified from contemporaneous strata in other sections (Zuo et al. 2019a, 2019b), suggesting limited Neoproterozoic source rocks.

5.2 Huge sedimentary hiatus of the southern NCC from mid-Mesoproterozoic to Neoproterozoic

In Songshan-Jishan area, Ma’anshan and Puyu sequences are quite different from the Luotuopan and Hejiazhai sequences in sedimentary facies, and both of them comprise two sedimentary sequences (Zhou 2019; Huang 2020). Detrital zircons from the upper portion of the Ma’anshan Formation yield a dominant peak at ca. 1800 Ma and youngest age at ca. 1655 Ma (Zhang et al. 2016; Meng et al. 2018). In contrast, mid-Mesoproterozoic to Neoproterozoic aged detrital zircon grains were developed in the Hejiazhai and Luotuopan formations (minimum peak age at ca. 1000 Ma) (Jia 2018; Huang 2020; Li et al. 2021) (Figure 8). In Mianchi-Queshan area, Neoproterozoic strata disconformably overlies the Paleoproterozoic to early-Mesoproterozoic sedimentary rocks (Su 2016; Zuo et al. 2019b; Pang et al. 2021).

Volcanic tuff from Longjiayuan Formation of the Guandaokou Group in Lushi-Luanchuan area yielded U–Pb ages from 1594 to 1541 Ma (Zhang et al. 2019), which are consistent with the minimum peak age (1511 Ma) of detrital zircons from sandstone above the Fengjiawan sedimentary rocks (Li et al. 2018). Tuffite beds from the Baishugou Formation yielded U–Pb age of ca. 1330 Ma (Figure 2) (Zhu et al. 2020). Therefore, Guandaokou Group could be deposited from ca. 1600 to ca. 1330 Ma. Luanchuan Group can be constrained by ca. 830 Ma gabbro (in the Meiyaogou and Yuku formations) (Wang et al. 2011), 840–860 Ma trachyte (in the Dahongkou Formation) (Hu et al. 2019), and minimum peak age of detrital zircons at ca. 1000 Ma from the Sanchuan Formation (Jia 2018; Liu et al. 2019; Li et al. 2020c; this study). A huge sedimentary hiatus (at least 300 Ma), therefore, separates the mid-Mesoproterozoic from the Neoproterozoic deposits in the southern NCC.

Wide extensions led to subsidence of the southern NCC after the orogeny at ca. 1850 Ma (Zhai et al. 2015; Zhao et al. 2015, 2019; Li et al. 2019). Distribution and sedimentation of clastic rocks at the southern NCC were controlled by the Xiong’er volcanic event just existed in the Paleoproterozoic to early Mesoproterozoic (Changcheng System, 1800–1600 Ma) (Zhao et al. 2015; Meng et al. 2018; Deng et al. 2021) (Figure 2). Epicontinental sea is supposed to develop in the Jixian System (1600–1400 Ma) and marine carbonate-clastic sequences deposited in the southern NCC (Hu et al. 2016). Limited mid-Mesoproterozoic sediments (Baishugou and Xiamaling sequences) deposited later (Su 2016; Zhu et al. 2020). Transgressive sedimentary sequences were deposited in Neoproterozoic.
Figure 8. Multidimensional scaling (MDS) plots of detrital zircon U–Pb ages. The MDS plots were produced with R software and based on methods outlined by Vermesch (2013). (a) MDS of the detrital zircon age spectra of the late-Paleoproterozoic to Neoproterozoic sedimentary successions deposited in the Yanliao and Zha’ertai-Bayan Obo-Huade basins. Sources of the U–Pb data: Qingbaikou Group from Gao et al. (2011), Wan et al. (2011) and Wang et al. (2017); Changcheng Group from Wan et al. (2011) and Ying et al. (2011); Jixian Group from Ying et al. (2011); Bayan Obo Group from Zhou et al. (2018), Ma et al. (2014), Zhong et al. (2015) and Liu et al. (2017), (2020); Huade Group from Hu et al. (2009) and Liu et al. (2014), Liu et al. (2018), 2020); Sailinhudong Group from Ma et al. (2014); Zha’ertai Group from Liu et al. (2020).(b) MDS of the detrital zircon age spectra of the Meso- to Neoproterozoic sedimentary successions deposited in the Xuhuai Basin (Eastern NCC). Sources of the U–Pb data: Feishui and Huainan Groups from Sun et al. (2020); Jinxian Group from He et al. (2016); Huaian Group from He et al. (2016), Yang et al. (2012) and Sun et al. (2020); Penglai Group from Zhou et al. (2008); Tumen Group from Hu et al. (2012b); Diaoyutai Formation from Gao et al. (2011),(c) MDS of the detrital zircon age spectra of the late-Paleoproterozoic to Neoproterozoic sedimentary successions deposited in the Xiong’er Basin (southern NCC). Sources of the U–Pb data: Luoyu Group from Lan et al. (2014) and Li et al. (2013), Li et al. (2020b)); Gaoshanhe Group from Zhu et al.
(Figure 9). The provenances of early-Mesoproterozoic to the mid-Mesoproterozoic sedimentary rocks are recycling of ancient crustal materials from the NCC before the depositional hiatus. After that, Greenville-aged detrital zircons from other cratons occurred as the source rocks of Neoproterozoic deposits in the southern NCC.

### 5.3 Implications for the evolution of the supercontinent

Cratonic and rift sedimentary assemblages developed widely and stabilized proto-cratons from Statherian to Ectasian, which featured the Earth’s middle age (Zhai et al. 2015; Zhai and Peng, 2020; Zheng and Zhao 2020; Cawood 2020). Although a number of lower angle unconformities or disconformities occurred in Mesoproterozoic sedimentary successions in the NCC, many of them are distributed locally and can be readily explained by relative sea-level variations (Meng et al. 2011). However, uplift(s) developed in both Yanliao and Zha’ertai–Bayan Obo–Huade basins from mid-Proterozoic to Neoproterozoic (Qu et al. 2010; Hu et al. 2016; Zhong et al. 2019; Liu et al. 2020; Zhang et al. 2020). Mesoproterozoic sedimentary sequences are absent in the Xuhuai Basin (He et al. 2016; Sun et al. 2020). Intense weathering occurred widely in the supercontinent cycle, and general planation can be encouraged by high denudation rate in vegetation-free landscapes (Eriksson et al. 1998; Campbell and Allen 2008). After the earlier, still nearly horizontal unconformity, subsequent unconformities tend to conform to this original cratonic planation surface. Thus, the Mesoproterozoic sequences are conformably overlain by the Neoproterozoic strata (Figure 9).

Greenville-aged detrital zircons also occurred in the Neoproterozoic sequences from these areas (Figure 9). Although the NCC might not involved in the Rodinia Supercontinent directly and was located far from the Grenville orogeny (Wei et al. 1998; Torsvik 2003; Li et al. 2008, 2019; Pisarevsky et al. 2014; Zhai et al. 2015; Cawood et al. 2016), NCC may not split from relict landmass of Columbia Supercontinent, and was connected with continents involved in Grenville–Sveconorwegian–Sunsas Orogeny. Huge uplift(s) likely lead to the long-term hiatus in the NCC.

(Figure 9). Generalized stratigraphic cross-section (2.5x vertical exaggeration) through the Xiong’er Basin, showing the lithostratigraphy and unconformities.
6. Conclusions

Detrital zircon ages in the Neoproterozoic and early Paleozoic sedimentary sequences indicate variable provenances in comparison with those from the Mesoproterozoic strata. Geochemistry compositions of mid-Mesoproterozoic carbonaceous slates (ca. 1330 Ma) show similar provenances to the underlying Mesoproterozoic sedimentary rocks in the southern NCC. Distribution and sedimentation of Mesoproterozoic clastic rocks at the southern NCC were controlled by the Xiong’er volcanic event just existed in the Paleoproterozoic to the early-Mesoproterozoic, and then epicontinental sea deposits occurred on the NCC until mid-Mesoproterozoic. Neoproterozoic sedimentary successions overlie the early-Mesoproterozoic strata disconformably. According to the constraints of magmatic and detrital zircon ages, the disconformity should represent a huge sedimentary hiatus, which should be more than 300 Ma. Uplift(s) could occurred widely from the Mesoproterozoic to Neoproterozoic in the NCC and caused the disconformities. We therefore proposed that the NCC might not split from relict landmass of Columbia Supercontinent before Neoproterozoic.

Highlights

1. Variations of sources–changes in detrital zircon age from Mesoproterozoic to Neoproterozoic.
2. Last sedimentary gap from mid-Mesoproterozoic to Neoproterozoic.
3. The North China Craton might not split from relict landmass of Columbia Supercontinent before Neoproterozoic.

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Disclosure statement

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