Early Neoarchean geodynamic regime in North China Craton: constraints from 2.7 Ga granitoids in southern Jilin terrane

Jin Liu[1,2], Hongxiang Zhang[1], Richard M. Palin[2 *], Zhenghong Liu[1,3], Jian Zhang[4], Changquan Cheng[5], Xiaoguang Liu[6], Chen Zhao[7]

[1]*College of Earth Sciences, Jilin University, 2199 Jianshe Street, Changchun, 130061, China*

[2]*Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN United Kingdom*

[3]*Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Natural Resources, Changchun 130061, China*

[4]*Department of Earth Sciences, The University of Hong Kong, Hong Kong SAR, China*

[5]*School of Earth Sciences and Engineering, Sun Yat-sen University, Zhuhai 519000, China*

[6]*Frontiers Science Center for Deep Ocean Multispheres and Earth System, Key Lab of Submarine Geosciences and Prospecting Techniques, MOE and College of Marine Geosciences, Ocean University of China, Qingdao 266100, China*

[7]*Shenyang Center of Geological Survey, China Geological Survey, Shenyang, Liaoning, China*

---

1 *

Corresponding author：Richard M. Palin

*E-mail: **richard.palin@earth.ox.ac.ukABSTRACT**

Identifying the processes responsible for generation and evolution of the Archean continental crust plays a crucial role in understanding the tectonic regimes present on the early Earth. A major episode of continental growth during the early Neoarchean has been identified in many cratons worldwide; indeed, early Neoarchean magmatism has been recognized from several terranes within the North China Craton (NCC) over the past decade, although the geodynamic regime in which such activity occurred remains highly debated. Here, we focus on newly recognized early Neoarchean mylonitic trondhjemite and granodiorite from the southern Jilin terrane to address this knowledge gap. Zircon U–Pb geochronology reveals that these granitoids formed at *ca.* 2.7 Ga. These granitoids display adakitic geochemical characteristics, such as high Sr/Y and La_N/Yb_N ratios. Their low MgO, Cr, and Ni contents, along with low $\delta^{18}O$ values (4.19–5.39‰) and positive $\varepsilon_{Hf(t)}$ (0.7–6.5) and $\varepsilon_{Nd(t)}$ (2.0–2.6) values, indicate that they originated from thickened juvenile lower continental crust. Thermodynamic modelling further constrains the *ca.* 2.7 Ga granitoids to have been generated from partial melting driven by amphibole breakdown under granulite-facies P–T conditions of 10–15 kbar and 800–900 ℃, with garnet and amphibole as the major residual minerals. Combined with previous studies, we suggest that the NCC underwent significant crustal growth during the early Neoarchean, which was likely attributed to the synergistic effects of waning mantle plume activity and the coeval onset of plate tectonics.

1. INTRODUCTION

The geodynamic processes that have driven the formation and evolution of the continental crust through time is a fundamental point of debate in earth sciences (Cawood et al., 2013). Despite the mechanisms of growth of the continental crust on the early Earth—whether episodic or continuous—remaining controversial (Arndt and Davaille, 2013; Hawkesworth et al., 2013), there is a broad consensus that most (~70%) of the preserved continental crust had formed by the end of the Neoarchean (Cawood et al., 2013; Condie et al., 2009; Dhuime et al., 2012; Hawkesworth et al., 2019). Indeed, the Neoarchean is considered as the most important period of continental crust formation in most cratons based on global compilations of igneous and detrital zircon ages that reveal a significant peak at *ca.* 2.7 Ga (Condie et al., 2009), suggesting widespread growth at this time linked to the development of Earth's earliest recognized supercontinent/supercraton (Bleeker, 2003). This *ca.* 2.7 Ga growth event has been variably attributed to intraplate mantle plume magmatism (Condie, 1998; Milidragovic and Francis, 2016; Said et al., 2010), or via magmatism associated with subduction zones and terrane accretion (Ge et al., 2014; Manikyamba, 2004; Polat and Münker, 2004; Yang et al., 2013). Both plume-derived komatiite–tholeiitic sequences and subduction-related calc-alkaline to tholeiitic basalt–dacite sequences have been identified in several *ca.* 2.7 Ga greenstone belts, such as the Veligallu (India) (Dey et al., 2018) and Abitibi–Wawa (Canada) (Polat, 2009; Wyman et al., 2002). Thus, it seems likely that both mantle plume and subduction activity played critical roles in this *ca.* 2.7 Ga crustal growth event (Gao et al., 2019; Kerrich et al., 1998; Wyman and Kerrich, 2012).

It has been previously proposed that the North China Craton (NCC) underwent significant continental growth during the late Neoarchean (*ca.* 2.5 Ga) (Diwu et al., 2011; Mao et al., 2024), while the tectothermal event in the early Neoarchean (*ca.* 2.7 Ga) is considered less intense. However, many early Neoarchean granitoids have been discovered across nearly all terranes of the NCC in the past decade (**Fig. 1**). The published geochronological data are briefly summarized in **Supplemental Table S1**. These *ca.* 2.7 Ga granitoids have been mainly recognized from the central and eastern NCC, including areas such as Hengshan (Kröner et al., 2005), Wutai (Mao et al., 2024), Fuping (Han et al., 2012; Lu et al., 2014), Zanhuang (Yang et al., 2013), Zhongtiao (Zhang et al., 2023; Zhu et al., 2013), Lushan (Diwu et al., 2010; Huang et al., 2010; Zhou et al., 2014), Yumengshan (Zhou et al., 2021), Huixian (Diwu et al., 2020), eastern Shandong (Jiang et al., 2016; Yao et al., 2020), western Shandong (Ren et al., 2016; Wan et al., 2011b; Wang et al., 2016d), Bengbu (Liu et al., 2019), Huoqiu (Wan et al., 2010; Wang et al., 2014a), northern Liaoning (Bao et al., 2022; He et al., 2024; Wang et al., 2016b), and southern Jilin (Bao et al., 2022; Wu et al., 2021). Additionally, *ca.* 2.7 Ga ultramafic-mafic volcanic sequences (e.g., Al-depleted komatiite, pillow basalt, amphibolite, meta-tholeiite, and hornblende plagioclase schist) were widely distributed within the western Shandong terrane (Gao et al., 2019; Polat et al., 2006; Wan et al., 2011b). Some *ca.* 2.7 Ga mafic volcanic rocks also sporadically identified from the Zanhuang and southern Jilin terranes (Guo et al., 2015; Zhong et al., 2021) (**Fig. 1** and **Supplemental Table S1**). Increasing discoveries of *ca.* 2.7 Ga igneous rocks within the NCC suggest that the intensity of the early Neoarchean tectothermal event may previously have been underestimated. Therefore, conducting comprehensive research on *ca.* 2.7 Ga igneous rocks could provide critical insights into whether the NCC participated in the global crustal growth event during the early Neoarchean, alongside the type of geodynamic regime that was responsible.

This study focuses on newly identified *ca.* 2.7 Ga granitoids from the southern Jilin terrane, from which we present new petrological observations, geochemical analyses, zircon U–Pb ages, zircon Hf–O isotopes, and whole-rock Sm–Nd isotopes. We combine these integrated analyses with published data from other terranes within the NCC to elucidate their petrogenesis and to delineate the crustal evolution history of the NCC during the early Neoarchean.

2. GEOLOGICAL BACKGROUND

The NCC records a long-lived evolutionary history of the continental crust, traceable back to 3.8 Ga (Wan et al., 2023). Eoarchean rocks (>3.6 Ga) have been identified exclusively in three terranes: Anshan (Wan et al., 2023), Eastern Hebei (Dong et al., 2024), and Xinyang (Ma et al., 2020) (**Fig. 1**). During the Mesoarchean, the NCC experienced intensive crustal reworking, as evidenced by the presence of large-scale potassic granites in the Anshan area (Bao et al., 2020; Dong et al., 2017; Wang et al., 2020). In addition, Mesoarchean magmatic activity has also been identified in several regions of the eastern NCC (**Fig. 1**), such as northern Liaoning

(Liu et al., 2022), eastern Hebei (Liou et al., 2019), and eastern Shandong (Jahn et al., 2008; Wu et al., 2014; Yao et al., 2023). The Archean basement of the NCC is primarily composed of Neoarchean TTG (tonalite–trondhjemite–granodiorite), volcanic-sedimentary sequences, and diverse potassic granites. Among these, late Neoarchean (2.6–2.5 Ga) TTG and supracrustal rocks form the major constituents of the NCC (Zhao and Cawood, 2012). In contrast, early Neoarchean (2.8–2.7 Ga) rocks are sporadically distributed in the central and eastern NCC (**Fig. 1**).

The Longgang Block comprises the Anshan continental nucleus in its southwestern segment (**Fig. 2A**). Other domains of the Longgang Block are characterized by Neoarchean granite-greenstone belts, including the Benxi, Qingyuang, Jiapigou, and Helong granite-greenstone belts. The Archean crystalline basement of the Longgang Block primarily consists of late Neoarchean TTG and supracrustal rocks, with minor potassic granites. Notably, a E–W trending *ca.* 2.7 Ga magmatic belt has recently been identified, extending from the Benxi to Baishan areas (Bao et al., 2022). The southern Jilin terrane is a major component of the Longgang Block (**Fig. 2A**). This region is characterized by widespread 2.6–2.5 Ga TTG and contemporaneous supracrustal rocks distributed within the Jiapigou and Helong greenstone belts. In addition, this region underwent a variety of magmatic activities at the end of the Neoarchean, resulting in the formation of various lithologies such as monzogranite, syenogranite, diorite, and mafic dykes (Cheng et al., 2024; Li et al., 2023). Previous studies revealed that the Neoarchean rocks from the southern Jilin terrane underwent widespread greenschist- to amphibolite-facies metamorphism around 2.5 Ga, recording anticlockwise pressure–temperature–time (*P*–*T*–*t*) paths (Ge et al., 2003).

Based on field investigation and zircon U–Pb dating, we have newly identified abundant *ca.* 2.7 Ga granitoids in the Baishan region, which is the easternmost segment of the E–W granitoid belt. The Archean basement of this region comprises *ca.* 2.7 and 2.5 Ga granitoids, exhibiting ductile shear fault contacts with the Paleoproterozoic sedimentary rocks (**Fig. 2B**). These ductile shear faults predominantly exhibit NE-oriented strikes with varying dips. The precise timing of the ductile deformation has not yet been reported. However, given that the Archean to Paleoproterozoic rocks underwent intensive mylonitization, while the Jurassic granites remained unaffected by such deformation, it is likely that the mylonitization occurred in the period following the Paleoproterozoic and preceding the Jurassic. The region extending from Liaodong Peninsula to southern Jilin experienced intensive extensional deformations during the Mesozoic era, which correspondingly formed various NE-oriented extensional structures, such as detachment faults, half grabens, metamorphic core complexes (Liu et al., 2011). Thus, it is plausible that the mylonitization of the study area occurred during the early Mesozoic era.

3. FIELD INVESTIGATION AND PETROGRAPHY

The newly identified *ca.* 2.7 Ga granitoids underwent intensive ductile deformation, and display a variety of mylonitic macrofabrics (**Fig. 3A–I**), including foliations, lineations, S–C fabrics, elongated quartz ribbons, and asymmetric porphyroclasts. The *ca.* 2.7 Ga granitoids mainly consist of mylonitic trondhjemite and granodiorite. Owing to varying degrees of mylonitization, these *ca.* 2.7 Ga granitoids contain diverse proportions and sizes of porphyroclasts, which are mainly composed of plagioclase and K-feldspar. The matrices exhibit fine-grained textures due to dynamic recrystallization during ductile deformation. Those equigranular or slightly elongated grains show no preferred orientation. Oriented biotite/muscovite, hornblende, or elongated quartz ribbons define the foliations. The orientations of mylonitic foliations and lineations observed in different regions vary significantly, reflecting the complexity of later tectonic superimposition.

The mylonitic trondhjemite samples are mainly composed of quartz (40%) and plagioclase (55%), with minor hornblende, biotite, and chlorite (**Fig. 4A–D**). Fine-grained quartz and plagioclase aggregates commonly occur around plagioclase/hornblende porphyroclasts. The mylonitic trondhjemite samples 23HX01-1 and 23HX05-1 record slight epidotization (**Fig. 4C, D**). In comparison, the mylonitic granodiorite samples contain a higher proportion (10–15%) of biotite and hornblende (**Fig. 4E–J**). Elongated quartz grains (**Fig. 4E, F**) and plagioclase/hornblende porphyroclasts (**Fig. 4G–J**) also occur throughout each sample. Within the mylonitic granodiorite, the porphyroclasts primarily consist of plagioclase (40%), while the matrices (40%) are composed of fine-grained recrystallized quartz and feldspar. Fine-grained muscovites are aligned in foliation planes (**Fig. 4G, H**). The mylonitic granodiorite samples 22BS13-1 and 22BS14-1 underwent epidotization, chloritization, and sericitization. In contrast, the granitic mylonite sample 23HX04-1 exhibits a higher proportion (70%) of recrystallized muscovite and matrix (**Fig. 4L**). These muscovites are exclusively found along the mylonitic foliations (**Fig. 4L**), suggesting that they may be products of the syn-deformation stage.

4. ANALYTICAL METHODS AND RESULTS

Detailed descriptions of analytical methods for major and trace elements, zircon U–Pb dating, zircon Lu–Hf and O isotopes, whole-rock Sm–Nd isotopes, as well as phase-equilibrium and trace-element modelling, can be found in **Supplemental materials**.

4.1. Major and trace elements

Twelve mylonitic granitoid samples were analyzed in this study. Detailed results of the major and trace elements can be found in **Supplemental Table S2**. Based on their mineral assemblages and geochemistry, these samples are further classified as mylonitic trondhjemite, mylonitic granodiorite, and granitic mylonite. The mylonitic trondhjemites exhibit high SiO_2 (68.0–72.0 wt. %) and Al_2O_3 (14.2–15.7 wt. %) contents, along with moderate $Fe_2O_3^T$ (1.68–3.58 wt. %) and MgO (0.62–1.59 wt. %) contents. They show enrichment in Na_2O but depletion in K_2O, exhibiting Na_2O/K_2O ratios of 2.44–11.47. In contrast, the mylonitic granodiorites display similar SiO_2 (64.3–70.2 wt. %) contents, higher $Fe_2O_3^T$ (3.06–4.75 wt. %) and MgO (1.02–2.43 wt. %) contents, and lower Al_2O_3 (13.7–14.2 wt. %) contents. Moreover, the mylonitic granodiorites are slightly enriched in K_2O, exhibiting lower Na_2O/K_2O

ratios of 0.99–1.59 than mylonitic trondhjemite. In a conventional total alkali–silica (TAS) diagram (**Fig. 5A**), the mylonitic trondhjemites and granodiorites plot within the granodiorite and granite fields. The majority of mylonitic trondhjemite samples plot within the trondhjemite field in an An–Ab–Or normative diagram (**Fig. 5B**), although one sample plots within the tonalite field. The mylonitic granodiorite samples plot within the granodiorite field or at the boundary between the granodiorite and granite fields in the An–Ab–Or diagram (**Fig. 5B**). In contrast, granitic mylonite samples 23HX04-2 and 23HX04-3 have higher SiO_2 (71.7–73.0 wt. %), lower Al_2O_3 (12.8–13.0 wt. %) contents and Na_2O/K_2O ratios (0.68–0.79), along with similar $Fe_2O_3^T$ (3.25–3.54 wt. %) and MgO (1.38–1.74 wt. %) contents. They plot within the granite fields in the TAS and An–Ab–Or diagrams (**Fig. 5A, B**). Considering the abundant recrystallized muscovites and the scarcity of K-feldspars within these granitic mylonites, it is possible that the high K_2O/Na_2O ratios and elevated K_2O contents were induced by later muscovitization. Although these samples were classified as granites in the the TAS and An–Ab–Or diagrams, it is worth noting that these granitic mylonites may have initially been TTG that later experienced significant mylonization and muscovitization, distinguishing them from typical granites. The mylonitic trondhjemites have geochemical characteristics matching tholeiitic to calc-alkaline magma series, whereas the mylonitic granodiorites and granitic mylonites more closely resemble the high-K calc-alkaline series (**Fig. 5C**). The mylonitic trondhjemite and granodiorite samples are classified as metaluminous to weakly peraluminous rocks with A/CNK ratios of 0.90–1.09 (**Fig. 5D**), whereas granitic mylonite samples 23HX04-2 and 23HX04-3 exhibit higher A/CNK ratios (1.25 and 1.20, respectively).

The mylonitic trondhjemites have total REE contents of 35.8–124.5 ppm, with positive Eu anomalies (δEu = 1.03–1.49) and slight negative Ce anomalies (δCe = 0.83–1.03). They display high La_N/Yb_N (22.1–34.4) and low Gd_N/Yb_N (2.28–3.17) ratios, with enrichment in light REE and depletion in heavy REE (**Fig. 6A**). The mylonitic trondhjemites have high Sr (241–532 ppm, mean value of 410 ppm) and low Y (3.26–10.3 ppm, mean value of 7.13 ppm) and Yb (0.24–0.97 ppm, mean value of 0.60 ppm) contents. They exhibit high Sr/Y (25.1–163.2) and Nb/Ta (11.9–41.0) ratios. In comparison to the mylonitic trondhjemites, the mylonitic granodiorites exhibit similar REE and trace element normalized patterns (**Fig. 6A, B**). They possess higher total REE contents (103.3–255.8 ppm), along with similar La_N/Yb_N (27.8–45.3), Gd_N/Yb_N (3.10–3.89), and Sr/Y (26.9–48.5) ratios. The mylonitic granodiorites display variable Eu anomalies (δEu = 0.82–1.47) and slight negative Ce anomalies (δCe = 0.89–0.97). The granitic mylonites display similar characteristics to the other two groups, such as high La_N/Yb_N (41.3–74.2) and Sr/Y (18.6–27.4) ratios, low Gd_N/Yb_N (2.65–3.88) ratios. They have insignificant Eu anomalies (δEu = 0.92–0.98) and Ce anomalies (δCe = 0.90–0.91). All these granitoid samples are enriched in large-ion lithophile elements (LILEs; e.g. Rb, Ba, and Sr) and light REE (e.g. La and Ce), but are depleted in high-field-strength elements (HFSEs; e.g. Nb, Ta, and Ti) and heavy REE (e.g. Y, Yb, and Lu) (**Fig. 6B**).

4.2. Zircon U-Pb dating

Six samples (21BS10-1, 23HX01-1, 23HX05-1, 22BS13-1, 22BS14-1, and 23HX04-1) were selected for geochronological analysis using LA–ICP–MS. To better constrain the timing of metamorphism, zircon from samples 21BS10-1 and 22BS13-1 was also analyzed by SHRIMP. Detailed analytic data of the LA–ICP–MS and SHRIMP dating are listed in **Supplemental Table S3** and **Table S4**, respectively.

The zircon grains of mylonitic trondhjemite sample 21BS10-1 display clear core-rim structures (**Fig. 7A, B**). The cores exhibit concentric oscillatory zones and high Th/U ratios (0.12–0.55, except for one analysis of 0.05), suggesting a magmatic origin, while the rims exhibit either no or blurred oscillatory zones, indicative of a metamorphic origin. Analyses conducted by LA–ICP–MS on zircon cores yield ^{207}Pb/^{206}Pb ages of 2680–2583 Ma, with an upper intercept age of 2654 ± 14 Ma (**Fig. 7A**). Among these, 14 analyses with minor discordance yield a weighted mean ^{207}Pb/^{206}Pb age of 2648 ± 14 (MSWD = 0.46) (**Fig. 7A**). In addition, SHRIMP analyses on zircon cores yield ^{207}Pb/^{206}Pb ages of 2695–2582 Ma with an upper intercept age of 2692 ± 33 Ma, consistent with the weighted mean age (2675 ± 7 Ma; MSWD = 1.9) (**Fig. 7B**). Thus, sample 21BS10-1 is interpreted to have crystallized at 2692 ± 33 Ma. Moreover, analyses from zircon rims yield ^{207}Pb/^{206}Pb ages of 2558–2415 Ma. Among these, the SHRIMP analyses yield a weighted mean age of 2490 ± 30 Ma and an upper intercept age of 2493 ± 22 Ma (**Fig. 7B**), indicating that sample 21BS10-1 underwent metamorphism at *ca*. 2.5 Ga.

Zircons from mylonitic trondhjemite sample 23HX01-1 display distinct concentric oscillatory zones (**Fig. 7C**), which are characteristics of magmatic zircons. Twenty-one LA–ICP–MS analyses showed high Th/U ratios (0.31–1.15) and yielded ^{207}Pb/^{206}Pb ages between 2733 and 2610 Ma, with an upper intercept age of 2653 ± 20 Ma (**Fig. 7C**). Of these, 12 concordant analyses yielded a weighted mean age of 2681 ± 14 Ma (MSWD = 0.80) (**Fig. 7C**). This age is intercepted as the crystallization age of sample 23HX01-1.

Zircons from mylonitic trondhjemite sample 23HX05-1 exhibit core-rim structures (**Fig. 7D**). The cores of these zircons show distinct concentric oscillatory zones and have high Th/U ratios (0.16–0.50, with one exception at 0.05), both of which are indicative of a magmatic origin. Sixteen of these zircon cores were analyzed by LA–ICP–MS, yielding ^{207}Pb/^{206}Pb ages between 2784 and 2601 Ma, with an upper intercept age of 2648 ± 20 Ma (**Fig. 7D**). Of these, nine concordant analyses yield a weighted mean age of 2675 ± 15 Ma (MSWD = 0.82), which is interpreted as the crystallization age of sample 23HX05-1. Additionally, three analyses conducted on the zircon rims yield ^{207}Pb/^{206}Pb ages of 2498–2480 Ma (**Fig. 7D**), indicating that sample 23HX05-1 underwent metamorphism around 2.5 Ga, which is consistent with the late Neoarchean regional metamorphism in the Longgang Block (Ge et al., 2003).

Zircon grains from mylonitic granodiorite sample 22BS13-1 show distinct core-rim structures. The cores exhibit concentric oscillatory zones, while the rims show blurred zones (**Fig. 7E, F**). Combined with the high Th/U ratios (0.25–1.14), these zircon cores have a magmatic origin. Fifteen analyses performed on the zircon cores yield concentrated ^{207}Pb/^{206}Pb ages of 2703–2662 Ma by SHRIMP, with an upper intercept age of 2682 ± 12 Ma and a weighted mean age of 2698 ± 4 Ma (MSWD = 1.4; **Fig. 7E**). Four analyses conducted on the rims using SHRIMP yield ^{207}Pb/^{206}Pb ages of 2503–2486 Ma, with a weighted mean age of 2495 ± 17 Ma (MSWD = 0.23; **Fig. 7E**). Additionally, twenty-four analyses conducted using LA–ICP–MS yield ^{207}Pb/^{206}Pb ages ranging from 2729 to 2490 Ma. These ages can be subdivided into two groups. Group 1, derived from zircon cores, yields ^{207}Pb/^{206}Pb ages of 2729–2687 Ma with an upper intercept age of 2701 ± 15 Ma (**Fig. 7F**). Of these, four concordant analyses yield a weighted mean age of 2717 ± 32 Ma (MSWD = 0.31; **Fig. 7F**), which is intercepted as the crystallization age. Group 2 consists of analyses conducted on the zircon rims, yielding ^{207}Pb/^{206}Pb ages of 2573–2490 Ma with an upper intercept age of 2525 ± 29 Ma (**Fig. 7F**), which representing the age of metamorphism. Other ages ranging from 2658 to 2585 Ma are absent in SHRIMP dating. They might represent mixing ages due to deficiency (larger erosion depth) of LA–ICP–MS dating and thus have little geological significance. Therefore, both SHRIMP and LA–ICP–MS analyses suggest that sample 22BS13-1 crystallized at *ca.* 2.7 Ga and underwent metamorphism at *ca.* 2.5 Ga.

Zircon from mylonitic granodiorite sample 22BS14-1 were analyzed using LA–ICP–MS. These grains display clear core-rim structures (**Fig. 7G**). The zircon cores exhibit distinct concentric oscillatory zones and high Th/U ratios (0.20–1.06), suggesting a magmatic origin. Fourteen analyses performed on the zircon cores yield ^{207}Pb/^{206}Pb ages of 2683–2565 Ma with an upper intercept age of 2674 ± 64 Ma (**Fig. 7G**). This age is intercepted as the crystallization age of sample 22BS14-1. One zircon has a ^{207}Pb/^{206}Pb age of 2790 Ma, suggesting that it could be either captured or inherited. Fifteen analyses conducted on the zircon rims or re-crystallization zones yield ^{207}Pb/^{206}Pb ages of 2549–2457 Ma with an upper intercept age of 2498 ± 24 Ma and a weighted mean age of 2495 ± 15 Ma (MSWD = 0.79; **Fig. 7G**). Therefore, sample 22BS14-1 also appears to have undergone metamorphism around 2.5 Ga.

Zircon from granitic mylonite sample 23HX04-1 was analyzed by LA–ICP–MS. The zircons in sample 23HX04-1 display distinct concentric oscillatory zones (**Fig. 7H**). Some grains show bright rims that were too thin for analysis. Eighteen analyses performed on the zircon cores yield ^{207}Pb/^{206}Pb ages of 2702–2602 Ma with high Th/U ratios (0.34–0.57). These analyses have a weighted mean age of 2668 ± 11 Ma (MSWD = 1.4; **Fig. 7H**). This age represents the crystallization age of sample 23HX04-1.

To sum up, the mylonitic trondhjemites and granodiorites, as well as the granitic mylonites examined in this study have crystallization ages of *ca.* 2.7 Ga. They subsequently underwent extensive metamorphism at *ca.* 2.5 Ga, which is consistent with previously reported metamorphic ages from the southern Jilin terrane (Ge et al., 2003).

4.3. Zircon Lu–Hf–O isotopes

Sixty-eight Lu–Hf and thirty-one O isotopic analyses were analyzed for zircons from samples 21BS10-1, 22BS13-1, and 22BS14-1. The zircon O and Lu–Hf isotopic data are listed in Supplemental **Table S4** and **Table S5**, respectively.

For sample 21BS10-1, twenty-seven Hf and twenty-one O isotopic analyses were conducted at the same locations as the LA–ICP–MS and SHRIMP dating. All analyses show a restricted range in ^{176}Hf /^{177}Hf ratios (0.281142–0.281219), positive $\varepsilon_{Hf(t)}$ values ranging from +0.7 to +3.7, and T_{DM}^2 ages between 3218 and 2983 Ma (**Fig. 8A**). The O isotopic analyses indicate that both zircon cores and rims exhibit low δ^{18}O values, varying from 3.03 to 5.42‰ (**Fig. 8B**). Of these, the δ^{18}O values of the *ca.* 2.7 Ga zircons range between 4.19‰ and 5.15‰ (**Fig. 8B**), which are within or slightly lower than the value of zircon with a mantle origin (Valley et al., 2005).

A total of twenty-four Hf and ten O isotopic analyses were conducted on the zircons of Sample 22BS13-1. These *ca.* 2.7 Ga zircons exhibit concentrated ^{176}Hf /^{177}Hf ratios of 0.281164–0.281246, with positive $\varepsilon_{Hf(t)}$ values of +1.6 to +4.1 (**Fig. 8A**). Their T_{DM}^2 ages range between 3148 and 2955 Ma, similar to those of Sample 21BS10-1. The *ca.* 2.7 Ga zircons of Sample 22BS13-1 possess low δ^{18}O values (4.26–5.39 ‰), similar to those of Sample 21BS10-1. Compared to Samples 21BS10-1 and 22BS13-1, Sample 22BS14-1 exhibits slightly higher radiogenic Hf compositions. Seventeen Hf isotopic analyses indicate that the *ca.* 2.7 Ga zircons of Sample 22BS14-1 have ^{176}Hf /^{177}Hf ratios of 0.281123–0.281306, positive $\varepsilon_{Hf(t)}$ values of +3.6 to +6.5, and T_{DM}^2 ages of 2982–2758 Ma (**Fig. 8A**).

To sum up, all zircons from the *ca.* 2.7 Ga granitoid samples display characteristics of depleted Hf isotopes (i.e. high ^{176}Hf /^{177}Hf ratios and positive $\varepsilon_{Hf(t)}$ values) and low δ^{18}O values.

4.4. Whole-rock Sm–Nd isotopes

Two mylonitic trondhjemites (21BS10-3 and 21BS11-1) and three mylonitic granodiorites (22BS13-2, 22BS13-3, and 22BS14-2) samples were used for Sm–Nd isotopic analyses, as shown in Supplemental **Table S6**. All samples exhibit a small range in Sm–Nd isotopic values, with initial $^{143}Nd/^{144}Nd$ ratios of 0.509239–0.509302 and $^{147}Sm/^{144}Nd$ ratios of 0.08769–0.09885. These samples have positive $\varepsilon_{Nd(t)}$ values ranging from +2.0 to +2.6 (**Fig. 8C**), with T_{DM}^{1} ages of 2829–2775 Ma and T_{DM}^{2} ages of 2870–2800 Ma.

5. DISCUSSION

5.1. Early Neoarchean granitoids in the NCC

The western and eastern Shandong areas in the Eastern Block are two terranes where early Neoarchean magmatism has been extensively documented (**Fig. 1**). Previous studies have revealed that the western Shandong terrane underwent a period of prolonged felsic magmatism from 2.74 to 2.61 Ga (Hu et al., 2019; Jiang et al., 2010; Ren et al., 2016; Wang et al., 2016d). Tonalite and trondhjemite are the primary lithologies, with the former having a slightly older formation age (**Fig. 9A**). A few diorites and granodiorites have also been reported in this region. Furthermore, western Shandong is the only area within the NCC where *ca.* 2.7 Ga basaltic to komatiitic rocks are widely distributed (Dong et al., 2021; Polat et al., 2006; Wang et al., 2013). Unlike western Shandong, eastern Shandong experienced a relatively shorter period of early Neoarchean felsic magmatism during 2.75–2.70 Ga (**Fig. 9B** and

Supplemental Table S1). The *ca.* 2.7 Ga granitoids in the eastern Shandong region primarily consist of tonalite, with minor granodiorite and trondhjemite (Jahn et al., 2008; Jiang et al., 2016; Wu et al., 2014). Meanwhile, a series of K-rich granitoids, including quartz monzodiorite, granodiorite, and monzogranite, were identified in the southeastern Qixia area (Yao et al., 2020). Recently, several early Neoarchean TTG gneisses and potassic granitic gneisses have been recognized in the Bengbu and Huoqiu areas (Liu et al., 2019; Liu et al., 2015; Wan et al., 2010; Wang et al., 2014a), located on the southeastern margin of the NCC. Their formation ages range from 2765 to 2708 Ma (**Fig. 9C**), similar to the ages of early Neoarchean granitoids in eastern Shandong.

Previous geochronological studies have identified substantial early Neoarchean granitoids along the N-S trending Trans-North China Orogen (TNCO) in the central NCC (**Fig. 1** and **Supplemental Table S1**). The early Neoarchean granitoids found within the southern segment of the TNCO (i.e. the Xiaoqingling and Lushan areas) are slightly older than other early Neoarchean granitoids within the NCC (**Supplemental Table S1**). The dominant lithologies are TTG gneisses, which formed at *ca*. 2.80–2.72 Ga (Diwu et al., 2010; Huang et al., 2010; Jia, 2016; Zhou et al., 2014). The other early Neoarchean granitoids within the TNCO are distributed across eight terranes, from north to south, including Miyun (Shi and Zhao, 2017), Hengshan (Kröner et al., 2005), Fuping (Han et al., 2012; Lu et al., 2014), Zanhuang (Song et al., 2018; Yang et al., 2013), Huixian (Diwu et al., 2020), Yunmengshan (Zhou et al., 2021), Zhongtiao (Zhang et al., 2023; Zhu et al., 2013) (**Supplemental**

Table S1). All of these terranes are predominantly composed of TTG. Minor monzogranite, syenogranite, as well as diorite were also identified within the Yunmengshan and Zhongtiao terranes (**Fig. 9D**). Their formation ages range from 2.75 to 2.65 Ga, which are slightly younger than the ages of the early Neoarchean granitoids found in the Lushan and Xiaoqingling areas (**Supplemental Table S1**).

Recently, a series of 2.72–2.60 Ga TTG gneisses have been identified within the north Liaoning to south Jilin regions (**Figs. 2A and 9E**). These *ca.* 2.7 Ga TTG gneisses are primarily found in the Waitoushan (Bao et al., 2022; He et al., 2024), Xinbin (He et al., 2024; Wang et al., 2016b), northern Qingyuan (Cheng et al., 2022), Liuhe (Wu et al., 2021), Baishan (Bao et al., 2022; Li, 2019). In addition, Wu et al. (2021) reported the presence of a *ca.* 2.78 Ga trondhjemitic gneiss in the Jiapigou area, representing the oldest Neoarchean igneous rock of this region. Guo et al. (2016) identified a series of 2.68–2.65 Ga mafic metavolcanic sequences in the Helong area. This study newly recognized a series of *ca.* 2.7 Ga mylonitic granitoids from the east Baishan area. These findings provide further support for the existance of an E-W trending *ca.* 2.7 Ga magmatic belt extending from north Liaoning to south Jilin (Bao et al., 2022; He et al., 2024). From a geochronological perspective, the north Liaoning to south Jilin area exhibits similarity to the western Shandong, in that both regions experienced prolonged crustal melting during 2.7–2.6 Ga (**Fig. 9**).

In summary, the distribution of early Neoarchean granitoids within the NCC is more extensive than previously thought. Most magmatism occurred during 2.8–2.6 Ga, with an age peak at *ca.* 2.7 Ga (**Fig. 9**). These early Neoarchean granitoids exhibit a diversity of lithologies, including tonalite, trondhjemite, granodiorite, diorite, and potassic granite, with tonalite and trondhjemite being the dominant rock types. Thus, the NCC was involved in the *ca.* 2.7 Ga global magmatic event, which is widely preserved in most cratons (Condie et al., 2009).

5.2. Early Neoarchean crust growth event in the NCC

The basement of the NCC primarily comprises late Neoarchean (2.55–2.50 Ga) TTG and basaltic meta-volcanic rocks. These rocks display positive $\varepsilon_{\mathrm{Hf}(t)}$ and $\varepsilon_{\mathrm{Nd}(t)}$ values that lie close to the depleted mantle evolutionary line. Thus, previous studies suggested that the NCC underwent significant crustal growth at the end of the Neoarchean (Diwu et al., 2011; Mao et al., 2024). In contrast, early Neoarchean rocks were once thought to be sporadically distributed within the NCC (Wan et al., 2014), leading to the perception that early Neoarchean crustal growth was relatively subdued compared to the period of growth documented at *ca.* 2.5 Ga. However, several studies of zircon Hf isotopes have indicated that considerable volumes of *ca.* 2.5 Ga granites within the NCC originated from the recycling of *ca.* 2.7 Ga crustal rocks (Geng et al., 2012; Wan et al., 2011a). As mentioned previously, abundant *ca.* 2.7 Ga TTG have been recently identified across nearly all terranes of the NCC. The majority of these lithologies display high $\varepsilon_{\mathrm{Hf}(t)}$ and $\varepsilon_{\mathrm{Nd}(t)}$ values, with two-stage model ages close to their formation ages (**Fig. 8A, C**). This suggests that their mafic precursors were extracted from the mantle during the early Neoarchean. Moreover, the *ca.* 2.7 Ga basaltic and komatiitic volcanic rocks provide direct evidence for early Neoarchean crustal growth event (Dong et al., 2021; Polat et al., 2006; Wan et al., 2011b; Wang et al., 2013). Therefore, similar to the global crustal growth event at *ca.* 2.7 Ga recorded in other cratons, the NCC also experienced intensive, craton-scale crustal growth in the early Neoarchean.

5.3. Petrogenesis of the *ca.* 2.7 Ga granitoids

5.3.1. Assessment of elemental mobility and crustal contamination

Previous studies have revealed that high-grade metamorphism or ductile deformation can significantly alter the concentrations of certain elements in rock (Ague, 2017; Dipple et al., 1990). As the *ca.* 2.7 Ga granitoids documented here underwent regional metamorphism at *ca.* 2.5 Ga and mylonitization during Mesozoic, it is necessary to evaluate elemental mobility before employing geochemical analysis to decipher their petrogenesis. Zirconium (Zr), which is considered highly immobile during metamorphism or metasomatism, can be utilized to assess the mobility of other major and trace elements. The major components (e.g. TiO_2, Na_2O, and K_2O) and trace elements (e.g., La, Ce, Sm, Eu, Yb, Lu, Y, Sr, Th, Ba, Ta, Nb) in the *ca.* 2.7 Ga mylonitic trondhjemites display strong linear correlations with Zr (**Fig. S1**). The *ca.* 2.7 Ga mylonitic granodiorite samples exhibit similar linear correlations in all of these elements, except for Th and Ba (**Fig. S1**). This suggest that the concentrations of these elements were not significantly influenced by later metamorphism or ductile deformation. Consequently, the geochemical data of mylonitic trondhjemite and granodiorite from this study can be utilized for petrogenetic interpretation.

Nonetheless, as the granitic mylonite samples 23HX04-2 and 23HX04-3 experienced severe mylonitization and muscovitization, they were precluded in the following petrogenesis discussion. In addition, the *ca.* 2.7 Ga granitoid samples of this study exhibit concentrated and homogeneous Hf and Nd isotopes (**Fig. 8A, C**), which precludes significant crustal contamination or assimilation during magma ascent that would otherwise induce heterogeneity in Hf and Nd isotopic compositions.

5.3.2. Eliminating the possibility of plagioclase- and amphibole-dominated fractionation

It is well understood that TTG-like magmas are derived from partial melting of hydrated mafic rocks (Moyen, 2011; Moyen and Stevens, 2006; Palin et al., 2016; Rapp and Watson, 1995); however, recent studies have highlighted the important role of amphibole fractionation in dioritic magma (Liou and Guo, 2019) and plagioclase-amphibole fractionation in tonalitic magma (Laurent et al., 2020) for generating compositional diversity within Archean TTG magmas. The *ca.* 2.7 Ga TTG samples from the northern Liaoning to southern Jilin regions, including the samples in this study, display linear relationships between (Ce/Zr) *vs.* Ce and (La/Hf) *vs.* La (**Fig. 10**). This suggests that the parental magmas were generated by partial melting and were not affected by fractional crystallization (Schiano et al., 2009). Furthermore, as no associated *ca.* 2.7 Ga diorites or coeval hornblendites have been recognized in the northern Liaoning to southern Jilin region, we eliminate the possibility that the *ca.* 2.7 Ga mylonitic trondhjemites and granodiorites of this study were derived from amphibole-dominated fractionation of dioritic magma.

Laurent et al. (2020) suggested that the Paleoarchean TTGs from South Africa are the crystal-rich residues of primary tonalitic magmas, which experienced fractionation of plagioclase and amphibole. Is it possible that the *ca.* 2.7 Ga trondhjemites and granodiorites of this study were produced by the fractionation of plagioclase and amphibole from the coeval tonalites in the Baishan area? The *ca.* 2.7 Ga mylonitic trondhjemites and granodiorites of this study exhibit positive Eu anomalies and high Sr contents (**Fig. 6A, B**), potentially indicative of plagioclase fractionation or partial melting of a hydrated metabasaltic source leaving behind a residue with minor or none plagioclase. Commonly, magmas that have undergone significant plagioclase fractionation would show strong linear trends between Al_2O_3, Na_2O, Sr, Eu anomaly, and SiO_2 content. Nevertheless, such linear trends are not observed between the *ca.* 2.7 Ga mylonitic trondhjemites and granodiorites of this study, nor the 2.7–2.62 Ga tonalites in the Baishan area reported by Li (2019) (**Fig. 11A–E**). In addition, the 2.7 Ga trondhjemites and granodiorites do not align with the fractional modelling results when the average composition of the *ca.* 2.7 Ga tonalites is taken as the starting material for modelling (**Fig. 11A–E**). Consequently, the positive Eu anomalies and high Sr contents of the samples may be attributed to their melting processes, rather than plagioclase fractionation. The *ca.* 2.7 Ga TTG samples from the Baishan area, including the samples of this study, display pronounced linear trends between CaO, MgO, $Fe_2O_3^T$, TiO_2 and SiO_2 contents (**Fig. 11F–I**). Despite 10–20% fractionation of 70–90% amphibole and 10–30% plagioclase in tonalitic magma being able to generate such trends, our modelling results contradict this interpretation due to inconsistencies with the Al_2O_3, Na_2O, and Sr contents, as well as the Sr/Y ratios and Eu anomalies of the samples (**Fig. 11A–E**). Alternatively, these linear trends might indicate that amphiboles and Ti-bearing minerals are the primary residues during partial melting. Thus, we conclude the *ca.* 2.7 Ga trondhjemites and granodiorites of this study were not derived from the fractionation of plagioclase or amphibole from the contemporaneous tonalites.

5.3.3. Magma sources and melting conditions

The *ca.* 2.7 Ga mylonitic trondhjemites of this study exhibit high SiO_2 (68.0–72.0 wt. %) and low MgO (0.62–1.59 wt. %), $Fe_2O_3^T$ (1.68–3.49 wt. %), and CaO (1.52–3.35 wt. %) contents (**Supplemental Table S2**), suggesting a crustal origin. In comparison, the *ca.* 2.7 Ga mylonitic granodiorites show similar SiO_2 (64.3–70.2 wt. %) but higher MgO (1.02–2.43 wt. %) and $Fe_2O_3^T$ (3.06–4.75 wt. %) contents (Supplemental **Table S2**), indicating that they are crustally derived but include a slight contribution of mantle materials. The *ca.* 2.7 Ga mylonitic trondhjemites and granodiorites display depleted zircon Hf isotopes and whole-rock Nd isotopes (**Fig. 8A, C**), with positive $\varepsilon_{Hf(t)}$ (0.67–6.45) and $\varepsilon_{Nd(t)}$ (2.01–2.64) values. Their crystallization ages are close to their Hf and Nd T_{DM}^2 ages, suggesting short crustal residence times for their mafic precursors. The early Neoarchean TTG rocks from other terranes of the NCC exhibit similar depleted Hf and Nd isotopes (**Fig. 8A, C**), indicating that the early Neoarchean granitoids in the NCC were mainly generated by partial melting of juvenile crust, and recycling of ancient crust materials are limited. The *ca.* 2.7 Ga TTG of this study and majority of other early Neoarchean granitoids mainly plot within the field of melts derived from low-K or high-K mafic rocks in an $Al_2O_3/(FeO^T+MgO)–(3CaO)–(5K_2O/Na_2O)$ ternary diagram (**Fig. 12A**). Thus, the protoliths for parental magmas of the early Neoarchean TTG could be juvenile mafic crusts.

The early Neoarchean TTG rocks in the NCC, inclusive of the *ca.* 2.7 Ga TTG samples from this study, display geochemical similarities with adakite (**Fig. 12B, C**), such as high Sr content, low Y and Yb contents, as well as high Sr/Y and $(La/Yb)_N$ ratios (Martin et al., 2005). The concentrations of heavy REE in melts during partial melting, such as Y and Yb, are predominantly controlled by garnet (Taylor et al., 2014). Consequently, the low Y and Yb contents, coupled with high LREE/HREE ratios of the early Neoarchean TTGs, suggest that a significant volume of garnet remained in the residue. In comparison to garnet, the medium REE, such as Gd and Dy, are more compatible in amphibole (Tiepolo et al., 2007). Thus, the low $(Gd/Yb)_N$ values and flat patterns between MREE and HREE in the majority of early Neoarchean granitoids suggest that amphibole was also a major residual mineral (**Fig. 6**). Sr and Eu are highly compatible in plagioclase (Bédard, 2006b); therefore, the positive Eu anomalies and high Sr concentrations in the early Neoarchean TTG samples suggest a plagioclase-free or -depleted residue. Given that early Neoarchean TTG rocks mainly display Ti, Nb, and Ta depletion, it is likely that some Ti-bearing minerals, such as ilmenite or rutile, might remain in the residue.

The breakdown of hydrous minerals (e.g. biotite and amphibole) in hydrated basaltic rocks via fluid-absent melting (i.e., dehydration melting; Moyen and Stevens, 2006; Rapp and Watson, 1995) or fluid-present melting (i.e., H_2O-fluxed melting; Ge et al., 2023; Huang et al., 2020; Pourteau et al., 2020; Yakymchuk et al., 2019) are considered as two primary mechanisms for generating TTG magma. To further constrain the P–T–H_2O conditions of the melting process, we conducted thermodynamic modelling. Ge et al. (2023) suggested that the sources of Archean granitoids with high H_2O/Ce ratios probably contain 1.5–2 or 3–4 wt. % H_2O, corresponding to H_2O contents in dehydration melting and H_2O-fluxed melting, respectively. Consequently, here we considered a range of H_2O contents (1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 wt. %) for the starting materials. Detailed descriptions of methods for phase-equilibrium and trace element modelling can be found in **Supplemental materials**.

Our results suggest an increase in melt content with rising temperature, varying from 10–55 wt. % within the temperature range 700–1000 ℃ (**Fig. 13A** and **Supplemental Table S9**). The stability of both garnet and plagioclase are primarily controlled by pressure (**Fig. 13A**). At pressures of 10–15 kbar, garnet constitutes a significant proportion of the residue (15–35 wt. %), while plagioclase makes up a smaller fraction (<10 wt. %). Conversely, the stability of amphibole is controlled by both temperature and pressure, with approximately 10–30 wt. % amphibole present at 10–15 kbar (**Fig. 13A** and Supplemental **Table S10**). Additionally, rutile is present when the pressure exceeds 10 kbar. Our modeling suggests that the median values of the *ca.* 2.7 Ga trondhjemites and granodiorites studied here are best matched by melt fractions of 20–25% generated at *P–T* conditions of 10–15 kbar and 800–900 ℃ with 2.0 wt. % H_2O within the starting material (**Fig. 14**). Although melts generated at higher pressures (>15 kbar) exhibit a similar HREE depletion to the 2.7 Ga TTGs, they are distinguished by noticeably higher LREE contents, Sr/Y and La_N/Yb_N ratios, as well as lower SiO_2, Nb, and Ta contents (**Fig. 14** and **Supplemental Table S9 and Table S11**). Moreover, melts generated at higher temperatures would display higher ($MgO+FeO^T$) contents, but lower SiO_2 contents (**Tables S9 and S11**). The residual mineralogy correlating with these best-matched melts is dominated by garnet (15–35 wt. %), amphibole (5–25 wt. %), and clinopyroxene (20–30 wt. %), with minor rutile and plagioclase (**Fig. 13A**). **Figure 13B** illustrates how phase abundances at 12 kbar vary according to temperature, indicating that increased melt production correlates with a reduction in the stability of amphibole, further suggesting that amphibole breakdown played a key role during partial melting.

To sum up, the modelling implies that the *ca.* 2.7 Ga TTG rocks of this study likely originated from amphibole-breakdown partial melting of late Mesoarchean to early Neoarchean mafic rocks under *P–T* conditions of 10–15 kbar and 800–900 ℃. The residual mineral assemblages were primarily garnet, amphibole, and clinopyroxene. Our phase equilibrium modelling results align with previous studies, suggesting that most TTG magmas primarily formed under granulite-facies *P–T* conditions (800–950 ℃ and 10–18 kbar), associated with the breakdown of amphibole (Palin et al., 2016).

5.3.4. Origin of low δ^{18}O zircons

It is noteworthy that over half of the zircons analyzed in this study display δ^{18}O values lower than the value of mantle-derived zircon (<5.3 ± 0.6 ‰; Valley et al., 2005; **Fig. 8B**). Previous studies have revealed that the geochemistry and O isotopes of radiation-damaged zircons may be variably altered (Mixon et al., 2023; Valley et al., 2015). Generally, radiation-damaged zircons yield discordant U–Pb ages and elevated U and Th contents (Wang et al., 2014b). Zircons used for O isotopic analysis of this study plot along or close to the concordant lines (**Fig. 7B, E**), indicating that they did not undergo significant radiation damage. Furthermore, CL images displaying rhythmic zonation patterns in these analyzed zircons show no evidence of later alteration. Additionally, the δ^{18}O values of the *ca.* 2.7 Ga zircons exhibit no linear relationships with U contents and Th/U ratios (**Fig. S2**), further supporting the conclusion that these zircons did not experience significant radiation damage. Therefore, the analyzed δ^{18}O values in this study represent the primary characteristics of the *ca.* 2.7 Ga zircons.

Generally, low-δ^{18}O values of granitoids zircons could be inherited from low-δ^{18}O mafic precursors (e.g., lower oceanic crust formed in mid-oceanic ranges), contaminated/assimilated low-δ^{18}O materials during magma ascent, or induced by either synchronous high-temperature water-rock interaction or subsequent high-temperature hydrothermal alteration (Lei et al., 2023; Moreira et al., 2020; Zhang and Zheng, 2011). If the low-δ^{18}O characteristics of TTG were inherited from a low-δ^{18}O mafic precursor, then the O isotopes should be uniformly and systematically low. However, most zircon cores display mantle-like δ^{18}O values, which argues against the inheritance origin for these low-δ^{18}O zircons. The concentrated Hf and Nd isotopes displayed by all the samples (**Fig. 8A, C**) further preclude the possibility that these low-δ^{18}O features were caused by crustal assimilation or contamination. In addition, the zircon cores with low δ^{18}O values in this study exhibit clear concentric oscillatory zones, providing no evidence for obvious high-temperature/near-surface hydrothermal alteration. Thus, the most plausible scenario for these early Neoarchean low-δ^{18}O zircons is that they were generated by high-temperature water-rock interaction synchronous with the magmatism. This mechanism requires the involvement of meteoric waters at shallow crustal levels that have high heat flows. Lithospheric extension or rifting induced by mantle plume activity is the most plausible environment that can contribute to the formation of the low-δ^{18}O magma (Troch et al., 2020; Zheng et al., 2007).

5.4. Coexistence of mantle plume and subduction during the early Neoarchean

Archean TTG magmas that retain geochemical signatures indicating formation from a garnet-rich source have been proposed as analogues of Cenozoic adakite, and thus suggested to have formed during partial melting of subducted oceanic crust (Drummond and Defant, 1990; Hastie et al., 2016), melting of subducted oceanic plateaus (Martin et al., 2014), melting of delamination-related lower crust (Zegers and van Keken, 2003), melting of thickened lower crust in an arc-like setting (Nagel et al.,

2012) or at the base of oceanic plateau (Bédard, 2006a). Correspondingly, both subduction-related and mantle plume-related tectonic regimes have been proposed for the crustal evolution of the NCC during the early Neoarchean.

Based on Phanerozoic arc-like geochemical characteristics, such as depletion of HFSE (e.g., Nb, Ta, Ti), enrichment of LREE (e.g. Rb, Sr, Ba), and high Sr/Y and $(La/Yb)_N$ ratios, some studies have proposed that early Neoarchean TTG rocks in the NCC were generated from partial melting of subducted oceanic crust in an arc setting (Huang et al., 2010; Yang et al., 2013; Zhou et al., 2014; Zhu et al., 2013). Nonetheless, several lines of evidence are inconsistent with the subduction-related regime: (1) generally, due to interaction with the mantle during magma ascent, subduction-related adakite/TTG would exhibit relatively high MgO, Cr, Ni, and low SiO_2 contents (Castillo, 2012). However, the early Neoarchean TTG rocks in the NCC primarily exhibit lower MgO, Cr, Ni contents, and Mg# ($MgO/(MgO + FeO^t)$) values than those of subduction-related adakite/TTG, and they mainly plot within the field of partial melting of thickened lower crust (**Fig. 12D–F**). Although a limited number of early Neoarchean TTG rocks exhibited relatively higher MgO, Cr, and Ni contents, this could be induced by mixing with mantle-derived magmas or fractional crystallization (Li et al., 2021). (2) The majority of these early Neoarchean TTG rocks are classified as medium- and low-pressure type TTG (**Fig. 12G, H**), rather than the high-pressure type, which is commonly the product of partial melting of subducted oceanic crust (cf. Moyen (2011)). Although a minor portion of early Neoarchean TTG samples (primarily trondhjemites) from the southern margin of the TNCO display higher Sr/Y ratios (>200), they can be categorized as high-pressure type TTG (Huang et al., 2010; Jia, 2016). However, the extremely low MgO contents (0.07–1.25 wt. %) preclude the possibility that they were derived from subducted oceanic crust. (3) Widespread early Neoarchean rocks without a systematic age progression across the NCC (**Fig. 1**) is inconsistent with modern-day features of arc magmatism, which is generally limited within a narrow and linear/arcuate zone parallel to the trench; (4) The 2.8–2.7 Ga komatiite-tholeiite metavolcanic rocks in the western Shandong terrane provide strong evidence for mantle plume activity in the NCC during the early Neoarchean (Dong et al., 2021; Polat et al., 2006; Wang et al., 2013). (5) Including zircon O isotopes of this study, voluminous early Neoarchean zircons (78% of our compilation) from the NCC display $\delta^{18}O$ values within or lower than the value of mantle-derived zircon (5.3 ± 0.6 ‰; Valley et al., 2005; **Fig. 8B**), indicative of a mantle plume regime.

Although mantle plume activity was common during the early Neoarchean, other lines of evidence for subduction operating at that time cannot be disregarded. Sun et al. (2021) proposed that the thermal state of early Archean continental crust in the northern Liaoning to southern Jilin region reflected a transition from mantle plume activity to hot subduction during late Mesoarchean to early Neoarchean. The *ca.* 2.7 Ga calc-alkaline greenstone sequences from the Helong granite-greenstone belt in the southern Jilin terrane are suggested to originate from a slab-derived fluid-metasomatized mantle (Guo et al., 2015). Additionally, komatiitic and tholeiitic to calc-alkaline volcanic sequences from the western Shandong terrane suggested a transition from mantle plume to plume-induced subduction during the Mesoarchean to early Neoarchean (Gao et al., 2019). Considering these pieces of evidence, Wang et al. (2024) advocated an early Neoarchean geodynamic transition from vertical mantle plume-dominated geodynamics to a subsequent regime dominated by horizontal motion associated with plate tectonics within the North China Craton. This interpretation aligns with a global perspective that the global onset of plate tectonics occurred during the late Mesoarchean/early Neoarchean based on the progressive establishment of a worldwide network of subduction zones at that time (Dhuime et al., 2012; Palin and Santosh, 2021; Palin et al., 2020; Tang et al., 2016). Subsequently, the coexistence of the early Neoarchean plume-related tholeiitic–komatiitic rocks and subduction-related calc-alkaline rocks have been widely identified in many terranes, such as Abitibi–Wawa (Canada) (Polat, 2009; Wyman et al., 2002), Veligallu (India) (Dey et al., 2018), Youanmi (Western Australia) (Wyman and Kerrich, 2012). Therefore, the early Neoarchean is deemed as a critical period during which geodynamic regimes were undergoing periods of transition (Kerrich et al., 1998; Wang et al., 2024).

Zircon O isotopes have been established as an effective tool for determining tectonic environments of formation of magmatic rocks. This study compiled a global dataset of O isotopes for the early Neoarchean igneous zircons (**Fig. 8B**). The new compilation reveals that these zircons exhibit both high (> 5.9 ‰) and low (≤ 5.3 ± 0.6 ‰) $\delta^{18}O$ values (**Fig. 8B**). Specifically, magmas with zircon $\delta^{18}O$ values that are within or lower than the recommended values of mantle-derived zircon (5.3 ± 0.6 ‰)

primarily reflect plume or plume-related (e.g. rifting zone) tectonic settings (Troch et al., 2020). Whereas magmas with elevated zircon $\delta^{18}O$ values (>5.9 ‰) suggest the involvement of subaerial materials that have experienced low-temperature water-rock interaction (Spencer et al., 2019), thus more likely having formed in a subduction zone setting (Moreira et al., 2020; Spencer et al., 2014). Therefore, the coexistence of zircons with high (> 5.9 ‰) and low (≤ 5.3 ± 0.6 ‰) $\delta^{18}O$ values supports the hypothesis of concurrent subduction and mantle plume activities during this era.

In summary, based on compelling evidence for both subduction and mantle plume processes, this study favors the hypothesis that the crustal evolution of the NCC during the early Neoarchean likely be attributed to the synergistic effects of waning mantle plume activity and the coeval onset of plate tectonics.

6. CONCLUSIONS

Combining previously identified early Neoarchean TTG in the NCC with our new geochronological, geochemical, Hf–O–Nd isotopic data, we can draw three major conclusions: (1) we have newly identified abundant *ca.* 2.7 Ga TTG rocks in the Baishan area, northeastern segment of the NCC, with geochemical analysis and thermodynamic modelling suggesting that these rocks originated from the partial melting of juvenile mafic crust under granulite-facies *P*–*T* conditions; (2) analysis of Hf–O–Nd isotopes indicates that the NCC underwent significant crustal growth during the early Neoarchean; and (3) the early Neoarchean represents a critical period of geodynamic transition, with an enhanced rate of crustal growth worldwide during this period likely being related to the synergistic effects of mantle plume and the onset of plate tectonics.

Acknowledgement

We would like to express our appreciation to Dr. Chuanyan Dong and Dr. Peizhi Wang for their assistance during the SHRIMP U–Pb and O isotope dating. We thank Dr. Hongchao Yu for his help during the field investigation. This study is financially supported by the National Natural Science Foundation of China [Grant NO. 42025204, 42172212, U2244211, and 42272224].

References

Ague, J. J., 2017, Element mobility during regional metamorphism in crustal and subduction zone environments with a focus on the rare earth elements (REE): American Mineralogist, v. 102, no. 9, p. 1796-1821, https://doi.org/:10.2138/am-2017-6130.

Arndt, N., and Davaille, A., 2013, Episodic Earth evolution: Tectonophysics, v. 609, p. 661-674, https://doi.org/:10.1016/j.tecto.2013.07.002.

Bao, H., Liu, S., Wan, Y., Wang, M., Sun, G., Gao, L., Wang, W., Guo, R., and Fu, J., 2022, Neoarchean granitoids and tectonic regime of lateral growth in northeastern North China Craton: Gondwana Research, v. 107, p. 176-200, https://doi.org/:10.1016/j.gr.2022.02.015.

Bao, H., Liu, S., Wang, M., Teng, G., and Sun, G., 2020, Mesoarchean geodynamic regime evidenced from diverse granitoid rocks in the Anshan-Benxi area of the North China Craton: Lithos, v. 366-367, https://doi.org/:10.1016/j.lithos.2020.105574.

Barker, F., 1979, Trondhjemite: definition, environment and hypotheses of origin: Developments in Petrology, v. 6, p. 1-12, https://doi.org/:10.1016/B978-0-444-41765-7.50006-X.

Bédard, J. H., 2006a, A catalytic delamination-driven model for coupled genesis of Archaean crust and sub-continental lithospheric mantle: Geochimica et Cosmochimica Acta, v. 70, no. 5, p. 1188-1214, https://doi.org/:10.1016/j.gca.2005.11.008.

Bédard, J. H., 2006b, Trace element partitioning in plagioclase feldspar: Geochimica et Cosmochimica Acta, v. 70, no. 14, p. 3717-3742, https://doi.org/:10.1016/j.gca.2006.05.003.

Bleeker, W., 2003, The late Archean record: a puzzle in ca. 35 pieces: Lithos, v. 71, no. 2-4, p. 99-134, https://doi.org/:10.1016/j.lithos.2003.07.003.

Castillo, P. R., 2012, Adakite petrogenesis: Lithos, v. 134-135, p. 304-316, https://doi.org/:10.1016/j.lithos.2011.09.013.

Cawood, P. A., Hawkesworth, C. J., and Dhuime, B., 2013, The continental record and the generation of continental crust: Geological Society of America Bulletin, v. 125, no. 1-2, p. 14-32, https://doi.org/:10.1130/b30722.1.

Cheng, C., Liu, J., Zhang, J., Chen, Y., Yin, C., Liu, X., Qian, J., Gao, P., and Wang, X., 2022, Petrogenesis of newly identified Neoarchean granitoids in the Qingyuan of NE China: Implications on crustal growth and reworking of the North China Craton: Journal of Asian Earth Sciences, v. 236, https://doi.org/:10.1016/j.jseaes.2022.105333.

Cheng, C., Zhang, J., Liu, J., Liu, Z., Li, Z., Yu, H., Zhao, C., Zhang, H., and Dong, Y., 2024, Distinct mafic magmatism of the northeastern Longgang Block: Evidence for coexisting mantle plume and subduction during the Neoarchean North China Craton: Geosystems and Geoenvironment, v. 3, no. 3, https://doi.org/:10.1016/j.geogeo.2024.100286.

Condie, K. C., 1998, Episodic continental growth and supercontinents: a mantle avalanche connection?: Earth and Planetary Science Letters, v. 163, p. 97-108.

Condie, K. C., Belousova, E., Griffin, W. L., and Sircombe, K. N., 2009, Granitoid events in space and time: Constraints from igneous and detrital zircon age spectra: Gondwana Research, v. 15, no. 3-4, p. 228-242, https://doi.org/:10.1016/j.gr.2008.06.001.

Dey, S., Pal, S., Balakrishnan, S., Halla, J., Kurhila, M., and Heilimo, E., 2018, Both plume and arc: Origin of Neoarchaean crust as recorded in Veligallu greenstone belt, Dharwar craton, India: Precambrian Research, v. 314, p. 41-61, https://doi.org/:10.1016/j.precamres.2018.04.019.

Dhuime, B., Hawkesworth, C., Cawood, P. A., and Storey, C. D., 2012, A Change in the Geodynamics of Continental Growth 3 Billion Years Ago: Science, v. 335, p. 1334-1336, https://doi.org/:10.1126/science.12160.

Dipple, G. M., Wintsch, R. P., and Andrews, M. S., 1990, Identification of the scales of differential element mobility in a ductile fault zone: Journal of Metamorphic Geology, v. 8, no. 6, p. 645-661, https://doi.org/:10.1111/j.1525-1314.1990.tb00493.x.

Diwu, C., Sun, Y., Guo, A., Wang, H., and Liu, X., 2011, Crustal growth in the North China Craton at ~2.5Ga: Evidence from in situ zircon U–Pb ages, Hf isotopes and whole-rock geochemistry of the Dengfeng complex: Gondwana Research, v. 20, no. 1, p. 149-170, https://doi.org/:10.1016/j.gr.2011.01.011.

Diwu, C., Sun, Y., Lin, C., and Wang, H., 2010, LA-(MC)-ICPMS U-Pb zircon geochronology and Lu-Hf isotope compositions of the Taihua complex on the southern margin of the North China Craton: Chinese Science Bulletin, v. 55, no. 23, p. 2557-2571, https://doi.org/:10.1007/s11434-010-3273-6.

Diwu, C., Wang, T., and Yan, J., 2020, New evidence for Neoarchean (ca. 2.7 Ga) crustal growth in the North China Craton: Precambrian Research, v. 350, https://doi.org/:10.1016/j.precamres.2020.105921.

Dong, C., Bai, W., Xie, H., Wilde, S. A., Wang, Y., Wang, S., Liu, D., and Wan, Y., 2021, Early Neoarchean oceanic crust in the North China Craton: Evidence from geology, geochemistry and geochronology of greenstone belts in western Shandong: Lithos, v. 380-381, https://doi.org/:10.1016/j.lithos.2020.105888.

Dong, C., Liu, S., Nutman, A. P., Li, P., Xie, H., Li, Y., Liu, D., and Wan, Y., 2024, New discovery of 3.84−3.64 Ga diverse granitoids in eastern Hebei, North China Craton: Petrogenesis and significance: Geological Society of America Bulletin, https://doi.org/:10.1130/b37553.1.

Dong, C., Wan, Y., Xie, H., Nutman, A. P., Xie, S., Liu, S., Ma, M., and Liu, D., 2017, The Mesoarchean Tiejiashan-Gongchangling potassic granite in the Anshan-Benxi area, North China Craton: Origin by recycling of Paleo- to Eoarchean crust from U-Pb-Nd-Hf-O isotopic studies: Lithos, v. 290-291, p. 116-135, https://doi.org/:10.1016/j.lithos.2017.08.009.

Drummond, M. S., and Defant, M. J., 1990, A model for Trondhjemite-Tonalite-Dacite Genesis and crustal growth via slab melting: Archean to modern comparisons: Journal of Geophysical Research, v. 95, no. B13, https://doi.org/:10.1029/JB095iB13p21503.

Ersoy, E. Y., 2013, PETROMODELER (Petrological Modeler): a Microsoft® Excel© spreadsheet program for modelling melting, mixing, crystallization and assimilation processes in magmatic systems: Turkish Journal of Earth Sciences, v. 22, p. 115-125, https://doi.org/:10.3906/yer-1104-6.

Gao, L., Liu, S., Zhang, B., Sun, G., Hu, Y., and Guo, R., 2019, A Ca. 2.8-Ga Plume-Induced Intraoceanic Arc System in the Eastern North China Craton: Tectonics, v. 38, no. 5, p. 1694-1717, https://doi.org/:10.1029/2018tc005432.

Ge, R.-F., Wilde, S. A., Zhu, W.-B., and Wang, X.-L., 2023, Earth's early continental crust formed from wet and oxidizing arc magmas: Nature, v. 623, no. 7986, p. 334-339, https://doi.org/:10.1038/s41586-023-06552-0.

Ge, R., Zhu, W., Wilde, S. A., Wu, H., He, J., and Zheng, B., 2014, Archean magmatism and crustal evolution in the northern Tarim Craton: Insights from zircon U–Pb–Hf–O isotopes and geochemistry of ~2.7Ga orthogneiss and amphibolite in the Korla Complex: Precambrian Research, v. 252, p. 145-165, https://doi.org/:10.1016/j.precamres.2014.07.019.

Ge, W., Zhao, G., Sun, D., Wu, F., and Lin, Q., 2003, Metamorphic P-T Path of the Southern Jilin Complex: Implications for Tectonic Evolution of the Eastern Block of the North China Craton: International Geology Review, v. 45, no. 11, p. 1029-1043, https://doi.org/:10.2747/0020-6814.45.11.1029.

Geng, Y., Du, L., and Ren, L., 2012, Growth and reworking of the early Precambrian continental crust in the North China Craton: Constraints from zircon Hf isotopes: Gondwana Research, v. 21, no. 2-3, p. 517-529, https://doi.org/:10.1016/j.gr.2011.07.006.

Guo, B., Liu, S., Zhang, J., Wang, W., Fu, J., and Wang, M., 2016, Neoarchean Andean-type active continental margin in the northeastern North China Craton: Geochemical and geochronological evidence from metavolcanic rocks in the Jiapigou granite-greenstone belt, Southern Jilin Province: Precambrian Research, v. 285, p. 147-169, https://doi.org/:10.1016/j.precamres.2016.09.025.

Guo, B., Liu, S., Zhang, J., and Yan, M., 2015, Zircon U–Pb–Hf isotope systematics and geochemistry of Helong granite-greenstone belt in Southern Jilin Province, China: Implications for Neoarchean crustal evolution of the northeastern margin of North China Craton: Precambrian Research, v. 271, p. 254-277, https://doi.org/:10.1016/j.precamres.2015.10.009.

Han, B.-F., Xu, Z., Ren, R., Li, L.-L., Yang, J.-H., and Yang, Y.-H., 2012, Crustal growth and intracrustal recycling in the middle segment of the Trans-North China Orogen, North China Craton: a case study of the Fuping Complex: Geological Magazine, v. 149, no. 4, p. 729-742, https://doi.org/:10.1017/s0016756811001014.

Hastie, A. R., Fitton, J. G., Bromiley, G. D., Butler, I. B., and Odling, N. W. A., 2016, The origin of Earth's first continents and the onset of plate tectonics: Geology, v. 44, no. 10, p. 855-858, https://doi.org/:10.1130/g38226.1.

Hawkesworth, C., Cawood, P., and Dhuime, B., 2013, Continental growth and the crustal record: Tectonophysics, v. 609, p. 651-660, https://doi.org/:10.1016/j.tecto.2013.08.013.

Hawkesworth, C., Cawood, P. A., and Dhuime, B., 2019, Rates of generation and growth of the continental crust: Geoscience Frontiers, v. 10, no. 1, p. 165-173, https://doi.org/:10.1016/j.gsf.2018.02.004.

He, X., Gao, L., Wang, W., Yao, J., Yang, W., Sun, G., Guo, R., Zhou, X., Hu, J., and Liang, X., 2024, Early to middle Neoarchean tonalite-trondhjemite-granodiorite (TTG) formation and outward continental growth in the North China Craton: Precambrian Research, v. 405, p. 107378, https://doi.org/:10.1016/j.precamres.2024.107378.

Hu, Y., Liu, S., Gao, L., Sun, G., Guo, R., Fu, J., Wang, M., and Hu, F., 2019, Diverse middle Neoarchean granitoids and the delamination of thickened crust in the Western Shandong Terrane, North China Craton: Lithos, v. 348-349, p. 105178, https://doi.org/:10.1016/j.lithos.2019.105178.

Huang, X.-L., Niu, Y., Xu, Y.-G., Yang, Q.-J., and Zhong, J.-W., 2010, Geochemistry of TTG and TTG-like gneisses from Lushan-Taihua complex in the southern North China Craton: Implications for late Archean crustal accretion: Precambrian Research, v. 182, no. 1-2, p. 43-56, https://doi.org/:10.1016/j.precamres.2010.06.020.

Jahn, B. M., Auvray, B., Shen, Q. H., Liu, D. Y., Zhang, Z. Q., Dong, Y. J., Ye, X. J., Zhang, Q. Z., Cornichet, J., and Mace, J., 1988, Archean crustal evolution in China: the Taishan complex, and evidence for juvenile crustal addition from long-term depleted mantle: Precambrian Research, v. 38, p. 381-403, https://doi.org/:10.1016/0301-9268(88)90035-6.

Jahn, B. m., Liu, D., Wan, Y., Song, B., and Wu, J., 2008, Archean crustal evolution of the Jiaodong Peninsula, China, as revealed by zircon SHRIMP geochronology, elemental and Nd-isotope geochemistry: American Journal of Science, v. 308, no. 3, p. 232-269, https://doi.org/:10.2475/03.2008.03.

Jia, X., Zhu, X., Zhai, M., Zhao, Y., Zhang, H., Wu, J., and Liu, T., 2016, Late Mesoarchean crust growth event: evidence from the ca. 2.8 Ga granodioritic gneisses of the Xiaoqinling area, southern North China Craton: Science Bulletin, v. 61, no. 12, p. 974-990, https://doi.org/:10.1007/s11434-016-1094-y.

Jia, X. L., 2016, Research for Taihua complex in Xiaoqingling and Lushan areas: Implications for the evolution of the crystalline basement in southern North China Craton [Ph.D: Northwest University, 1-190 p.

Jiang, N., Guo, J., Fan, W., Hu, J., Zong, K., and Zhang, S., 2016, Archean TTGs and sanukitoids from the Jiaobei terrain, North China craton: Insights into crustal growth and mantle metasomatism: Precambrian Research, v. 281, p. 656-672, https://doi.org/:10.1016/j.precamres.2016.06.019.

Jiang, N., Guo, J., Zhai, M., and Zhang, S., 2010, ~2.7Ga crust growth in the North China craton: Precambrian Research, v. 179, no. 1-4, p. 37-49, https://doi.org/:10.1016/j.precamres.2010.02.010.

Kerrich, R., Wyman, D., Fan, J., and Bleeker, W., 1998, Boninite series: low Ti-tholeiite associations from the 2.7 Ga Abitibi greenstone belt: Earth and Planetary Science Letters, v. 164, p. 303-316, https://doi.org/:10.1016/S0012-821X(98)00223-4.

Kröner, A., Wilde, S. A., Li, J. H., and Wang, K. Y., 2005, Age and evolution of a late Archean to Paleoproterozoic upper to lower crustal section in the Wutaishan/Hengshan/Fuping terrain of northern China: Journal of Asian Earth Sciences, v. 24, no. 5, p. 577-595, https://doi.org/:10.1016/j.jseaes.2004.01.001.

Laurent, O., Björnsen, J., Wotzlaw, J.-F., Bretscher, S., Pimenta Silva, M., Moyen, J.-F., Ulmer, P., and Bachmann, O., 2020, Earth's earliest granitoids are crystal-rich magma reservoirs tapped by silicic eruptions: Nature Geoscience, v. 13, no. 2, p. 163-169, https://doi.org/:10.1038/s41561-019-0520-6.

Laurent, O., Martin, H., Moyen, J. F., and Doucelance, R., 2014, The diversity and evolution of late-Archean granitoids: Evidence for the onset of "modern-style" plate tectonics between 3.0 and 2.5Ga: Lithos, v. 205, p. 208-235, https://doi.org/:10.1016/j.lithos.2014.06.012.

Lei, K., Zhang, Q., Liu, Y., Lu, K., Wu, L.-G., He, S., and Li, X.-H., 2023, Heavy silicon and oxygen isotope signatures of TTGs formed in distinct tectonic settings: Precambrian Research, v. 397, https://doi.org/:10.1016/j.precamres.2023.107202.

Li, P. C., 2019, Neoarchean tectonomagmatic events and crustal evolution in the Baishan area of the northeastern North China Craton [PhD: Jilin University, 1-133 p.

Li, Z., Shan, X., Liu, J., Zhang, J., Liu, Z., Cheng, C., Wang, Z., Zhao, C., and Yu, H., 2023, Late Neoarchean TTG and monzogranite in the northeastern North China Craton: Implications for partial melting of a thickened lower crust: Gondwana Research, v. 115, p. 201-223, https://doi.org/:10.1016/j.gr.2022.10.008.

Li, Z., Wei, C., Chen, B., Fu, B., and Gong, M., 2020, Late Neoarchean reworking of the Mesoarchean crustal remnant in northern Liaoning, North China Craton: A U–Pb–Hf–O–Nd perspective: Gondwana Research, v. 80, p. 350-369, https://doi.org/:10.1016/j.gr.2019.10.020.

Li, Z., Wei, C., Chen, B., Zhang, W., and Yang, F., 2021, U–Pb–Hf–O–Nd isotopic and geochemical constraints on the origin of Archean TTG gneisses from the North China Craton: Implications for crustal growth: Precambrian Research, v. 354, https://doi.org/:10.1016/j.precamres.2020.106078.

Liou, P., and Guo, J., 2019, Generation of Archaean TTG Gneisses Through Amphibole-Dominated Fractionation: Journal of Geophysical Research: Solid Earth, v. 124, no. 4, p. 3605-3619, https://doi.org/:10.1029/2018jb017024.

Liou, P., Guo, J., Huang, G., and Fan, W., 2019, 2.9 Ga magmatism in Eastern Hebei, North China Craton: Precambrian Research, v. 326, p. 6-23, https://doi.org/:10.1016/j.precamres.2017.11.002.

Liu, C. H., Zhao, G. C., Liu, F. L., and Cai, J., 2019, A Palaeoarchean–Mesoarchean micro-continent entrained in the Jiao-Liao-Ji Belt at the southeastern North China Craton: evidence from the zircon record in the Bengbu area: Geological Magazine, v. 156, no. 9, p. 1565-1586, https://doi.org/:10.1017/s0016756818000869.

Liu, D., Wilde, S. A., Wan, Y., Wang, S., Valley, J. W., Kita, N., Dong, C., Xie, H., Yang, C., Zhang, Y., and Gao, L., 2009, Combined U–Pb, hafnium and oxygen isotope analysis of zircons from meta-igneous rocks in the southern North China Craton reveal multiple events in the Late Mesoarchean–Early Neoarchean: Chemical Geology, v. 261, no. 1-2, p. 140-154, https://doi.org/:10.1016/j.chemgeo.2008.10.041.

Liu, J., Ji, M., Shen, L., Guan, H., and Davis, G. A., 2011, Early cretaceous extensional structures in the Liaodong Peninsula: Structural associations, geochronological constraints and regional tectonic implications: Science China Earth Sciences, v. 54, no. 6, p. 823-842, https://doi.org/:10.1007/s11430-011-4189-y.

Liu, J., Zhang, J., Liu, Z., Liu, X., Cheng, C., Wang, Z., Zhao, C., and Yu, H., 2022, Origin of the ca. 3.1 Ga Luanjiajie rock assemblage in the northeastern margin of the North China Craton: New constraints on the Mesoarchean geodynamic regime: Precambrian Research, v. 376, https://doi.org/:10.1016/j.precamres.2022.106697.

Liu, L., Yang, X., Santosh, M., and Aulbach, S., 2015, Neoarchean to Paleoproterozoic continental growth in the southeastern margin of the North China Craton: Geochemical, zircon U–Pb and Hf isotope evidence from the Huoqiu complex: Gondwana Research, v. 28, no. 3, p. 1002-1018, https://doi.org/:10.1016/j.gr.2014.08.011.

Lu, Z. L., Song, H. X., Du, L. L., Ren, L. D., Geng, Y. S., and Yang, C. H., 2014, Delineation of the ca. 2.7 Ga TTG gneisses in the Fuping complex, North China Craton and its geological significance: Acta Petrologica Sinica, v. 30, no. 10, p. 2872-2884.

Ma, M. Z., Xu, Z. Y., Zhang, L. C., Dong, C. Y., Dong, X. J., Liu, S. J., Liu, D. Y., and Wan, Y. S., 2013, SHRIMP dating and Hf isotope analysis of zircons from the Early Precambrian basement in the Xi Ulanbulang area, Wuchuan, Inner Mongolia: Acta Petrologica Sinica, v. 29, p. 501-516.

Ma, Q., Xu, Y.-G., Huang, X.-L., Zheng, J.-P., Ping, X., and Xia, X.-P., 2020, Eoarchean to Paleoproterozoic crustal evolution in the North China Craton: Evidence from U-Pb and Hf-O isotopes of zircons from deep-crustal xenoliths: Geochimica et Cosmochimica Acta, v. 278, p. 94-109, https://doi.org/:10.1016/j.gca.2019.09.009.

Maniar, P. D., and Piccoli, P. M., 1989, Tectonic discrimination of granitoids: Geological Society of America Bulletin, v. 1011, p. 635-643, https://doi.org/:10.1130/0016-7606(1989)101%3C0635:TDOG%3E2.3.CO;2.

Manikyamba, C., 2004, Geochemical systematics of tholeiitic basalts from the 2.7 Ga Ramagiri-Hungund composite greenstone belt, Dharwar craton: Precambrian Research, v. 134, no. 1-2, p. 21-39, https://doi.org/:10.1016/j.precamres.2004.05.010.

Mao, M., Liou, P., Du, L., and Guo, J., 2024, Petrogenesis of 2.7–2.65 Ga TTGs in the Wutai Complex: Constraints on the Neoarchean crustal evolution of the North China Craton: Precambrian Research, v. 400, https://doi.org/:10.1016/j.precamres.2023.107245.

Martin, H., 1986, Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas: Geology.

Martin, H., Moyen, J.-F., Guitreau, M., Blichert-Toft, J., and Le Pennec, J.-L., 2014, Why Archaean TTG cannot be generated by MORB melting in subduction zones: Lithos, v. 198-199, p. 1-13, https://doi.org/:10.1016/j.lithos.2014.02.017.

Martin, H., Smithies, R. H., Rapp, R., Moyen, J. F., and Champion, D., 2005, An overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoid: relationships and some implications for crustal evolution: Lithos, v. 79, no. 1-2, p. 1-24, https://doi.org/:10.1016/j.lithos.2004.04.048.

Middlemost, E. A. K., 1994, Naming materials in the magma/igneous rock system: Earth-Science Reviews, v. 37, p. 215-224, https://doi.org/:10.1016/0012-8252(94)90029-9.

Milidragovic, D., and Francis, D., 2016, Ca. 2.7 Ga ferropicritic magmatism: A record of Fe-rich heterogeneities during Neoarchean global mantle melting: Geochimica et Cosmochimica Acta, v. 185, p. 44-63, https://doi.org/:10.1016/j.gca.2015.09.023.

Mixon, E. E., Bauer, A. M., O'Neil, J., Rizo, H., Blum, T. B., Valley, J. W., and Bonamici, C. E., 2023, Mechanisms for generating elevated zircon δ18O in Archean crust: Insights from the Saglek-Hebron Complex, Canada: Earth and Planetary Science Letters, v. 624, https://doi.org/:10.1016/j.epsl.2023.118443.

Moreira, H., Storey, C., Fowler, M., Seixas, L., and Dunlop, J., 2020, Petrogenetic processes at the tipping point of plate tectonics: Hf-O isotope ternary modelling of Earth's last TTG to sanukitoid transition: Earth and Planetary Science Letters, v. 551, https://doi.org/:10.1016/j.epsl.2020.116558.

Moyen, J.-F., 2011, The composite Archaean grey gneisses: Petrological significance, and evidence for a non-unique tectonic setting for Archaean crustal growth: Lithos, v. 123, no. 1-4, p. 21-36, https://doi.org/:10.1016/j.lithos.2010.09.015.

Moyen, J., and Stevens, G., 2006, Experimental constraints on TTG petrogenesis: implications for Archean geodynamics, *in* Benn, K., Mareschal, J.-C., and Condie, K., eds., Archean Geodynamics and Environments, Volume 164: Washington, DC, American Geophysical Union p. 149-175.

Nagel, T. J., Hoffmann, J. E., and Münker, C., 2012, Generation of Eoarchean tonalite-trondhjemite-granodiorite series from thickened mafic arc crust: Geology, v. 40, no. 4, p. 375-378, https://doi.org/:10.1130/g32729.1.

Palin, R. M., and Santosh, M., 2021, Plate tectonics: What, where, why, and when?: Gondwana Research, v. 100, p. 3-24, https://doi.org/:10.1016/j.gr.2020.11.001.

Palin, R. M., Santosh, M., Cao, W., Li, S.-S., Hernández-Uribe, D., and Parsons, A., 2020, Secular change and the onset of plate tectonics on Earth: Earth-Science Reviews, v. 207, https://doi.org/:10.1016/j.earscirev.2020.103172.

Palin, R. M., White, R. W., and Green, E. C. R., 2016, Partial melting of metabasic rocks and the generation of tonalitic–trondhjemitic–granodioritic (TTG) crust in the Archaean: Constraints from phase equilibrium modelling: Precambrian Research, v. 287, p. 73-90, https://doi.org/:10.1016/j.precamres.2016.11.001.

Polat, A., 2009, The geochemistry of Neoarchean (ca. 2700Ma) tholeiitic basalts, transitional to alkaline basalts, and gabbros, Wawa Subprovince, Canada: Implications for petrogenetic and geodynamic processes: Precambrian Research, v. 168, no. 1-2, p. 83-105, https://doi.org/:10.1016/j.precamres.2008.03.008.

Polat, A., Li, J., Fryer, B., Kusky, T., Gagnon, J., and Zhang, S., 2006, Geochemical characteristics of the Neoarchean (2800–2700 Ma) Taishan greenstone belt, North China Craton: Evidence for plume–craton interaction: Chemical Geology, v. 230, no. 1-2, p. 60-87, https://doi.org/:10.1016/j.chemgeo.2005.11.012.

Polat, A., and Münker, C., 2004, Hf–Nd isotope evidence for contemporaneous subduction processes in the source of late Archean arc lavas from the Superior Province, Canada: Chemical Geology, v. 213, no. 4, p. 403-429, https://doi.org/:10.1016/j.chemgeo.2004.08.016.

Puetz, S. J., Spencer, C. J., Condie, K. C., and Roberts, N. M. W., 2024, Enhanced U-Pb detrital zircon, Lu-Hf zircon, delta(18)O zircon, and Sm-Nd whole rock global databases: Sci Data, v. 11, no. 1, p. 56, https://doi.org/:10.1038/s41597-023-02902-9.

Rapp, R. P., and Watson, E. B., 1995, Dehydration Melting of Metabasalt at 8-32 kbar: Implications for continental growth and crust-mantle recycling: Journal of Petrology, v. 36, p. 891-931, https://doi.org/:10.1093/petrology/36.4.891.

Ren, P., Xie, H., Wang, S., Nutman, A., Dong, C., Liu, S., Xie, S., Che, X., Song, Z., Ma, M., Liu, D., and Wan, Y., 2016, A ca. 2.60 Ga tectono-thermal event in Western Shandong Province, North China Craton from zircon U–Pb–O isotopic evidence: Plume or convergent plate boundary process: Precambrian Research, v. 281, p. 236-252, https://doi.org/:10.1016/j.precamres.2016.05.016.

Rickwood, P. C., 1989, Boundary lines within petrologic diagrams which use oxides of major and minor elements: Lithos, v. 22, p. 247-263, https://doi.org/:10.1016/0024-4937(89)90028-5.

Said, N., Kerrich, R., and Groves, D., 2010, Geochemical systematics of basalts of the Lower Basalt

Unit, 2.7Ga Kambalda Sequence, Yilgarn craton, Australia: Plume impingement at a rifted craton margin: Lithos, v. 115, no. 1-4, p. 82-100, https://doi.org/:10.1016/j.lithos.2009.11.008.

Schiano, P., Monzier, M., Eissen, J. P., Martin, H., and Koga, K. T., 2009, Simple mixing as the major control of the evolution of volcanic suites in the Ecuadorian Andes: Contributions to Mineralogy and Petrology, v. 160, no. 2, p. 297-312, https://doi.org/:10.1007/s00410-009-0478-2.

Shi, Y., and Zhao, X., 2017, Early Neoarchean Magmatic and Paleoproterozoic Metamorphic Events in the Northern North China Craton: SHRIMP Zircon Dating and Hf Isotopes of Archean Rocks from the Miyun Area, Beijing: Acta Geologica Sinica - English Edition, v. 91, no. 3, p. 988-1002, https://doi.org/:10.1111/1755-6724.13320.

Song, H. X., Yang, C. H., Du, L. L., Ren, L. D., and Geng, Y. S., 2018, Delineation of the ~2.7 Ga TTG gneisses in Zanhuang Complex, Hebei Province, and its geological significance: Acta Petrologica Sinica, v. 34, no. 6, p. 1599-1611.

Spencer, C. J., Cawood, P. A., Hawkesworth, C. J., Raub, T. D., Prave, A. R., and Roberts, N. M. W., 2014, Proterozoic onset of crustal reworking and collisional tectonics: Reappraisal of the zircon oxygen isotope record: Geology, v. 42, no. 5, p. 451-454, https://doi.org/:10.1130/g35363.1.

Spencer, C. J., Partin, C. A., Kirkland, C. L., Raub, T. D., Liebmann, J., and Stern, R. A., 2019, Paleoproterozoic increase in zircon $\delta^{18}O$ driven by rapid emergence of continental crust: Geochimica et Cosmochimica Acta, v. 257, p. 16-25, https://doi.org/:10.1016/j.gca.2019.04.016.

Sun, G., Liu, S., Cawood, P. A., Tang, M., van Hunen, J., Gao, L., Hu, Y., and Hu, F., 2021, Thermal state and evolving geodynamic regimes of the Meso- to Neoarchean North China Craton: Nat Commun, v. 12, no. 1, p. 3888, https://doi.org/:10.1038/s41467-021-24139-z.

Sun, S. s., and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes: Geological Society, London, Special Publications, v. 42, no. 1, p. 313-345, https://doi.org/:10.1144/gsl.Sp.1989.042.01.19.

Tang, M., Chen, K., and Rudnick, R. L., 2016, Archean upper crust transition from mafic to felsic marks the onset of plate tectonics: Science, v. 351, no. 6271, p. 372-375, https://doi.org/:10.1126/science.aad5513.

Taylor, R. J. M., Harley, S. L., Hinton, R. W., Elphick, S., Clark, C., and Kelly, N. M., 2014, Experimental determination of REE partition coefficients between zircon, garnet and melt: a key to understanding high-T crustal processes: Journal of Metamorphic Geology, v. 33, no. 3, p. 231-248, https://doi.org/:10.1111/jmg.12118.

Tiepolo, M., Oberti, R., Zanetti, A., Vannucci, R., and Foley, S. F., 2007, Trace-Element Partitioning Between Amphibole and Silicate Melt: Reviews in Mineralogy and Geochemistry, v. 67, no. 1, p. 417-452, https://doi.org/:10.2138/rmg.2007.67.11.

Troch, J., Ellis, B. S., Harris, C., Bachmann, O., and Bindeman, I. N., 2020, Low-δ18O silicic magmas on Earth: A review: Earth-Science Reviews, v. 208, https://doi.org/:10.1016/j.earscirev.2020.103299.

Valley, J. W., Lackey, J. S., Cavosie, A. J., Clechenko, C. C., Spicuzza, M. J., Basei, M. A. S., Bindeman, I. N., Ferreira, V. P., Sial, A. N., King, E. M., Peck, W. H., Sinha, A. K., and Wei, C. S., 2005, 4.4 billion years of crustal maturation: oxygen isotope ratios of magmatic zircon: Contributions to Mineralogy and Petrology, v. 150, no. 6, p. 561-580, https://doi.org/:10.1007/s00410-005-0025-8.

Valley, J. W., Reinhard, D. A., Cavosie, A. J., Ushikubo, T., Lawrence, D. F., Larson, D. J., Kelly, T. F., Snoeyenbos, D. R., and Strickland, A., 2015, Nano- and micro-geochronology in Hadean and Archean zircons by atom-probe tomography and SIMS: New tools for old minerals: American Mineralogist, v. 100, no. 7, p. 1355-1377, https://doi.org/:10.2138/am-2015-5134.

Wan, Y., Dong, C., Xie, H., Wilde, S. A., Liu, S., Li, P., Ma, M., Li, Y., Wang, Y., Wang, K., and Liu, D., 2023, Hadean to early Mesoarchean rocks and zircons in the North China Craton: A review: Earth-Science Reviews, v. 243, p. 104489, https://doi.org/:10.1016/j.earscirev.2023.104489.

Wan, Y., Liu, D., Wang, S., Dong, C., Yang, E., Wang, W., Zhou, H., Ning, Z., Du, L., Yin, X., Xie, H., and Ma, M., 2011a, Juvenile magmatism and crustal recycling at the end of the Neoarchean in Western Shandong Province, North China Craton: Evidence from SHRIMP zircon dating: American Journal of Science, v. 310, no. 10, p. 1503-1552, https://doi.org/:10.2475/10.2010.11.

Wan, Y., Liu, D., Wang, S., Yang, E., Wang, W., Dong, C., Zhou, H., Du, L., Yang, Y., and Diwu, C., 2011b, ~2.7Ga juvenile crust formation in the North China Craton (Taishan-Xintai area, western Shandong Province): Further evidence of an understated event from U–Pb dating and Hf isotopic composition of zircon: Precambrian Research, v. 186, no. 1-4, p. 169-180, https://doi.org/:10.1016/j.precamres.2011.01.015.

Wan, Y., Xie, S., Yang, C., Kröner, A., Ma, M., Dong, C., Du, L., Xie, H., and Liu, D., 2014, Early Neoarchean (~2.7 Ga) tectono-thermal events in the North China Craton: A synthesis: Precambrian Research, v. 247, p. 45-63, https://doi.org/:10.1016/j.precamres.2014.03.019.

Wan, Y. S., Dong, C. Y., Wang, W., Xie, H. Q., and Liu, D. Y., 2010, Archean basement and a Paleoproterozoic collision orogen in the Huoqiu area at the southeastern margin of North China Craton: evidence from sensitive high resolution ion micro-probe U-Pb zircon geochronology: Acta Geologica Sinica (English Edition), v. 84, no. 1, p. 91-104.

Wang, C., Huang, H., Tong, X., Zheng, M., Peng, Z., Nan, J., Zhang, L., and Zhai, M., 2016a, Changing provenance of late Neoarchean metasedimentary rocks in the Anshan-Benxi area, North China Craton: Implications for the tectonic setting of the world-class Dataigou banded iron formation: Gondwana Research, v. 40, p. 107-123, https://doi.org/:10.1016/j.gr.2016.08.010.

Wang, M., Liu, S., Wang, W., Wang, K., Yan, M., Guo, B., Bai, X., and Guo, R., 2016b, Petrogenesis and tectonic implications of the Neoarchean North Liaoning tonalitic-trondhjemitic gneisses of the North China Craton, North China: Journal of Asian Earth Sciences, v. 131, p. 12-39, https://doi.org/:10.1016/j.jseaes.2016.09.012.

Wang, Q., Xu, J.-F., Jian, P., Bao, Z.-W., Zhao, Z.-H., Li, C.-F., Xiong, X.-L., and Ma, J.-L., 2006, Petrogenesis of Adakitic Porphyries in an Extensional Tectonic Setting, Dexing, South China: Implications for the Genesis of Porphyry Copper Mineralization: Journal of Petrology, v. 47, no. 1, p. 119-144, https://doi.org/:10.1093/petrology/egi070.

Wang, Q., Zheng, J., Pan, Y., Dong, Y., Liao, F., Zhang, Y., Zhang, L., Zhao, G., and Tu, Z., 2014a, Archean crustal evolution in the southeastern North China Craton: New data from the Huoqiu Complex: Precambrian Research, v. 255, p. 294-315, https://doi.org/:10.1016/j.precamres.2014.10.005.

Wang, W., Liu, S., Cawood, P. A., Bai, X., Guo, R., Guo, B., and Wang, K., 2016c, Late Neoarchean subduction-related crustal growth in the Northern Liaoning region of the North China Craton: Evidence from ~2.55 to 2.50 Ga granitoid gneisses: Precambrian Research, v. 281, p. 200-223, https://doi.org/:10.1016/j.precamres.2016.05.018.

Wang, W., Liu, S., Cawood, P. A., Yao, J., Gao, L., Guo, R., Hu, F., Lu, D., and He, X., 2024, Early Neoarchean alternation of plate subduction and deep mantle upwelling: Precambrian Research, v. 402, https://doi.org/:10.1016/j.precamres.2024.107303.

Wang, W., Yang, E., Zhai, M., Wang, S., Santosh, M., Du, L., Xie, H., Lv, B., and Wan, Y., 2013, Geochemistry of ~2.7Ga basalts from Taishan area: Constraints on the evolution of early Neoarchean granite-greenstone belt in western Shandong Province, China: Precambrian

Research, v. 224, p. 94-109, https://doi.org/:10.1016/j.precamres.2012.09.009.

Wang, W., Zhai, M.-G., Wang, S.-J., and Santosh, M., 2016d, Neoarchean crustal evolution in western Shandong Province of the North China Craton: The role of 2.7–2.6 Ga magmatism: Precambrian Research, v. 285, p. 170-185, https://doi.org/:10.1016/j.precamres.2016.09.010.

Wang, X.-L., Coble, M. A., Valley, J. W., Shu, X.-J., Kitajima, K., Spicuzza, M. J., and Sun, T., 2014b, Influence of radiation damage on Late Jurassic zircon from southern China: Evidence from in situ measurements of oxygen isotopes, laser Raman, U–Pb ages, and trace elements: Chemical Geology, v. 389, p. 122-136, https://doi.org/:10.1016/j.chemgeo.2014.09.013.

Wang, Y.-F., Li, X.-H., Jin, W., Zeng, L., and Zhang, J.-H., 2020, Generation and maturation of Mesoarchean continental crust in the Anshan Complex, North China Craton: Precambrian Research, v. 341, https://doi.org/:10.1016/j.precamres.2020.105651.

Wang, Y.-F., Li, X.-H., Jin, W., and Zhang, J.-H., 2015, Eoarchean ultra-depleted mantle domains inferred from ca. 3.81 Ga Anshan trondhjemitic gneisses, North China Craton: Precambrian Research, v. 263, p. 88-107, https://doi.org/:10.1016/j.precamres.2015.03.005.

Wu, M., Lin, S., Wan, Y., Gao, J.-F., and Stern, R. A., 2021, Episodic Archean crustal accretion in the North China Craton: Insights from integrated zircon U-Pb-Hf-O isotopes of the Southern Jilin Complex, northeast China: Precambrian Research, v. 358, https://doi.org/:10.1016/j.precamres.2021.106150.

Wu, M., Zhao, G., Sun, M., Li, S., Bao, Z., Tam, P. Y., Eizenhöefer, P. R., and He, Y., 2014, Zircon U–Pb geochronology and Hf isotopes of major lithologies from the Jiaodong Terrane: Implications for the crustal evolution of the Eastern Block of the North China Craton: Lithos, v. 190-191, p. 71-84, https://doi.org/:10.1016/j.lithos.2013.12.004.

Wyman, D. A., and Kerrich, R., 2012, Geochemical and isotopic characteristics of Youanmi terrane volcanism: the role of mantle plumes and subduction tectonics in the western Yilgarn Craton: Australian Journal of Earth Sciences, v. 59, no. 5, p. 671-694, https://doi.org/:10.1080/08120099.2012.702684.

Wyman, D. A., Kerrich, R., and Polat, A., 2002, Assembly of Archean cratonic mantle lithosphere and crust: plume-arc interaction in the Abitibi-Wawa subduction-accretion complex: Precambrian Research, v. 115, p. 37-62, https://doi.org/:10.1016/S0301-9268(02)00005-0.

Yang, C., Du, L., Ren, L., Song, H., Wan, Y., Xie, H., and Geng, Y., 2013, Delineation of the ca. 2.7Ga TTG gneisses in the Zanhuang Complex, North China Craton and its geological implications: Journal of Asian Earth Sciences, v. 72, p. 178-189, https://doi.org/:10.1016/j.jseaes.2012.09.031.

Yao, J., Wang, W., Gao, L., Hu, F., Lu, D., He, X., and Guo, L., 2023, Initiation of Mesoarchean nascent subduction zone in the North China Craton: Geological Society of America Bulletin, https://doi.org/:10.1130/b36877.1.

Yao, J., Wang, W., Liu, S., Cawood, P. A., Niu, P., Lu, D., and Guo, L., 2020, Crust-mantle geodynamic origin of ~2.7 Ga granitoid diversification in the Jiaobei terrane, North China Craton: Precambrian Research, v. 346, https://doi.org/:10.1016/j.precamres.2020.105821.

Zegers, T. E., and van Keken, P. E., 2003, Middle Archean continent formation by crustal delamination: Geology, v. 29, no. 12, p. 1083-1086, https://doi.org/:10.1130/0091-7613(2001)029<1083:MACFBC>2.0.CO;2.

Zhang, R., Zhai, M., and Zhao, Y., 2023, Petrogenesis of two episodes of Neoarchean TTG gneisses (∼2.72 Ga and 2.56–2.54 Ga) from the Zhongtiao Mountains, North China Craton: Implications for crustal evolution: Lithos, v. 460-461, https://doi.org/:10.1016/j.lithos.2023.107377.

Zhang, S. B., and Zheng, Y. F., 2011, On the origin of low δ^{18}O magmatic rocks: Acta Petrologica Sinica, v. 27, p. 520-530.

Zhao, G., and Cawood, P. A., 2012, Precambrian geology of China: Precambrian Research, v. 222-223, p. 13-54, https://doi.org/:10.1016/j.precamres.2012.09.017.

Zheng, Y., Wu, Y., Gong, B., Chen, R., Tang, J., and Zhao, Z., 2007, Tectonic driving of Neoproterozoic glaciations: Evidence from extreme oxygen isotope signature of meteoric water in granite: Earth and Planetary Science Letters, v. 256, no. 1-2, p. 196-210, https://doi.org/:10.1016/j.epsl.2007.01.026.

Zhong, Y., Kusky, T., Wang, L., Polat, A., Liu, X., Peng, Y., Luan, Z., Wang, C., Wang, J., and Deng, H., 2021, Alpine-style nappes thrust over ancient North China continental margin demonstrate large Archean horizontal plate motions: Nat Commun, v. 12, no. 1, p. 6172, https://doi.org/:10.1038/s41467-021-26474-7.

Zhou, Y., Sun, Q., Zheng, Y., Zhao, T., and Zhai, M., 2021, Delineation of the early Neoarchean (2.75 to 2.70 Ga) crustal growth and reworking processes in the southeast base of Taihang Mountain, North China Craton: Lithos, v. 380-381, https://doi.org/:10.1016/j.lithos.2020.105829.

Zhou, Y., Zhao, T., Zhai, M., Gao, J., and Sun, Q., 2014, Petrogenesis of the Archean tonalite–trondhjemite–granodiorite (TTG) and granites in the Lushan area, southern margin of the North China Craton: Implications for crustal accretion and transformation: Precambrian Research, v. 255, p. 514-537, https://doi.org/:10.1016/j.precamres.2014.06.023.

Zhu, X., Zhai, M., Chen, F., Lyu, B., Wang, W., Peng, P., and Hu, B., 2013, ~2.7-Ga Crustal Growth in the North China Craton: Evidence from Zircon U-Pb Ages and Hf Isotopes of the Sushui Complex in the Zhongtiao Terrane: The Journal of Geology, v. 121, no. 3, p. 239-254, https://doi.org/:10.1086/669977.

FIGURE CAPTIONS

Figure 1. Simplified geological map of the North China Craton showing exposed Archean-Paleoproterozoic basement and the locations of Eoarchean to early Neoarchean rocks (modified after Wan et al. (2014b)). The details of early Neoarchean granitoids and volcanic rocks refer to **Supplemental Table S1**. Abbreviations of terranes: BB-Bengbu; ES-Eastern Shandong; EH-eastern Hebei; FP-Fuping; HQ-Huoqiu; HS-Hengshan; HX-Huixian; LS-Lushan; MY-Miyun; NL-northern Liaoning; SJ-southern Jilin; WC-Wuchuan; WS-western Shandong; XQL-Xiaoqingling; ZH-Zanhuang; ZT-Zhongtiao.

Figure 2. (A) Geological map of the northern Liaoning to southern Jilin regions showing the Archean basement, the locations and ages of previously reported *ca.* 2.7 Ga rocks, and the location of the study area. **(B)** Geological map of study area showing the sampling locations.

Figure 3. Representative outcrop photographs of the early Neoarchean mylonitic trondhjemites (A–E) and granodiorites (F–I) in the Baishan area used for U–Pb dating. (A and B) Mylonitic trondhjemite sample 21BS10-1 exhibits asymmetric porphyroclasts and mylonitic foliations. (C) Mineral and stretching lineations preserved in the mylonitic trondhjemite sample 23HX01-1. (D and E) Steep mylonitic foliations and elongated quartz ribbons preserved in the mylonitic trondhjemite sample 23XH05-1. (F) Mylonitic granodiorite sample 22BS13-1 displays mylonitic

foliations defined by oriented biotites and elongated quartzs. (G and H) Sample 22BS14-1 displays distinct mylonitic fabrics, e.g., flat mylonitic foliations and asymmetric porphyroclasts. (I) Elongated quartz ribbons and folds within the granitic mylonite sample 22BS14-1.

Figure 4. Photomicrographs of the mylonitic trondhjemites (**A-D**) and the mylonitic granodiorites (**E-I**) in the Baishan area. Mineral abbreviations: Bt = biotite; Chl = chlorite; Ep = epidote; Hbl = hornblende; Mus = muscovite; Pl = plagioclase; Qtz = quartz; Ser = sericite.

Figure 5. (**A**) (Na_2O+K_2O) vs SiO_2 diagram (after Middlemost (1994)). (**B**) An-Ab-Or diagram (after Barker (1979)). (**C**) K_2O vs SiO_2 diagram (after Rickwood (1989)). (**D**) A/NK vs A/CNK diagram (after Maniar and Piccoli (1989)). The data for the early Neoarchean rocks in the Trans–North China Orogen (TNCO) are cited from Diwu et al. (2020); Huang et al. (2010); Jia (2016); Lu et al. (2014); Song et al. (2018); Yang et al. (2013); the data for Eastern Shandong are from Jahn et al. (2008); Jiang et al. (2016); Yao et al. (2020); the data for Western Shandong are from Hu et al. (2019); Jiang et al. (2010); Wan et al. (2014); the data for North Liaoning to South Jilin are from Bao et al. (2022); Li (2019); the data for Bengbu–Huoqiu are from Liu et al. (2015).

Figure 6. Chondrite-normalized REE patterns and primitive mantle-normalized multi-element diagrams for the mylonitic trondhjemites and granodiorites of this study (**A,**

B) and the early Neoarchean TTG in other terranes in the NCC (**C–F**). Normalized chondrite and primitive mantle values are from Sun and McDonough (1989). The references for the cited data are consistent to those listed in **Figure 5**.

Figure 7. Concordia diagrams and representative zircon CL images for the mylonitic trondhjemites (**A–D**) and granodiorites (**E–H**).

Figure 8. Zircon $\varepsilon_{\mathrm{Hf}(t)}$ value vs age diagram (**A**). Zircon δ^{18}O value vs age diagram (**B**). Whole-rock $\varepsilon_{\mathrm{Nd}(t)}$ vs age diagram (**C**). The $\varepsilon_{\mathrm{Hf}(t)}$ data for the early Neoarchean rocks in the NCC are cited from Bao et al. (2022); Diwu et al. (2010); Diwu et al. (2020); Han et al. (2012); Huang et al. (2010); Jia et al. (2016); Jia (2016); Jiang et al. (2016); Jiang et al. (2010); Li (2019); Li et al. (2020); Liu et al. (2009); Ma et al. (2013); Ma et al. (2020); Song et al. (2018); Wan et al. (2011b); Wan et al. (2014); Wang et al. (2014a); Wang et al. (2016c); Wang et al. (2015); Wu et al. (2021); Wu et al. (2014); Yao et al. (2020); Zhou et al. (2014); Zhu et al. (2013). The δ^{18}O data for the early Neoarchean rocks in the NCC are cited from Diwu et al. (2020); Jiang et al. (2016); Ma et al. (2020); Ren et al. (2016); Wang et al. (2016a); Wang et al. (2020); Wang et al. (2015); Wu et al. (2021). The δ^{18}O data for the early Neoarchean rocks in other cratons are cited from the dataset compiled by Puetz et al. (2024). The $\varepsilon_{\mathrm{Nd}(t)}$ data for the early Neoarchean rocks in the NCC are cited from Huang et al. (2010); Jahn et al. (1988); Jahn et al. (2008).

Figure 9. Histogram of summarized reported zircon U–Pb ages of the Neoarchean igneous rocks in the NCC. The references for the cited data are listed in **Supplemental Table S1**.

Figure 10. (**A**) Ce/Zr *vs* Ce and (**B**) La/Hf *vs* La diagrams (after Schiano et al. (2009)) indicating partial melting origins for the *ca.* 2.7 Ga TTGs.

Figure 11. Plots of SiO_2 *vs* major oxides and trace elements, suggesting that the *ca.* 2.7 Ga TTG in the study area did not originate from amphibole-plagioclase fractionation of tonalitic or dioritic magmas. The fractionation modelling was performed using PETROMODELER.v4 (Ersoy, 2013).

Figure 12. (**A**) $Al_2O_3/(FeO^T+MgO)$–3CaO–5(K_2O/Na_2O) ternary diagram (after Laurent et al. (2014)). (**B**) Sr/Y *vs* Y diagram (after Drummond and Defant (1990)). (**C**) $(La/Yb)_N$ *vs* Yb_N diagram (after Martin (1986)). (**D–F**) Geochemical discrimination diagrams for the adakites (after Wang et al. (2006)). Plots of Sr *vs* Y (**G**) and Nb *vs* Ta (**H**) diagrams (after Moyen (2011)).

Figure 13. (**A**) Phase diagram calculated for the median composition of the late Mesoarchean to early Neoarchean mafic rocks in the NCC with H_2O = 2 wt. %. (**B**) The variation of mineral assemblages and melt contents during heating processes at a fixed condition of pressure (12 kbar) and H_2O (2.0 wt. %). Red cross represents the estimated *P–T* condition range for the *ca.* 2.7 Ga TTG samples. The bold solid lines represent the occurrence lines of garnet, rutile, and plagioclase. The dotted lines represent melt, plagioclase, amphibole, garnet proportions (wt. %). Amph-amphibole; Bio-biotite; Cpx-clinopyroxene; Kf-K-feldspar; Pl-plagioclase; Gt-garnet; Ilm-ilmenite; Opx-orthopyroxene; Sph-sphene; Mica-muscovite; ru-rutile; q-quartz.

Figure 14. Comparisons of selected trace elements between the modelled melts and the median values of the *ca.* 2.7 Ga TTGs. Normalized primitive mantle values are

from Sun and McDonough (1989).

[1]Supplemental Material. Detailed analytic methods, summary of early Neoarchean granitoids, and results of zircon U-Pb dating and trace-element modelling. Please visit https://doi.org/10.1130/XXXX to access the supplemental material, and contact editing@geosociety.org with any questions.