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**A Neoproterozoic appinite rock suite records the early tectonic  
evolution of the northern margin of the Yangtze Block during  
convergence with Rodinia**

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## Abstract

Appinite rock suites generally consist of bimodal mafic–silicic hornblende-bearing igneous rocks, mostly generated by post-subduction processes along ancient convergent plate margins. In this study, we investigated the Neoproterozoic Duanfangxi appinite rock suite from the south Kongling terrane, South China, which is key to understanding the tectonic evolution of the Yangtze Block and for the reconstruction of its association with Rodinia. Based on field observations, mineralogical and whole-rock geochemical analyses, the appinites are divided into the early Zhaibao and Yazikou and the late Taipingxi sub-series. Zircon U–Pb dating constrains the age of formation of the early Zhaibao and Yazikou and the later Taipingxi sub-series to 890–870 Ma and 870–865 Ma, respectively. The three successions are characterised by high hornblende, biotite, and Mg calc-alkaline compositions, and low Th, Nb, and Zr content. While the early sub-series is rich in large-ion lithophile elements, the late sub-series is enriched in high-field-strength elements. Collectively, the geochemical composition of the three rock units is typical of arc-related rocks, with slightly positive to negative  $\epsilon_{\text{Hf}}(\text{t})$  values spanning 11.5 to –14.8 for the Zhaibao and –1.2 to –18.1 for the Yazikou sub-series, indicating an asthenospheric mantle source that interacted with subducted slab-derived fluids and hydrous melts. Together, the appinite suites suggest a switch from subduction to a post-subduction depositional setting between 890–865 Ma. Our results, supported by previous lines of evidence, indicate that formation of the northern margin of the Yangtze Block was associated with a complete Wilson cycle during the late Mesoproterozoic to early Neoproterozoic.

**Keywords:** Appinite rock suite; Neoproterozoic; Geochemistry; Yangtze Block; South China Block; Rodinia

## 1. Introduction

The early tectonic evolution of the South China Block (SCB) and its links with the

Rodinia supercontinent are two hotly debated topics in Precambrian geology. The SCB is divided into the Yangtze Block (YB) to the northwest and the Cathaysian Block (CB) to the southeast, separated by the Jiangnan Orogen (Li et al., 2021c; Shu et al., 2019; Wang et al., 2007, 2008; Yao et al., 2019). Among them, the YB contains Archean to Neoproterozoic rock records vital for deciphering the tectonic evolution of the SCB. In the past decades, a series of 1118–974 Ma ophiolitic mélanges (Peng et al., 2012c), 1049–1026 and 1000–970 Ma subduction-related rocks (Deng et al., 2012, 2017a), and 942–935 Ma amphibolite-facies metamorphic rocks (Jiang et al., 2016), documented in the YB, indicate formation associated with complex tectonic processes.

Although the YB has been recognized as a key part of the Rodinia supercontinent, long-lasting debates about the location of the YB-SCB in Rodina remain to be resolved (Cawood et al., 2013, 2018, 2020; Johansson et al., 2022; Li et al., 2024; Merdith et al., 2017; Shu, 2012; Shu et al., 2021; Wang et al., 2021b; Zhao and Cawood, 1999, 2012; Zhao et al., 2018). Some researchers suggest that the YB-SCB existed as a continental fragment located between the Australian craton and Laurentia in the core of Rodina (Li et al., 1995; Li et al., 2008b; Li et al., 2002b). Others, however, believe that the YB-SCB was situated in the northwestern margin of the Rodina supercontinent, possibly linked to the Indian Craton and/or Australian Craton based on a comparison of magmatism and sedimentation dynamics (e.g., Cawood et al., 2013, 2018; Zhao et al., 2017; Cawood et al.; Rino et al., 2008; Trond, 2003; Wang et al., 2021b). Understanding the processes that formed the YB–SCB is a key step in reconstructing the links between the SCB, and the assembly and rifting of Rodinia during the Neoproterozoic (Dong et

al., 2024b; Li et al., 2002a, 2008a; Shu et al., 2021; Zhao and Cawood, 2012). However, the absence of evidence for the end of this subduction event has made it difficult to determine the tectonic processes that formed the YB and SCB. Moreover, early Neoproterozoic magmatic activity (Dong et al., 2024b) and orogenic events in the YB are poorly documented (Cawood et al., 2020; Huang et al., 2021; Johansson et al., 2022; Li et al., 2008a; Lu et al., 2022; Wang et al., 2017; Wu et al., 2020; Yao et al., 2019; Yao et al., 2014; Zhang et al., 2012a; Zhang et al., 2020). Furthermore, the complex geochemical composition of the dominant granitoid rocks in the YB, has led to a lack of consensus regarding their formation (Huang et al., 2023b; Zhao et al., 2013). Consequently, this has resulted in controversies regarding the nature of the geodynamic setting of the YB and its evolution, including its association with an active continental margin or extensional setting (Dong et al., 2024a; Li et al., 2002a, 2008a; Peng et al., 2012a; Peng et al., 2012b; Shu et al., 2021; Zhao and Cawood, 2012). Thus, evidence of more subduction-collision-related magmatism along the margin of the YB is required to trace the tectonic evolution of the SCB and the reconstruction of its paleogeographic location in the Rodinia supercontinent.

In this paper, we describe a newly discovered Neoproterozoic appinite suite from the South Kongling (SKL) sub-terrane at the northern margin of the YB. Appinites can form in a variety of geodynamic settings, including subduction, collisional, and orogenic intracontinental environments (Zhong et al., 2014; Murphy, 2020). Consequently, the identification of appinite suites, their petrogenesis and tectonic depositional setting, can provide important clues for the tectonic evolution of ancient

convergent plate margins (Atherton and Ghani, 2002; Murphy, 2013; Murphy et al., 1990, 2004; Neilson et al., 2009; Pe-Piper et al., 2010; Ye et al., 2008; Zhang et al., 2012b; Zhao et al., 2021). Our geochemical and isotopic data suggest that the studied appinites formed during the terminal phase of an ancient subduction event that led to the formation of the YB, in association with the assembly of Rodinia during the Neoproterozoic.

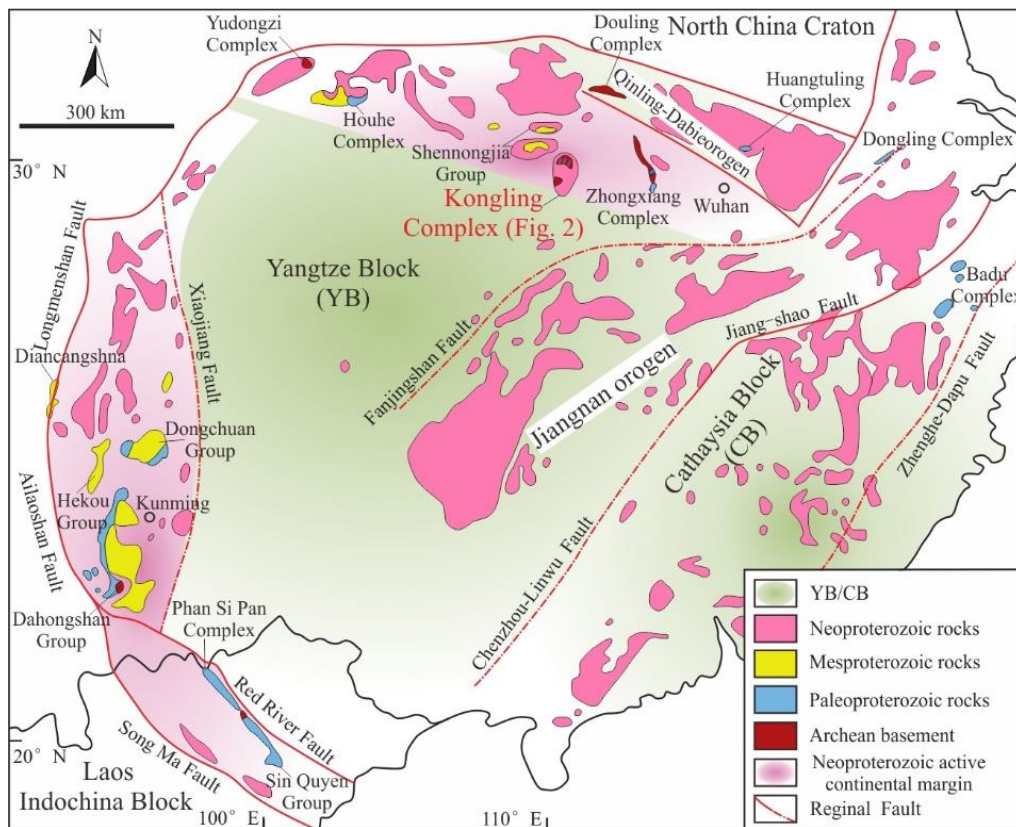


Fig. 1. Distribution of Precambrian rocks and the present-day tectonic framework of the South China Block (SCB). Adapted from Cawood et al. (2020).

## 2. Geological setting and sample descriptions

The continental nucleus of the northern margin of the YB may be the Kongling Terrane, which consists of the north Kongling (NKL) and SKL sub-terrane. These sub-terrane

experienced multiple stages of Archean–Paleoproterozoic magmatism and metamorphism (Chen et al., 2013; Gao et al., 2001; Guo et al., 2014; Guo et al., 2021; Han et al., 2018; Li et al., 2020; Li et al., 2022; Peng et al., 2023; Qiu et al., 2018, 2020; Wei, 2021; Wei et al., 2020; Wei et al., 2019; Xiong et al., 2009; Zhang et al., 2006; Zhou et al., 2022). The SKL hosts rare Archean granitoid gneisses (Han et al., 2023), along with Neoproterozoic post-subduction mafic dykes, diorites, and granites (Cui et al., 2021; Jiang et al., 2018, 2021; Li et al., 2021b; Wu et al., 2016; Zhang et al., 2021b; Zhang et al., 2008; Zhao et al., 2013). Neoproterozoic subduction-related rocks are also exposed in the western SKL sub-terrane (Deng et al., 2012, 2017a; Jiang et al., 2016; Peng et al., 2012c), with Neoproterozoic diorite–granite plutons (e.g., the Huanglingmiao granitic complex) located in the centre (Fig. 2).

Similar to other appinite rock suites worldwide (Atherton and Ghani, 2002; Bea and Montero, 1999; Castro et al., 2003; Li et al., 2021a; Murphy, 2020; Murphy et al., 2019; Pitcher, 1997; Ye et al., 2008; Zhao et al., 2021), the Duanfangxi appinites (DFX) occur as satellite bodies emplaced around the Huanglingmiao granitic complex and as enclaves in the Sandouping tonalite. The appinite intrusive lithologies are E–W-trending and form the Zhaibao (ZB)–Yazikou (YZK)–Tiapingxi (TPX) sub-series (ZB and YZK = early sub-series; TPX = later sub-series). Based on temporal and spatial relationships, petrography, and geochemistry, the rocks can be divided into the ZB medium- to coarse-grained hornblende diorite, Yazikou (YZK) medium- to coarse-grained quartz–biotite–hornblende diorite, and TPX fine- to medium-grained biotite–hornblende–quartz diorite units.

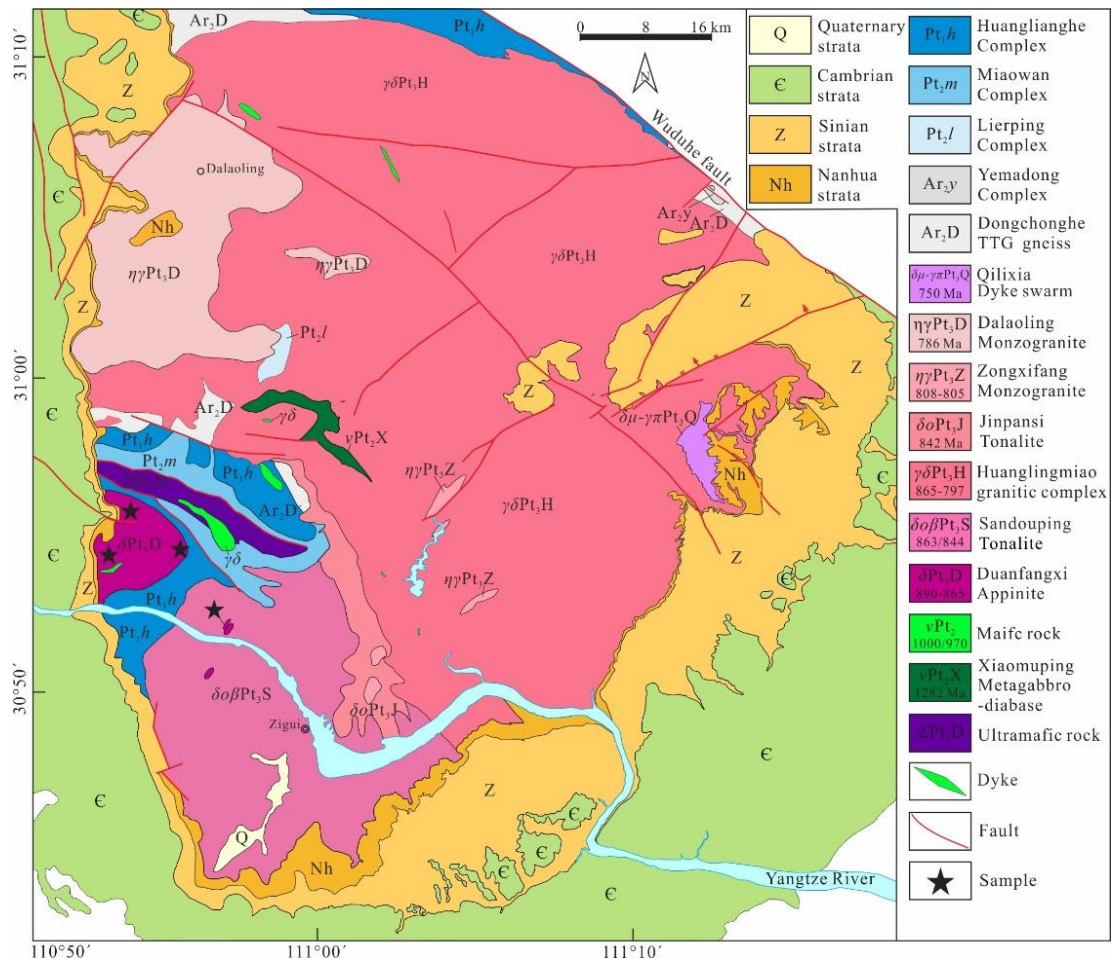


Fig. 2. Geological map of the SKL sub-terrane.

The pronounced contact boundary between the ZB in the Zhaibao–Changling–Henyuanzi area (Fig. 2) and the YZK sub-series (Fig. 3a–b), is covered by the Nanhua Group strata in the west. The exposed YZK rocks cover a  $\sim 6.7 \text{ km}^2$  area in Yazikou, Chenpiya, and Zhifangpu (Fig. 2). They intrude the Huanglianghe complex, Miaowan ophiolitic mélangé, and the ZB sub-series (Fig. 3b), and are covered by the Liantuo Formation in the west. The TPX sub-series occurs as enclaves in the Sandouping tonalite in the Wenchangge–Taipingxi region (Fig. 2 and Fig. 3e). Compared with the ZB and YZK, the TPX sub-series is granular, medium- to coarse-grained, and is

138 composed of a low hornblende content.

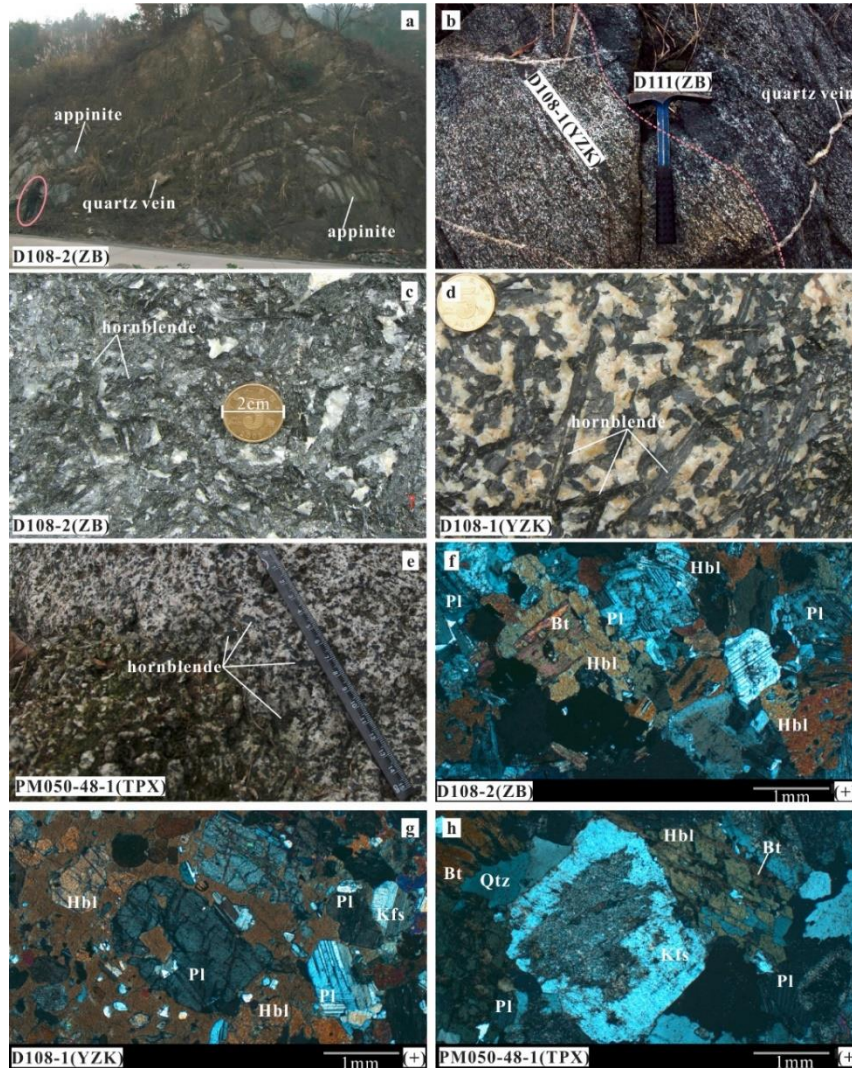


Fig. 3. Field photographs and photomicrographs of the DFX appinite suite. Samples D108-2 and D111, PM050-48-1, and D108-1 are from the ZB, the TPX, and the YZK sub-series, respectively. (a) Outcrop of the ZB sub-series showing appinite cut by quartz veins. (b) Sharp contact between the ZB and YZK sub-series. (c) Cross-polarised light photomicrograph showing the hornblende–biotite–plagioclase-rich nature of the ZB sub-series. (d) Cross-polarised light photomicrograph showing the hornblende–plagioclase–K-feldspar-rich composition of the YZK sub-series. (e) Outcrop of the TPX sub-series containing abundant black hornblende. (f) Cross-polarised light photomicrograph of the TPX sub-series showing strongly sericitised K-feldspar, plagioclase, hornblende, biotite, and quartz. Pl, plagioclase; Kfs, K-feldspar; Hbl, hornblende; Qtz, quartz.

### 3. Results

#### 3.1 Petrography

The ZB rocks are subhedral to granular, poikilotopic, and massive. They contain ~40% plagioclase, 25%–40% hornblende, 10% K-feldspar, 5% biotite, and minor clinopyroxene, quartz, and secondary (e.g., sericite) and magnetite (Fig. 3f). Euhedral–subhedral plagioclase is 0.2–1.5 mm in size and has multiple twinning. Acicular hornblende grains that are  $0.5 \times 1.2$  to  $1.2 \times 3.5$  mm in size and exhibit greenish to brownish pleochroism. The plagioclase–hornblende mineral boundaries are smooth or straight, and the minerals occur as mosaics, with large hornblende crystals containing abundant plagioclase inclusions. Subhedral K-feldspar grains are 0.5–1.5 mm long and are always in contact with coarse-grained plagioclase. The  $0.5 \times 1.2$  to  $1.2 \times 2.5$  mm flaky biotite grains exhibit brown to light green pleochroism, while quartz occurs mainly as an interstitial mineral. Early clinopyroxene is replaced in some instances by late magmatic hornblende minerals, as well as partial replacement of quartz by plagioclase. Sericitisation of feldspar and chloritisation of biotite represent the main minerals associated with alteration, while altered plagioclase contains epidote and calcite.

The YZK rocks consist of 30%–50% plagioclase, 18%–25% hornblende, ~15% biotite, and 5%–10% quartz, along with minor K-feldspar, apatite, zircon, titanite, and magnetite. Alteration products include sericite and chlorite, along with magnetite (Fig. 3g). Subhedral  $0.3 \times 0.5$  to  $1.5 \times 3.0$  mm plagioclase grains exhibit multiple twinning. Acicular to anhedral hornblende varies in size from  $0.1 \times 0.5$  to  $0.5 \times 2.5$  mm and

exhibits brown to green pleochroism. These hornblende grains containing plagioclase inclusions intergrow with  $0.1 \times 0.2$  to  $0.2 \times 1.2$  mm biotite grains that exhibit a brown to light green pleochroism. Quartz is revealed as anhedral 0.1–1.5 mm grains filling interstitial spaces between coarse-grained plagioclase.

The TPX rocks contain 40% plagioclase, 15% quartz, 10% hornblende, 10% K-feldspar, 10% biotite, 5% sericite, and minor zircon, apatite, and magnetite minerals (Fig. 3h). Subhedral  $0.5 \times 2.5$  to  $1.5 \times 4.5$  mm plagioclase minerals exhibit multiple twinning features, while anhedral 0.1–1.5 mm quartz grains occur interstitially between plagioclase minerals, locally replacing plagioclase in some instances. Subhedral  $0.5 \times 2.5$  to  $1.2 \times 3.5$  mm acicular hornblende occurs as a brown mineral displaying green pleochroism, while subhedral 0.1–2.5 mm K-feldspar grains have been affected by sericitisation.

The amount of hornblende and biotite in the studied rocks decreases from the ZB to TPX units, likely reflecting a change in magmatic fractionation. The low modal abundances of sericite, chlorite, epidote, and calcite are indicative of low degrees of alteration and metamorphism.

### **3.2 Zircon U-Pb ages**

Zircon U-Pb ages were analyzed using a LA-ICP-MS at the State Key Laboratory of Continental Dynamics in Northwest University with the detailed analytical method and results listed in [Supplementary Text](#) and [Table S1](#), respectively.

The results of 30 analyses obtained from 25 zircon crystals for sample D111 from

the group 1 of ZB sub-series (are provided in Table S1 and Fig. 4a. Most of the short subhedral to long prismatic zircons exhibited primary magmatic oscillatory zoning, with three having narrow regrowth rims. The Th and U contents of these zircons vary from 36–238 and 57–366 ppm, respectively, with corresponding Th/U ratios of spread between 0.50–0.98. Their associated  $^{206}\text{Pb}/^{238}\text{U}$  ages span 806–887 Ma, with an upper intercept age of  $886.3 \pm 4.3$  Ma (MSWD = 0.23) (Fig. 4a). A weighted-mean age of  $886.6 \pm 5.3$  Ma (MSWD = 0.68) was calculated from eight concordant analyses (Fig. 4b).

The data for 30 analyses conducted on 29 zircon crystals for the group 1 D108-2 sample belonging to the ZB sub-series, can be found in Table S1 and Fig. 4c. Five of them had rimmed overgrowths and three that yielded discordant ages due to Pb loss were excluded from the age calculations (Table S1). Their Th and U contents ranged from 46–565 and 86–628 ppm, respectively and their corresponding Th/U ratios were 0.48–1.27, except for one value that was  $<0.4$ . The  $^{206}\text{Pb}/^{238}\text{U}$ – $^{207}\text{Pb}/^{235}\text{U}$  ratios yielded ages of 859–896 Ma, with an upper intercept age of  $886.4 \pm 1.8$  Ma (MSWD = 0.14) (Fig. 4c). A weighted-mean age of  $879.0 \pm 5.0$  Ma (MSWD = 0.38) was calculated from 25 concordant analyses (Fig. 4d).

The result of 30 analyses on 29 zircon grains from sample D104-1 obtained from the ZB group 2 samples, are given in Table S1 and Fig. 4e. Most of the subhedral or short prismatic crystals exhibit magmatic oscillatory zoning, while three zircons possessing narrow rimmed overgrowths, were excluded from the age calculations. The associated Th and U content of these crystals varied from 31–92 and 71–179 ppm, respectively,

with corresponding Th/U ratios of 0.34–0.79, most being >0.4. Greater than 96% concordance data produced ages of 835–896 Ma, with an upper intercept age of  $878.2 \pm 3.1$  Ma (MSWD = 0.14) (Fig. 4e). A weighted-mean age of  $884.5 \pm 2.7$  Ma (MSWD = 1.12) was calculated from 29 concordant analyses (Fig. 4d).

The values for 30 analyses conducted on 30 zircon crystals with length to width ratios of 4:1 for sample D108-1 from the YZK sub-series, are presented in Table S1 and Fig. 4g. Three of the zircons were found to have narrow rimmed overgrowths around a magmatic core and two to have experienced Pb loss and therefore, were not used in the age calculations. The range of Th and U concentrations in the remaining zircons was spread between 48–590 and 61–555, respectively, with associated Th/U ratios ranging from 0.45–1.34. The greater than >95% concordance data yielded  $^{206}\text{Pb}/^{238}\text{U}$ – $^{207}\text{Pb}/^{235}\text{U}$  ages of 857–883 Ma, with an upper intercept age of  $870.6 \pm 1.9$  Ma (MSWD = 0.049) (Fig. 4g). A weighted-mean age of  $872.4 \pm 2.4$  Ma (MSWD = 0.83) was calculated from 28 concordant analyses (Fig. 4h).



### 3.3 Whole-rock geochemistry

Whole-rock major and trace element data for the DFX appinites obtained at the Zhongnan Mineral Resource Supervision and Testing Center of MLR with the detailed analytical method and results listed in [Supplementary Text](#) and [Table S2](#), respectively. Loss-on-ignition (LOI) values of 0.83–1.77 wt.% indicate a low degree of alteration of the samples. The ZB-1 sample was found to be compositionally different from the others, because of a higher MnO and P<sub>2</sub>O<sub>5</sub>, and a lower CaO and Na<sub>2</sub>O content ([Fig. 5d–e and g](#)). The different geochemical characteristics of the DFX appinites reflect those of the *ca.* 880 Ma intrusive mafic rocks emplaced in the Bikou Terrane on the northern margin of the YB ([Hui et al., 2021](#)).

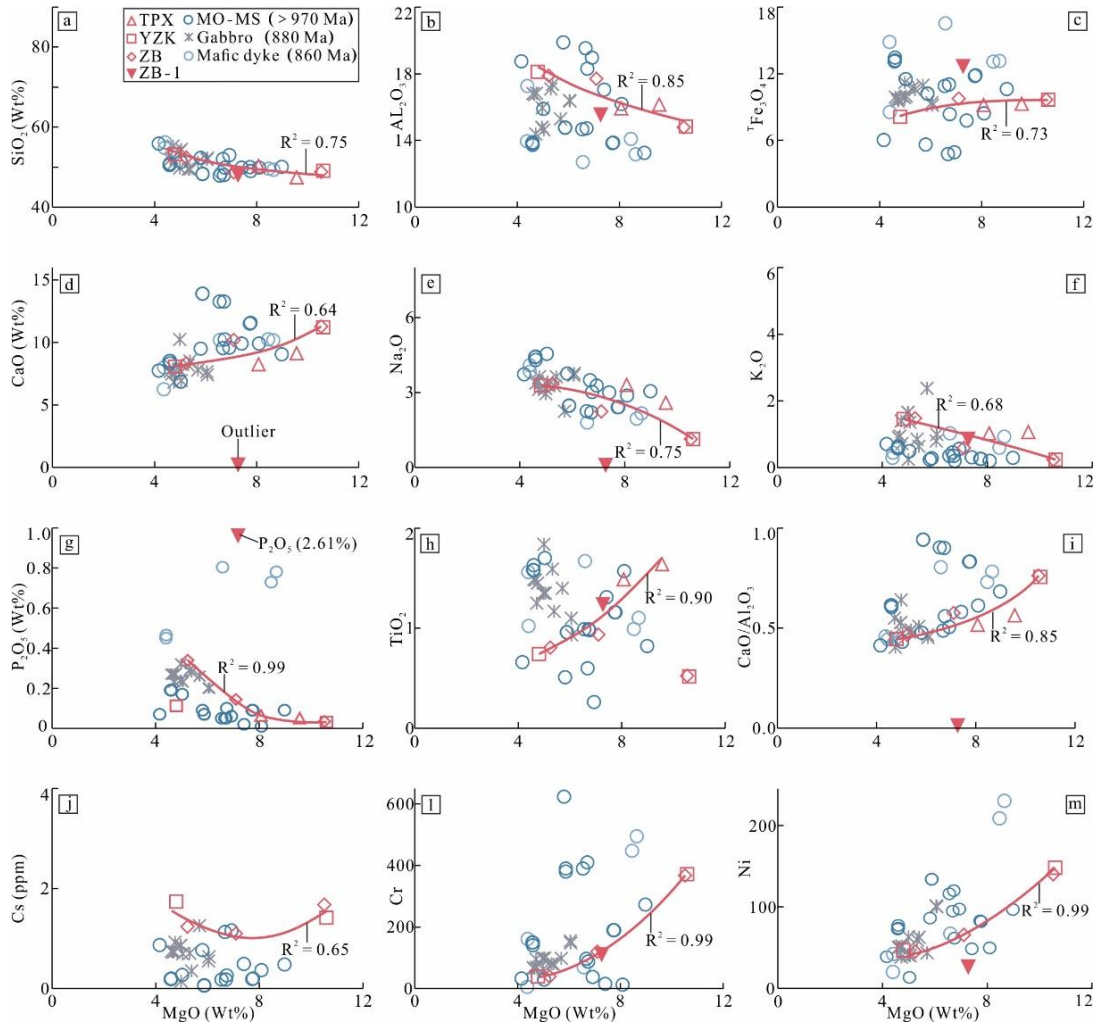


Fig. 5. Plots of (a)  $\text{SiO}_2$ –MgO, (b)  $\text{Al}_2\text{O}_3$ –MgO, (c)  $\text{TFe}_2\text{O}_3$ –MgO, (d)  $\text{CaO}$ –MgO, (e)  $\text{Na}_2\text{O}$ –MgO, (f)  $\text{K}_2\text{O}$ –MgO, (g)  $\text{P}_2\text{O}_5$ –MgO, (h)  $\text{TiO}_2$ –MgO, (i)  $\text{CaO}/\text{Al}_2\text{O}_3$ –MgO, (j)  $\text{Sc}$ –MgO, (l)  $\text{Cr}$ –MgO, and (m)  $\text{Ni}$ –MgO for the Duanfangxi appinite rocks. The Duanfangxi appinite rock suite comprises the TPX, YZK, and ZB sub-series; all oxides are in wt.% and trace elements in ppm; the red lines represent the relationships between the different sub-series based on a second-order polynomial.

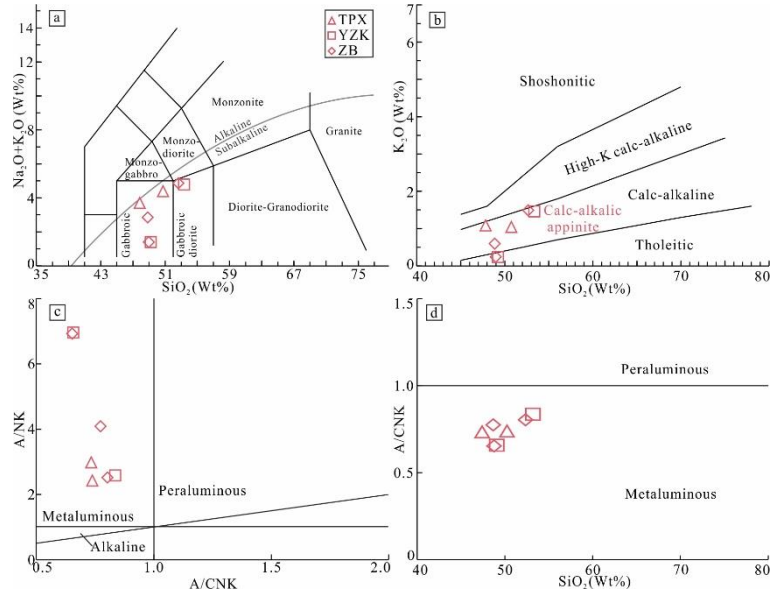


Fig. 6. (a) TAS diagram (after [Le Maitre et al. \(2005\)](#)); (b) K<sub>2</sub>O versus SiO<sub>2</sub> diagram (after [Murphy \(2020\)](#); [Peccerillo and Taylor \(1976\)](#)); (c) A/NK versus A/CNK diagram (after [Chappell \(1974\)](#); [Zen \(1986\)](#)); and (d) A/CNK versus SiO<sub>2</sub> diagram for the Duanfangxi appinite rocks (after [Zhang et al. \(2011\)](#)) .

The ZB rocks were low in SiO<sub>2</sub>, Na<sub>2</sub>O, and K<sub>2</sub>O, with concentrations ranging from 48.7–52.4 wt.%, 1.14–3.34 wt.% 0.24–1.48 wt.%, respectively, and high in MgO (2.24–10.5 wt.%) and total Fe<sub>2</sub>O<sub>3</sub> (9.67–9.77 wt.%), as well as high Mg<sup>#</sup> (56–65). In a total alkali–silica (TAS) classification diagram, the studied rocks were found to be of subalkaline gabbro composition ([Fig. 6a](#)). Their associated A/NK and A/CNK ratios spanned 2.52–4.92 and 0.65–0.77, respectively, with a metaluminous affiliation ([Fig. 6c–d](#)). The total rare earth element content of the rocks varied from 25–169 ppm, and showed enrichment in light REEs (LREEs; 19–154 ppm) and depletion in heavy REEs (HREEs; 6.5–16 ppm), similar to Oceanic island basalt or Island arc basalts (OIB/IAB-type) rocks ([Fig. 7a](#)). Furthermore, they exhibited a small negative to slightly positive Eu anomalies, with a  $\delta$ Eu of 0.9–1.20. Primitive-mantle-normalised trace element diagrams, indicated enrichment in large-ion lithophile elements (LILEs; e.g., Rb) and

depletion in high-field-strength elements (HFSEs; e.g., Th, Nb, and Zr) (Fig. 7b).

The major element compositions of the YZK rocks showed similar patterns to those of the ZB rocks (Fig. 5). These lithologies are characterised by a low 49.1–53.2 wt.% SiO<sub>2</sub>, 1.14–3.30 wt.% Na<sub>2</sub>O, and 0.23–1.46 wt.% K<sub>2</sub>O content, and a corresponding high 4.80–10.6 wt.% MgO, 8.11–9.67 wt.% total Fe<sub>2</sub>O<sub>3</sub>, and 51–66 Mg<sup>#</sup> values. In a TAS classification diagram, they affiliate with subalkaline gabbros and diorites (Fig. 6a). Their associated A/NK and A/CNK ratios ranged from 2.58–6.96 and 0.66–0.84, respectively, with a metaluminous affinity (Fig. 6c–d). Total REE concentrations varies from 25–310 ppm, marked by 18–293 ppm LREEs enrichment and 6–17 ppm HREEs depletion, similar to OIB/IAB-type rocks (Fig. 7a). Furthermore, they are characterized by small negative to slightly positive Eu anomalies that range from 0.86–1.26. Primitive-mantle-normalized trace element diagrams indicate LILEs enrichment (e.g., Rb, Sr, and U) and HFSEs depletion (e.g., Th, Nb, and Zr) (Fig. 7b).

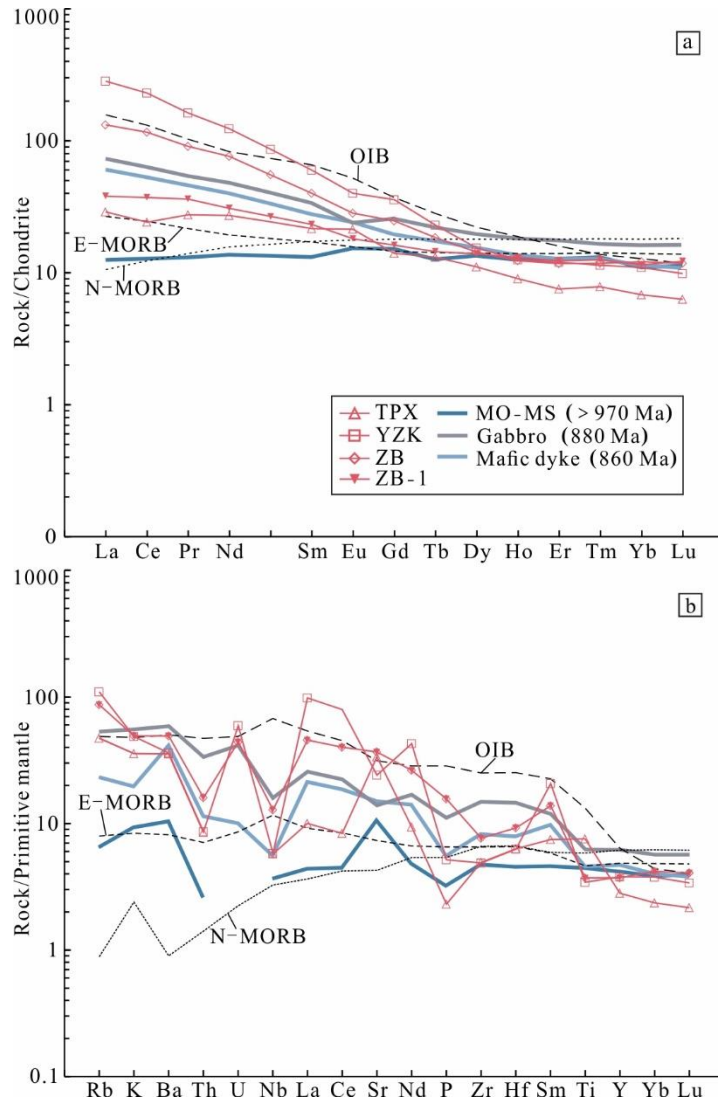


Fig. 7. (a) Chondrite-normalised REE patterns and (b) primitive-mantle-normalised trace element diagrams for the Duanfangxi appinites (normalisation values are from Sun and McDonough (1989)).

The major element compositions of the TPX, ZB, and YZK rocks are similar, except for  $\text{TiO}_2$  (Fig. 5). Their  $\text{SiO}_2$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{MgO}$ , total  $\text{Fe}_2\text{O}_3$  concentrations spread from 47.4–50.3 wt.%, 2.59–3.31 wt.%, 1.03–1.07 wt.%, 8.07–9.56 wt.%, and 9.18–9.29 wt.%, respectively, with 61–64  $\text{Mg}^\#$  values. Like the YZK, the TPX rocks are suggested to be of a subalkaline gabbro and diorite category (Fig. 6a). Their A/NK and A/CNK ratios range from 2.43–2.98 and 0.73–0.74, respectively, and are of a

metaluminous affinity (Fig. 6c–d), while the corresponding trace element content differs from those of the ZB and YZK rocks. A high total REE concentration of 50.99–63.21 ppm, is associated with 41.52–53.76 ppm enrichment in LREEs and depletion in HREEs (9.45–9.47 ppm), similar to OIB-type lithologies (Fig. 7a). Their small and slightly positive Eu anomalies vary from 1.18–1.23. Primitive-mantle-normalised trace element diagrams suggest enrichment in LILEs (e.g., Sr) and depletion in HFSEs (e.g., Th, Nb, P, and Zr) (Fig. 7b). In summary, a gabbroic to dioritic, high-Mg, calc-alkaline appinite, OIB-like composition, is suggested by the data for the ZB, YZK, and TPX rocks.

### 3.4 Zircon Lu–Hf isotopes

The detailed Zircon Lu–Hf isotope analytical method and results are listed in Supplementary Text and Table S2, respectively. Twenty one test results from the sample D111 in group 1 of ZB subseries (Table S3), yield  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios ranging from 0.282044–0.282201,  $\varepsilon_{\text{Hf}}(t)$  values of –7.8 to –1.5, and  $T_{\text{DM1}}$  and  $T_{\text{DM2}}$  ages of 1491–1702 and 1850–2188 Ma (Fig. 8). Sixteen test results from sample D108-1 in group 1 of ZB subseries, (Table S3), after discarding one outlier, showed  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of 0.281813–0.282255,  $\varepsilon_{\text{Hf}}(t)$  values of –14.8 to 0.9, and  $T_{\text{DM1}}$  and  $T_{\text{DM2}}$  ages of 1389–2001 and 1699–2680 Ma (Fig. 8). Twenty test results from sample D104-1 in group 2 samples from ZB (Table S3) produced  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of 0.282294–0.282569, with  $\varepsilon_{\text{Hf}}(t)$  values of 2.2 to 11.5 and  $T_{\text{DM1}}$  ages of 975–1336 Ma (Fig. 8).

Eighteen test results from sample YZK D108-1 (Table S3), after removal of one outlier, revealed  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of 0.281742–0.282199. Their associated  $\varepsilon_{\text{Hf}}(t)$  values

were spread between  $-18.1$  to  $-1.2$ , with  $T_{DM1}$  and  $T_{DM2}$  ages of 1463–2139 and 1826–2871 Ma (Fig. 8).

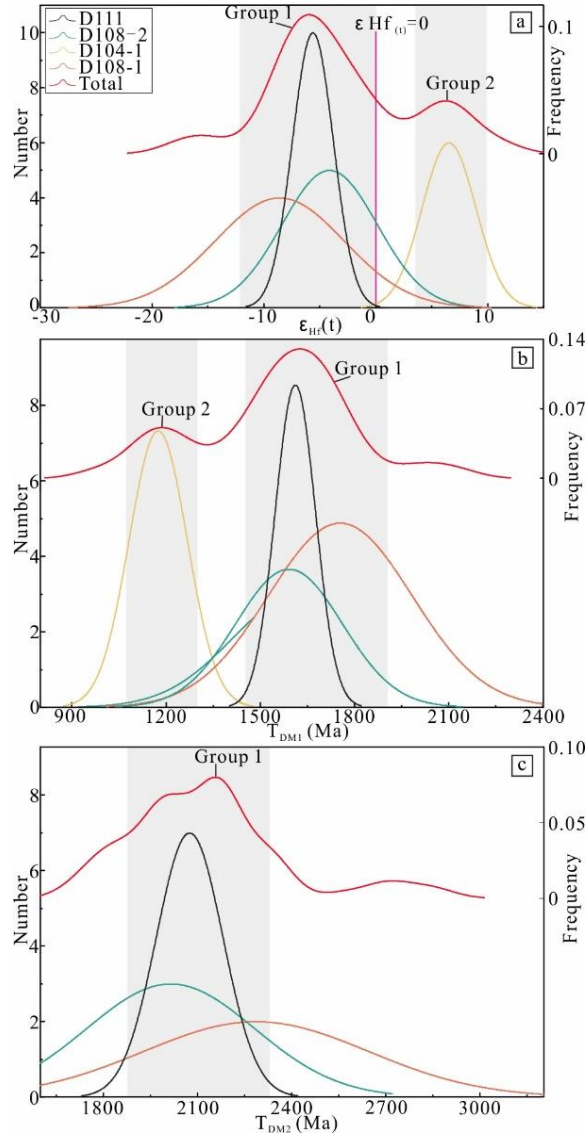


Fig. 8. Plots of (a)  $\epsilon_{Hf}(t)$  values, (b)  $T_{DM1}$  ages, and (c)  $T_{DM2}$  ages for the Duanfangxi appinite rocks.

## 4. Discussion

### 4.1 Age and petrogenesis

#### 4.1.1 Age of the appinites

Previous studies have shown that the youngest units of the Miaowan ophiolitic mélange

formed before 970 Ma (Deng et al., 2012, 2017b; Peng et al., 2012c), were intruded by the early ZB sub-series. Based on field observations, the YZK rocks intruded the ZB sub-series. Our new zircon U–Pb age data, combined with the field relationships, indicate the ZB sub-series rocks were emplaced at 886–880 Ma (Fig. 4a–c), with an age of *ca.* 870 Ma inferred for the YZK rocks (Fig. 4d). The Sandouping tonalites intruding the TPX rocks yielded the youngest ages of *ca.* 865 Ma, defining a minimum age for the formation of the TPX rocks. Based on these U–Pb ages and geochemical data, the DFX appinite rock suites can be subdivided into two formation stages related to two main intrusive events—i.e., at 886–870 Ma for the ZB and YZK rocks and 870–865 Ma for the TPX rocks (Figs 2–3 and 7).

#### *4.1.2 Petrogenesis*

The studied rocks exhibit alteration features in thin section, such as the occurrence of sericite, chlorite, epidote, and calcite, which formed primarily by the alteration of hornblende and plagioclase. Moreover, they have variable LOI values of 0.83–1.77 wt.% (that can be attributed to primary hornblende), indicating that the whole-rock geochemical composition has been modified by post-magmatic alteration. Thus, as the REEs and HFSEs are expected to be immobile during post-depositional modification, they were used for petrogenetic assessment. However, crustal assimilation and fractional crystallisation (AFC) can modify the geochemical composition of magmas (Foley et al., 2002; Pearce and Norry, 1979). In the case of the studied appinites, crustal contamination may have increased their Al, Si, and LILE contents. Therefore, some of

the major element, HFSE, REE, and Lu–Hf isotope data were used to constrain the petrogenesis and tectonic setting of the appinites. Positive correlations are evident between  $\text{La}_N/\text{Yb}_N$  and La, and La/Sm and La (Fig. 9a–b). In plots of La/Sm and Sm versus Sm/Yb (Fig. 9c–d), the samples plot between melts derived from spinel–garnet and garnet lherzolite, suggesting that partial melting controlled the generation of the DFX appinites, and that AFC processes (Fig. 9a–b) had little effect on their formation. This is consistent with emplacement in the deep crust.

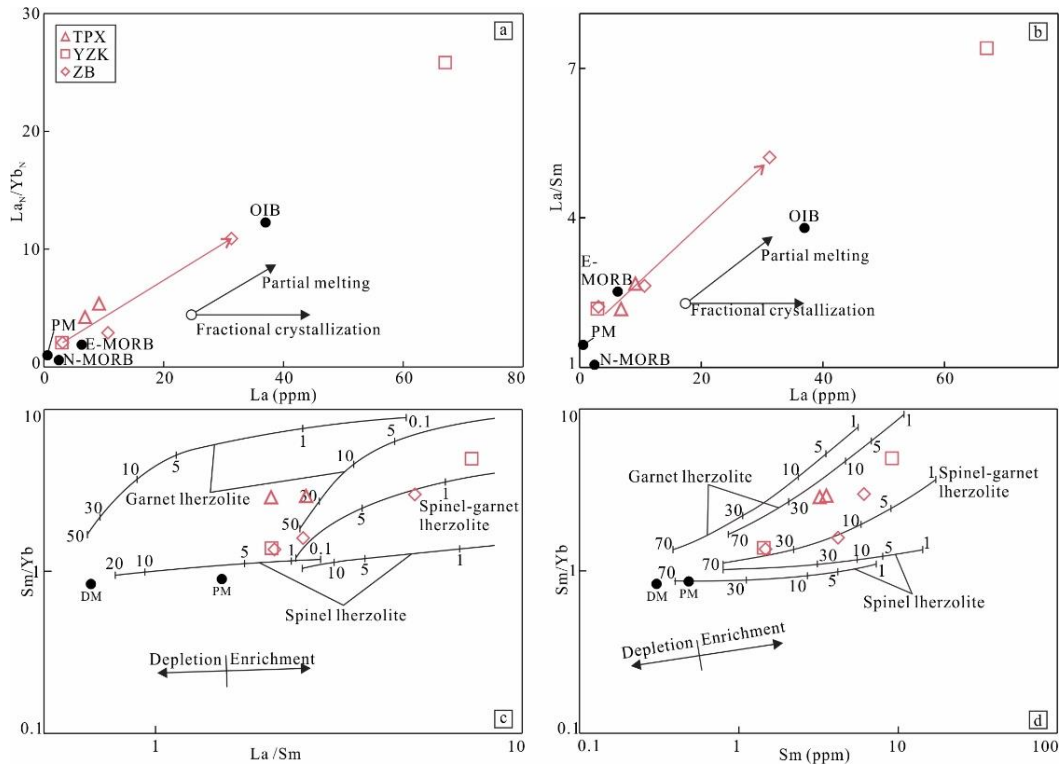


Fig. 9. (a)  $\text{La}_N/\text{Yb}_N$  versus La; (b) La/Sm versus La; (c) La/Sm versus Sm/Yb; (d) Sm versus Sm/Yb diagrams for the Duanfangxi appinitite rocks (Hui et al., 2021; Zhao and Zhou, 2007). The black lines in (c–d) represent the melts of spinel and garnet peridotite. The numbers annotated along the lines represent the degree of partial melting.

In the KL terrane, the Miaowan ophiolitic mélange and late Magmatic Suite

suggest a mid-ocean ridge to subduction zone environment existed prior to 970 Ma. Moreover, the Miaowan ophiolitic *mélange* indicates a small ocean was present existed between the KL and paleo-YB, with its closure before 970 Ma recorded by the ophiolitic *mélange* (Deng et al., 2012, 2017a; Peng et al., 2012c). In addition, *ca.* 860 Ma mafic dykes were emplaced contemporaneously with olivine gabbroic rocks, and 850 Ma diorites and granites in a post-subduction setting at the northern margin of the YB (Cui et al., 2021; Jiang et al., 2018, 2021; Li et al., 2021b; Wu et al., 2016; Zhang et al., 2021b; Zhang et al., 2008; Zhao et al., 2013). Furthermore, the presence of 830–800 Ma Au deposits (Wang et al., 2023) and *ca.* 820 Ma granitic rocks (Wu et al., 2016; Zhang et al., 2009) in this area suggest that the tectonic setting of the KL terrane transitioned to a within-plate setting after *ca.* 820 Ma. These data point to early Neoproterozoic tectonic transition from an active continental margin to intracontinental setting in the Kongling area.

For the DFX appinite rock suite, the whole-rock trace element data for the older ZB and YZK rocks, along with the younger TPX rocks, exhibit OIB-like patterns (Fig. 7). Most of these rocks contain abundant mafic minerals and have a calc-alkaline affinity (Fig. 6b), negative Nb–Ta anomalies, and LREE enrichments (Fig. 7). Some samples resemble calc-alkaline, volcanic arc rocks, island arc volcanic rocks, and continental arc/back-arc basalts (Figs 6c, 7, and 10). In summary, the geochemical composition of the DFX appinites indicate a continental arc setting associated with slab rollback (Figs 6b, 7, and 10) (Canning et al., 1996; Varne, 1985; Ye et al., 2008; Zhao et al., 2021; Zhong et al., 2014).

The DFX appinites are characterised by low SiO<sub>2</sub>, Na<sub>2</sub>O, and K<sub>2</sub>O content that is generally much lower than the expected values for the deep crust of the YB (Gao et al., 1998). Furthermore, their trace element ratios (e.g., Nb/Ta–Th/Yb, Nb/Th–Th, and Nb/Ta–Zr/Hf) are similar to those of primitive mantle and trend towards average crustal values (Fig. 13). The variable  $\varepsilon_{\text{Hf}}(t)$  values of the DFX appinites are mostly higher than typical lower crustal values derived from 2.5 Ga mantle. Their slightly enriched to depleted zircon Lu–Hf isotopic compositions (Fig. 12) further indicate that the inferred mantle source for the DFX appinites is consistent with whole-rock trace element geochemistry. As such, the studied appinite samples were probably formed by partial melting of an enriched asthenospheric mantle (Fig. 9 and Fig. 13).

Although appinites are generally considered to form by hydrous melting of sub-arc mantle, their original compositions may be strongly modified by contributions from slab-derived fluids (Hirose, 1997), melts of basaltic oceanic crust (Kelemen, 1995), sediment-derived silicic melts (Fowler et al., 2008; Tatsumi, 2006), and melt–mantle interactions (Cawood et al., 2021; Shimoda et al., 1998; Tatsumi, 2006). Partial melting of a subducted slab at depths usually produces fluids or silicic melts with low Th contents and slight enrichment of HFSEs (Brenan et al., 1994; Ringwood, 1990; Zhao et al., 2015). In this regard, the low 2.24–2.85 ppm Th content of the DFX appinites, enriched in HFSEs, indicate contribution from the partial melting of a subducted slab. Their calc-alkaline affinity, the associated high LREE and LILE concentrations, together with depletion of Nb and Ta (Murphy, 2013, 2020), collectively point to metasomatism of the mantle wedge by subducted-slab-derived fluids (Fig. 7). As such,

a subducted slab affected the generation of the DFX appinites, due to mantle upwelling and slab rollback (Fig. 13).

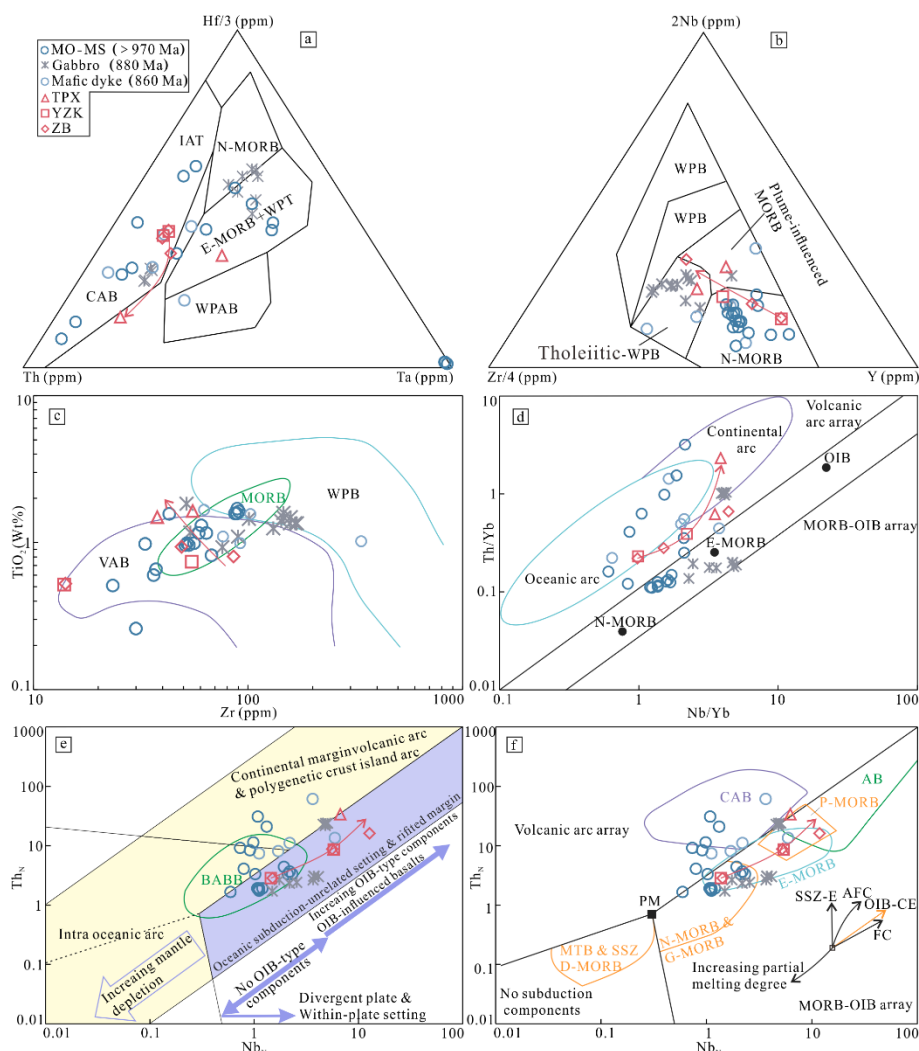


Fig. 10. Tectonic discrimination diagrams for the ZB, YZK, and TPX appinites. (a) Th–Hf–Ta discrimination diagram after Wood (1979); (b) 2Nb–Zr/4–Y discrimination diagram after Meschede (1986); (c) TiO<sub>2</sub>–Zr discrimination diagram after Pearce (1982); (d) Th/Yb–Nb/Yb discrimination diagram after Dilek and Furnes (2011); Pearce (2008); (e–f), Th<sub>N</sub>–Nb<sub>N</sub> plot after Saccani (2015). Th<sub>N</sub> and Nb<sub>N</sub> are normalised to primitive mantle (Sun and McDonough, 1989). CAB = calc-alkaline basalt; IAT = island arc tholeiite; N-MORB = normal-type mid-ocean ridge basalt; E-MORB = enriched-type mid-ocean ridge basalt; WPT = within-plate tholeiite; WPB (WPAB) = within-plate (alkaline) basalt; VAB = volcanic arc basalt; AB = alkaline basalt; BABB = back-arc basin basalt; MTB = medium-Ti basalt; PM = primitive mantle; G-MORB = garnet-influenced mid-ocean ridge basalt; SSZ D-MORB =

supra-subduction zone depleted mid-ocean ridge basalt; P-MORB = plume-type mid-ocean ridge basalt; AFC = assimilation–fractional crystallisation; FC = fractional crystallisation; OIB-CE = ocean island-type (plume-type) component enrichment; SSZ-E = supra-subduction zone enrichment.

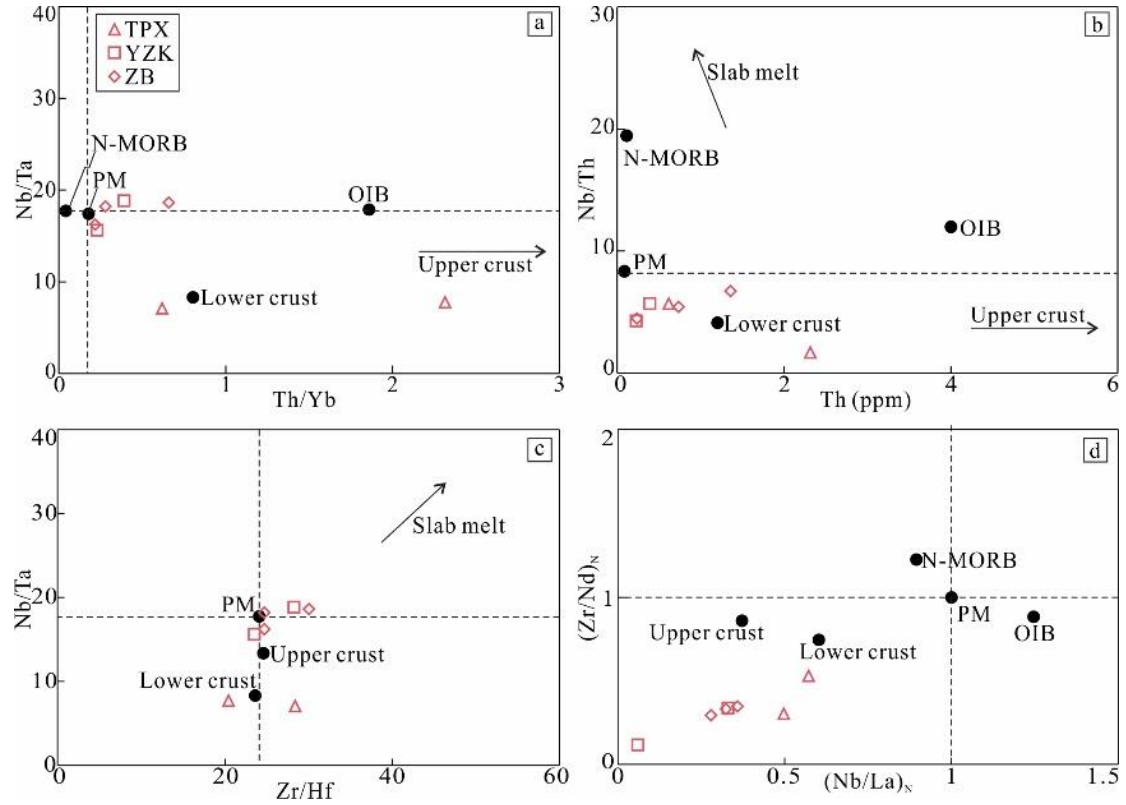


Fig. 11. Plots of (a) Nb/Ta versus Th/Yb, (b) Nb/Th versus Th, (c) Nb/Ta versus Zr/Hf, and (d) (Zr/Nd)<sub>N</sub> versus (Nb/La)<sub>N</sub> for the Duanfangxi appinite rocks. (Zr/Nd)<sub>N</sub> and (Nb/La)<sub>N</sub> are normalised to primitive mantle (Sun and McDonough, 1989). The PM, OIB, N-MORB, and E-MORB data are from Sun and McDonough (1989), and upper and lower crust data are from Wedepohl (1995).

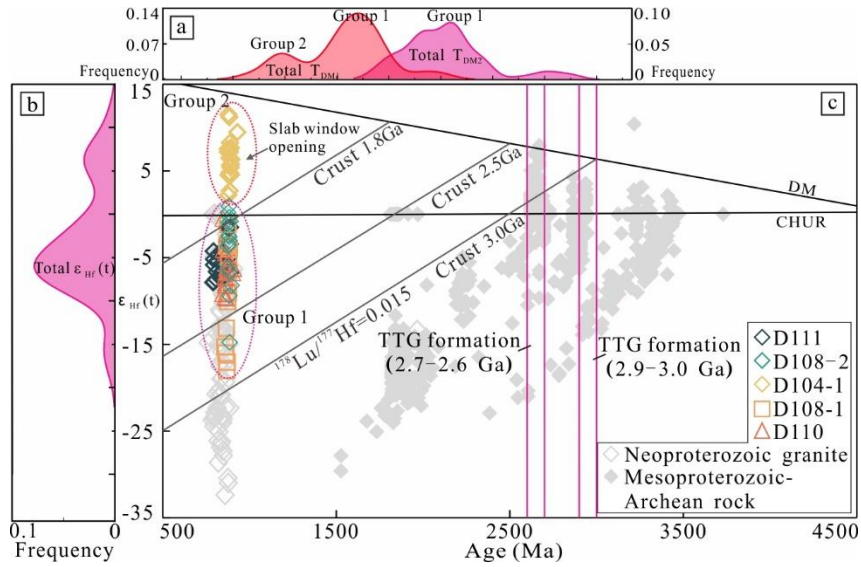


Fig. 12. Diagrams showing the potential magmatic sources and processes involved in the formation of the Duanfangxi appinites, including  $T_{DM1}$ , and  $T_{DM2}$ ,  $\epsilon_{Hf}(t)$  values, and the plots of  $\epsilon_{Hf}(t)$  versus age. The figure also shows published data for the KL terrane (Chen et al., 2013; Gao et al., 1999, 2011; Guo et al., 2014; Guo et al., 2018, 2021; Li et al., 2020; Peng et al., 2012a; Qiu et al., 2018; Wei et al., 2019; Xiong et al., 2009; Zhang et al., 2008; Zhao et al., 2013). The left Y-axis in Fig. a. represent the  $T_{DM1}$  values frequencies, the right Y-axis Fig. a. represent the  $T_{DM2}$  values frequencies, and the X-axis in Fig. b. represent the  $\epsilon_{Hf}(t)$  values frequencies of Duanfangxi appinites, respectively. The X-axis of Fig. a. and the Y-axis of Fig. a. are corresponding to Fig. c.

## 4.2 Tectonic significance

### 4.2.1 Wilson cycle at the northern margin of the Yangtze Block

The start and end of subduction are important stages of the tectonic cycle (Cloetingh et al., 1984; Fu et al., 2022, 2023; Hall, 2019; Huang et al., 2022a, 2023a; Stern, 2002; Wan et al., 2019; Yao et al., 2021). However, the rock record is incomplete in most ancient orogenic belts and suture zones. In some cases, only intraplate extension-related rocks are preserved (e.g., Huang et al. (2022b)). An increasing number of observations indicate that appinites can be generated during post-subduction slab break-off or

delamination during the final stages of subduction, and thus record the termination of subduction activity at a convergent plate margin (Atherton and Ghani, 2002; Murphy, 2020; Murphy et al., 1990; Neilson et al., 2009; Pe-Piper et al., 2010; Ye et al., 2008; Zhang et al., 2012b).

The late Mesoproterozoic to early Neoproterozoic volcanic rocks adjacent to the Shennongjia area (Qiu et al., 2011), along with contemporaneous MORB-type oceanic rocks, record the tectonic framework of the north–northwest margin of the YB, which comprised a paleo-oceanic basin and passive continental margin (Huang et al., 2022b; Peng et al., 2012c; Wang et al., 2021a). The history of oceanic subduction in the early Neoproterozoic (i.e., before *ca.* 970 Ma) is recorded by the Miaowan ophiolitic mélange and Late Magmatic Suite in the SKL sub-terrane (Deng et al., 2012, 2017a; Peng et al., 2012c), the Huashan ophiolite and Xixiang dacite–rhyolite in adjacent areas (Ling et al., 2003), the *ca.* 880 Ma Yudongzi–Bikou gabbro–diorite (Hui et al., 2021; Hui et al., 2022; Xiao et al., 2007), the Hannan 900–870 gabbro–granite (Dong et al., 2012; Dong et al., 2011), the 960–850 Ma dolerites, and the Xiaomaoling diorite–quartz monazite (Dong et al., 2017; Yan et al., 2014). These rocks record a long-lived paleo-continental margin along the northern YB. Moreover, the composition of the Miaowan ophiolitic mélange and the Late Magmatic Suite imply the formation in a mid-ocean ridge to supra-subduction zone (SSZ) setting prior to 970 Ma (Deng et al., 2012, 2017a; Peng et al., 2012c). Association of the *ca.* 860 Ma Miaowan mafic dykes with contemporaneous olivine gabbros and *ca.* 850 Ma diorite–granite assemblages indicate an intracontinental setting in the KL terrane (Cui et al., 2021; Jiang et al., 2018, 2021;

Wu et al., 2016; Zhang et al., 2008, 2009; Zhao et al., 2013). However, it is difficult to reconstruct a complete tectonic record of the KL Terrane along the northern margin of the YB due to the scarcity of rocks older than *ca.* 880 Ma (Dong et al., 2024b), and the timing of the termination of the subduction event remains unclear. We propose that the DFX appinite rock suite formed in an arc setting associated with slab rollback.

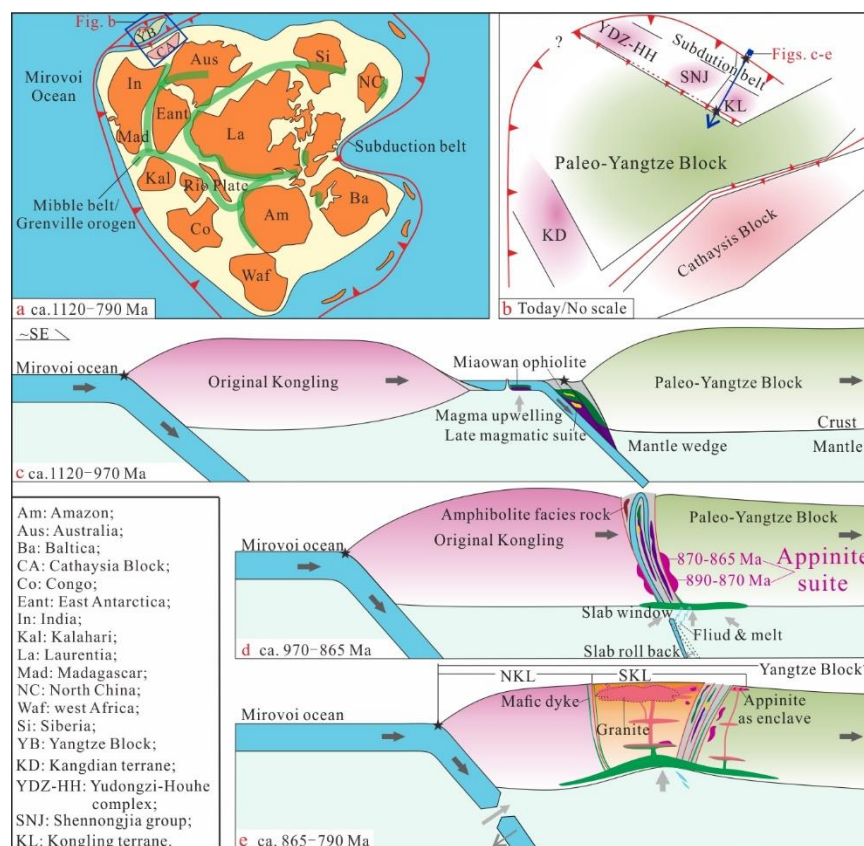


Fig. 13. Tectonic evolution of the northern margin of the YB (not drawn to scale). (a) Reconstruction of Rodinia during 1120–790 Ma (modified after Cawood et al., 2018; Rino et al., 2008; Trond, 2003). (b) The peripheral Mirovoi Ocean continued to affect the YB, leading to the formation of the South China Block (SCB) and amalgamation with Rodinia. Sections (c–e) are located on the northern margin of the YB. (c) The lithosphere of a peripheral paleo-ocean and small ocean between the Kongling–Yudongzi complex and paleo-YB was subducted under the northern margin of the YB before 970 Ma. (d) Terminal subduction of a small ocean at the northern margin of the YB (890–865 Ma) and generation of the appinite rock suite occurred at 890–865 Ma. The appinite model is based on Murphy (2020); Murphy et

al. (2022); Murphy et al. (2019) (e) Intraplate setting at the northern margin of the YB, following the end of subduction in the peripheral Mirovoi Ocean. See the text for discussion. The NKL and SKL sub-terrane have preserved Neoproterozoic igneous rock records.

The 890–865 Ma DFX appinites in the SKL sub-terrane suggest that subduction ended by *ca.* 890 Ma, followed by a transition to a post-subduction setting before 865 Ma (Fig. 13). This inference is consistent with the emplacement of the Bikou gabbro at the northwestern margin of the YB (Hui et al., 2021), indicating a similar tectonic setting at the northern to northwestern margins of the YB. Analysis of the DFX appinites enables identification of the (post-)subduction events that led to the assembly of the northern margin of the YB, and provide evidence for a complete Neoproterozoic Wilson Cycle.

In summary, the northern margin of the YB was characterised by three key tectonic stages: (1) sub-oceanic basin evolution during 1120–970 Ma that resulted in the generation of MORB- and SSZ-type ophiolitic mélanges (Fig. 13c); (2) a tectonic transition from subduction to post-subduction during 970–865 Ma, leading to the formation of gabbros and appinites, including the DFX appinites that represent the end of subduction (Fig. 13d); and (3) formation of an Andean-type continental margin and a protracted within-plate environment after *ca.* 865 Ma that generated I- and A-type granites and mafic dykes (Fig. 13e). The absence of evidence for a collisional setting is similar to most continental arc plate boundary systems (Li et al., 2018; Murphy et al., 2022; Zhang et al., 2021a).

#### 4.2.2 Formation of the South China Block

Ancient cratons are important for reconstruction of the convergence and break-up of supercontinents (Cawood et al., 2018; Liu et al., 2021; Mitchell et al., 2021; Murphy et al., 2023; Nance and Murphy, 2013). Subduction, collision, magma ascent, and regional strike-slip faulting are typically related to the presence of thick and rigid plates (Korenaga, 2021; Palin and Santosh, 2021; Zhou et al., 2021). The geological evidence preserved in the YB since the Archean (Fig. 1) and corresponding accretion of the Nuna supercontinent suggest that the studied rocks were spatially associated with northwestern Laurentia and possibly Siberia, whereas the CB was attached to northern India (Cawood et al., 2018). It has been suggested that the SCB was generated following convergence of the YB and CB along the Jiangnan orogenic belt during the Neoproterozoic (Cawood et al., 2018, 2020; Dong et al., 2012, 2017; Shu et al., 2019; Yao et al., 2019; Zhou et al., 2002; Zhou et al., 2006). The onset of oceanic subduction by 880–870 Ma resulted in continental margin arc magmatism and sedimentation in the central and southwest Jiangnan orogen (Lyu et al., 2017; Yao et al., 2019; Zhang et al., 2015), with final amalgamation of the YB and CB during 835–815 Ma (Cawood et al., 2018; Li et al., 2009; Wang et al., 2012; Wang et al., 2014; Xia et al., 2018; Zhang et al., 2012c; Zhao et al., 2011). These events were characterised by the widespread emplacement of S- and minor I-type granites in the central and southwest Jiangnan Orogen.

The northern margin of the YB was associated with several micro-blocks (Fig. 13b) that converged with the paleo-YB to form the present-day YB during the

Neoproterozoic. Based on this reconstruction of the tectonic processes operating at the northern margin of the YB (Fig. 13), we propose that formation of the SCB was a multi-stage tectonic event, during which micro-blocks along the northern margin (e.g., the KL and YDZ–HH terranes) converged with the paleo-YB before *ca.* 890 Ma to form the present-day YB. Southeastward plate motion led to progressive subduction in the paleo-ocean beneath the northern margin of the YB. This geodynamic process may have had far-reaching regional effects that led to the convergence of the YB and CB. Since 815 Ma, these two blocks have remained an intact component of the SCB (Hu et al., 2019).

#### *4.2.3 Links of the South China Block to Rodinia supercontinent*

Most of the major continental blocks were assembled into the Rodinia supercontinent by collisional orogenies during 1300–1000 Ma (Chiarenzelli and McLelland, 1991; McLelland et al., 1996; Moore Jr and Thompson, 1980; Wu et al., 2019), which was represented to the early Neoproterozoic Grenvillian Orogeny (Johansson et al., 2022; McLelland et al., 1996; Rino et al., 2008). The Grenvillian orogenic belts have not been fully described in many continents, except for the type locality in Canada, North America, and some terranes in various continental fragments (Rino et al., 2008) (Fig. 13a). There are different views on the geodynamic setting of the SCB and Rodinia (Cawood et al., 2013, 2018, 2020; Dong et al., 2024b; Johansson et al., 2022; Shu, 2012; Shu et al., 2021; Wang et al., 2021b; Zhao and Cawood, 1999, 2012; Zhao et al., 2018). Based on the generally accepted model for formation of the SCB and Rodinia,

the SCB was located close to the northwestern margin of Rodinia (Cawood et al., 2018; Huang et al., 2022b; Huang et al., 2021; Wu et al., 2019), with the northern YB margin being in direct contact with the adjacent Mirovoi Ocean (Fig. 13a). It is thus important to constrain the early Neoproterozoic SSZ to back-arc environments located along the north-northwest margin of the YB to understand the connection and structural relationships between the different blocks and the Mirovoi Ocean (Cawood et al., 2018; Zhou et al., 2019). The SCB contains geochemical evidence that is critical for understanding the assembly of Rodinia.

Based on plate reconstructions, the SCB was located along the northwestern periphery of Rodinia, but was disconnected from the main body of the supercontinent (Cawood et al., 2013, 2018, 2020; Johansson et al., 2022; Shu, 2012; Shu et al., 2021; Wang et al., 2021b; Zhao and Cawood, 1999, 2012; Zhao et al., 2018). This location implies that the oceanic basin between the YB and CB did not experience major subduction activity related to Rodinia, as compared with the north–northwest margin that preserves a record of Neoproterozoic subduction (Deng et al., 2012, 2017a; Hu et al., 2019; Huang et al., 2022b; Jiang et al., 2016; Peng et al., 2012c; Wang et al., 2021a; Wu et al., 2019; Zhang et al., 2016; Zhou et al., 2019). The history of events associated with the SCB with respect to the Grenvillian Orogeny does not enable the reconstruction of a complete tectonic cycle at the north-northwest margin of Rodinia, given the delayed start of tectonism in the main part of the supercontinent. This makes it difficult to determine the role and tectonic location of the SCB within Rodinia. In this regard, the newly described DFX appinites provide an opportunity to reconstruct a

complete tectonic record, including the spatial extent, duration, and paleogeographic affiliation of the SCB (i.e., YB) to Rodinia (He et al., 2023; Huang et al., 2023b; Hui et al., 2021). Combined with recent studies of the north-northwest margin of the YB (He et al., 2023; Huang et al., 2022b; Huang et al., 2023b; Hui et al., 2021; Wang et al., 2023; Wang et al., 2019; Wang et al., 2021a; Zhou et al., 2022), the results of this study suggest that subduction had ended by *ca.* 890 Ma. The presence of post-subduction extension-related rocks further implies that convergence was terminated before *ca.* 865 Ma (Fig. 13), after which the SCB was amalgamated into the main part of Rodinia.

## 5. Conclusions

The Duanfangxi appinite rock suite intruded the SKL sub-terrane between 890–865 Ma. These rocks had an asthenospheric mantle source and were generated in a continental margin arc setting associated with slab rollback and mantle upwelling. We propose a transition from subduction to post-subduction activity at the northern margin of the YB. Moreover, the association of the Duanfangxi appinites with a complete Wilson cycle at the northern margin of the YB is consistent with the presence of similar rock types in the SCB. These observations indicate that these tectonic processes eventually led to the formation of the SCB and its subsequent convergence with and incorporation into Rodinia during the early Neoproterozoic.

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