Precambrian Research 418 (2025) 107692

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

The Tonian sedimentary records in the southwestern West Qinling orogen, central China, reveal an active margin setting

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ARTICLE INFO

Keywords:
West Qinling orogen
Yangtze Block
Neoproterozoic
Baiyigou Group
Sedimentary provenance analysis
Active margin tectonic setting

ABSTRACT

Neoproterozoic geological records are uncommon in the West Qinling orogen (central China), restricting a clear understanding of its early evolution and the relationships between the West Qinling terrane and surrounding blocks in the Neoproterozoic. The infrequent Neoproterozoic sedimentary successions in the southwestern West Qinling orogen, named as the Baiyigou Group, may provide important insights into these issues. In this contribution, we present comprehensive analysis results, including sedimentological, petrographic, heavy mineral, zircon U-Pb-Hf isotopic and trace element, and whole-rock element geochemical data from Baiyigou Group samples, to determine their depositional ages, provenance and tectono-sedimentary settings. The Baiyigou Group is characterized by mixed volcaniclastic and siliciclastic deposits. Zircon U-Pb dating results from seven tuffaceous sandstones show overwhelming Tonian ages (ca. 840–780 Ma), with major age peaks at the range of ca. 820–800 Ma. Three granite gravel samples from conglomerate strata show crystallization ages at ca. 809–802 Ma, providing maximum depositional age constraints. All these geochronological data indicate that the Baiyigou Group succession accumulated during the middle–late Tonian (ca. 820–800 Ma for the Saiyikuo Formation and possibly largest duration of ca. 800–720 Ma for the overlying Xianglongka Formation). Tephra-rich sandstones are poorly sorted and are featured by abundant embayed grains, whereas tephra-free sandstones are moderate-well sorted and are rich in detrital feldspar grains. Several heavy mineral samples indicate extremely high zircon contents and most zircon grains are texturally euhedral, representing first-cycle detritus. We propose that this sedimentary system was dominantly fed by intermediate-acid igneous rocks from localized source terranes with small drainage networks and was also contributed by extensive wind-carried volcanic clasts. Our petrographic, whole-rock geochemical and zircon trace element data reveal a continental arc setting for the sedimentary sources during the middle–late Tonian. We suggest that the middle–late Tonian West Qinling terrane was in an active margin setting, being involved in the long-lived subduction-related system along the western margin of the Yangtze Block. These findings are crucial to a better understanding of the Neoproterozoic tectono-sedimentary settings of the central China micro-terranes along with the Rodinia supercontinent evolution.

1. Introduction

The Neoproterozoic Era is one of the most important times in the Earth tectonic evolutionary history related to the assembly and break-up of the Rodinia supercontinent (e.g., Dalziel, 1997; Hoffman et al., 1998; Lenton et al., 2014; Merdith et al., 2017). The South China Craton is an essential part of the Rodinia during the Neoproterozoic, however, how the South China was involved in the supercontinent evolving process remain enigmatic. The Neoproterozoic sedimentary and magmatic records occur widely along the margins of the Yangtze Block, South China and provide significant clues for understanding the Neoproterozoic tectonic evolution and sedimentary settings (Wang and Li, 2003; Zhao and Cawood, 2012; Gu et al., 2023; Dong et al., 2024a, b). The Neoproterozoic sedimentary successions within the current West Qinling orogen (connecting the current northwest margin of the Yangtze Block, Fig. 1A) are less well documented and has not received much attention. Their depositional ages, sediment provenance and tectono-sedimentary settings, which are crucial for deciphering the Neoproterozoic tectonic affinity and evolution of the Yangtze Block, however, remain poorly constrained.

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https://doi.org/10.1016/j.precamres.2025.107692
Received 14 June 2024; Received in revised form 15 November 2024; Accepted 10 January 2025

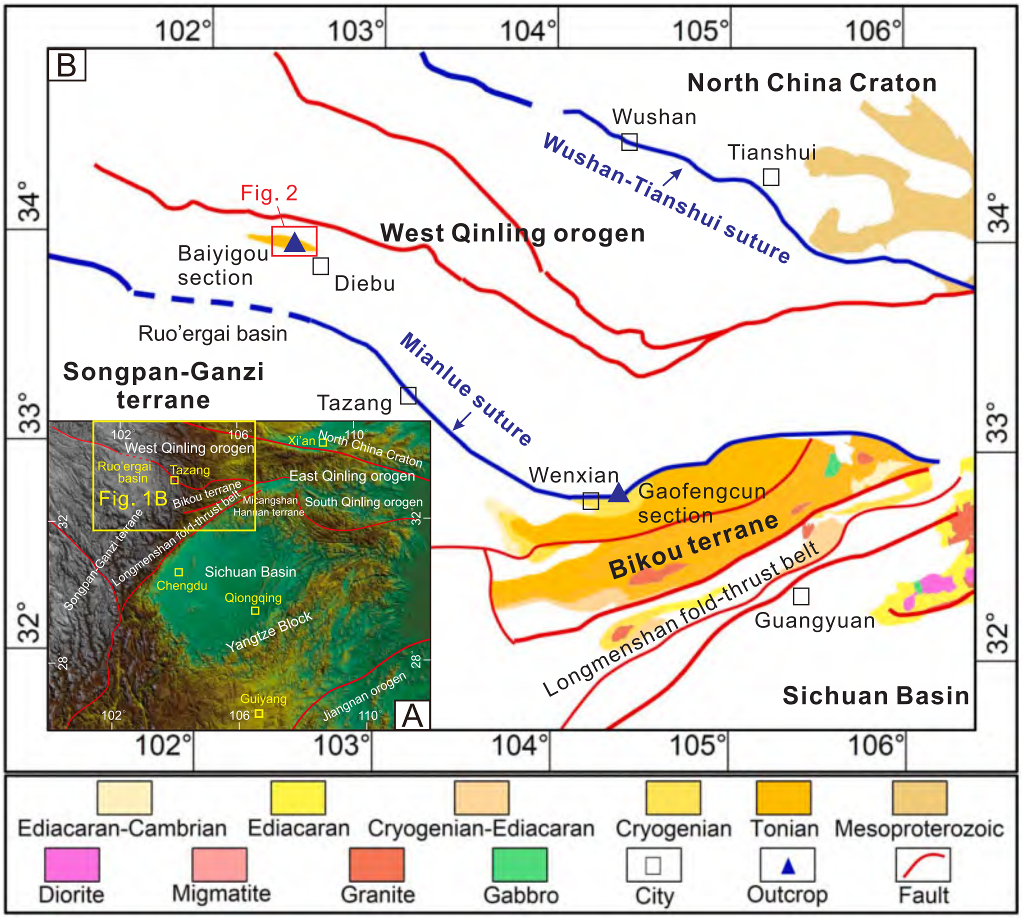

Fig. 1. Location and simplified geological map of the West Qinling orogen (modified from Gu et al. (2023)). To better show Neoproterozoic outcrop in this region, only Precambrian records are marked here. The Bikou terrane is bounded to the south by the Mianlue suture and is dominated by Neoproterozoic geological records (Gu et al., 2023), whereas the Neoproterozoic outcrop is uncommon in the West Qinling orogen. This region has undergone significant reworking due to Cenozoic tectonics and the Tazang fault typically represent the westward extension of the Mianlue suture (Qin et al., 2008; Ren et al., 2013; Xu et al., 2017).

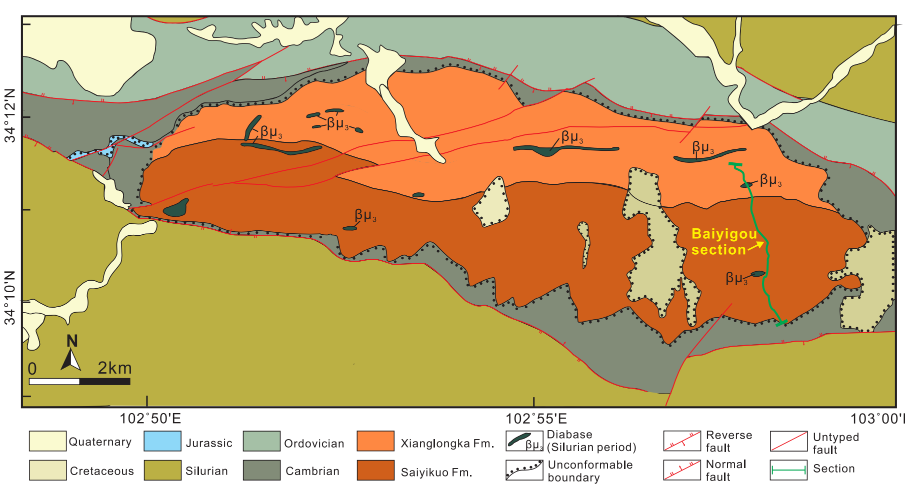

Fig. 2. Geological map of the study area. The investigated outcrop section (named as the Baiyigou section) is along the Baiyigou river. The Baiyigou Group successions are exposed as an anticline structure and are overlain by the Cambrian Taiyangding Group. This outcrop section was firstly investigated by Chinese geologists in the 1970 s–1980 s (Li et al., 1987; Zhang et al., 1988).

The Baiyigou Group is thought to be the oldest Neoproterozoic sedimentary sequence in the West Qinling orogen (Li et al., 1987; Zhang et al., 1988). The Baiyigou anticline in southwestern West Qinling near the Diebu county (Figs. 1–2) is possibly the only Precambrian outcrop discovered by now. Several investigations were performed by Chinese geologists more than 30 years ago. The depositional age of the Lower Baiyigou Group was constrained at ∼ 738.59 Ma based dating a tuff sample using the Rb-Sr method (Li et al., 1987). In terms of the tectonic setting, the Baiyigou Group was previously considered to be formed in a failed rifting setting (Li et al., 1987; Yang et al., 1989) or in an active

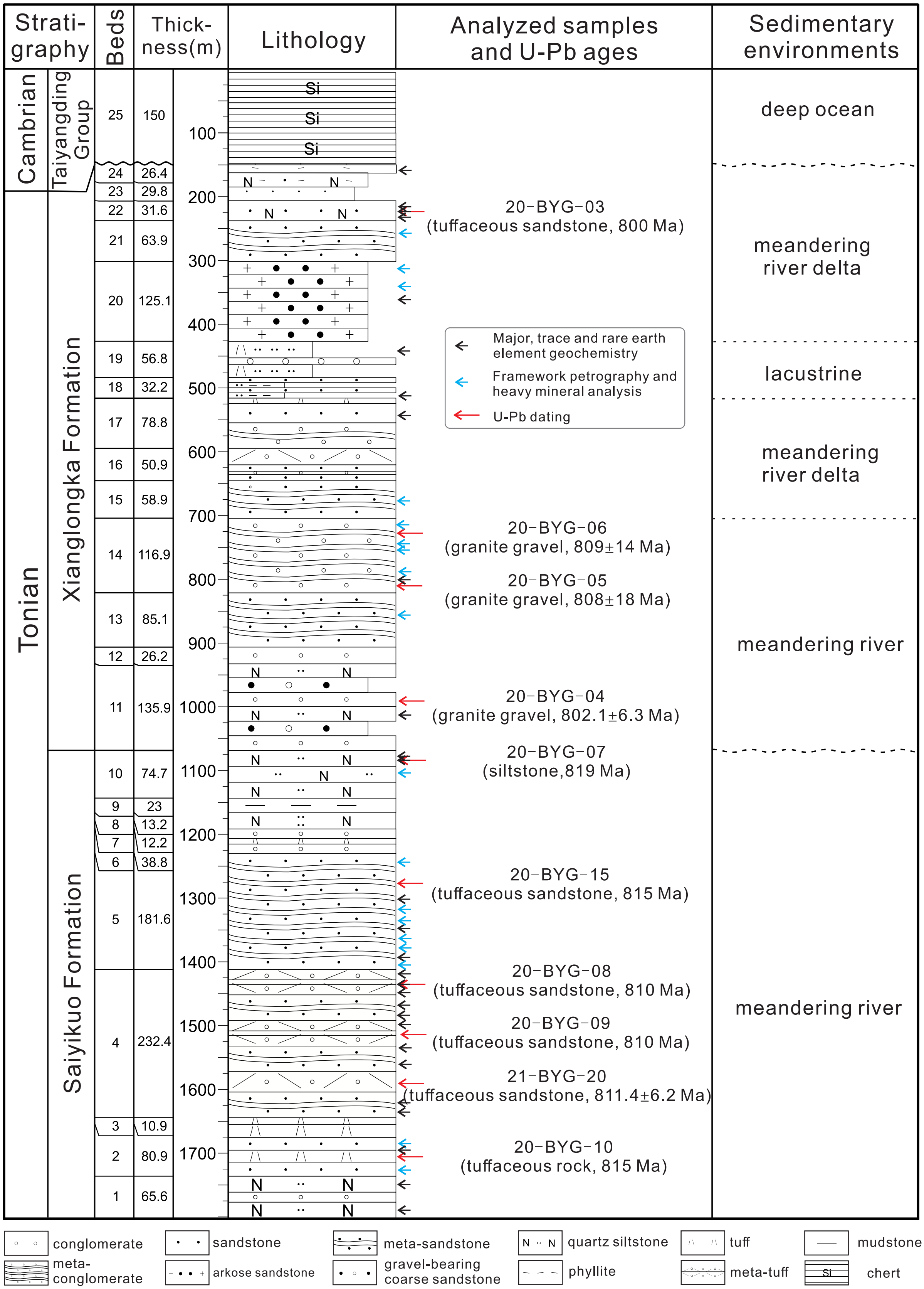

Fig. 3. Outcrop lithology, zircon U-Pb dating samples and sedimentary environments for the Tonian strata at the Baiyigou section. For the detrital zircon dating samples, major peak ages are shown; for the granite gravel samples, weighted average ages are shown here. Representative outcrop photographs are shown in Figs. 4–5.

margin setting (Zhang et al., 1988; Min and Wen, 1991). Furthermore, there are two views regarding the sedimentary environment of the Baiyigou Group (Li et al., 1987). Most researchers considered it to be a terrigenous fluvial depositional record, but marine deposition dominated by turbidite was still proposed for sedimentary environment interpretation. For instance, Li et al. (1987) proposed that the Baiyigou Group may represent as a molasse sequence in an alluvial environment, including alluvial fan, river and lake facies; Zhang et al. (1988) regarded the Baiyigou Group as terrigenous fluvial deposits involving alluvial fan to meandering stream facies; and Min and Wen (1991) thought it as products of a braided river sedimentary system near to a proximal alluvial fan environment. These early investigations only provided some superficial understanding and explanations. After that, the Baiyigou Group sedimentary succession has not been studied and related analysis data have not been reported.

In this study, we revisited previously measured section (named as the Baiyigou section, Fig. 2) and carried out detailed sample analysis integrating substantial sedimentological, petrographic, whole-rock geochemical, zircon U-Pb geochronological and Hf isotopic data. The aims are 1) to constrain depositional ages of the sedimentary successions, 2) to determine the sedimentary provenance and depositional environment, and 3) to specify the tectonic setting of the Baiyigou Group development. This study does not only shed light on the tectonic and sedimentary evolution for the westmost West Qinling orogen, but may also provide crucial insights on the tectonic relationships between the West Qinling terrane and surrounding blocks in the Neoproterozoic.

2. Geological setting

2.1. Regional tectonic setting

Our study area is located in the westmost Qinling orogen, central China, which is an interactive site among multiple tectonic units. It is situated between the northeast part of the Songpan-Ganzi terrane, the northwestern corner of the Yangtze Block, and the southwestern North China Craton (Fig. 1A).

The W-E-trending Qinling orogen in central China is considered as a result of the Late Triassic collision between the North China and South China Cratons along the Mianlue suture (Mattauer et al., 1985; Zhang et al., 1995; Meng and Zhang, 1999; Zheng, et al., 2010; Dong et al., 2015). The Qinling orogen, from west to east, can be divided into the West Qinling and East Qinling orogens (Zhang et al., 1995, 1996; Zheng, et al., 2010; Li et al., 2018) (Fig. 1A); the East Qinling orogen, from north to south, is further subdivided into the North Qinling and South Qinling orogens separated by the early Paleozoic Sangdan suture, which is also regarded as the major suture between the North China and South China Cratons (Meng and Zhang, 1999; Zheng et al., 2010; Dong et al., 2015, 2017). The South Qinling orogen has long been considered as the passive margin of the Yangtze Block during the late Neoproterozoic to early Paleozoic (Zhang et al., 1995; Meng and Zhang, 1999; Zheng et al., 2010; Dong et al., 2015, 2017; Dong and Santosh, 2016).

The West Qinling orogen is a western extension of the South Qinling orogen (Fig. 1A), which is bounded with the North China Craton by the Wushan-Tianshui suture in the north and separates from the Songpan-Ganzi terrane and the Bikou terrane by the Mianlue suture in the south (Pei et al., 2004; Li et al., 2018; Yang et al., 2018) (Fig. 1B). The Wushan-Tianshui suture is considered as the westward extension of the Sangdan suture and comprises the ophiolite complexes and island-arc units (Pei et al., 2004, 2007; Dong et al., 2007; Li et al., 2007; Yang et al., 2018). The northern Wushan-Tianshui and Sangdan sutures, as well as the southern Mianlue suture mark the closures of the northern parts of the Proto-Tethys Ocean during the late Neoproterozoic to early Paleozoic and the Paleo-Tethys Ocean during the late Paleozoic to Middle Triassic, respectively (Xu et al., 1998; Meng and Zhang, 1999; Dong et al., 2015, 2017; Li et al., 2018). All the tectonic domains in this region, including the West Qinling orogen, the Songpan-Ganzi terrane, the Ruo'ergai basin and the surrounding sutures (Fig. 1A), have undergone significant reworking due to Cenozoic tectonics (Ren et al., 2013; Xu et al., 2017), making the southern boundary of the West Qinling orogen unclear partly. The Tazang fault is regarded as the easternmost continuation of the Kunlun fault system and is the typically designated location for marking the Mianlue suture (Fig. 1).

2.2. Stratigraphy

The Baiyigou Group is the oldest sedimentary succession occurred in the West Qingling orogen, which is outcropped in the core of the Baiyigou anticline, NE Ruo'ergai county of the Sichuan Province, covering an area of ~ 50 km^2 (Fig. 2). Its base is not present at this section, and there are more strata in the north limb of anticline than those in the south limb (Li et al., 1987; Zhang et al., 1988). This stratigraphic succession was originally named as the Bailongjiang System in 1944, then was renamed the Baiyigou Group as pre-Silurian records in 1960–70 s, and finally was regarded as the Precambrian in 1980 s (Li et al., 1987; Zhang et al., 1988). The Baiyigou Group includes the lower Saiyikuo Formation and the upper Xianglongka Formation and mainly consists of shallow metamorphic sedimentary strata which are dominantly composed of interbedded siliciclastic and volcaniclastic rocks (Zhang et al., 1988; Min and Wen, 1991). Moreover, there are some diabase dykes with the Silurian ages intruded into the Baiyigou Group strata (Zhang et al., 1988).

The Baiyigou Group was measured along the north limb of the Baiyigou anticline (Zhang et al., 1988). The lower Saiyikuo Formation (~733 m) is composed mainly of interbedded medium- to fine-grained greywacke, tuffaceous siltstone, and sedimentary tuff (Zhang et al., 1988; Min and Wen, 1991). The upper Xianglongka Formation (~945 m) comprises the lower coarse-grained clastic rocks interbedded with a few layers of gravels and the upper fine-grained sandstone to siltstone successions. The gravels include moyite, monzonitic granite, plagioclase-rich granite and quartz, with an average diameter of 10–20 cm (Zhang et al., 1988). The volcaniclastic rocks from both of the formations are dominated by felsic rhyolitic tuff and dacitic tuff (Yang et al., 1989). The Saiyikuo Formation is unconformably overlain by the Cambrian Taiyangding Formation without the presence of the Xianglongka Formation due to the erosion in the south limb of anticline (Zhang et al., 1988). The Taiyangding Formation consists of thick black cherts interbedded with black shales and thinly limestone with a thickness of ~ 140 m (Yang et al., 1989).

3. Samples and methods

3.1. Samples

The investigated Neoproterozoic outcrop sedimentary successions comprise various rock types (including mudstone, siltstone, sandstone, conglomerate and tuff-rich rocks) and more than 60 samples were collected from the Baiyigou section during two rounds of field work. Most samples were cut into standard thin sections and 18 sandstone samples therein were selected for detrital framework petrography analysis. Twenty sandstone samples were targeted for transparent heavy mineral analysis. We selected 10 samples for zircon U-Pb dating, including 7 tuffaceous sandstone samples for detrital zircon ages and 3 granite gravel samples (from the Xianglongka Formation conglomerate strata) for igneous zircon U-Pb ages (Fig. 3). In-situ trace element data were simultaneously collected from the dated detrital zircon grains in 6 tuffaceous sandstone samples therein. Furthermore, some dated detrital zircon grains were also selected for Hf isotopic analysis. Twenty-eight sedimentary rock samples were selected for whole-rock major, trace and rare earth element geochemical analysis.

Fig. 4. Representative outcrop photographs and sedimentological features of the Tonian Saiyikuo Formation strata at the Baiyigou section. (A) Location of the Baiyigou anticline core; (B) medium to thick bedded, slightly metamorphosed siltstone strata at the bottom of the Saiyikuo Formation; (C)–(D) outcrop features of two dating samples, located at Bed 2 and Bed 4; (E)–(F) thick-bedded, metamorphosed tuffaceous sandstone strata; (G) thick siltstone; (H) the unconformity boundary between Saiyigkuo Formation and Cambrain Taiyangding Group. Note that the Saiyikuo Formation is dominated by slightly metamorphosed volcanic material-rich sandstones and siltstones, with subordinate thin-bedded mudstone layers.

3.2. Methods

3.2.1. Sandstone framework petrography and heavy mineral analysis

The collected sandstone samples were made into standard thin sections for petrographic analysis. Sandstone compositions were then analyzed and micro-texture features were observed under a polarizing microscope. Major framework grain modal analysis of 18 selected samples was performed through the widely-used Gazzi-Dickinson method (Dickinson, 1985), with greater than 400 points counted per sample (Gu et al., 2023; Jian et al., 2023). A total of 20 sandstone samples were selected for transparent heavy mineral analysis at Xiamen University, following the procedures given by Jian et al. (2023). Fresh samples were preliminarily crushed and 63–250 μm fractions were sieved. Carbonate components were removed from the separated fractions by soaking in 1 N acetic acid. Heavy mineral grains were then separated using heavy liquid tribromomethane (2.89 g/cm^3) from the 63–250 μm fractions and subsequently mounted on glass slides with Canada balsam. Transparent heavy mineral grains were identified and counted for each sample using a polarizing microscope. Detrital grain texture features were also observed and documented for the mounted heavy fractions.

3.2.2. Zircon U-Pb dating and trace element analysis

Zircon grains were hand-picked under a binocular microscope after

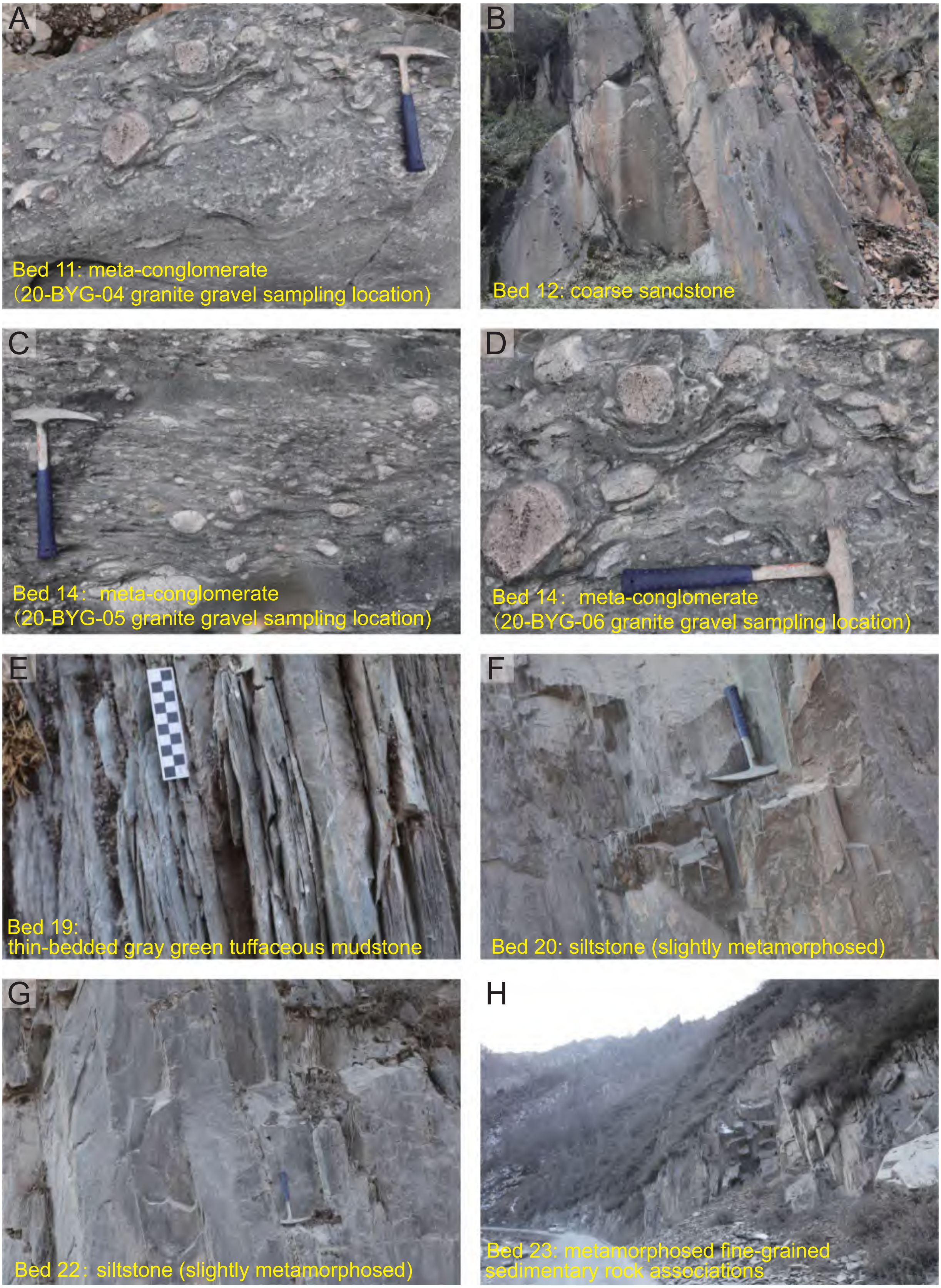

Fig. 5. Representative outcrop photographs and sedimentological features of the Tonian Xianglongka Formation strata at the Baiyigou section. (A) *meta*-conglomerate strata at the bottom of the Xianglongka Formation; (B) coarse sandstone strata with cross-beddings; (C)–(D) *meta*-conglomerate strata and the locations for two granite gravel dating samples; (E)–(F) thin-bedded, slightly metamorphosed gray green tuffaceous mudstone and siltstone layers; (G) medium bedded siltstone; (H) top of the Xionglongka Formation. Note that the *meta*-conglomerate strata at the bottom are clast-supported and the gravels are moderately-sorted and are dominated by felsic rocks, such as granite.

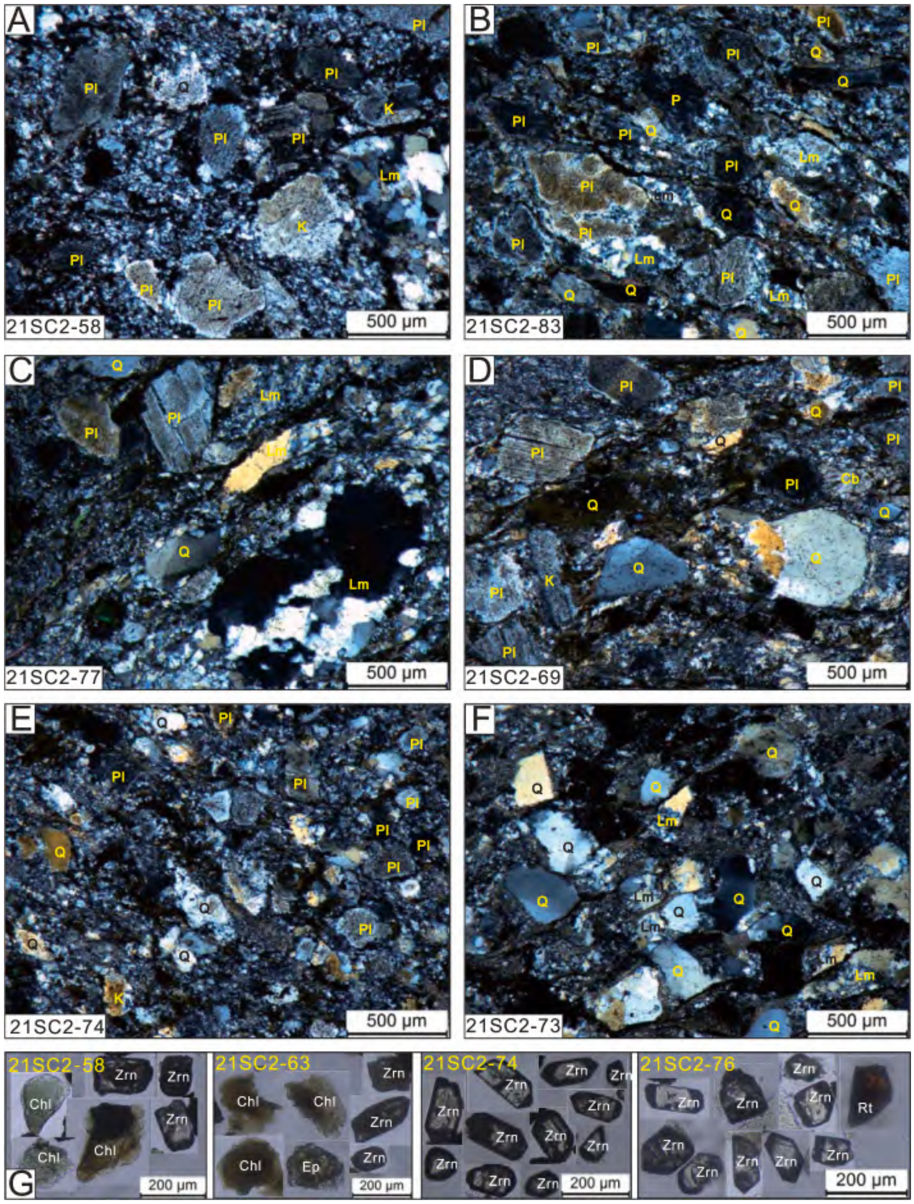

Fig. 6. Representative photomicrographs of the analyzed sandstone thin-sections and transparent heavy minerals. (A) sample 21SC2-58, arkose sandstone; (B) sample 21SC2-83, arkose sandstone; (C) sample 21SC2-77, feldspathic litharenite; (D) sample 21SC2-69, feldspathic quartzose sandstone; (E) sample 21SC2-74, feldspathic quartzose sandstone; (F) sample 21SC2-73, lithic quartzose sandstone; (G) representative heavy minerals in four samples. Note that the investigated clastic strata were slightly metamorphosed and are composed of diverse framework compositions. Embayed detrital grains are common in these strata. Transparent heavy minerals are dominated by stable minerals, such as zircon and tourmaline, with subordinate chlorite, epidote and hornblende. Most zircon grains from the Xianglongka Formation samples are euhedral or subhedral. Chlorite- and epidote-rich samples from the Saiyikuo Formation have partly eroded zircon grains. Q: quartz; Pl: plagioclase; K: K-feldspar; Lm: metamorphic lithic fragments; Zrn: zircon; Chl: chlorite; Rt: rutile; Ep: epidote.

density and magnetic separation treatments. The separated zircon grains were then mounted in epoxy resin, polished and imaged. Zircon U-Pb isotopic analyses of samples 20-BYG-04, 20-BYG-05, 20-BYG-06 and 21-BYG-20 were conducted on a SHRIMP at the Beijing SHRIMP Center, the Institute of Geology, Chinese Academy of Geological Sciences. The critical operating conditions included 5-scan duty cycle, 4.5nA and 10 kV primary O-2 beam, and mass resolution ca. 5000. The method of SHRIMP U-Pb dating was given in detail by Yan et al. (2003) and Druschke et al. (2006). About 15–20 zircon grains were dated for each sample. Zircon standard SL13 (U = 238 ppm, reference age of 572 Ma) was used for calibrating the U contents, and zircon standard TEMORA ($^{206}Pb/^{238}U = 0.0668$, reference age of 417 Ma) was used for calibrating the $^{206}Pb/^{238}U$ ratios. Zircon U-Pb dating analyses for other 6 detrital samples (20-BYG-03, 20-BYG-07, 20-BYG-08, 20-BYG-09, 20-BYG-10 and 20-BYG-15) were performed on a LA-ICP-MS at the Mineral Laser Microprobe Analysis Laboratory (Milma Lab), China University of Geosciences, Beijing (CUGB), China. About 100 grains were dated for each sample. Zircon standards 91,500 (1065 Ma) and GJ-1 (607 Ma) were simultaneously measured for analytical quality control. The detailed analytical methods have been described by Zhang et al. (2019). Measured compositions were corrected for common Pb using measured ^{204}Pb. Zircon U–Pb ages with poor precision and high discordance were omitted from the kernel density estimation plots and from interpretation. Ages < 1000 Ma were based on common Pb corrected $^{206}Pb/^{238}U$ ratios, whereas ages > 1000 Ma were based on common Pb corrected $^{206}Pb/^{207}Pb$ ratios. Furthermore, trace and rare earth element concentrations of the dated zircon grains were also determined during the LA-ICP-MS U-Pb dating using NIST SRM 610 glass for monitoring.

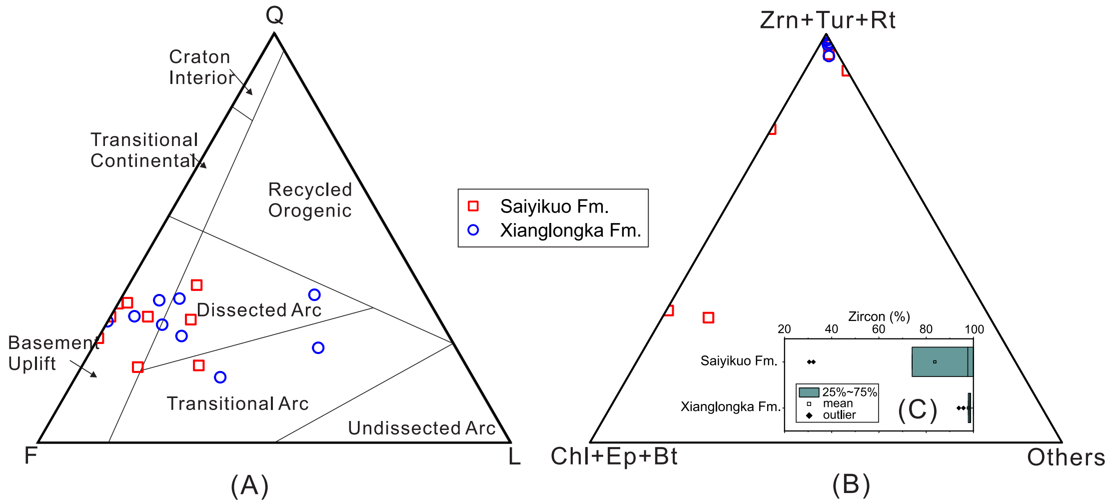

Fig. 7. (A) Quartz (Q)-Feldspar (F)-Lithic fragment (L) ternary diagram. The tectonic fields are from Dickinson (1985). (B) A ternary diagram for transparent heavy mineral assemblages. Zrn: zircon; Tur: tourmaline; Rt: rutile; Ep: epidote; Chl: chlorite; Bt: Biotite. All the raw data are shown in Tables A1-A2 in the supplemental materials.

3.2.3. Detrital zircon Hf isotopic analysis

Some zircon grains with concordant U-Pb ages from 5 samples (20-BYG-03, 20-BYG-07, 20-BYG-08, 20-BYG-09 and 20-BYG-10) were selected for Lu–Hf isotopic analyses by using a GeoLas 193 nm laser ablation system attached to a Neptune (Plus) MC-ICP-MS at MiDeR-NJU. The GJ-1, Plesovice, 91,500 and zircon Mud Tank ($^{176}Hf/^{177}Hf$ = 0.282507 ± 6; Woodhead and Hergt, 2005) standards were used to monitor accuracy and precision of Hf isotopic ratios. The measured $^{176}Hf/^{177}Hf$ ratios and ^{176}Lu decay constant of 1.867×10^{-11} $year^{-1}$ were used to calculate initial $^{176}Hf/^{177}Hf$ ratios. The εHf values were calculated based on chondritic values of $^{176}Lu/^{177}Hf$ = 0.0336 ± 1 and $^{176}Hf/^{177}Hf$ = 0.282785 ± 11 (2σ). Detailed Hf isotopic analysis methods were described by Li et al. (2018, 2021).

3.2.4. Whole-rock major-, trace- and rare earth element geochemical analysis

Geochemical pretreatment and element composition determination were performed at the Analytical Laboratory, Beijing Research Institute of Uranium Geology. All the elemental geochemical analysis samples were firstly powdered by using an agate mortar. The Loss on ignition (LOI) values were obtained by measuring the weight loss after heating sample powders at 980 °C. Major element compositions were measured using an Xray fluorescence spectrometer (XRF), by testing well-mixed glass disks which were made by high-temperature fusion of samples powders and lithium metaborate flux. Trace- and rare earth elements were analyzed using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Before the ICP-MS measurement, sample powders were completely dissolved by Hf–HNO_3–$HClO_4$ mixture acid solutions and diluted with 1 % HNO_3.

4. Results

4.1. Outcrop descriptions and sedimentological features

The Neoproterozoic sedimentary succession in the study area was named as Baiyigou Group in some Chinese literatures, including the Saiyikuo and Xianglongka Formations. The Baiyigou Group and the overlying Cambrian–Ordovician represent as an anticlinal dome (Fig. 2), with a diameter of ca. 15 km. The Neoproterozoic stratigraphic column of the Baiyigou section is shown in Fig. 3 and representative outcrop photographs are shown in Figs. 4–5.

The exposed Saiyikuo Formation is about 730 m. The lower parts are mainly composed of slightly metamorphosed, tuffaceous, medium to thick bedded sandstone and siltstone strata (Fig. 4). Thin-bedded mudstone layers are subordinate and represent as interbeds in the volcanic material-rich sandstone or siltstone layers (Fig. 4B, 4E). Although these rock associations have been metamorphosed in various grades (mostly low), the lower Saiyikuo Formation strata (Beds 1–5) are featured by multiple upward-fining cycles. The upper Saiyikuo Formation comprises relatively fine-grained, tuff-bearing clastic rocks, including siltstone, mudstone, slate and minor fine-grained sandstones (Fig. 4G). These strata indicate horizontal beddings and sand laminations.

The lower parts of the Xianglongka Formation are characterized by gravel-supported conglomerates and pebbly coarse sandstones. These coarse-grained rocks have been slightly metamorphosed. The gravels therein are dominated by granitoids and are moderately-well sorted (mostly 10–20 cm, Fig. 5A–D). Some coarse-grained sandstone strata indicate cross-beddings and upward-fining sequences. The upper Xianglongka Formation mainly consists of thin-bedded, slightly metamorphosed gray green tuffaceous mudstone and siltstone strata, with subordinate sandstone successions (Bed 20) (Fig. 5). The Neoproterozoic Xianglongka Formation is unconformably overlain by the Cambrian Taiyangding Group, which is mainly composed of black or gray lamellated chert.

4.2. Sandstone framework grain and heavy mineral compositions

The analyzed Neoproterozoic sandstone samples from the Baiyigou section have been slightly metamorphosed and some samples indicate high contents of recrystallized interstitial materials (Fig. 6). The framework grains from most analyzed samples are moderate-well sorted and have relatively high feldspar contents (Fig. 6). The feldspar grains are dominated by plagioclase (Fig. 6; Table A1 in the supplemental materials) and indicate traces of alteration through the microscope-based observations. These samples display various lithic fragment contents which are mainly metamorphic lithic fragments (e.g., quartzite, schist and phyllite). Several samples from the upper strata (i.e., the Xianglongka Formation) indicate comparatively high lithic fragment contents (> 40 % in total framework grains). Modal analysis results show that the quartz, feldspar and lithic fragment (Q-F-L) contents of the Saiyikuo and Xianglongka Formations samples are averaged at 29:62:9 (n = 9) and 29:52:19 (n = 9), respectively. The analyzed samples are plotted in the fields of “basement uplift”, “dissected arc” and “transitional arc” in the Dickinson ternary diagram (Fig. 7A).

The analyzed samples from the Saiyikuo Formation indicate variable

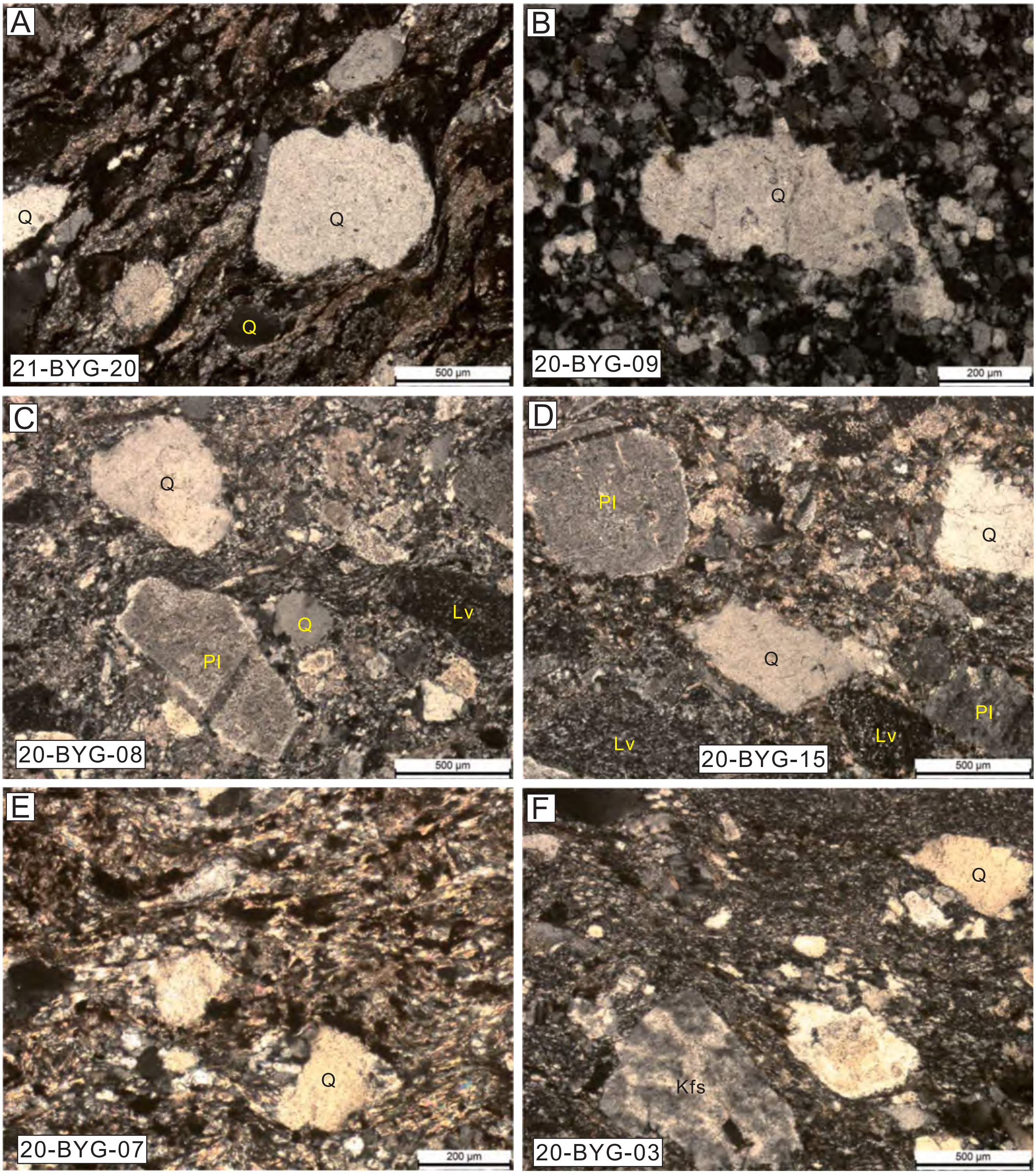

Fig. 8. Representative micrographs for the detrital zircon dating samples. (A) 21-BYG-20; (B) 20-BYG-09; (C) 20-BYG-08; (D) 20-BYG-15; (E) 20-BYG-07; (F) 20-BYG-03. These samples are rich in volcanic materials, mostly crystal pyroclasts, such as Embayed feldspar and quartz grains. These samples are slightly metamorphosed and detrital grains are poorly-sorted. Q: quartz; Pl: plagioclase; Kfs: K-feldspar; Lv: volcanic lithic fragment.

transparent heavy mineral compositions (Table A2; Fig. 7B), with widespread eroded zircon in most samples (Fig. 6G) and certain amounts of chlorite, epidote and tourmaline in some samples. By contrast, the heavy minerals from the Xianglongka Formation sandstone samples are dominated by euhedral and subhedral zircon grains (Table A2; Fig. 6G). Furthermore, rutile, hornblende, apatite and barite are occasionally present in some samples (Table A2).

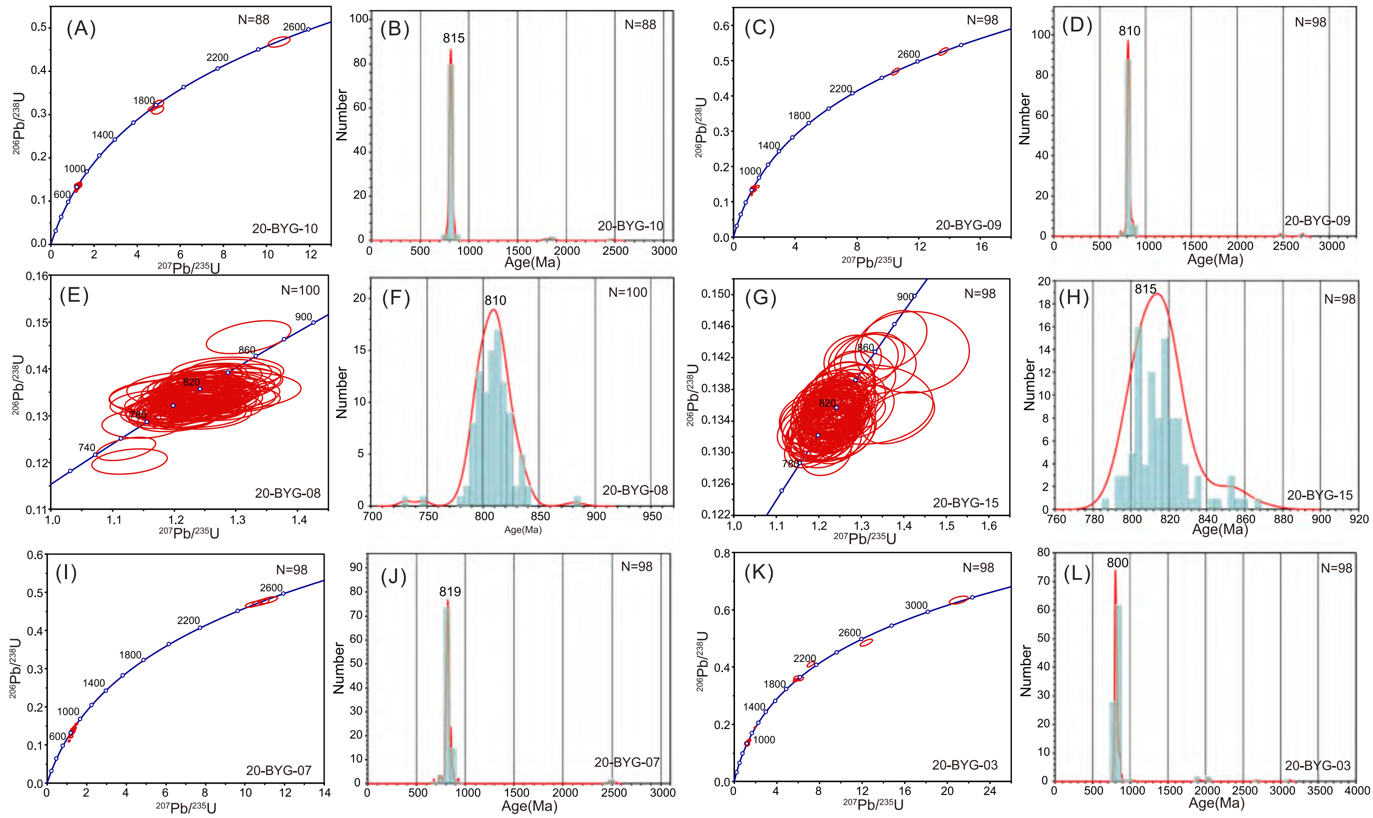

Fig. 9. Detrital zircon U-Pb age data (including Concordia and relative probability diagrams) for the analyzed tuffaceous sandstone samples from the Tonian strata. (A)–(B) 20-BYG-10; (C)–(D) 20-BYG-09; (E)–(F) 20-BYG-08; (G)–(H) 20-BYG-15; (I)–(J) 20-BYG-07; (K)–(L) 20-BYG-03. For locations of the samples at the stratigraphic column and for representative micrographs, see Fig. 3 and Fig. 8, respectively.

4.3. Zircon U-Pb ages, Hf isotopes and trace elements

The dated detrital samples in this study are tuffaceous, poorly-sorted sandstones or siltstones (Fig. 3; Fig. 8). The results indicate that detrital zircons (611 grains) from all the 7 samples have overwhelming Tonian U-Pb ages (mostly ca. 840–780 Ma), with age peaks at the range of ca. 820–800 Ma (Figs. 9–10). The 5 samples from the Saiyikuo Formation therein display zircon age peaks at 810–819 Ma, while the tuffaceous sandstone sample (i.e., 20-BYG-03) from the Xianglongka Formation has zircon age peak at 800 Ma (Fig. 3). Furthermore, the fine-grained detritus-rich, inequigranular sandstone samples (e.g., 20-BYG-03, 20-BYG-07, 20-BYG-09, 20-BYG-10, Fig. 8) have some pre-Neoproterozoic zircon grains (mostly 2600–1800 Ma), whereas the medium-coarse sandstone samples (i.e., 20-BYG-08 and 20-BYG-15, Fig. 8) do not indicate the pre-Neoproterozoic zircon ages (Fig. 9). The three dated granite gravel samples (45 zircon grains were analyzed) from the Xianglongka Formation conglomerate strata have close Tonian ages, i.e., 802 Ma, 808 Ma and 809 Ma (Fig. 10). All the raw U-Pb dating data of the 10 samples are shown in Tables A3–A4 in the supplemental materials.

The Hf isotope results of the 180 detrital zircon grains from 5 tuffaceous sandstone samples are illustrated in Fig. 11. Most analyzed zircon grains yielded negative εHf(t) values, except the sample 20-BYG-07 (Fig. 11). The Tonian zircons of the samples 20-BYG-03, 20-BYG-08, 20-BYG-09 and 20-BYG-10 have εHf(t) values in the ranges of −15.2 to −1.5 (averaging at −11.1), −27.3 to 1.2 (averaging at −11.3), −30.0 to −5.8 (averaging at −20.7) and −33.2 to 1.9 (averaging at −14.9), respectively, whereas the Tonian zircon grains from sample 20-BYG-07 yielded relatively positive εHf(t) values, ranging from −8.6 to 9.0 (averaging at 2.9). All the raw Hf isotopic data are shown in Table A5.

In-situ zircon trace and rare earth element concentrations of the 6 LA-ICP-MS U-Pb dating samples were measured. We selected representative element ratios, such as U/Yb, Nb/Yb, Sc/Yb, Nb/Hf and Th/U, to interpret potential tectonic settings where the zircons formed. The results indicate that most zircons are plotted in the field of the continental arc setting (Fig. 12). These analyzed zircons display relatively low Eu/Eu* values (0.01–0.28) and variable Th/U ratios (0.4–3) (Table A6; Fig. 12F).

4.4. Major-, trace- and rare earth element compositions

The major element analysis results indicate that the SiO_2 and Al_2O_3 contents of the analyzed samples have the ranges of 62–80 wt% and 11–20 wt% (Table A7), respectively. Most samples are plotted in the "wacke" and adjacent fields (e.g., the shale, litharenite and arkose fields) in the binary diagram of Log (SiO_2/Al_2O_3) and Log (Fe_2O_3/K_2O) (Fig. 13). Element Ca and Mg are depleted in most samples, compared with the Upper Continental Crust (UCC) compositions (Fig. 14). Most analyzed samples show uniform rare earth element (REE) patterns of light REEs enrichment, negative Eu anomaly and relatively flat heavy REEs by chondrite-normalization (Fig. 15). The Eu anomaly values of the Saiyikuo Formation samples are fairly variable (Fig. 16), ranging from 0.4 to 1.0 (averaging at 0.7). By contrast, the Xianglongka Formation samples indicate comparatively small Eu anomaly values, with the range of 0.47–0.77 (averaging at 0.6). These samples have relatively high La/Th ratios, variable Sc contents and Zr/Sc ratios and low U, V, Ni and Cu contents (Fig. 17; Table A8). The raw element analysis data are shown in Tables A7–A8. While the U/Al ratios are quite low for these samples (0.09–0.25, averaging at 0.17), the Mo/Al ratios are variable and are relatively higher in the Xianglongka Formation samples (averaging at 0.97) than those in the Saiyikuo Formation samples (averaging at 0.55).

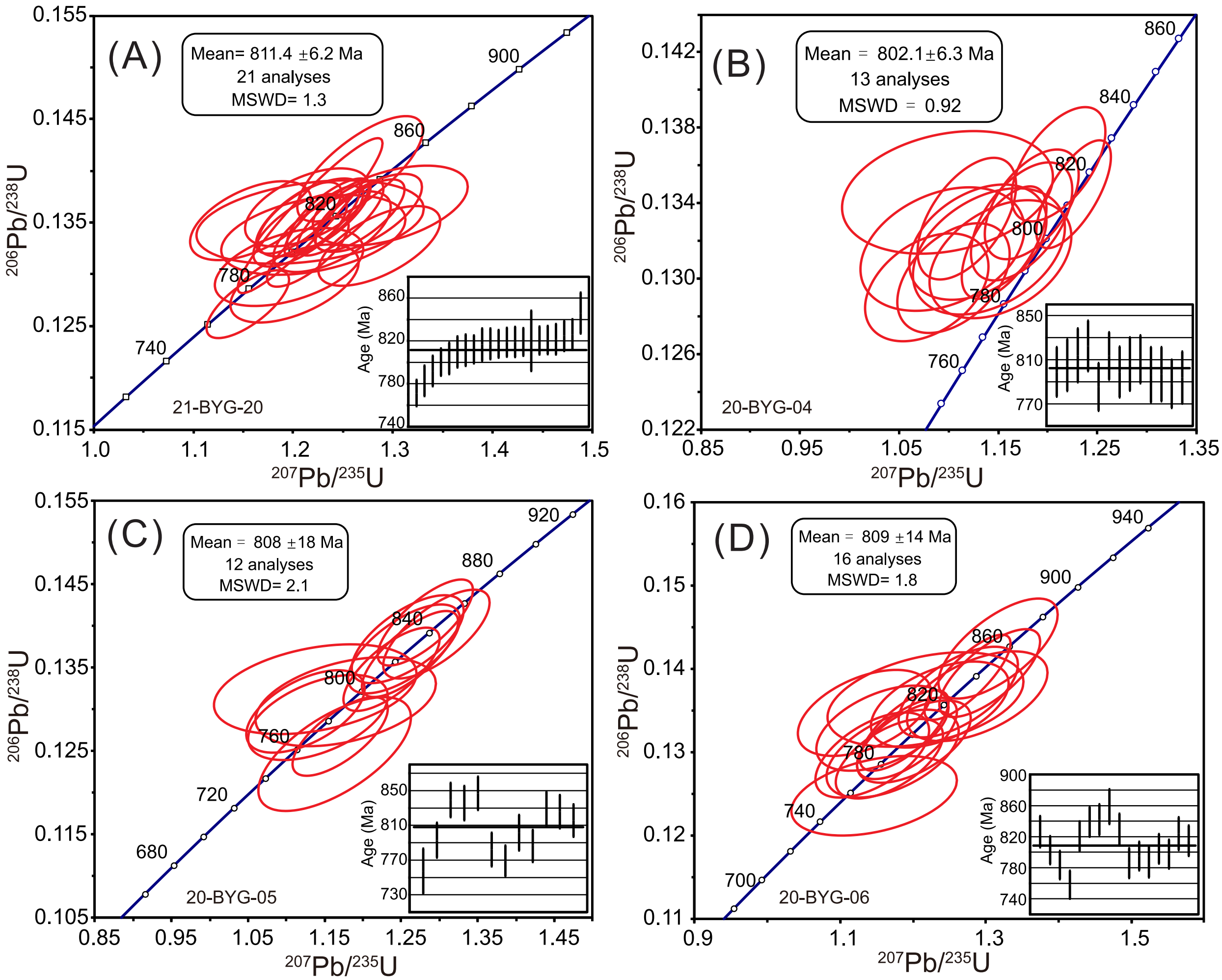

Fig. 10. U-Pb Concordia diagrams for one tuffaceous siltstone (A) and three granite gravel samples from the *meta*-conglomerate strata (B–D). For locations of the samples at the stratigraphic column, see Fig. 3.

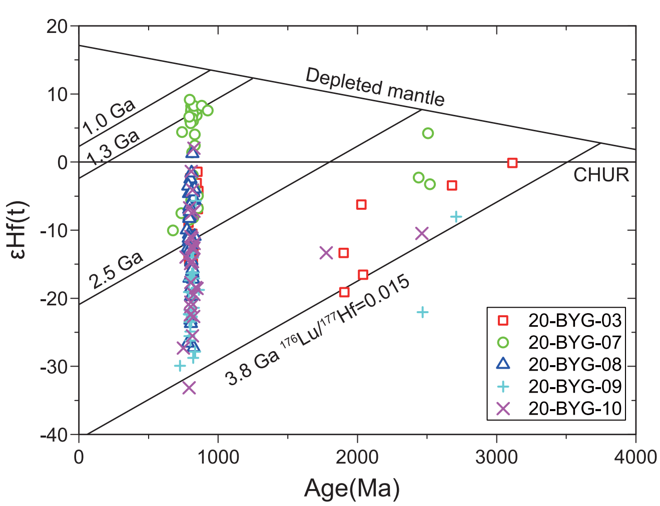

Fig. 11. Hf isotopic data of representative detrital zircon grains from five samples.

5. Discussion

5.1. Depositional processes and sedimentary environments of the Baiyigou Group

The Baiyigou Group sedimentary successions are characterized by mixed volcaniclastic and siliciclastic records. The Saiyikuo Formation is composed of dominant medium to thick bedded sandstone and siltstone strata, with thin mudstone interbeds (Fig. 4). These strata indicate erosional surfaces at the bottom and upward-fining structures, revealing fluvial sedimentary environments. These sandstones are mediumly-well sorted (Fig. 6) and were probably deposited in meandering river channels or point bars, while the thin-bedded mudstones are records in floodplain environments. The widespread embayed detrital grains are most likely of volcanic origin. We note that volcaniclastic detritus-rich sandstones are poorly sorted (Fig. 8) and volcano clasts therein are commonly much larger in size than those nonvolcaniclastic sediments, implying different transport agents or depositional dynamics for these two kinds of clasts. We infer that most volcano clasts accumulated as eolian dust, rather than water-carried detritus. This interpretation is reinforced by the transparent heavy mineral results which show that there are at least two kinds of textural features for zircon grains (Fig. 6G). The detrital zircon grains in Xianglongka Formation samples are mostly euhedral; whereas some Saiyikuo Formation samples indicate certain amounts of eroded grains (Fig. 6G). These euhedral zircons, as first-cycle detritus, might be derived from erupted volcanic rocks or

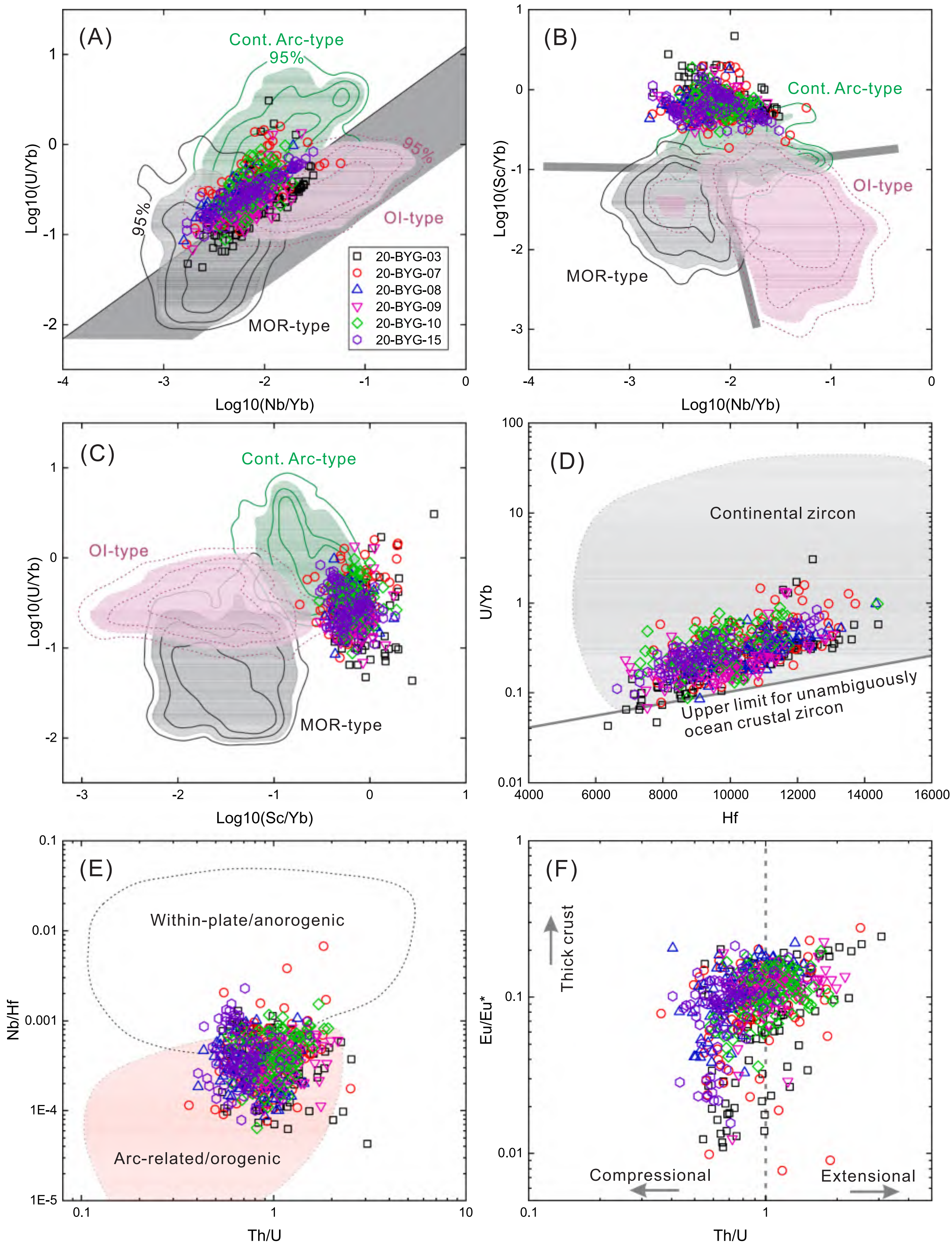

Fig. 12. Representative trace element data of the dated Neoproterozoic detrital zircon grains from the samples. (A) Log_{10}(U/Yb) vs. Log_{10}(Nb/Yb); (B) Log_{10}(Sc/Yb) vs. Log_{10}(Nb/Yb); (C) Log_{10}(U/Yb) vs. Log_{10}(Sc/Yb); (D) U/Yb vs. Hf; (E) Nb/Hf vs. Th/U; (F) Eu/Eu* vs. Th/U. The fields indicated in A-C are density distribution plots from Grimes et al. (2015). The contours shown are for 50, 80, 90, and 95 % levels. MOR-type: mid-ocean ridge setting; OI-type: ocean-island setting; Cont. Arc-type: continental arc setting. The fields indicated in D-E are from Grimes et al. (2007) and Yang et al. (2012), respectively. Zircon Th/U ratios and Eu/Eu* values are proposed to be related to tectonic stress regimes (McKay et al., 2018) and crustal thickness (Tang et al., 2020), respectively.

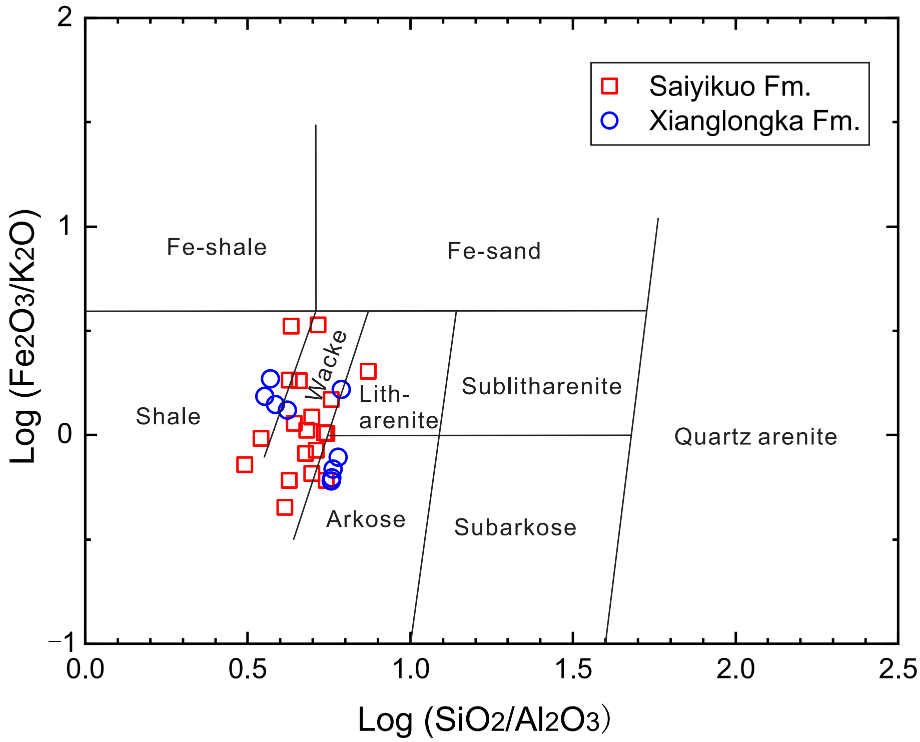

Fig. 13. Chemical classification diagram for discriminating the analyzed sedimentary rocks by their logarithmic ratios of SiO_2/Al_2O_3 vs. Fe_2O_3/K_2O after Herron (1988).

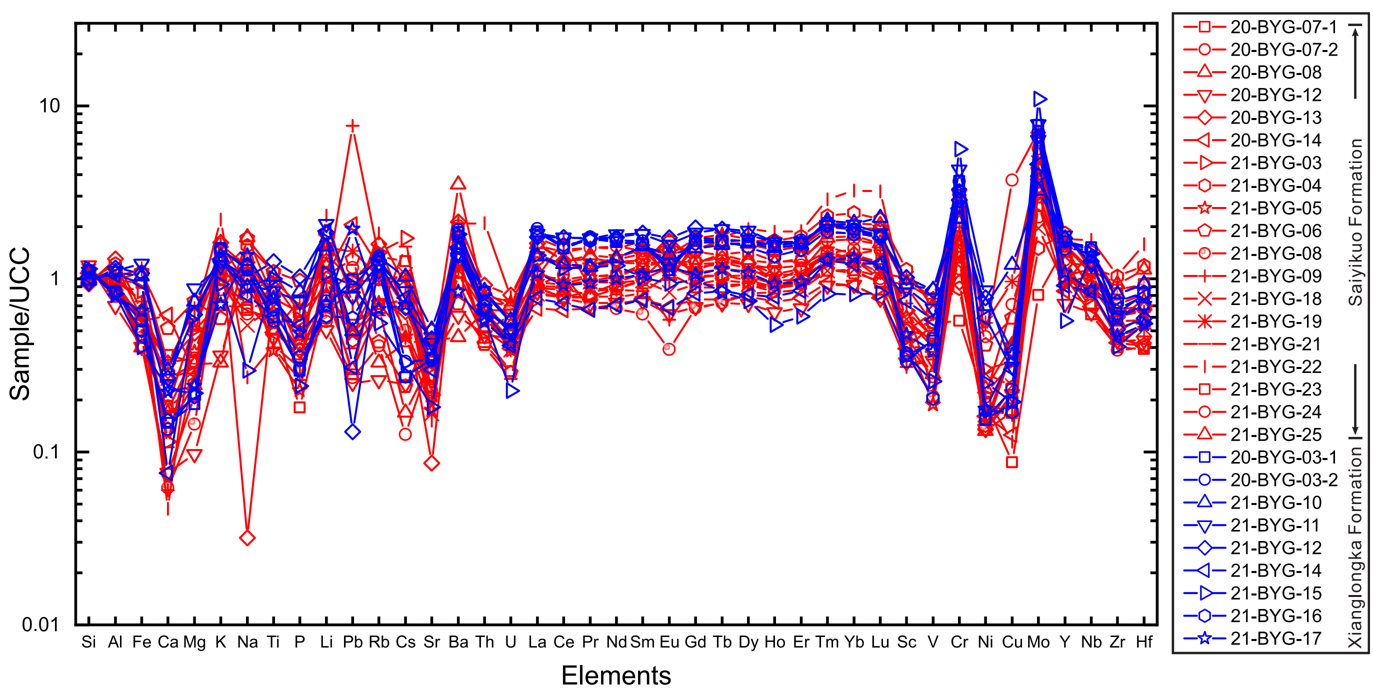

Fig. 14. Upper Continental Crust (UCC) compositions-normalized major and trace element geochemical plots for all the analyzed samples. The UCC data are from Rudnick and Gao (2014).

intermediate-acid igneous rocks in nearby source terranes and experienced different depositional processes from those eroded zircon grains. Our propositions are inconsistent with previous explanations from some early Chinese literatures which contend that these volcano clasts were transported in fluvial systems (e.g., Li et al., 1987; Min and Wen, 1991).

The conglomerates-dominated strata from the lower Xianglongka Formation are gravel-supported and moderately-sorted (Fig. 5). These coarse records may be interpreted as fluvial channel deposits with intensive hydrodynamic conditions. The overlying cross-bedding sandstone and gray green mudstone beds (Beds 15–17 and 20–24) might accumulate in fluvial delta environments. The Beds 18–19 from the middle Xianglongka Formation are characterized by gray green, thin-bedded lamina, revealing relatively deep-water, low energy lacustrine settings.

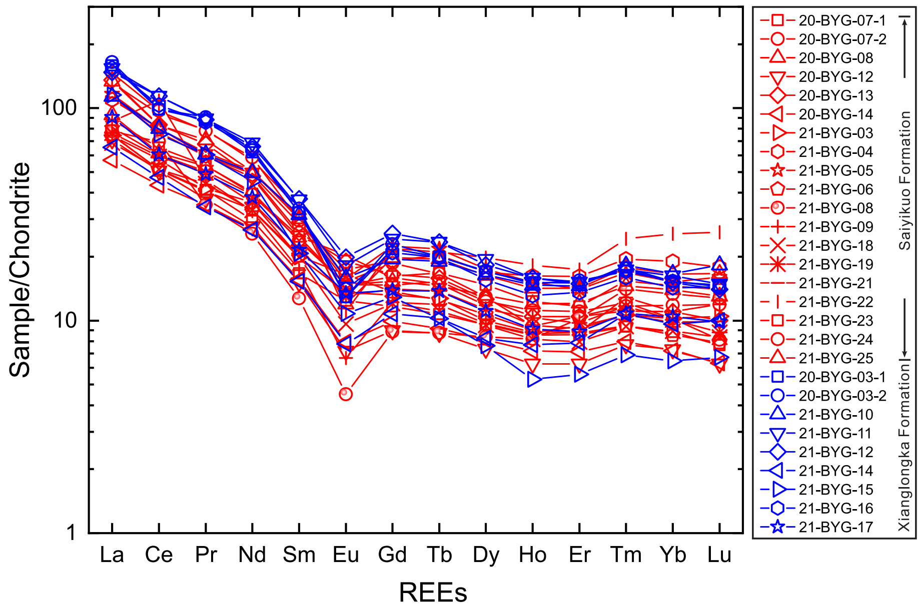

Fig. 15. Chondrite-normalized REE patterns of the analyzed samples. The chondrite data are from McDonough and Sun (1995).

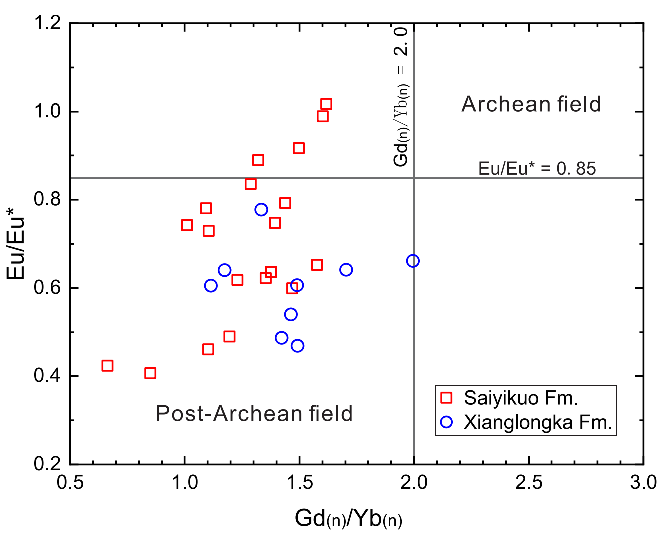

Fig. 16. The Eu/Eu* vs. Gd(n)/Yb(n) (after McLennan et al. (1993)) binary plots for the analyzed sedimentary rock samples from the Baiyigou section. The data of chondrite are from McDonough and Sun (1995).

5.2. Depositional ages of the Baiyigou Group

Constraining depositional ages of the Baiyigou Group is essential for investigating its tectonic evolution and for understanding its role in the Neoproterozoic global supercontinent and climate history. Before our study, previous investigators only obtained an age of ~ 738.59 Ma from a tuff sample in the lower Baiyigou Group using the Rb-Sr isotopic method in 1980 s (Li et al., 1987). Dating more tuffs from the Baiyigou Group strata is distinctly beneficial for better constraining the depositional ages. Unfortunately, pure tuffs were not collected from the section; instead we dated some tuffaceous clastic rocks and granite clasts (within conglomerate strata, lower part of the Xianglongka Formation) to constrain the maximum depositional ages. A striking feature is that all of the zircon U-Pb ages from the dated tuffaceous clastic rocks have very narrow age groups of 840–780 Ma (with age peaks in the range of 820–800 Ma), with minor older ages of 2500–1800 Ma (Figs. 9–10). These Tonian zircons have weighted mean ages in 821–804 Ma, but indicate quite large MSWD values (2.6–8) and low p(χ^2) values (zero or very close to zero) (Table A9). This reveals multistage magmatic/volcanic events, rather than a single event, in the detrital source for a tuffaceous sandstone sample. As mentioned above, the predominant euhedral zircons and the widespread embayed detrital grains are most likely of volcanic origin and the disproportionate, large-size grains in the fine-grained tuffaceous sandstones (Fig. 8) represent wind-carried, dropping volcanic clasts. This implies that the depositional processes were very close to the magmatic /volcanic events at 820–800 Ma.

The peak ages of 815.0 Ma and 811.4 Ma from two layers of tuffaceous sandstones (i.e., samples 20-BYG-10 and 21-BYG-20, respectively) in the lower Saiyikuo Formation indicate the depositional age of the base of the Baiyigou Group (or the Saiyikuo Formation) is most likely close to ca. 815 Ma. The age peaks of four tuffaceous clastic rocks (samples 20-BYG-07 ~ 09, and 20-BYG-15) from the upper Saiyikuo Formation are in the range of 819–810 Ma, implying the depositional ages are less than 810 Ma. Moreover, the ages of the three granite clasts (samples 20-BYG-04 ~ 06) from the Xianglongka Formation conglomerate strata are between 802 and 809 Ma, revealing that the maximum depositional ages are ~ 800 Ma. Together, we suggest that the depositional ages of the exposed Saiyikuo Formation strata are possibly 820–800 Ma. The age peak of the tuffaceous sandstone (sample 20-BYG-03) from the top Xianglongka Formation is ~ 800 Ma, indicating that the depositional ages are less than 800 Ma. It is not possible to get an accurate age for the top Xianglongka Formation due to lack of pure tuff rocks. Nevertheless, based on the characteristics of overwhelming zircon U-Pb age peaks at ~ 800 Ma and the non-glacial sedimentary successions, we infer that the maximum depositional duration of the Xianglongka Formation is tens of Million years (possibly from 800 to 720 Ma). Collectively, conclusions can be drawn that the depositional ages of the Saiyikuo Formation are 820–800 Ma, and the maximum depositional duration of the Xianglongka Formation is from 800 to 720 Ma.

5.3. Sedimentary provenance interpretations

Both conglomerate gravel compositions and sandstone framework grain compositions indicate that the Baiyigou Group was dominantly fed by granitoid-rich source terranes. These granitic parent-rocks provided plenty of detrital feldspar and detrital zircon grains to the sandstone successions (Figs. 6–7). Detrital zircon U-Pb dating results and the conglomerate gravel age data show that these granitoids formed during

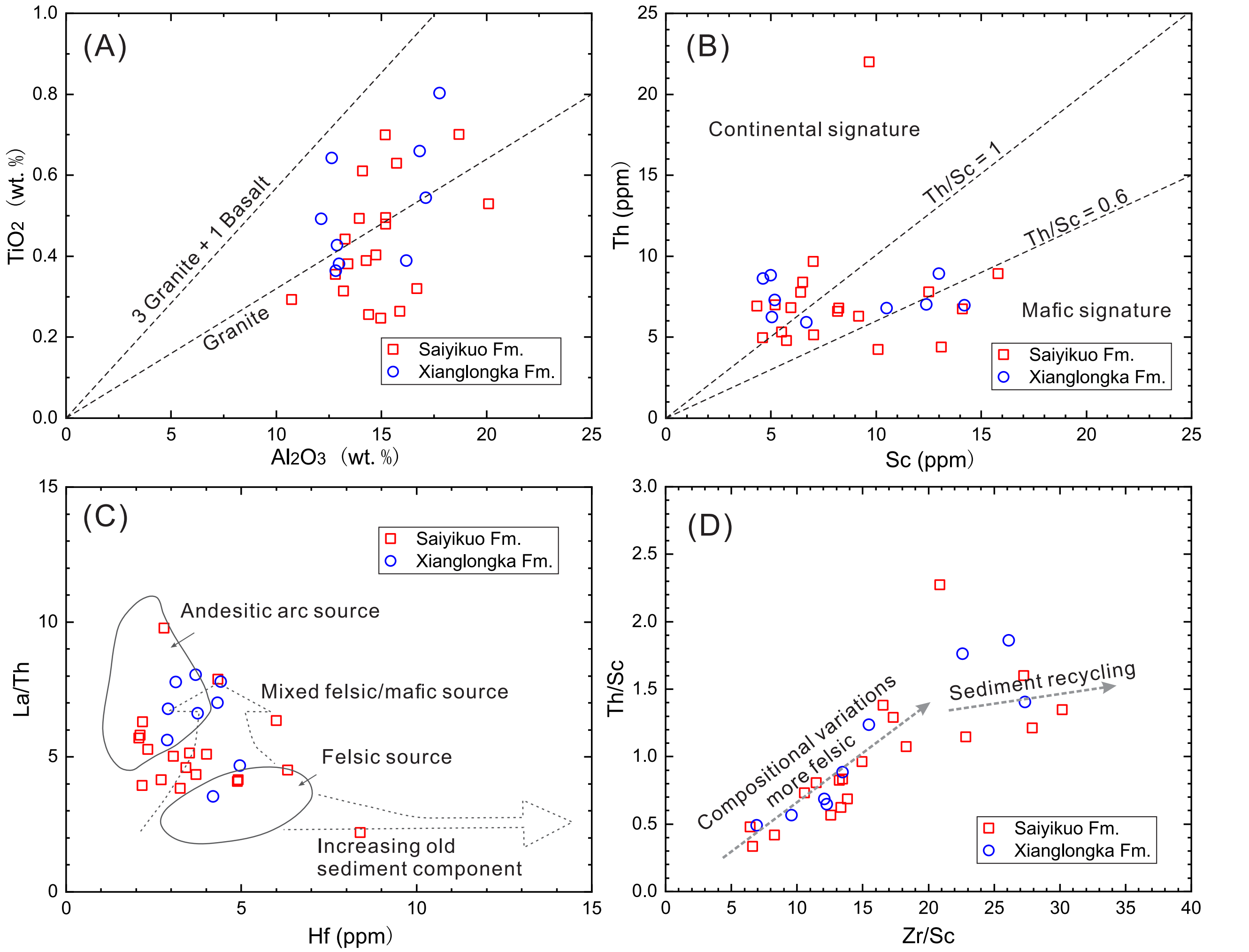

Fig. 17. Sedimentary parent-rock interpretations based on binary plots by major and trace element geochemical data. (A) TiO_2 vs. Al_2O_3 (modified from Schieber (1992)); (B) Th vs. Sc (modified from Totten et al. (2000)); (C) La/Th vs. Hf (after Floyd and Leveridge, 1987); (D) Th/Sc vs. Zr/Sc (after McLennan et al. (1993)).

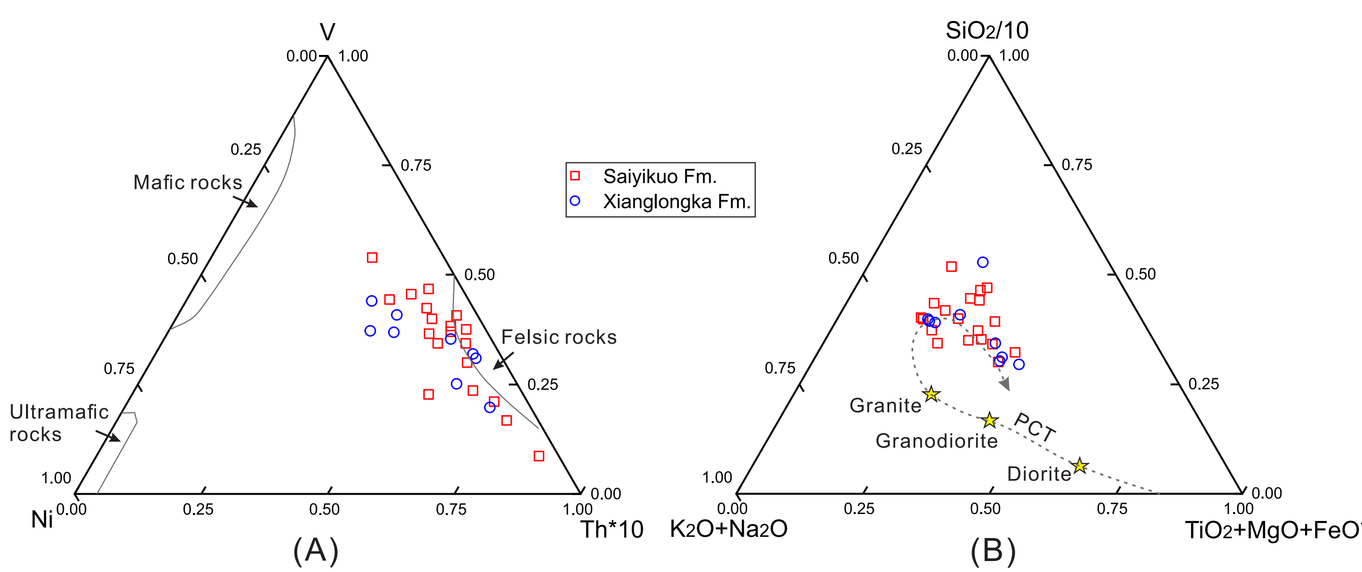

Fig. 18. Sedimentary parent-rock interpretations based on major and trace element geochemical data. (A) V-Ni-Th*10 ternary diagram (after Bracciali et al. (2007)) and (B) SiO_2/10-K_2O + Na_2O-TiO_2 + MgO + FeO* ternary diagram (modified from Kroonenberg (1994)); the PCT therein is a primary igneous source composition line, using the gabbro to granite averages.

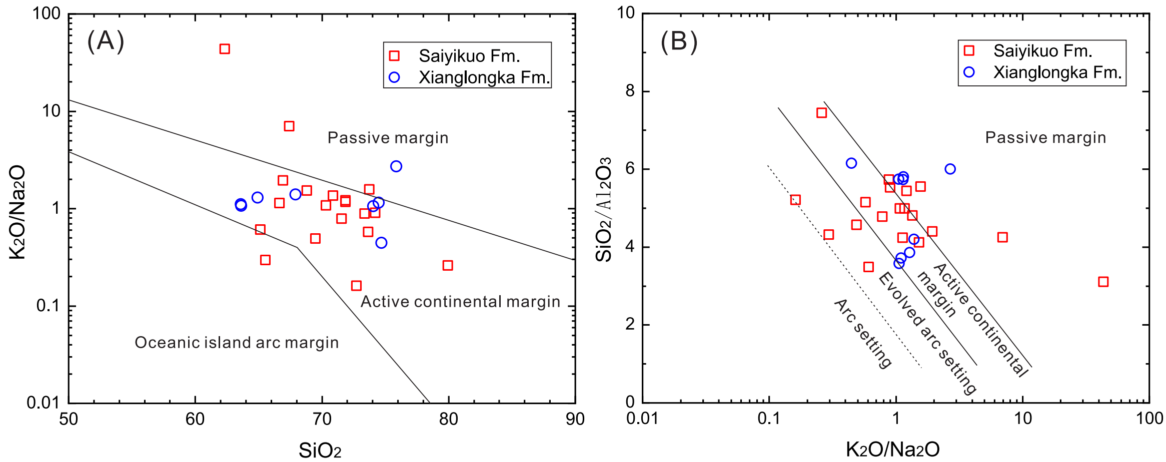

Fig. 19. Major elements-based tectonic setting interpretations for the analyzed Neoproterozic sedimentary rocks from the Baiyigou section. (A) SiO_2 vs. K_2O/Na_2O and (B) K_2O/Na_2O vs. SiO_2/Al_2O_3 (modified from Roser and Korsch (1986)).

the early–mid Neoproterozoic (Figs. 9–10). The occurrence of metamorphic lithic fragments and heavy minerals of metamorphic origin in some samples (Figs. 6–7) implies the exposure of basement metamorphic rocks in source terranes during the depositional time. As mentioned above, the predominant coarse-grained volcano clasts interpreted as drop dusts, if reasonable, imply that these sediments were supplied by nearby intermediate-acid volcanos. These felsic volcanic rocks supplied those disproportionate, embayed, large-size grains to form tuffaceous sandstones (Fig. 8). The elemental geochemical data are also consistent with the parent-rock interpretations. Various element proxies, such as Ti/Al, Th/Sc, La/Th ratios, and the V-Ni-Th and SiO_2-($K_2O + Na_2O$)-($TiO_2 + MgO + FeO$) ternary diagram plot results indicate predominant detritus supply from felsic rocks with minor mafic contributions (Figs. 17–18). This is also supported by the REEs patterns of most samples, including light REEs enrichment, negative Eu anomaly and relatively flat heavy REEs (Figs. 15–16). Some samples only have slightly negative Eu anomaly (even positive Eu anomaly) (Fig. 16). This is attributed to high plagioclase contents, rather than extensive mafic parent-rock contributions.

Most studies advocate that the South Qinling terrane (including the West Qinling area) had tectonic affinity with the Yangtze Block before the Rodinia breakup (e.g., Dong et al., 2011; Zhang et al., 2016) and most likely connected the north and west margin of the Yangtze Block. Although the northern and western Yangtze and South Qinling regions have extensive 780–840 Ma granitoids and other felsic rocks with similar ages (Wang et al., 2013; Zhao et al., 2018), we suggest that the Baiyigou Group sedimentary rocks were from localized sources with small drainage networks in the southwestern West Qinling terrane, rather than the distant source terranes. This can be explained as follows. The detrital zircon ages from the analyzed samples are quite narrow and have few 900–1000 Ma ages, however, zircons with 900–1000 Ma ages are common in far northern and western Yangtze and South Qinling regions (Chen et al., 2006; Sun et al., 2009; Wang et al., 2013; Zhao et al., 2018; Zhang et al., 2023). Furthermore, the early-mid Neoproterozoic zircons in these regions have variable εHf(t) values (positive values are significant, Sun et al., 2009; Zhao et al., 2018; Li et al., 2021), which are different from most of the zircon Hf isotopic records in the West Qinling orogen (Fig. 11). The analyzed sandstones display low compositional and textural maturity and are dominated by first-cycle detritus (such as the widespread euhedral zircon grains, Fig. 6), also revealing nearby sources and relatively rapid depositional processes. All the petrography, heavy mineral and detrital zircon evidences suggest that distant source terranes hardly contributed to the depositional system in the study area.

5.4. *Tectonic setting*

The West Qinling orogen is located in the interactive region among the North China Craton, the Yangtze Block, and the Songpan-Ganzi terrane (Fig. 1A). The formation and evolution of this orogen is very important for understanding the tectonic evolution and assembly history of central China. However, the early history of the West Qinling terrane, such as its tectonic affinity and the Neoproterozoic tectonic setting, remains poorly known due to rare Precambrian exposure in this area.

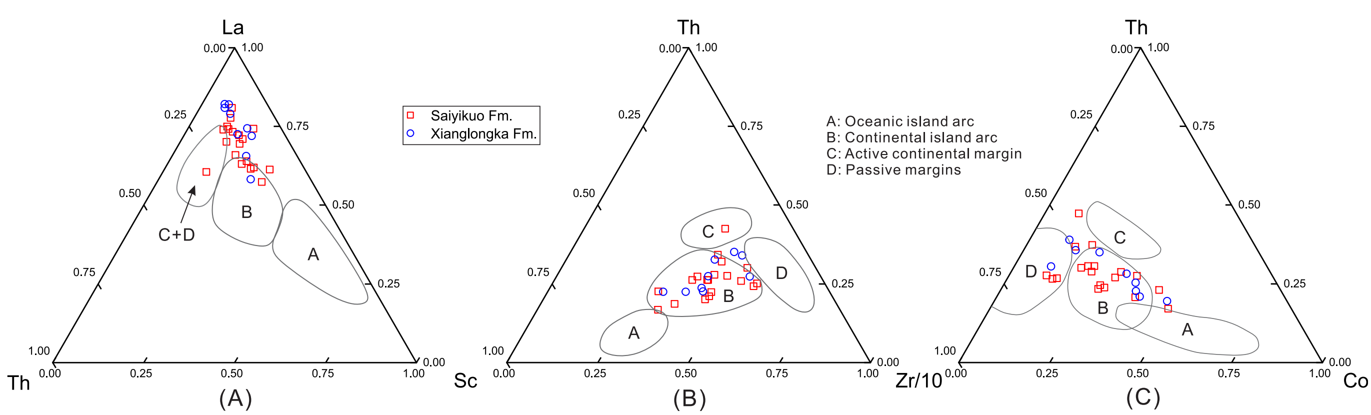

Fig. 20. Trace and rare elements-based tectonic setting interpretations for the analyzed Neoproterozic sedimentary rocks from the Baiyigou section. (A) La-Th-Sc ternary diagram, (B) Th-Sc-Zr/10 ternary diagram and (C) Th-Co-Zr/10 ternary diagram (after Bhatia and Crook (1986)).

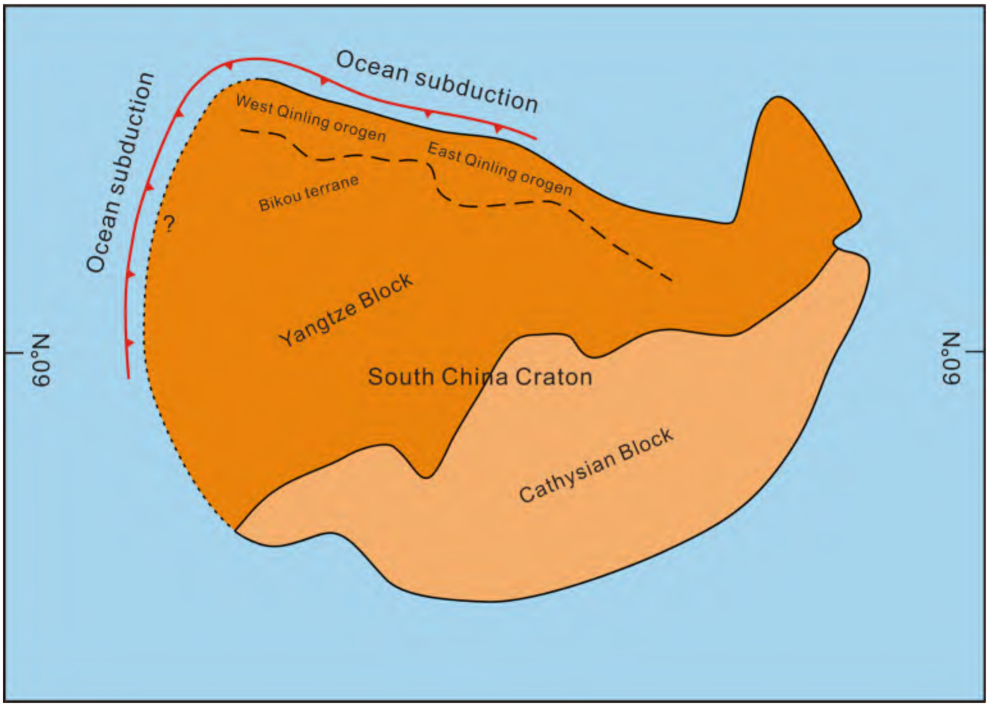

Fig. 21. A sketch showing the regional tectonic setting around the West Qingling orogen during the Tonian. The paleogeography reconstruction was based on propositions from Merdith et al. (2017, 2021); the dotted lines denote the possible boundaries among different terranes using the present-day sites.

In this contribution, we decipher the Neoproterozoic tectonic setting for the West Qinling orogen by integrating sedimentological, petrographic, geochemical and geochronological data from the Baiyigou Group. Our sandstone petrography results (Fig. 7), major and trace element data (Figs. 19–20) and the detrital zircon trace element data (Fig. 12) point to continental arc settings for the sediment source-to-sink system. The detrital zircon U-Pb age spectra for the Baiyigou Group mainly show a prominent, similar peak (from 820 to 800 Ma, Fig. 9) which is close to the inferred depositional ages, implying a possible convergent setting for the West Qinling terrane during the Tonian (Cawood et al., 2012). As discussed above, the Baiyigou Group sedimentary successions have similar characteristics with the western Yangtze Block (e.g., the Bikou terrane, Gu et al., 2023) in terms of depositional ages, sequences and environments. Furthermore, previous studies demonstrate widespread arc-related rocks with 900–800 Ma ages in the South Qinling and the northern and western Yangtze regions (e.g., Xu et al., 2016; Zhao et al., 2018; Liu and Zhao, 2019; Hui et al., 2022; Huang et al., 2023; Liu et al., 2023; Wu et al., 2024 and references therein). Thus, we infer that the West Qinling terrane was connected with the Yangtze Block during the Tonian time, most likely being located in the western margin of the integrated continental block as an extension of the South Qinling terrane (Fig. 21), rather than an isolated microterrane. Another hypothesis is that a paleo-ocean separated the West Qinling terrane from the Bikou terrane, however, there is not robust evidence to support existence of a Tonian ocean due to limited geological records in our study area.

Paleogeographical reconstruction is also crucial for unraveling tectonic setting of the study area and has important implications for understanding global supercontinent cycles. Based on previous paleogeography reconstruction results (e.g., Merdith et al., 2017, 2021), the Yangtze Block (South China Craton) was thought to drift southward from polar latitudes to mid-high latitudes (on the north pole) during the middle–late Tonian (820–800 Ma) and was in a convergent tectonic setting along its present-day western and northern margins. Combining our new findings from the West Qinling orogen, we propose that the West Qinling terrane was involved in the Tonian evolution of the South China Craton with a paleo-ocean subduction zone along its present-day northern margin (Fig. 21). The proposition of an active margin setting is consistent with the widely accepted, continuous, long-lived subduction and arc magmatic system along the western margin of the Yangtze Block during the early–mid Neoproterozoic (e.g., Druschke et al., 2006; Sun et al., 2009; Zhao et al., 2018; Hui et al., 2021; Dong et al., 2024a). The Bikou terrane, which is mainly composed of Tonian–Cryogenian sedimentary strata and igneous rocks, has been also considered to be involved in the convergent arc system (Hui et al., 2021; Gu et al., 2023). Several distant terranes, such as the microterranes in the northern Tibet and the terranes related to the northwestern India, are thought to connect with the western Yangtze Block and as fragments from the greater India during the Rodinia-Gondwana transition (Jian et al., 2020; Wang et al., 2021). This means that the early–mid Neoproterozoic long-lived arc system was broader than previously known. Furthermore, the dominated negative εHf(t) values of the 840–780 Ma zircons (Fig. 11) reveal an involvement of ancient crustal materials during the arc magmatism process. This reinforces the proposition of a continental arc setting, rather than oceanic island arc settings for the West Qinling terrane.

The zircon Th/U and Eu/Eu* ratios are thought to be related to tectonic stress regimes (Mckay et al., 2018) and crustal thickness (Tang et al., 2020), respectively. The variable Th/U ratios indicate that the zircon-bearing parent rocks could form under both compressional and extensional settings (Fig. 12). The low Eu/Eu* ratios (Fig. 12) reveal possible relatively thin crust conditions with shallow arc-related magma emplacement depths. The relatively shallow emplacement depths of those felsic rocks make the proximity of the depositional ages of the Baiyigou Group to the parent-rock crystallization ages (Fig. 3) reasonable.

6. Conclusions

In this study, the Baiyigou Group strata in the southwestern West Qinling orogen, which are the only Neoproterozoic outcrop in this region (named as the Baiyigou section), were revisited to better understand their depositional ages, sedimentary environments, provenance and tectonic evolution. Zircon U-Pb dating results from tuffaceous sandstones and granite gravels in conglomerates demonstrate that the Saiyikuo Formation accumulated during 820–800 Ma, while the Xianglongka Formation was most likely deposited in the period of 800–720 Ma. The Baiyigou Group presents as mixed volcaniclastic and siliciclastic records and was derived from localized sources with predominant intermediate-acid igneous rocks. These sediments were transported by at least two different agents, including wind (carrying volcanic clasts) and water (in small drainage networks), and were eventually deposited in a fluvial-lake system. The integrated analysis results suggest a continental arc setting in the West Qinling terrane during the middle–late Tonian. We favor that the West Qinling terrane was in an active margin setting, being involved in the long-lived subduction-related system along the western margin of the Yangtze Block during the early–mid Neoproterozoic.

CRediT authorship contribution statement

Zhidong Gu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis. **Xing Jian:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Guixia Liu:** Visualization, Resources, Investigation, Formal analysis. **Hanjing Fu:** Resources, Investigation, Formal analysis, Data curation. **Xiaotian Shen:** Resources, Investigation, Formal analysis, Data curation. **Xiufen Zhai:** Resources, Investigation. **Hua Jiang:** Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Science and Technology Major Project of PetroChina (No. 2023ZZ0201, 2022KT0101, and KT2020-01-03), the National Science and Technology Major Project of the Ministry of Science and Technology of China (No. 2016ZX05004005-001), and the Science and Technology Project of RIPED (No. YGJ2023-01). Dr. Wuling Mo and Tong Lin, and Prof. Ping Luo from the RIPED contributed to field work during 2020–2021. Xiamen University master student Ling Wang contributed to some sample analysis and discussions. We also appreciate the editor, associate editor and the two reviewers for their thoughtful comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.precamres.2025.107692.

Data availability

Data will be made available on request.

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