



Diverse middle Neoproterozoic granitoids and the delamination of thickened crust in the Western Shandong Terrane, North China Craton

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ABSTRACT

Middle Neoproterozoic granitoids contain crucial clues for understanding crust–mantle interactions and further investigating the mechanism of the compositional transformation of the crust in the Neoproterozoic. In the Western Shandong Terrane (WST), diverse Neoproterozoic magmatism is recognized, including ~2.62 Ga tonalitic gneisses, ~2.59 Ga granodioritic gneisses and ~2.61–2.58 Ga monzogranitic gneisses, which generally intruded into ~2.70 Ga tonalite–trondhjemite–granodiorite (TTG) gneisses. The ~2.70 Ga TTG gneisses show high SiO₂ contents (70.17–72.89 wt%), but low MgO contents (0.58–0.69 wt%) and high (La/Yb)_N ratios (30–48) and originated from partial melting of low-K mafic rocks at lower crustal levels. The ~2.62 Ga tonalitic gneisses exhibit low K₂O/Na₂O ratios (0.10–0.39), but high (La/Yb)_N (7.60–12.7) and Sr/Y (18.8–48) ratios and Mg# (47–57). With high εHf(t₂) values ranging from +2.7 to +7.4, these rocks were derived from dehydration melting of subducted oceanic slabs. The ~2.61–2.58 Ga monzogranitic gneisses show high SiO₂ (70.35–75.12 wt%) and K₂O (4.35–5.81 wt%) contents but low MgO (0.20–0.77 wt%) contents with positive εHf(t₂) values (+2.0–+6.6), suggesting they were derived from partial melting of juvenile greywackes. The ~2.59 Ga granodioritic gneisses exhibit high SiO₂ (66.34–73.04 wt%), K₂O (2.23–4.32 wt%) and MgO (1.39–3.51 wt%) contents with dispersed εHf(t₂) values (–0.2–+5.3), indicating a mixing process between crust- and mantle-sourced magmas. The ~2.59 Ga granodioritic gneisses show consistent major and trace element compositions (i.e., high Mg#, lack of Eu anomalies and uniform chondrite-normalized REE patterns), and accordingly, their magmatic precursors were derived from partial melting of delaminated lower crustal materials.

The lithological assemblages in the WST became increasingly diverse between ~2.71–2.58 Ga, changing from TTG gneisses to arc-related rock series, and then to delamination-related granodioritic gneisses, crust-derived monzogranitic and trondhjemitic gneisses and mantle-derived tholeiitic basalts and diorites. By integrating these data with a reduction in the continental crustal thickness from ~2.70 Ga to 2.55 Ga, a subduction–delamination model is proposed in which a long-term lateral accretion beginning at ~2.7 Ga and persisting through ~2.68–2.62 Ga led to the delamination of the lower crust at ~2.61–2.58 Ga, which may have further triggered the transition of the continental crust composition from basaltic to andesitic.

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1. Introduction

The Meso- to Neoproterozoic (~3.0–2.5 Ga) is a key transition period in the formation and evolution of the global continental crust, during which a mass of K-rich granitoids appeared in the continental crust and coexisted with the tonalite–trondhjemite–granodiorite (TTG) gneisses, whereas Na-rich TTG gneisses were the dominant lithological assemblages of the Paleoproterozoic continental crust, which is suggestive of a crucial variation in the geodynamic mechanism

forming the early continental crust. The Na-rich TTG gneisses are almost the only lithological assemblage of granitoids in the Paleoproterozoic to early Mesoproterozoic continental crust and were produced by the partial melting of mafic rocks or the fractional crystallization of mafic magmas. Although TTG gneisses still predominate, the granitoids in the Mesoproterozoic to Neoproterozoic exhibit significant diversity, with the appearance of a mass of K-rich granodiorites–monzogranites–syenogranites, sanukitoids and monzodiorites. These K-rich granitoid rocks originated from the recycling of ancient crust materials and magmatic mixing between crust- and mantle-sourced melts, except for the sanukitoids which are associated with a metasomatized depleted mantle wedge (Fu et al., 2018; Laurent et al., 2013; Moyen and Laurent, 2018; Sun et al., 2019a).

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The mechanism of the chemical composition transformation of the Meso- to Neoarchean continental crust remains vigorously debated. Some scholars have suggested that as the Earth's cooling progressed and the plate tectonic regime began, the whole planetary system may have changed, including the crustal composition of the newly generated continental crust. It has commonly been suggested that K-rich rock sequences represent the operation of a modern style plate tectonic regime, based on the involvement of depleted mantle materials that have been enriched in the petrogenesis of sanukitoids and extensive coeval calc-alkaline volcanic rocks that exhibit geochemical affinities with arc magmatism throughout the greenstone belts (Arndt, 2013; Laurent et al., 2014; Martin et al., 2005; Poujol et al., 2003; Prevec et al., 2004; Wyman and Kerrich, 1988). Other scholars noted that the extensive crust-derived TTG gneisses require a thickened mafic lower crust in the Paleo- to early Mesoarchean; however, the mass balance, isotopic and physical nature of the overheated crustal state imply that a thin Archean crust is preserved (Keller and Schoene, 2012). Therefore, a crustal delamination model associated with this dilemma is proposed, in which the over thickened continental crust including large volumes of dense eclogitic to pyroxenitic restites can break off into the mantle and lead to a mafic magma underplating derived from the upwelling of the hot asthenosphere, crustal uplift and extensive magmatism (Herzberg et al., 1983; Jull and Kelemen, 2001). The lowest crustal delamination could lead to changes in the composition of the continental crust from mafic and Na-rich to felsic and K-rich (Arndt et al., 2002; Gao et al., 1998; Nelson, 1991; Rudnick and Fountain, 1995). Due to the relatively high mantle potential temperatures, the lower crust delamination may have been more prevalent in the Archean (Bédard, 2006; Jull and Kelemen, 2001; Percival and Pysklywec, 2007; Petford and Atherton, 1996). However, the predominant mechanism of the chemical composition transformation is still unknown. As important geological signatures, the granitoids formed in the transformation period may provide direct evidence for the geodynamic transformation from the ancient Na-rich to K-rich continental crust. Therefore, detailed investigations of their petrogenesis and crust–mantle interactions may yield crucial insight into the evolution mechanism of the Archean continental crust.

The emplacement ages of the Neoarchean granitoids are obviously different in every craton of the globe (Laurent et al., 2014; Poujol et al., 2003; Prevec et al., 2004), and zircon dating data reveal that the predominant crustal formation events are recorded by ~2.7 Ga TTG gneisses and ~2.5 Ga TTG gneisses with a mass of potassic granitoids in the North China Craton (NCC) (Bai et al., 2014; Fu et al., 2018; Wan et al., 2011; Wang et al., 2015, 2016a, 2016b, 2017a, 2017b; Wu et al., 2014). The Western Shandong Terrane (WST) is a typical Precambrian terrane in the eastern margin of the NCC, containing ~2.7–2.5 Ga granitoids (Gao et al., 2018; Jahn et al., 1988; Sun et al., 2019a, 2019b; Wan et al., 2011). Although less in volume, the middle Neoarchean (~2.68–2.58 Ga) granitoids are well preserved in the WST, providing an excellent opportunity to investigate the crust–mantle interactions of the middle to late Neoarchean continental crust. Based on the extensive TTG gneisses and potassic granitoids that lack the signatures of preserved supracrustal rocks, previous studies have suggested that this period represented regional metamorphism and anatexis (Dong et al., 2017; Ren et al., 2016, 2017; Wang et al., 2016c). However, extensive mantle-derived volcanic and plutonic rocks have recently been identified (Gao et al., 2019a; Wan et al., 2014; Yang and Santosh, 2017), indicating the extensive magmatism derived from crust–mantle interactions (Gao et al., 2018; Gao et al., 2019a, 2019b, unpublished data; Hu et al., unpublished data; Sun et al., 2019a; Wang et al., 2009, 2016b). Moreover, a

recent study on TTG gneisses indicates that the crustal thickness decreased by ~10 km from ~2.70 to 2.55 Ga in the WST (Sun et al., 2019b). However, the thinning mechanism of the Neoarchean continental crust is still an enigma. Therefore, it is necessary to further investigate the petrogenesis of diverse granitoids and their middle to late Neoarchean crust–mantle interactions in the WST.

In this contribution, we report new petrological, whole-rock geochemical, and zircon U–Pb–Lu–Hf isotope data from the middle to late Neoarchean granitoids in the WST of the NCC and aim to determine the formation ages, to investigate their petrogenesis and to further explore the geodynamic process acting on the continental crust between ~2.68–2.58 Ga in the WST.

2. Geological background

The NCC has been considered to be composed of the Western Block (WB), the Eastern Block (EB) and the Trans-North China Orogen (TNCO), which finally stabilized at ~1.85 Ga (Fig. 1A; Zhao et al., 2005). More recently, however, a two-stage Archean cratonization model (2.6–2.7 Ga and ~2.5 Ga) involving the amalgamation of seven microblocks was suggested (Fig. 1B; Zhai and Santosh, 2011). A large Neoarchean (~2.6–2.5 Ga) tectonic belt involving multiple arc-back-arc basins has also been identified in the north-western EB (Bai et al., 2014; Fu et al., 2018, unpublished data; Guo et al., 2015, 2017; Liu et al., 2018a, 2018b; Wang et al., 2016b, 2017b).

The Precambrian WST is situated in the eastern EB (Fig. 1A; Zhao et al., 2005) and southwestern Jiaoliao microblock (Fig. 1B; Zhai and Santosh, 2011). Bounded by the Tanlu Fault in the east, it extends in a northwest-southeast direction with an exposure of ~10,000 km² (Fig. 1C).

Supracrustal rocks occur as lenses and ribbons within granitoids on various scales (Fig. 1C) and consist of three main rock assemblages: (1) early Neoarchean (2.75–2.70 Ga) ultramafic–mafic sequences are exposed in the Yanlingguan, Qixingtai and Mengjiatun areas with komatiites, tholeiitic pillow basalts and thick pyroclastic and sedimentary rocks preserved in the lower part and overlain by amphibolite, garnet–biotite plagioclase gneiss and garnetiferous quartzites; (2) middle Neoarchean (2.68–2.58 Ga) mafic sequences in the Taishan and Yishui areas are composed chiefly of amphibolites and mafic granulites; and (3) late Neoarchean (2.55–2.52 Ga) metamorphic volcano-sedimentary sequences in the Jining and Zaozhuang areas mainly comprise banded iron formations (BIFs), sericite phyllites, chlorite-sericite phyllites and slates (Cao, 1996; Du et al., 2003; Gao et al., 2019a; Lu et al., 2008; Wang et al., 2015).

The extensive Neoarchean intrusive rocks in the WST show relatively continuous ages and can be divided into three episodes of magmatism, including 2.75–2.70 Ga, 2.68–2.58 Ga and 2.55–2.49 Ga. (1) Early Neoarchean magmatism (2.75–2.70 Ga) mainly produced TTG gneisses in the Taian–Pingyi–Feixian areas, which underwent strong deformation and metamorphism forming intense structural foliations and bands (Fig. 2A). (2) Middle Neoarchean (2.68–2.56 Ga) intrusive rocks consist mainly of tonalitic gneisses, trondhjemitic gneisses, high-K granodioritic gneisses, monzogranitic gneisses, diorites and hornblendites, most of which are deformed and show gneissic or banded structures (Fig. 2B–F). The tonalitic gneisses were emplaced into the early ~2.7 Ga TTG gneisses and show consistent foliations (Fig. 2C). The trondhjemitic gneisses are identified as veins developed in the earlier amphibolites and TTG gneisses in the Taishan area, and are considered anatectic products derived from a tectono-thermal event (Ren et al., 2016, 2017). The monzogranitic gneisses exposed in the Yishui area are intruded locally by late Neoarchean TTG gneisses and charnockites (Gao et al., 2019a). The granodioritic

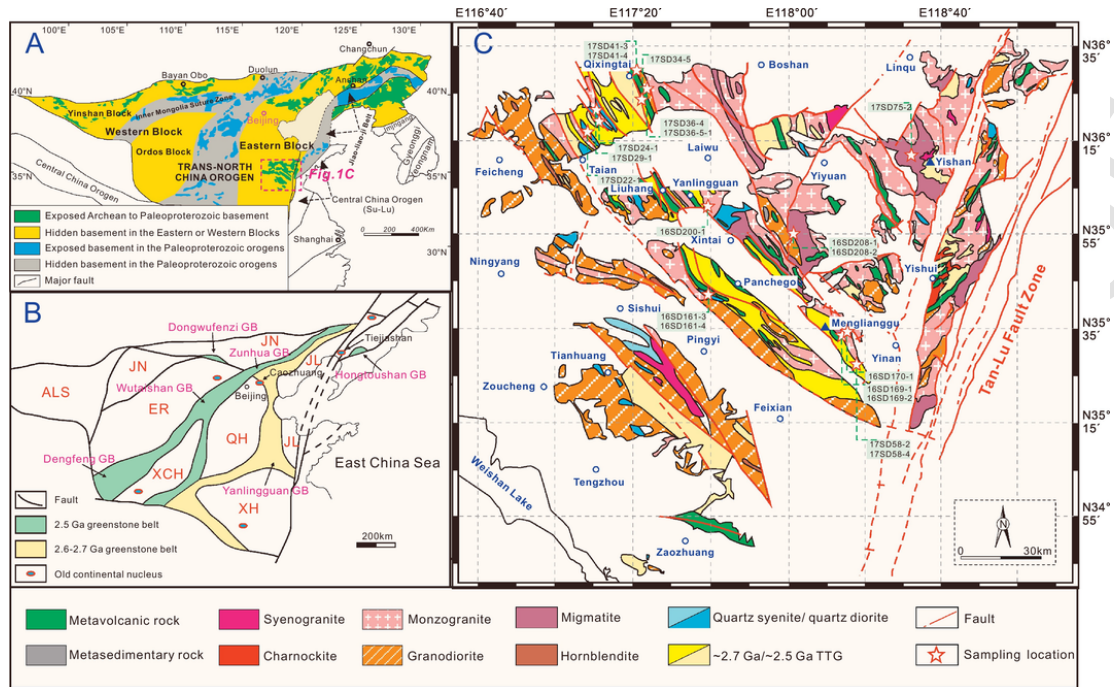


Fig. 1. (A) Tectonic subdivision of the North China Craton (modified after Zhai and Santosh, 2011); (B) Tectonic subdivision of the North China Craton (NCC) illustrating major early Precambrian basement terranes and late Paleoproterozoic tectonic framework (modified from Zhao et al., 2005). Archean crystalline basement of the Western Shandong Terrane (WST) is shown by the black rectangle; (C) Simplified geological map of the WST showing major lithological units. The sampling locations and sample numbers are shown in the map.

gneisses exposed mainly in the Qixingtai–Menglianggu–Yishan areas are intruded by monzogranitic veins (Fig. 2E). The early Neoproterozoic TTG gneisses and the middle Neoproterozoic granitoid gneisses were extensively intruded by small stocks of late Neoproterozoic diorite and hornblende. (3) The late Neoproterozoic (2.56–2.49 Ga) mantle-crust magmatism produced complicated lithological assemblages, including TTG gneisses, granodiorites-monzogranites-syenogranites, quartz syenites, quartz diorites (sanukitoids) and hornblendites. The TTG gneisses are mainly distributed in the Taishan-Qixingtai, Yishan and Tengzhou areas, with ages of ~2.56–2.52 Ga, showing weak gneissosity (Sun et al., 2019b). The granodiorites-monzogranites-syenogranites are exposed in the eastern and western WST and intruded into the ~2.7 Ga TTG gneisses (Fig. 1C; Gao et al., 2018, Gao et al., 2019a; Sun et al., 2019a). The quartz syenites, quartz diorites and hornblendites occur as either small stocks or bands within the lithological assemblage of granodiorites-monzogranites-syenogranites.

The Archean crystallization basement in the WST is characterized by the generally parallel trending of both the geological bodies and tectonic lineaments or structures, resulting from successive and multi-stage deformations (Fig. 1C). The eastern margin of the WST was strongly influenced by the Mesozoic Tanlu Fault, leading to ductile shear zones with a strike 20°–50° and NE-trending intrusions and volcanic rocks in the Yishui area (Cao, 1996). In the Taishan-Menglianggu area, the granitoids and the metavolcanic lenses extend in the NW-SE directions, parallel to the regional ductile shear zones and faults. The tectonic stress field in the WST varies over time, including early extension, NE-SW-oriented compression and sinistral strike-slip shearing (Cao, 1996). Through structural restoration, thick layers of ~2.80 Ga plume-related komatiitic-tholeiitic pillow lava and other supracrustal series have been identified as erupting within rift basins, suggesting extension at ~2.85–2.80 Ga (Cao, 1996; Hou et al., 2004). The thickness of the overlying sedimentary sequences de-

creases abruptly, indicating that the structural system changed significantly. Some tilted folds dipping to the ENE and WSW and penetrative foliations dipping to the ENE and WSW-SW are well preserved in the supracrustal rocks in the WST and integrated with the NE and SW mineral stretching lineations measured on the foliations, confirming that the rocks underwent dominantly NE-SW-oriented horizontal compression prior to ~2.71 Ga, which may have led to a thickened crust in the WST (Gao et al., 2019b). In addition, sinistral strike-slip shearing is identified by asymmetric folds and δ -type augen structures, which may have resulted from the superposition of later tectonic events, which is not precisely constrained (Gao et al., 2019b).

3. Sampling and petrology

Twenty-two granitoid gneiss samples were collected in the WST, including five early Neoproterozoic TTG gneisses and seventeen middle Neoproterozoic granitoids including four tonalitic gneisses, four monzogranitic gneisses and eight granodioritic gneisses associated with one mafic magmatic enclave (MME) sample (Table 1; Fig. 2).

The five early Neoproterozoic gneiss samples comprise one tonalitic gneisses (sample 17SD34-5), three trondhjemitic gneisses (samples 17SD58-2, 17SD58-4 and 16SD189-1) and one granodioritic gneiss (sample 16SD157-3) (TTG gneisses), all of which show fine-grained textures and gneissic structures. They have a major mineral association of quartz (25–30%), plagioclase (50–60%), alkali-feldspar (5–8%), biotite (5–8%), and amphibole (3–5%) (Fig. 2G) with accessory minerals ilmenite, magnetite, zircon and titanite. These rocks were metamorphosed in the lower amphibolite facies and some amphiboles and plagioclases were altered to epidotes and zoisites.

The middle Neoproterozoic tonalitic gneisses (samples 17SD22-1, 17SD24-1, 16SD161-3 and 16SD161-4) show fine-grained textures and gneissic structures and comprise quartz (17–19%), plagioclase

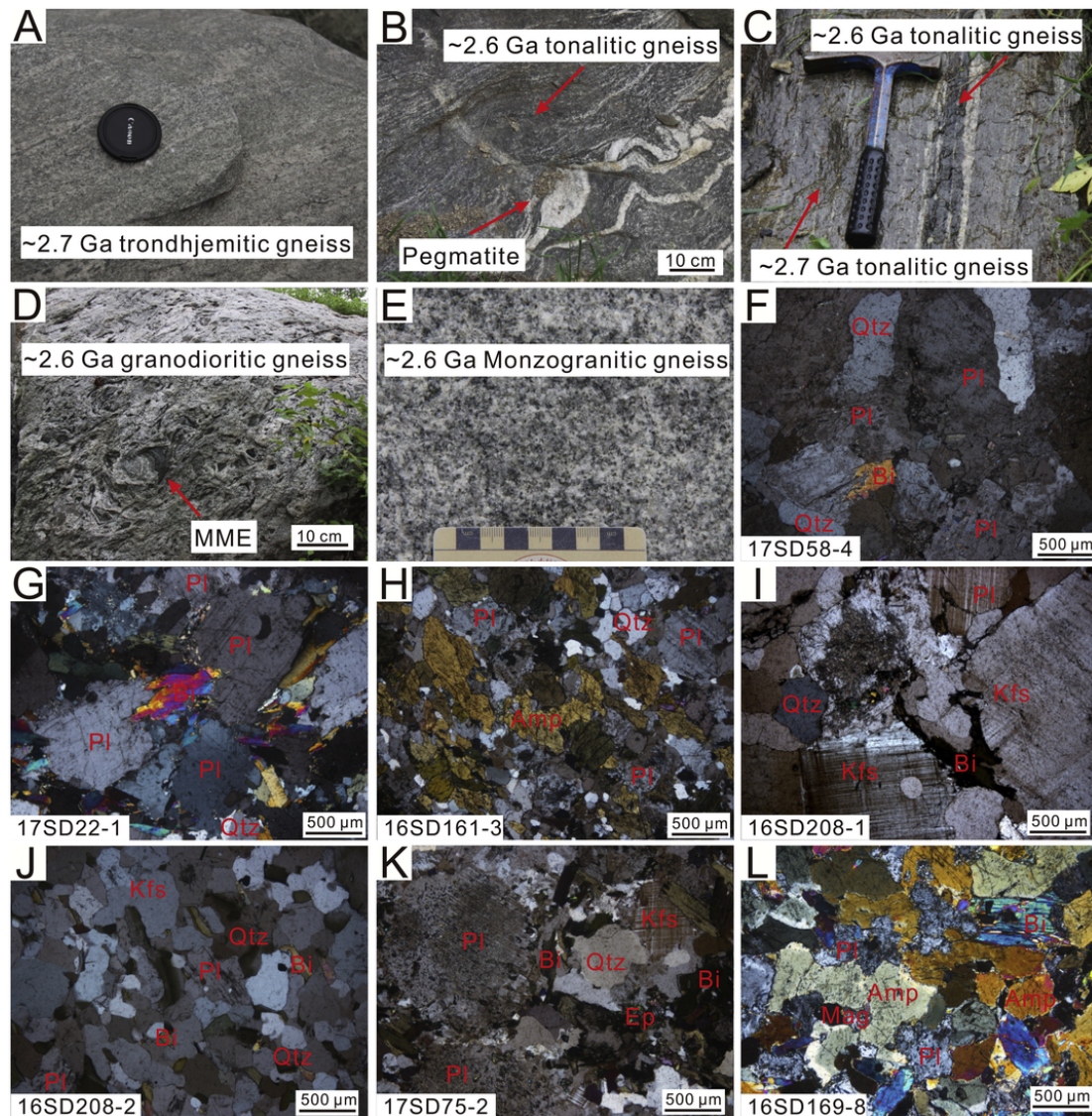


Fig. 2. Field photographs showing typical geological relationships and macroscopic lithological features on the field outcrops (A–F): (A) The structure of the ~2.7 Ga trondhjemitic gneiss; (B) ~2.6 Ga tonalitic gneisses with intruded pegmatite veins; (C) The similar foliation of the ~2.7 Ga tonalitic gneiss and ~2.6 Ga tonalitic gneiss; (D) ~2.6 Ga granodioritic gneiss with mafic magmatic enclaves (MMEs); (E) Hand specimen of the ~2.6 Ga monzogranitic gneiss. Photomicrographs showing the typical petrographic features of the representative samples (F–L; under cross-polarized light): (F) ~2.7 Ga trondhjemitic gneiss (sample 17SD58-4); (G) ~2.6 Ga tonalitic gneiss (Sample 17SD22-1); (H) ~2.6 Ga tonalitic gneiss (Sample 16SD161-3); (I) ~2.6 Ga monzogranitic gneiss (sample 16SD208-1); (J) ~2.6 Ga granodioritic gneiss (sample 16SD208-2); (K) ~2.6 Ga granodioritic gneiss (sample 17SD75-2); (L) MME (sample 16SD169-8). Mineral abbreviations: Qtz-quartz; Pl-plagioclase; Kfs-K-feldspar; Bi-biotite; Amp-amphibole; Ep-epidote; Mag-magnetite.

(58–62%), alkali-feldspar (3–6%), biotite (5–8%) and amphibole (6–15%) with accessory minerals zircon and magnetite (Fig. 2H–I). These samples were subjected to lower amphibolite facies metamorphism, and the feldspar crystals were altered to sericites and kaolinites. The monzogranitic gneisses (samples 16SD200-1, 16SD208-1, 17SD41-3 and 17SD41-4) show fine-grained or porphyritic textures and weakly gneissic structures. The microcline and plagioclase phenocrysts show grain sizes of 1–2 mm, and the matrix displays a fine-grained texture (0.5–1 mm) (Fig. 2J). These samples are composed of quartz (33–35%), plagioclase (19–21%), alkali-feldspar (38–40%), biotite (4–6%) and amphibole (2–3%) with zircon and epidote as the accessory minerals. These rocks were metamorphosed in the lower amphibolite facies and some plagioclases and alkali-feldspars were altered to zoisites and kaolinites, respectively. The

granodioritic gneisses (samples 16SD169-1, 16SD169-2, 16SD170-1, 16SD208-2, 17SD29-1, 17SD36-4, 17SD36-5-1 and 17SD75-2) show fine-grained or porphyritic textures and gneissic structures, comprising quartz (21–28%), plagioclase (37–45%), alkali-feldspar (17–20%), biotite (2–21%) and amphibole (6–14%) and accessory zircon, magnetite and epidote (Fig. 2K). The mafic minerals show an inhomogeneous distribution. The plagioclases and alkali-feldspars are partially altered to zoisites and kaolinites, respectively. The MME sample (16SD169-8, monzodiorite) is composed of quartz (6%), plagioclase (25%), alkali-feldspar (10%), biotite (12%), amphibole (45%) and magnetite (2%) with accessory zircon and epidote (Fig. 2L). Some amphiboles and plagioclases were altered to epidotes and zoisites.

Table 1

Sampling locations and simplified petrological features of the granitoid rock samples from the Western Shandong Terrane.

Sample	Latitude(N)	Longitude(E)	Lithology	Mineral assemblage
16SD157-3	35°41'48.14"	117°38'31.77"	Tonalitic gneiss	Qz(30%)+Pl(50%)+Kfs(5%)+Amp(5%)+Bi(10%)
16SD189-1	35°23'29.24"	118°09'31.89"	Trondhjemitic gneiss	Qz(28%)+Pl(58%)+Kfs(8%)+Bi(6%)
17SD34-5	36°25'00.25"	117°22'12.80"	Tonalitic gneiss	Qz(30%)+Pl(55%)+Kfs(5%)+Amp(3%)+Bi(7%)
17SD58-2	35°27'40.38"	118°17'21.07"	Trondhjemitic gneiss	Qz(28%)+Pl(59%)+Kfs(5%)+Bi(8%)
17SD58-4	35°27'40.38"	118°17'21.07"	Trondhjemitic gneiss	Qz(25%)+Pl(60%)+Kfs(5%)+Bi(5%)
17SD24-1	36°19'52.18"	117°09'29.17"	Tonalitic gneiss	Qz(18%)+Pl(62%)+Kfs(4%)+Amp(8%)+Bi(8%)
17SD22-1	36°17'59.20"	117°09'29.60"	Tonalitic gneiss	Qz(19%)+Pl(61%)+Kfs(6%)+Amp(6%)+Bi(8%)
16SD161-3	35°43'25.82"	117°37'08.44"	Tonalitic gneiss	Qz(18%)+Pl(60%)+Kfs(3%)+Amp(15%)+Bi(5%)
16SD161-4	35°43'25.82"	117°37'08.44"	Tonalitic gneiss	Qz(17%)+Pl(58%)+Kfs(6%)+Amp(14%)+Bi(5%)
16SD169-1	35°33'09.34"	118°12'53.80"	Granodioritic gneiss	Qz(22%)+Pl(38%)+Kfs(19%)+Amp(21%)
16SD169-2	35°33'09.34"	118°12'53.80"	Granodioritic gneiss	Qz(22%)+Pl(40%)+Kfs(18%)+Amp(20%)
17SD36-4	36°26'10.52"	117°23'01.54"	Granodioritic gneiss	Qz(26%)+Pl(38%)+Kfs(19%)+Amp(3%)+Bi(14%)
16SD208-2	35°56'02.04"	118°00'26.28"	Granodioritic gneiss	Qz(28%)+Pl(37%)+Kfs(20%)+Amp(2%)+Bi(13%)
17SD36-5-1	36°26'10.52"	117°23'01.54"	Granodioritic gneiss	Qz(25%)+Pl(39%)+Kfs(18%)+Amp(5%)+Bi(13%)
17SD75-2	36°10'05.39"	118°32'46.66"	Granodioritic gneiss	Qz(24%)+Pl(44%)+Kfs(17%)+Amp(3%)+Bi(12%)
17SD29-1	36°21'44.19"	117°11'23.31"	Granodioritic gneiss	Qz(21%)+Pl(42%)+Kfs(19%)+Amp(12%)+Bi(6%)
16SD170-1	35°33'47.35"	118°13'25.45"	Granodioritic gneiss	Qz(23%)+Pl(45%)+Kfs(18%)+Amp(6%)+Bi(8%)
16SD208-1	35°56'02.04"	118°00'26.28"	Monzogranitic gneiss	Qz(35%)+Pl(20%)+Kfs(40%)+Amp(2%)+Bi(6%)
17SD41-4	36°29'25.19"	117°21'18.84"	Monzogranitic gneiss	Qz(33%)+Pl(21%)+Kfs(39%)+Amp(2%)+Bi(5%)
17SD41-3	36°29'25.19"	117°21'18.84"	Monzogranitic gneiss	Qz(34%)+Pl(19%)+Kfs(40%)+Amp(2%)+Bi(5%)
16SD200-1	35°59'58.67"	117°39'44.61"	Monzogranitic gneiss	Qz(35%)+Pl(20%)+Kfs(38%)+Amp(3%)+Bi(4%)
16SD169-8	35°33'09.34"	118°12'53.80"	Monzodiorite	Qz(6%)+Pl(25%)+Kfs(10%)+Amp(45%)+Bi(12%)+Mag(2%)

Note: Qz, Quartz; Kfs, K-feldspar; Pl, Plagioclase; Amp, Amphibole; Bi, Biotite; Mag, Magnetite.

4. Analytical methods

Nineteen Neoproterozoic granitoid samples from the WST were selected for whole-rock major and trace element analyses by X-ray fluorescence (XRF) and Agilent 7500 inductively coupled plasma mass spectrometry (ICP-MS), respectively. The measurement precisions of the major and trace elements were 0.5% and 5%, respectively. Four representative samples were selected for in situ zircon U-Pb dating by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), and the dated zircon grains were further used for Lu-Hf isotope analyses by a Neptune Plus multiple collector ICP-MS with a Geolas 2005 excimer ArF laser ablation system. The analytical results and detailed procedures are presented in Tables 2–4 and Supplementary Table S1.

5. Analytical results

5.1. Whole-rock geochemical characteristics

5.1.1. The ~2.7 Ga TTG gneisses

A total of twenty-four chemical data of ~2.7 Ga TTG gneisses, including our newly analysed samples 17SD34-5, 17SD58-2, 17SD58-4, 16SD157-3 and 16SD189-1 and some recently published data (Supplementary Table S2; Gao et al., 2019b; Hu et al., unpublished data; Jiang et al., 2010; Sun et al., 2019b; Wan et al., 2011) are discussed together here. However, an average value of seven ~2.7 Ga grey gneiss samples' major element contents published by Jahn et al. (1988), is not used in the discussion because the compositions of each sample are unknown, and the defined grey gneisses including dioritic gneisses are not equated to the TTG gneisses. These TTG gneisses exhibit high contents of SiO₂ (65.10–72.89 wt%), with an average of 70.10 wt%, Al₂O₃ (14.17–17.36 wt%) and Na₂O (3.64–5.66 wt%) but lower contents of TiO₂, MgO, TFe₂O₃, CaO and K₂O of 0.09–0.57 wt%, 0.58–2.02 wt%, 1.04–5.37 wt%, 1.71–4.93 wt% and 0.78–2.95 wt%, respectively, and low K₂O/Na₂O ratios of 0.15–0.56. They belong to granodiorite to granite fields and medium-K calc-alkaline to low-K tholeiitic series based on the total alkali-silica (TAS)

and K₂O-SiO₂ diagrams, respectively (Fig. 3A–B). In the An-Ab-Or diagram, six samples (16SD188-2, 16SD186-2, 6LB03-1, SY0336, S0732 and 16SD189-1) plot to the trondhjemite field and four samples (16SD185-1, 16SD199-1, S0741 and 16SD157-3) plot to the granodiorite field, while the others plot in the tonalite field (Fig. 3C). These samples show relatively high A/CNK values (0.90–1.16) and plot in the metaluminous to peraluminous fields in the A/CNK-A/NK diagram (Fig. 3D). They plot in the experimentally derived partial melts from metabasaltic rocks (PMB) range in the MgO-SiO₂ diagram with low Mg# values of 34–45 (except for sample S0732, with a value of 49 due to its low TFe₂O₃ content; Fig. 3E–F).

These TTG gneisses display transition metal Cr, Ni, V and Co concentrations of 4.45–61 ppm, 1.77–11.1 ppm, 11.6–49 ppm and 3.01–14.4 ppm, respectively. They are characterized by middle total rare earth element (TREE) contents of 27–256 ppm and fractionated rare earth element (REE) patterns with (La/Yb)_N ratios of 7.84–93 and slightly negative to positive Eu anomalies ($\delta\text{Eu} = \text{Eu}_N / \sqrt{\text{Sm}_N \times \text{Gd}_N}$) = 0.78–1.38, except for 1.66 for sample 16SD160-1 and 2.22 for 6LB03-1; Fig. 4A). In the spider diagram of the trace elements, these samples show enrichments in Ba, Rb, Zr, K, and Hf and significant depletions in Nb, Ti, Y and Yb (Table 2; Fig. 4B).

5.1.2. The ~2.62 Ga tonalitic gneisses

The four tonalitic gneisses display low contents of SiO₂ (63.22–65.44 wt%), K₂O (0.46–1.52 wt%) and TiO₂ (0.41–0.50 wt%) but high contents of Al₂O₃ (15.40–16.45 wt%), Na₂O (3.90–4.94 wt%), MgO (2.11–3.18 wt%), TFe₂O₃ (4.14–5.24 wt%) and CaO (4.99–6.97 wt%) with K₂O/Na₂O ratios of 0.10–0.39 and high Mg# values of 47–57. These samples plot in the granodiorite domain and low-K tholeiitic to medium-K calc-alkaline series in the TAS and K₂O-SiO₂ diagrams, respectively (Fig. 3A–B) and in the tonalite range in the An-Ab-Or diagram (Fig. 3C). Moreover, they show A/CNK values of 0.77–0.93 and are attributed to the metaluminous rock series based on the A/CNK-A/NK plot (Fig. 3D). All these samples fall within the high-silica adakite (HSA) area and the adakite range in the MgO-SiO₂ and Mg# versus SiO₂ diagrams, respectively (Fig. 3E–F).

The tonalitic gneisses show V and Co contents of 18.3–26 ppm and 3.01–4.48 ppm, respectively. They are characterized by lower

Table 2

Analytical results of major and trace elements for granitoid rocks and an enclosed MME from the Western Shandong Terrane.

Sample	~2.7 Ga TTG gneisses					~2.6 Ga tonalitic gneisses			~2.6 Ga monzogranitic gneisses		
	16SD157-3	16SD189-1	17SD34-5	17SD58-2	17SD58-4	17SD24-1	17SD22-1	16SD161-3	16SD161-4	16SD208-1	17SD41-4
Data source	Sun et al., 2019b	Sun et al., 2019b	This study	This study	This study	This study	This study	This study	This study	This study	This study
SiO ₂	72.03	69.89	72.89	70.17	70.77	65.44	63.49	63.22	64.64	75.12	72.55
Al ₂ O ₃	14.67	15.60	14.51	14.83	14.65	15.40	16.13	16.45	15.66	13.10	14.25
TF ₂ O ₃	2.92	2.46	2.33	2.11	1.74	4.90	5.24	4.25	4.14	1.38	2.04
CaO	2.86	2.14	2.59	1.71	1.96	4.99	5.07	6.97	6.47	0.98	1.09
MgO	0.95	0.74	0.59	0.69	0.58	2.16	3.18	2.11	2.74	0.23	0.30
K ₂ O	2.03	2.75	2.04	2.95	2.75	1.22	1.52	0.58	0.46	5.74	5.81
Na ₂ O	3.78	5.25	3.96	5.66	4.88	3.92	3.90	4.94	4.55	2.69	2.74
MnO	0.03	0.04	0.03	0.03	0.03	0.08	0.08	0.08	0.08	0.01	0.02
TiO ₂	0.33	0.36	0.28	0.32	0.26	0.41	0.48	0.50	0.44	0.15	0.27
P ₂ O ₅	0.08	0.08	0.08	0.12	0.08	0.13	0.12	0.22	0.14	0.02	0.09
LOI	0.21	0.50	0.56	1.23	2.15	1.22	0.64	0.55	0.56	0.42	0.66
Total	99.89	99.81	99.88	99.81	99.84	99.87	99.85	99.87	99.90	99.85	99.84
Mg#	39	37	34	40	40	47	55	50	57	25	23
K ₂ O/Na ₂ O	0.54	0.52	0.52	0.52	0.56	0.31	0.39	0.12	0.10	2.13	2.12
A/NK	1.74	1.34	1.66	1.19	1.33	1.98	2.00	1.88	1.96	1.23	1.32
A/CNK	1.08	1.00	1.08	0.95	1.00	0.91	0.93	0.77	0.79	1.05	1.11
AFM	2.39	3.11	3.24	3.33	3.97	1.31	1.09	1.52	1.28	5.58	4.22
CFM	0.85	0.78	1.06	0.70	0.97	0.77	0.62	1.17	0.96	0.76	0.59
Cr	13.2	43	8.55	15.3	6.4	37	88	53	74	31	8.03
Ni	8.54	4.93	1.95	6.69	3.12	25	46	31	27	3.22	1.72
Co	8.09	4.58	4.48	3.90	3.01	12.8	16.6	15.2	9.54	2.43	2.84
V	49	40	26	26	18.3	71	94	83	67	22	25
Rb	110	93	39	148	127	32	55	12.6	7.71	238	151
Sr	227	459	348	565	486	411	449	427	429	130	265
Y	3.95	3.32	7.89	9.80	10.1	22	11.7	10.9	9.00	9.59	9.56
Nb	2.13	5.42	5.46	10.5	10.1	4.98	4.50	3.85	4.42	8.36	2.76
Ta	0.40	0.28	0.28	0.65	0.75	0.36	0.44	0.49	0.71	0.33	0.24
Cs	9.49	4.35	0.59	5.06	2.65	0.74	1.33	0.14	0.10	3.26	2.30
Ba	390	796	574	774	729	600	682	179	197	448	936
La	14.3	31	26	59	61	19.6	14	17.7	13.2	54	91
Ce	32	69	53	116	123	45	28	41	34	102	176
Pr	2.96	5.51	6.29	12.1	12.9	5.83	3.48	4.77	3.42	11.6	16.9
Nd	10.0	16.8	22	39	42	23	13.5	16.9	11.8	41	49
Sm	1.64	1.93	4.04	5.52	5.74	5.25	3.01	3.27	2.56	7.02	6.04
Eu	0.52	0.80	1.06	1.45	1.34	1.13	1.07	0.99	0.82	0.84	1.01
Gd	1.41	2.61	3.58	4.71	4.79	5.32	2.96	3.13	2.49	7.03	5.26
Tb	0.17	0.20	0.43	0.47	0.49	0.78	0.42	0.41	0.34	0.64	0.47
Dy	0.81	0.78	1.87	2.02	2.05	4.37	2.28	2.05	1.77	2.46	1.95
Ho	0.16	0.14	0.32	0.35	0.36	0.85	0.45	0.40	0.35	0.38	0.37
Er	0.43	0.49	0.74	0.90	0.92	2.23	1.23	1.09	0.95	1.12	1.02
Tm	0.06	0.06	0.10	0.14	0.14	0.31	0.18	0.15	0.14	0.12	0.15
Yb	0.43	0.43	0.61	0.91	0.91	1.85	1.14	1.00	0.90	0.82	1.01
Lu	0.07	0.06	0.10	0.14	0.14	0.26	0.17	0.15	0.14	0.12	0.16
Pb	9.31	11.4	10.7	13.6	18.3	11.6	9.42	2.97	2.18	40	30
Th	7.69	11.4	4.69	12.3	14.8	1.52	2.61	2.34	2.70	62	24
U	1.52	11.0	0.38	2.53	3.17	0.22	0.56	0.54	0.69	7.50	1.38
Zr	121	64	140	195	144	134	103	133	132	160	283
Hf	3.60	1.59	3.71	5.03	3.82	3.45	2.83	3.3	3.41	4.98	7.37
δCe	1.22	1.31	1.03	1.07	1.08	1.03	1.00	1.11	1.24	1.00	1.10
δEu	1.04	1.09	0.86	0.87	0.78	0.66	1.09	0.95	1.00	0.36	0.55

Table 2 (Continued)

Sample	~2.7 Ga TTG gneisses					~2.6 Ga tonalitic gneisses				~2.6 Ga monzogranitic gneisses		
	16SD157-3	16SD189-1	17SD34-5	17SD58-2	17SD58-4	17SD24-1	17SD22-1	16SD161-3	16SD161-4	16SD208-1	17SD41-4	
Data source	Sun et al., 2019b	Sun et al., 2019b	This study	This study	This study	This study	This study	This study	This study	This study	This study	
(La/Yb) _N	24	50	30	46	48	7.60	8.85	12.7	10.6	47	64	
(Gd/Yb) _N	2.74	4.87	4.77	4.17	4.27	2.33	2.11	2.54	2.25	6.92	4.19	
Sr/Y	57	138	44	58	48	18.8	38	39	48	13.6	28	
TREE	65	130	120	243	256	116	72	93	73	228	350	
Sample	~2.6 Ga monzogranitic gneisses			~2.6 Ga granodioritic gneisses								MME
	17SD41-3	16SD200-1	S1507	16SD169-1	16SD169-2	17SD36-4	16SD208-2	17SD36-5-1	17SD75-2	17SD29-1	16SD170-1	16SD169-8
Data source	This study	This study	Ren et al., 2017	This study	This study	This study	This study	This study	This study	This study	This study	This study
SiO ₂	73.13	74.29	70.35	67.76	67.31	71.09	73.04	70.80	70.10	66.34	69.00	53.27
Al ₂ O ₃	14.83	13.36	14.72	13.25	14.34	13.41	13.62	13.51	14.25	14.85	14.57	16.55
TFe ₂ O ₃	1.08	1.60	0.00	6.13	4.73	4.30	3.02	3.91	3.35	4.43	3.88	11.51
CaO	1.68	1.24	2.07	3.09	2.21	1.31	1.14	1.34	2.50	4.00	2.44	1.84
MgO	0.33	0.20	0.77	3.51	2.57	2.08	1.39	1.96	1.57	2.24	1.84	5.85
K ₂ O	4.72	4.35	4.66	2.66	3.25	3.16	4.32	3.12	2.82	2.23	2.85	4.94
Na ₂ O	3.28	4.14	3.38	2.23	2.98	2.58	2.41	3.20	4.05	3.64	4.01	2.63
MnO	0.01	0.02	0.08	0.07	0.06	0.06	0.04	0.05	0.05	0.07	0.04	0.13
TiO ₂	0.12	0.16	0.34	0.49	0.45	0.46	0.25	0.39	0.31	0.49	0.40	1.14
P ₂ O ₅	0.07	0.03	0.11	0.07	0.21	0.15	0.08	0.08	0.11	0.20	0.15	0.13
LOI	0.56	0.49	0.60	0.58	1.70	1.23	0.46	1.45	0.72	1.34	0.69	1.79
Total	99.82	99.88	100.22	99.86	99.81	99.83	99.76	99.83	99.82	99.83	99.87	99.77
Mg#	26	20	34	53	52	49	48	50	48	50	49	50
K ₂ O/Na ₂ O	1.44	1.05	1.38	1.19	1.09	1.22	1.79	0.97	0.70	0.61	0.71	1.88
A/NK	1.41	1.16	1.39	2.02	1.70	1.75	1.57	1.56	1.47	1.77	1.51	1.71
A/CNK	1.09	0.97	1.02	1.09	1.15	1.33	1.27	1.22	1.00	0.95	1.03	1.27
AFM	6.65	5.25	2.52	0.79	1.14	1.24	1.84	1.35	1.72	1.31	1.51	–
CFM	1.37	0.88	0.64	0.34	0.32	0.22	0.28	0.24	0.55	0.64	0.46	–
Cr	15.9	12.1	8.25	195	102	164	91	4.61	41	46	81	252
Ni	6.19	0.97	4.40	60	44	59	29	1.08	14.6	23	32	98
Co	3.00	1.47	–	22	17.9	13.9	9.27	2.82	8.96	12.6	12.6	36
V	20	14.3	–	122	81	78	52	21	53	90	70	192
Rb	130	209	225	122	133	144	240	161	115	82	177	213
Sr	334	103	202	329	323	353	353	342	467	631	390	291
Y	16.0	5.68	23	16.1	11.3	7.35	13.6	5.96	9.24	13.2	5.40	8.24
Nb	3.73	5.19	16.4	4.76	8.41	11.0	4.91	9.74	5.84	4.88	10.8	3.38
Ta	0.36	0.36	1.79	0.48	1.12	0.60	0.73	1.00	0.68	0.42	0.53	0.19
Cs	2.01	7.57	–	4.65	4.83	4.03	6.51	2.09	3.48	4.95	5.32	7.90
Ba	931	359	772	328	755	733	2338	1288	990	693	545	823
La	66	51	89	22	49	28	19.4	53	30	42	49	21
Ce	136	98	167	43	98	55	40	92	53	85	90	39
Pr	15.5	10.0	16.2	5.28	10.5	6.38	4.79	8.95	5.26	9.82	9.25	4.65
Nd	50	29	54	19.6	35	22	18.2	26	17.0	35	28	15.4
Sm	8.29	3.90	9.32	3.71	5.64	3.66	3.48	3.13	2.65	6.07	3.57	2.85
Eu	1.35	0.57	0.99	0.93	1.08	0.88	1.42	1.02	0.92	1.55	0.92	1.15
Gd	6.60	3.30	7.92	3.62	4.84	3.22	3.89	2.75	2.65	5.31	3.11	2.54
Tb	0.71	0.29	1.03	0.52	0.54	0.36	0.50	0.25	0.33	0.61	0.27	0.31
Dy	3.16	1.08	4.88	2.91	2.35	1.62	2.74	1.02	1.72	2.89	1.06	1.49
Ho	0.61	0.19	0.90	0.61	0.43	0.29	0.51	0.20	0.35	0.53	0.19	0.30
Er	1.77	0.56	2.62	1.67	1.13	0.71	1.58	0.59	0.95	1.40	0.52	0.91

Table 2 (Continued)

Sample	~2.6 Ga monzogranitic gneisses			~2.6 Ga granodioritic gneisses								MME
	17SD41-3	16SD200-1	S1507	16SD169-1	16SD169-2	17SD36-4	16SD208-2	17SD36-5-1	17SD75-2	17SD29-1	16SD170-1	16SD169-8
Data source	This study	This study	Ren et al., 2017	This study	This study	This study	This study	This study	This study	This study	This study	This study
Tm	0.29	0.10	0.36	0.25	0.16	0.09	0.20	0.10	0.14	0.19	0.08	0.15
Yb	2.08	0.74	2.38	1.65	1.01	0.57	1.30	0.65	0.97	1.24	0.53	1.08
Lu	0.36	0.14	0.36	0.25	0.15	0.09	0.18	0.10	0.16	0.18	0.09	0.18
Pb	28	36	—	14.1	40	18.5	25	23	16.2	14.6	20	6.77
Th	49	43	45	6.52	16.3	10.9	10.0	34	21	7.99	16.1	7.37
U	9.42	18.5	7.24	1.95	2.06	0.83	3.05	3.53	4.35	2.95	1.46	2.38
Zr	468	182	267	126	229	136	61	220	163	178	237	46
Hf	14.8	6.16	6.56	3.51	6.22	3.77	1.94	5.60	4.58	4.69	6.43	1.27
δCe	1.05	1.07	1.08	0.99	1.06	1.01	1.02	1.04	1.04	1.02	1.04	0.22
δEu	0.56	0.49	0.35	0.78	0.63	0.78	1.18	1.06	1.06	0.83	0.84	0.46
$(\text{La}/\text{Yb})_{\text{N}}$	23	49	27	9.41	34	35	10.7	58	22	24	67	13.8
$(\text{Gd}/\text{Yb})_{\text{N}}$	2.56	3.59	2.69	1.77	3.87	4.58	2.42	3.42	2.22	3.48	4.79	1.90
Sr/Y	21	18.1	8.86	20	29	48	26	57	51	48	72	35
TREE	293	198	357	106	210	123	98	190	116	191	186	91

Notes: wt%, major and minor element oxides in weight percent; ppm, trace elements in parts per million; LOI, Loss on ignition; $\text{Mg\#} = 100 \times \text{molar Mg}^{2+} / (\text{Mg}^{2+} + \text{TFe}^{2+})$; A/CNK = molar $\text{Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$; TREE, total rare earth elements; $\delta\text{Eu} = \text{Eu}_{\text{N}} / \sqrt{(\text{Sm}_{\text{N}} \times \text{Gd}_{\text{N}})}$; $\delta\text{Ce} = \text{Ce}_{\text{N}} / \sqrt{(\text{La}_{\text{N}} \times \text{Pr}_{\text{N}})}$; subscript N, chondrite normalized value. “—” represents not given.

Table 3

Analysed zircon U-Pb isotopic data and calculated apparent ages for representative granitoid samples from the Western Shandong Terrane.

Sample and analytical spot number	Isotopic ratios						Apparent ages(Ma)							
	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	
16SD157-3-01	0.71	0.1836	0.0041	13.1004	0.2746	0.5171	0.0100	2685	15	2687	20	2687	43	
16SD157-3-02	0.54	0.1827	0.0045	13.0819	0.3110	0.5187	0.0109	2678	18	2686	22	2694	46	
16SD157-3-03	0.44	0.1850	0.0041	13.2787	0.2766	0.5201	0.0101	2698	15	2700	20	2700	43	
16SD157-3-04	0.28	0.1825	0.0040	11.7906	0.2399	0.4680	0.0089	2676	15	2588	19	2475	39	
16SD157-3-05	0.39	0.1817	0.0041	12.8465	0.2781	0.5123	0.0101	2668	16	2668	20	2666	43	
16SD157-3-06	0.66	0.1849	0.0040	13.2584	0.2680	0.5196	0.0099	2697	15	2698	19	2698	42	
16SD157-3-07	0.59	0.1824	0.0040	12.9450	0.2693	0.5142	0.0099	2675	15	2676	20	2674	42	
16SD157-3-08	0.71	0.1831	0.0040	12.2334	0.2523	0.4841	0.0093	2681	15	2622	19	2545	40	
16SD157-3-09	0.73	0.1852	0.0040	13.3040	0.2735	0.5205	0.0100	2700	15	2701	19	2701	42	
16SD157-3-10	0.07	0.1726	0.0037	11.7410	0.2367	0.4930	0.0093	2583	15	2584	19	2584	40	
16SD157-3-11	0.91	0.1835	0.0042	13.0749	0.2815	0.5165	0.0102	2684	16	2685	20	2684	43	
16SD157-3-12	0.73	0.1874	0.0044	13.5728	0.3045	0.5248	0.0106	2720	16	2720	21	2719	45	
16SD157-3-13	0.48	0.1846	0.0040	13.2266	0.2704	0.5193	0.0099	2694	15	2696	19	2696	42	
16SD157-3-14	0.39	0.1831	0.0044	11.7742	0.2739	0.4659	0.0096	2682	17	2587	22	2466	42	
16SD157-3-15	0.40	0.1856	0.0041	13.3327	0.2745	0.5207	0.0100	2703	15	2703	19	2702	42	
16SD157-3-16	0.39	0.1848	0.0041	13.2500	0.2794	0.5196	0.0101	2697	16	2698	20	2697	43	
16SD157-3-17	0.33	0.1852	0.0041	13.2963	0.2756	0.5203	0.0100	2700	15	2701	20	2701	42	
16SD157-3-18	0.48	0.1853	0.0041	12.6768	0.2612	0.4960	0.0095	2700	15	2656	19	2596	41	
16SD157-3-19	0.62	0.1828	0.0042	12.9961	0.2862	0.5152	0.0103	2679	16	2679	21	2679	44	
16SD189-1-01	1.08	0.1821	0.0041	13.1272	0.2747	0.5229	0.0100	2672	15	2689	20	2711	42	
16SD189-1-02	0.23	0.1731	0.0053	10.0413	0.2389	0.4208	0.0081	2588	52	2439	22	2264	37	
16SD189-1-03	0.24	0.1868	0.0042	13.4920	0.2849	0.5238	0.0101	2714	16	2715	20	2715	43	
16SD189-1-04	0.58	0.1820	0.0040	12.8821	0.2669	0.5133	0.0098	2672	15	2671	20	2671	42	
16SD189-1-05	1.07	0.1814	0.0042	12.8168	0.2810	0.5124	0.0101	2666	16	2666	21	2667	43	
16SD189-1-06	0.53	0.1832	0.0042	13.0361	0.2811	0.5161	0.0101	2682	16	2682	20	2683	43	
16SD189-1-07	0.69	0.1848	0.0041	13.2288	0.2768	0.5191	0.0099	2697	15	2696	20	2696	42	
16SD189-1-08	0.40	0.1823	0.0041	12.9098	0.2692	0.5138	0.0098	2674	15	2673	20	2673	42	
16SD189-1-09	0.35	0.1785	0.0043	12.4379	0.2835	0.5055	0.0102	2639	17	2638	21	2637	44	
16SD189-1-10	0.68	0.1790	0.0041	12.5063	0.2681	0.5068	0.0098	2644	16	2643	20	2643	42	
16SD189-1-11	0.39	0.1825	0.0041	12.9424	0.2728	0.5145	0.0099	2675	16	2675	20	2676	42	
16SD189-1-12	0.38	0.1850	0.0042	13.2587	0.2804	0.5199	0.0100	2698	16	2698	20	2699	42	
16SD189-1-13	0.67	0.1851	0.0044	13.2972	0.2978	0.5210	0.0104	2699	16	2701	21	2703	44	
16SD189-1-14	0.68	0.1837	0.0042	13.0872	0.2794	0.5167	0.0100	2687	16	2686	20	2685	42	
16SD189-1-15	0.17	0.1842	0.0041	13.1494	0.2740	0.5179	0.0098	2691	15	2690	20	2690	42	
16SD189-1-16	0.21	0.1761	0.0052	9.6352	0.2160	0.3969	0.0076	2616	50	2401	21	2155	35	
16SD189-1-17	0.42	0.1828	0.0051	12.9839	0.3534	0.5154	0.0117	2678	20	2678	26	2679	50	
16SD189-1-18	0.25	0.1827	0.0041	10.6014	0.2232	0.4209	0.0080	2678	16	2489	20	2265	36	
16SD189-1-19	0.56	0.1867	0.0043	13.4767	0.2900	0.5236	0.0102	2713	16	2714	20	2714	43	
16SD189-1-20	0.25	0.1828	0.0041	12.9817	0.2741	0.5151	0.0098	2678	16	2678	20	2679	42	
16SD189-1-21	0.28	0.1831	0.0042	13.0212	0.2782	0.5158	0.0099	2681	16	2681	20	2681	42	
16SD189-1-22	0.24	0.1832	0.0042	13.0312	0.2784	0.5161	0.0099	2682	16	2682	20	2683	42	
17SD22-1-01	0.93	0.1767	0.0039	12.2397	0.2342	0.5022	0.0088	2622	14	2623	18	2623	38	
17SD22-1-02	0.97	0.1778	0.0039	12.3745	0.2336	0.5046	0.0087	2633	14	2633	18	2634	37	
17SD22-1-03	0.60	0.1770	0.0041	12.2774	0.2471	0.5030	0.0091	2625	15	2626	19	2626	39	
17SD22-1-04	0.65	0.1772	0.0040	12.2856	0.2459	0.5028	0.0091	2627	15	2626	19	2626	39	
17SD22-1-05	0.67	0.1768	0.0039	12.2515	0.2334	0.5026	0.0088	2623	14	2624	18	2625	38	
17SD22-1-06	0.94	0.1775	0.0039	12.3226	0.2289	0.5035	0.0086	2629	14	2629	17	2629	37	
17SD22-1-07	0.69	0.1769	0.0040	12.2599	0.2372	0.5027	0.0088	2624	14	2625	18	2625	38	
17SD22-1-08	0.62	0.1773	0.0040	12.2939	0.2422	0.5029	0.0089	2628	15	2627	19	2626	38	
17SD22-1-09	0.66	0.1751	0.0039	12.0378	0.2310	0.4986	0.0087	2607	14	2607	18	2608	37	
17SD22-1-10	0.64	0.1764	0.0039	12.1934	0.2340	0.5012	0.0088	2620	14	2619	18	2619	38	
17SD22-1-11	0.66	0.1771	0.0040	12.2709	0.2381	0.5025	0.0088	2626	14	2625	18	2625	38	
17SD22-1-12	0.59	0.1758	0.0040	12.1177	0.2356	0.4998	0.0088	2614	14	2614	18	2613	38	
17SD22-1-13	0.85	0.1770	0.0040	12.2731	0.2434	0.5028	0.0090	2625	15	2626	19	2626	38	
17SD22-1-14	0.52	0.1765	0.0041	12.1986	0.2516	0.5013	0.0092	2620	15	2620	19	2619	39	
17SD22-1-15	0.72	0.1752	0.0039	12.0381	0.2317	0.4984	0.0087	2607	14	2607	18	2607	37	
17SD22-1-16	0.53	0.1779	0.0040	11.5878	0.2289	0.4724	0.0084	2633	15	2572	18	2494	37	
17SD22-1-17	0.56	0.1759	0.0039	12.1297	0.2346	0.5002	0.0087	2614	14	2614	18	2615	38	
17SD22-1-18	0.72	0.1752	0.0039	12.0405	0.2271	0.4984	0.0086	2608	14	2608	18	2607	37	
17SD22-1-19	0.71	0.1777	0.0041	12.3526	0.2468	0.5040	0.0090	2632	15	2632	19	2631	39	
17SD22-1-20	0.62	0.1771	0.0040	12.2803	0.2408	0.5029	0.0089	2626	15	2626	18	2626	38	
17SD22-1-21	0.62	0.1747	0.0039	12.0018	0.2268	0.4981	0.0086	2603	14	2605	18	2606	37	
17SD22-1-22	0.89	0.1750	0.0040	12.0236	0.2376	0.4984	0.0088	2606	15	2606	19	2607	38	
17SD22-1-23	0.69	0.1765	0.0040	12.2058	0.2441	0.5014	0.0089	2621	15	2620	19	2620	38	
17SD22-1-24	0.87	0.1763	0.0040	10.9425	0.2134	0.4501	0.0079	2618	14	2518	18	2396	35	

Table 3 (Continued)

Sample and analytical spot number	Isotopic ratios						Apparent ages(Ma)							
	Th/ U	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	
17SD22-1-25	0.93	0.1757	0.0039	12.1093	0.2300	0.4997	0.0086	2613	14	2613	18	2612	37	
16SD169-1-01	0.80	0.1720	0.0037	11.6621	0.2321	0.4917	0.0093	2577	15	2578	19	2578	40	
16SD169-1-02	0.75	0.1718	0.0037	10.6189	0.2158	0.4483	0.0086	2575	15	2490	19	2388	38	
16SD169-1-03	0.93	0.1727	0.0038	8.3464	0.1730	0.3506	0.0067	2583	15	2269	19	1937	32	
16SD169-1-04	0.56	0.1767	0.0038	12.2342	0.2460	0.5021	0.0095	2622	15	2623	19	2623	41	
16SD169-1-05	0.60	0.1770	0.0039	12.2713	0.2550	0.5027	0.0097	2625	15	2625	20	2625	42	
16SD169-1-06	0.82	0.1879	0.0041	13.6259	0.2780	0.5258	0.0101	2724	15	2724	19	2724	43	
16SD169-1-07	0.60	0.1733	0.0058	10.8467	0.2941	0.4540	0.0091	2590	57	2510	25	2413	40	
16SD169-1-08	0.79	0.1762	0.0038	12.1667	0.2449	0.5009	0.0095	2617	15	2617	19	2617	41	
16SD169-1-09	0.70	0.1717	0.0037	11.6258	0.2340	0.4909	0.0093	2575	15	2575	19	2575	40	
16SD169-1-10	0.06	0.1871	0.0040	13.5203	0.2737	0.5241	0.0100	2717	15	2717	19	2717	42	
16SD169-1-11	0.45	0.1515	0.0052	2.9667	0.0829	0.1420	0.0028	2363	60	1399	21	856	16	
16SD169-1-12	0.61	0.1710	0.0036	11.5458	0.2290	0.4896	0.0092	2568	15	2568	19	2569	40	
16SD169-1-13	0.43	0.1881	0.0041	13.6591	0.2789	0.5265	0.0101	2726	15	2726	19	2727	43	
16SD169-1-14	0.22	0.1846	0.0043	13.2124	0.2956	0.5191	0.0105	2695	16	2695	21	2695	45	
16SD169-1-15	0.64	0.1664	0.0036	6.5315	0.1299	0.2846	0.0054	2522	15	2050	18	1615	27	
16SD169-1-16	0.54	0.1717	0.0037	11.6310	0.2335	0.4912	0.0093	2574	15	2575	19	2576	40	
16SD169-1-17	1.09	0.1724	0.0037	11.7118	0.2336	0.4926	0.0093	2581	15	2582	19	2582	40	
16SD200-1-01	0.28	0.1706	0.0051	8.3479	0.2218	0.3551	0.0063	2563	22	2270	24	1959	30	
16SD200-1-02	0.69	0.1846	0.0057	10.6235	0.2735	0.4173	0.0073	2695	53	2491	24	2248	33	
16SD200-1-03	0.54	0.1749	0.0057	10.3614	0.2787	0.4298	0.0078	2605	55	2468	25	2305	35	
16SD200-1-04	0.34	0.1709	0.0053	11.5136	0.3214	0.4890	0.0091	2566	24	2566	26	2566	39	
16SD200-1-05	0.54	0.1719	0.0055	11.6272	0.3421	0.4909	0.0094	2576	25	2575	28	2575	41	
16SD200-1-06	0.18	0.1631	0.0054	7.5405	0.2099	0.3353	0.0060	2488	57	2178	25	1864	29	
16SD200-1-07	1.35	0.3360	0.0106	35.1898	1.0055	0.7601	0.0139	3644	23	3644	28	3645	51	
16SD200-1-08	0.53	0.1645	0.0055	5.8779	0.1775	0.2592	0.0050	2503	27	1958	26	1486	25	
16SD200-1-09	0.42	0.1981	0.0070	15.2682	0.5123	0.5592	0.0124	2811	28	2832	32	2863	51	
16SD200-1-10	0.64	0.1694	0.0061	8.0093	0.2413	0.3430	0.0066	2552	61	2232	27	1901	31	
16SD200-1-11	0.48	0.1639	0.0058	6.9148	0.2087	0.3060	0.0057	2496	61	2101	27	1721	28	
16SD200-1-12	0.69	0.1761	0.0062	12.1496	0.3914	0.5006	0.0097	2617	29	2616	30	2616	41	
16SD200-1-13	0.09	0.1547	0.0057	4.2145	0.1340	0.1976	0.0037	2399	64	1677	26	1162	20	
16SD200-1-14	0.15	0.1626	0.0061	8.5658	0.2737	0.3820	0.0073	2483	64	2293	29	2086	34	
16SD200-1-15	0.39	0.1919	0.0070	14.1238	0.4792	0.5341	0.0109	2758	30	2758	32	2759	46	
16SD200-1-16	0.15	0.1609	0.0062	3.6230	0.1213	0.1633	0.0032	2465	67	1555	27	975	18	
16SD200-1-17	0.50	0.1631	0.0060	7.2262	0.2451	0.3216	0.0063	2488	32	2140	30	1797	31	
16SD200-1-18	0.36	0.1804	0.0069	7.3940	0.2445	0.2973	0.0058	2656	65	2160	30	1678	29	
16SD200-1-19	0.40	0.1698	0.0069	7.4404	0.2593	0.3178	0.0065	2555	69	2166	31	1779	32	
16SD200-1-20	0.24	0.1901	0.0082	12.1824	0.4497	0.4648	0.0105	2743	73	2619	35	2461	46	
16SD208-1-01	0.50	0.1800	0.0041	11.7106	0.2571	0.4839	0.0094	2611	16	2582	21	2544	41	
16SD208-1-02	0.42	0.1700	0.0039	8.0581	0.1698	0.3396	0.0064	2578	16	2238	19	1885	31	
16SD208-1-03	0.34	0.1800	0.0040	12.1921	0.2598	0.5012	0.0096	2619	16	2619	20	2619	41	
16SD208-1-04	0.32	0.1000	0.0053	1.3076	0.0658	0.0968	0.0020	1585	105	849	29	596	12	
16SD208-1-05	0.63	0.1700	0.0038	11.2572	0.2376	0.4839	0.0092	2545	16	2545	20	2544	40	
16SD208-1-06	0.72	0.1500	0.0034	3.8667	0.0821	0.1897	0.0036	2321	16	1607	17	1120	20	
16SD208-1-07	0.55	0.1300	0.0060	3.4770	0.1410	0.1928	0.0040	2108	82	1522	32	1137	22	
16SD208-1-08	0.83	0.1000	0.0065	0.9926	0.0613	0.0725	0.0016	1611	126	700	31	451	10	
16SD208-1-09	0.70	0.1300	0.0029	2.4110	0.0513	0.1382	0.0026	2050	17	1246	15	834	15	
16SD208-1-10	1.13	0.0900	0.0046	0.8106	0.0376	0.0649	0.0013	1439	99	603	21	405	8	
16SD208-1-11	0.70	0.1700	0.0052	9.1952	0.2221	0.3991	0.0077	2529	53	2358	22	2165	36	
16SD208-1-12	0.20	0.1800	0.0040	12.1506	0.2612	0.5005	0.0096	2616	16	2616	20	2616	41	
16SD208-1-13	0.27	0.1800	0.0042	12.1970	0.2731	0.5012	0.0099	2620	17	2620	21	2619	42	
16SD208-1-14	0.35	0.1800	0.0061	10.3887	0.2810	0.4152	0.0082	2666	57	2470	25	2239	37	
16SD208-1-15	0.38	0.1800	0.0041	10.4171	0.2253	0.4221	0.0081	2643	16	2473	20	2270	37	
16SD208-1-16	0.62	0.1700	0.0040	10.8401	0.2327	0.4512	0.0086	2599	16	2510	20	2401	38	
16SD208-1-17	0.32	0.1200	0.0043	1.0059	0.0298	0.0599	0.0012	1982	64	707	15	375	7	
16SD208-1-18	0.30	0.1700	0.0053	8.4048	0.2062	0.3585	0.0069	2558	54	2276	22	1975	33	
16SD208-1-19	0.05	0.1400	0.0032	3.2106	0.0683	0.1651	0.0031	2239	16	1460	16	985	17	
16SD208-1-20	0.37	0.1700	0.0040	10.8788	0.2356	0.4574	0.0088	2582	16	2513	20	2428	39	
16SD208-1-21	0.49	0.1500	0.0034	4.0225	0.0862	0.1974	0.0037	2320	16	1639	17	1161	20	
16SD208-1-22	0.69	0.1600	0.0038	5.0057	0.1081	0.2237	0.0043	2480	16	1820	18	1301	22	
16SD208-1-23	0.39	0.1600	0.0038	6.2708	0.1351	0.2803	0.0053	2479	16	2014	19	1593	27	
16SD208-1-24	0.63	0.1500	0.0036	4.2359	0.0912	0.1982	0.0038	2402	16	1681	18	1166	20	
16SD208-1-25	0.48	0.1600	0.0037	4.1423	0.0889	0.1854	0.0035	2477	16	1663	18	1096	19	
16SD208-1-26	0.50	0.1300	0.0030	1.7042	0.0372	0.0975	0.0019	2054	17	1010	14	600	11	
16SD208-1-27	0.65	0.1600	0.0038	4.8167	0.1047	0.2153	0.0041	2480	16	1788	18	1257	22	

Table 3 (Continued)

Sample and analytical spot number	Isotopic ratios						Apparent ages(Ma)						
	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$
16SD208-1-28	0.81	0.1400	0.0033	3.1877	0.0702	0.1636	0.0031	2243	17	1454	17	977	17
16SD208-1-29	0.64	0.1700	0.0042	11.9034	0.2723	0.4961	0.0098	2597	17	2597	21	2597	42

TREE contents of 72–116 ppm and moderately fractionated REE patterns with $(\text{La}/\text{Yb})_N$ ratios of 7.60–12.7 and slightly negative to positive Eu anomalies ($\delta\text{Eu}=0.66\text{--}1.09$; Fig. 4C). Moreover, these samples are enriched in Ba, Rb, Zr, K, and Hf and depleted in Nb, Ti, Y and Yb (Table 2; Fig. 4D).

5.1.3. The ~2.61–2.58 Ga monzogranitic gneisses

Together with sample S1507 from Ren et al. (2017), the five monzogranitic gneisses are characterized by high contents of SiO_2 (70.35–75.12 wt%), Al_2O_3 (13.36–14.83 wt%), and K_2O (4.35–5.81 wt%) but low contents of MgO (0.20–0.77 wt%), TFe_2O_3 (1.08–3.05 wt%), Na_2O (2.69–4.14 wt%), TiO_2 (0.12–0.34 wt%) and CaO (0.98–1.68 wt%) with $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of 1.05–2.13. They belong to the granite and high-K calc-alkaline series in the TAS and $\text{K}_2\text{O}-\text{SiO}_2$ diagrams, respectively (Fig. 3A–B). In the An-Ab-Or diagram, they plot within the granite domain (Fig. 3C). With relatively high A/CNK values (0.97–1.11), they belong to the metaluminous to peraluminous series (Fig. 3D). All five samples plot within the PMB range in the MgO- SiO_2 diagram with low Mg# values of 20–34 (Fig. 3E–F).

These monzogranitic samples show low contents of Cr (8.03–31 ppm) and Ni (0.97–6.19 ppm), high contents of TREE (198–357 ppm), and strong enrichments in LREE related to HREE with high $(\text{La}/\text{Yb})_N$ ratios of 23–64 and negative Eu anomalies ($\delta\text{Eu}=0.35\text{--}0.56$; Fig. 4E). These samples show significant depletion in Sr, P, Nb, Ti, Y and Yb and enrichment in Ba, Rb, Zr, K, and Hf in the spider diagram of trace elements (Table 2; Fig. 4F).

5.1.4. The ~2.59 Ga granodioritic gneisses

The granodioritic gneisses feature relatively high contents of SiO_2 (66.34–73.04 wt%), Al_2O_3 (13.25–14.85 wt%), K_2O (2.23–4.32 wt%), MgO (1.39–3.51 wt%) and TFe_2O_3 (3.02–6.13 wt%) but low contents of Na_2O (2.23–4.05 wt%) and TiO_2 (0.25–0.49 wt%), with moderate contents of CaO (1.14–4.00 wt%) and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of 0.61–1.79. These samples plot in the granodiorite to granite fields in the TAS diagram and are medium-K calc-alkaline to high-K calc-alkaline series (Fig. 3A–B). In the An-Ab-Or diagram, these samples plot in the granodiorite domain, except for one sample plotting in the granite domain (Fig. 3C). They plot within the peraluminous field in the A/CNK-A/NK diagram ($\text{A}/\text{CNK}=0.95\text{--}1.33$; Fig. 3D) and the HSA area in the MgO- SiO_2 diagram with high Mg# values of 48–53.

The granodioritic gneisses show Co and V contents of 2.82–22 ppm and 21–122 ppm, respectively, and various TREE contents from 98 ppm to 210 ppm. These samples display fractionated REE patterns with high $(\text{La}/\text{Yb})_N$ ratios of 9.41–67 and slightly negative to positive Eu anomalies ($\delta\text{Eu}=0.63\text{--}1.18$; Fig. 4G). Moreover, these samples are enriched in Ba, Rb, Zr, K, and Hf and depleted in Nb, Ti, Y and Yb, as shown in the spider diagram of trace elements (Table 2; Fig. 4H).

5.1.5. The MME

The MME sample shows relatively low contents of SiO_2 (53.27 wt%) and Na_2O (2.63 wt%) but high contents of Al_2O_3

(16.55 wt%), K_2O (4.94 wt%), MgO (5.85 wt%), TFe_2O_3 (11.51 wt%) and TiO_2 (1.14 wt%), with a moderate content of CaO (1.84 wt%), $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio of 1.88, a higher A/CNK value of 1.27 (Fig. 3D) and a Mg# value of 50. This sample plots in the monzodiorite fields in the TAS diagram and is within a shoshonite series (Fig. 3A–B).

The MME shows Cr, Ni, Co and V contents of 252 ppm, 98 ppm, 36 ppm and 192 ppm, respectively, and a TREE content of 91 ppm. This sample displays a fractionated REE pattern with a $(\text{La}/\text{Yb})_N$ ratio of 13.8 and slightly positive Eu anomaly ($\delta\text{Eu}=1.30$; Fig. 4G). Moreover, this sample is enriched in Ba, Rb, Zr and K and depleted in Nb, Y and Yb, as shown in the spider diagram of trace elements (Table 2; Fig. 4H).

5.2. Zircon U-Pb and Lu-Hf isotopes

Six representative Neoproterozoic granitoid samples, including two published TTG gneisses, one granodioritic gneiss, one granodioritic gneiss and two monzogranitic gneisses were analysed for zircon U-Pb-Lu-Hf isotopes (Tables 3–4; Sun et al., 2019b). Zircon grains separated from these rocks show stubby or prismatic shapes on cathodoluminescence (CL) images with lengths and length/width ratios of 100–300 μm and 1:1–3:1, respectively, and most zircons exhibit oscillatory zoning domains surrounded by structureless and dark rims (Fig. 5A–D).

5.2.1. Sample 16SD157-3

A total of nineteen spots were measured on eighteen zircon grains from the granodioritic gneiss 16SD157-3. These analyses show high Th/U ratios of 0.33–0.91 (except for spot #13 with a low Th/U ratio of 0.07), and a magmatic origin is preferred based on the zircon morphologies and structures on the CL images (Fig. 5A; Table 3; Hoskin and Schaltegger, 2003; Rubatto, 2002).

All the analyses yield apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from $2583\pm 15\text{ Ma}$ to $2720\pm 16\text{ Ma}$, and can be divided into three age groups. Spot #15 shows a Th/U ratio of 0.73 and the oldest apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2720\pm 16\text{ Ma}$, which is the oldest single age; thus, this zircon is considered a captured zircon grain with a magmatic genesis. The second age group consists of seventeen analyses, defining a discordant line with an upper intercept age of $2692\pm 7\text{ Ma}$ (MSWD=1.8; Fig. 6A) and a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2690\pm 10\text{ Ma}$ (MSWD=0.57). Twelve of the analyses plotted on the concordia curve give a concordia age of $2692\pm 7\text{ Ma}$ (MSWD=0.021; Fig. 6A), which is consistent with the upper intercept age and weighted mean age within errors and taken as the magmatic crystallization age of the sample 16SD157-3. The youngest group consists only of one zircon grain (spot #13), which shows an apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2583\pm 15\text{ Ma}$ and a Th/U ratio of 0.07 (Fig. 6A). This age is consistent with those of the ~2.6 Ga granitoids in this study, and is considered a result of a regional thermal event.

Sixteen dated spots were analysed for in situ Lu-Hf isotopes, of which those from the second age group yield $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.281239–0.281313, while the metamorphic and captured zircon spots show $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.281232 and 0.281261, respec-

Table 4

Analysed zircon Lu-Hf isotopic data and calculated parameters for the dated granitoid samples from the Western Shandong Terrane.

Sample and analytical spot number	Apparent age (t_1)	Crystallization age (t_2)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 2\sigma$	$\varepsilon\text{Hf}(t_2)$	$T_{\text{DM}}(\text{Ma})$
16SD157-3-01	2678	2690	0.015087	0.000589	0.281239	0.000024	5.2	2776
16SD157-3-02	2676	2690	0.010283	0.000465	0.281243	0.000020	5.6	2761
16SD157-3-03	2668	2690	0.008606	0.000404	0.281250	0.000023	5.9	2748
16SD157-3-04	2697	2690	0.010256	0.000515	0.281262	0.000021	6.2	2739
16SD157-3-05	2675	2690	0.012385	0.000490	0.281242	0.000022	5.5	2765
16SD157-3-06	2681	2690	0.008869	0.000399	0.281239	0.000024	5.6	2763
16SD157-3-07	2700	2690	0.029164	0.001202	0.281313	0.000027	6.7	2719
16SD157-3-08	2583	2690	0.008989	0.000427	0.281261	0.000019	3.8	2735
16SD157-3-09	2720	2690	0.009979	0.000418	0.281232	0.000021	6.0	2773
16SD157-3-10	2694	2690	0.017643	0.000754	0.281275	0.000024	6.2	2739
16SD157-3-11	2682	2690	0.005398	0.000288	0.281284	0.000022	7.4	2694
16SD157-3-12	2697	2690	0.009511	0.000451	0.281264	0.000024	6.3	2733
16SD157-3-13	2703	2690	0.012203	0.000569	0.281256	0.000024	5.9	2751
16SD157-3-14	2700	2690	0.017385	0.000770	0.281265	0.000023	5.8	2754
16SD157-3-15	2700	2690	0.004795	0.000236	0.281263	0.000029	6.7	2718
16SD157-3-16	2679	2690	0.009859	0.000410	0.281251	0.000023	6.0	2747
16SD189-1-01	2682	2681	0.010942	0.000465	0.281246	0.000011	5.5	2758
16SD189-1-02	2681	2681	0.004469	0.000218	0.281228	0.000010	5.3	2764
16SD189-1-03	2678	2681	0.011562	0.000498	0.281237	0.000012	5.1	2772
16SD189-1-04	2713	2681	0.020019	0.000833	0.281254	0.000014	5.1	2772
16SD189-1-05	2678	2681	0.024065	0.000948	0.281265	0.000011	5.2	2767
16SD189-1-06	2691	2681	0.005207	0.000274	0.281232	0.000014	5.3	2763
16SD189-1-07	2699	2681	0.035659	0.001503	0.281241	0.000011	3.4	2839
16SD189-1-08	2698	2681	0.017049	0.000739	0.281259	0.000013	5.4	2760
16SD189-1-09	2644	2681	0.016782	0.000670	0.281257	0.000014	5.5	2757
16SD189-1-10	2674	2681	0.007882	0.000341	0.281224	0.000012	4.9	2778
16SD189-1-11	2697	2681	0.012893	0.000557	0.281245	0.000010	5.3	2765
16SD189-1-12	2672	2681	0.026055	0.001092	0.281286	0.000010	5.7	2748
16SD189-1-13	2714	2681	0.019863	0.000792	0.281249	0.000012	5.0	2776
16SD189-1-14	2639	2681	0.018090	0.000750	0.281229	0.000012	4.3	2801
16SD189-1-15	2672	2681	0.015769	0.000664	0.281234	0.000011	4.7	2788
17SD22-1-01	2633	2620	0.019810	0.000491	0.281252	0.000065	4.3	2751
17SD22-1-02	2625	2620	0.013267	0.000330	0.281223	0.000059	3.5	2779
17SD22-1-03	2623	2620	0.010998	0.000310	0.281246	0.000049	4.4	2746
17SD22-1-04	2629	2620	0.019340	0.000479	0.281245	0.000062	4.0	2760
17SD22-1-05	2607	2620	0.015300	0.000378	0.281242	0.000068	4.1	2756
17SD22-1-06	2620	2620	0.019146	0.000449	0.281292	0.000058	5.8	2694
17SD22-1-07	2614	2620	0.022530	0.000547	0.281237	0.000065	3.6	2775
17SD22-1-08	2625	2620	0.027720	0.000659	0.281252	0.000065	4.0	2763
17SD22-1-09	2620	2620	0.014790	0.000366	0.281298	0.000061	6.1	2681
17SD22-1-10	2607	2620	0.018850	0.000454	0.281310	0.000065	6.4	2671
17SD22-1-11	2614	2620	0.014910	0.000367	0.281333	0.000062	7.4	2634
17SD22-1-12	2608	2620	0.019330	0.000482	0.281207	0.000063	2.7	2811
17SD22-1-13	2632	2620	0.031880	0.000770	0.281302	0.000069	5.5	2703
17SD22-1-14	2626	2620	0.017340	0.000425	0.281275	0.000066	5.2	2716
17SD22-1-15	2613	2620	0.017650	0.000442	0.281262	0.000054	4.7	2734
16SD169-1-01	2581	2591	0.020057	0.000818	0.281224	0.000026	2.0	2813
16SD169-1-02	2574	2591	0.011581	0.000538	0.281231	0.000030	2.8	2782
16SD169-1-03	2695	2716	0.010415	0.000417	0.281253	0.000020	6.6	2745
16SD169-1-04	2726	2716	0.019523	0.000822	0.281278	0.000026	6.8	2740
16SD169-1-05	2568	2591	0.022414	0.000903	0.281250	0.000022	2.8	2783
16SD169-1-06	2575	2591	0.025345	0.001098	0.281175	0.000027	-0.2	2899
16SD169-1-07	2617	2591	0.021917	0.000975	0.281324	0.000026	5.3	2688
16SD169-1-08	2724	2716	0.013745	0.000618	0.281279	0.000023	7.2	2724
16SD169-1-09	2625	2591	0.009005	0.000425	0.281215	0.000027	2.4	2796
16SD169-1-10	2583	2591	0.016174	0.000755	0.281215	0.000026	1.8	2820
16SD169-1-11	2575	2591	0.019379	0.000906	0.281264	0.000090	3.3	2764
16SD169-1-12	2577	2591	0.023088	0.000930	0.281261	0.000024	3.2	2770
16SD200-1-01	2563	2581	0.040320	0.001044	0.281241	0.000061	2.0	2806
16SD200-1-02	2566	2581	0.019780	0.000565	0.281266	0.000056	3.7	2738
16SD200-1-03	2504	2581	0.021298	0.000553	0.281273	0.000059	4.0	2727
16SD200-1-04	2503	2581	0.028610	0.000733	0.281314	0.000054	5.2	2685
16SD200-1-05	2505	2581	0.015974	0.000420	0.281257	0.000049	3.7	2739
16SD200-1-06	2617	2581	0.020520	0.000577	0.281274	0.000045	4.0	2728
16SD200-1-07	2758	2756	0.024610	0.000617	0.281278	0.000063	8.1	2725
16SD200-1-08	2573	2581	0.029090	0.000727	0.281282	0.000059	4.0	2727
16SD208-1-01	2479	2613	0.029752	0.001145	0.281307	0.000021	4.9	2723
16SD208-1-02	2582	2613	0.022520	0.000954	0.281314	0.000028	5.5	2700
16SD208-1-03	2558	2613	0.013334	0.000599	0.281301	0.000025	5.7	2692

Table 4 (Continued)

Sample and analytical spot number	Apparent age (t_1)	Crystallization age (t_2)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 2\sigma$	$\epsilon\text{Hf}(t_2)$	$T_{\text{DM}}(\text{Ma})$
16SD208-1-04	2599	2613	0.018597	0.000819	0.281319	0.000026	5.9	2684
16SD208-1-05	2620	2613	0.011246	0.000489	0.281293	0.000023	5.6	2696
16SD208-1-06	2616	2613	0.020765	0.000899	0.281308	0.000026	5.4	2704
16SD208-1-07	2619	2613	0.029614	0.001203	0.281358	0.000026	6.6	2658
16SD208-1-08	2578	2613	0.016147	0.000679	0.281303	0.000024	5.6	2696

Notes: t_1 , apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age; t_2 , crystallization age of zircon grains; the present $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of chondrite and depleted mantle are 0.282772 and 0.0332, and 0.28325 and 0.0384, respectively, from Blichert-Toft and Albarède (1997) and Griffin et al. (2000). $\lambda = 1.867 \times 10^{-11} \text{ a}^{-1}$ from Söderlund et al. (2004); $\epsilon\text{Hf}(t_2) = 10,000 \{ [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} \times (e^{\lambda t_2} - 1)] / [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t_2} - 1)] - 1 \}$; $T_{\text{DM}} = 1/\lambda \times \ln \{ 1 + [(^{176}\text{Hf}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}] / [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{S}} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}] \}$.

tively (Table 4). When corrected to their crystallization age (2692 Ma, t_2), the analyses from the second age group show positive $\epsilon\text{Hf}(t_2)$ values ranging from +5.2 to +7.4 with $T_{\text{DM}}(\text{Hf})$ values of 2694–2775 Ma. The captured and metamorphic zircon grains were corrected to the individual apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages (t_1), thereby yielding $\epsilon\text{Hf}(t_1)$ values of +6.0 and +3.8, respectively, with $T_{\text{DM}}(\text{Hf})$ values of 2773 and 2734 Ma.

5.2.2. Sample 16SD189-1

A total of twenty-two spots were measured on twenty-five zircon grains from the trondhjemitic gneiss 16SD189-1. These analyses show high Th/U ratios of 0.17–1.08, and a magmatic origin is preferred based on the zircon morphologies and structures on the CL images (Fig. 5B; Table 3; Hoskin and Schaltegger, 2003; Rubatto, 2002).

All the analyses yield apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2639 ± 17 Ma to 2714 ± 16 Ma, defining a discordant line with an upper intercept age of 2682 ± 11 Ma (MSWD = 1.8; Fig. 6) and yielding a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2680 ± 9 Ma (MSWD = 1.5; Fig. 6B). Eighteen of the analyses plotted on the concordia curve give a concordia age of 2681 ± 4 Ma (MSWD = 0.0013), which is consistent with the upper intercept age and weighted mean age within errors and taken as the magmatic crystallization age of the sample 16SD189-1 (Fig. 6B).

Fifteen dated spots were analysed for in situ Lu-Hf isotopes, yielding $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.281224–0.281286 (Table 4). When corrected to their crystallization age (2681 Ma, t_2), they show positive $\epsilon\text{Hf}(t_2)$ values ranging from +3.4 to +5.9 with $T_{\text{DM}}(\text{Hf})$ values of 2757–2839 Ma.

5.2.3. Sample 17SD22-1

A total of twenty-five spots were measured on twenty-five zircon grains from the tonalitic gneiss 17SD22-1. These analyses show high Th/U ratios of 0.52–0.97; together with the zircon morphologies and structures on the CL images, a magmatic origin is thus preferred (Fig. 5C; Table 3; Hoskin and Schaltegger, 2003; Rubatto, 2002).

All the analyses yield apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2607 ± 14 Ma to 2633 ± 14 Ma, defining a discordant line with an upper intercept age of 2620 ± 6 Ma (MSWD = 0.42; Fig. 6C) and yielding a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2620 ± 6 Ma (MSWD = 0.39; Fig. 6C). Twenty-three of the analyses plotted on the concordia curve give a concordia age of 2620 ± 4 Ma (MSWD = 0.001), which is consistent with the upper intercept age and weighted mean age within errors (Fig. 6C). Therefore, the concordia age of 2620 ± 4 Ma is taken as the magmatic crystallization age of the sample 17SD22-1.

Fifteen dated spots were analysed for in situ Lu-Hf isotopes, yielding $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.281207–0.281333 (Table 4). When corrected to their crystallization age (2620 Ma, t_2), they show positive

$\epsilon\text{Hf}(t_2)$ values ranging from +2.7 to +7.4 and $T_{\text{DM}}(\text{Hf})$ values of 2681–2811 Ma.

5.2.4. Sample 16SD169-1

Seventeen spots were measured on seventeen zircon grains from the granodioritic sample 16SD169-1, showing apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2522 ± 15 Ma to 2726 ± 15 Ma and Th/U ratios of 0.22–1.09; these analyses may be divided into two age groups (Table 3; Fig. 6D).

The older age group comprises four analyses (spots #06, #10, #13 and #14), all of which plot on the concordia curve and yield a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2716 ± 15 Ma (MSWD = 0.82) and a concordia age of 2716 ± 8 Ma (MSWD = 0.0011; Fig. 6D). This age is much older than that from other analyses and consistent with the regional supracrustal and intrusive rocks (2700–2750 Ma; Cao, 1996), therefore these zircons are interpreted as inherited. The younger age group comprises thirteen analyses, yielding a discordant upper intercept age of 2594 ± 15 Ma (MSWD = 1.9; Fig. 6D). Eight of them plot along the concordia curve and show a concordia age of 2591 ± 5 Ma (MSWD = 0.001), which is consistent with the upper intercept age (Fig. 6D). Therefore, the concordia age of 2591 ± 5 Ma is considered as the crystallization age of this granodioritic gneiss.

Twelve spots were analysed for in situ Lu-Hf isotopes. The zircons in the older group show $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.2812529–0.2812785 with positive $\epsilon\text{Hf}(t_2)$ and $T_{\text{DM}}(\text{Hf})$ values of +6.6–+7.2 and 2724–2745 Ma, respectively (Table 4). The younger zircons show $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.2811752–0.281324. Corrected to the crystallization age (2591, t_2), the analyses with young ages show wide ranges of $\epsilon\text{Hf}(t_2)$ values (from –0.2 to +5.3) and $T_{\text{DM}}(\text{Hf})$ values (2688–2899 Ma).

5.2.5. Sample 16SD200-1

Twenty spots were analysed on eighteen zircon grains from the monzogranitic gneiss sample 16SD200-1, showing Th/U ratios of mostly >0.1 (0.18–1.35; except for spot #13 at 0.09; Table 3). These analyses yield apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2399 ± 64 Ma to 3644 ± 23 Ma, and can be divided into three groups (Fig. 6E).

Spot #07 was measured on an oscillatory zoning core, has a Th/U ratio of 1.35 and shows the oldest apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3644 ± 23 Ma (Fig. 6E). This grain is considered an inherited zircon with a magmatic genesis, indicating that 3.64 Ga geological information is preserved in the WST. The second age group consists of six analyses, yielding an upper intercept age of 2756 ± 26 Ma (MSWD = 1.3; Fig. 6E), which is consistent with the formation ages of the early metamorphic volcanic rock assemblages (Gao et al., 2019b). The youngest age group comprises thirteen analyses and defines a discordant upper intercept age of 2587 ± 21 Ma (MSWD = 1.5; Fig. 6E). Three of them plot on the concordia curve and give a concordia age of 2581 ± 15 Ma (MSWD = 0.002; Fig. 6E). In the density plot, all the analyses form a single age peak of ~2.59 Ga (Fig. 6E).

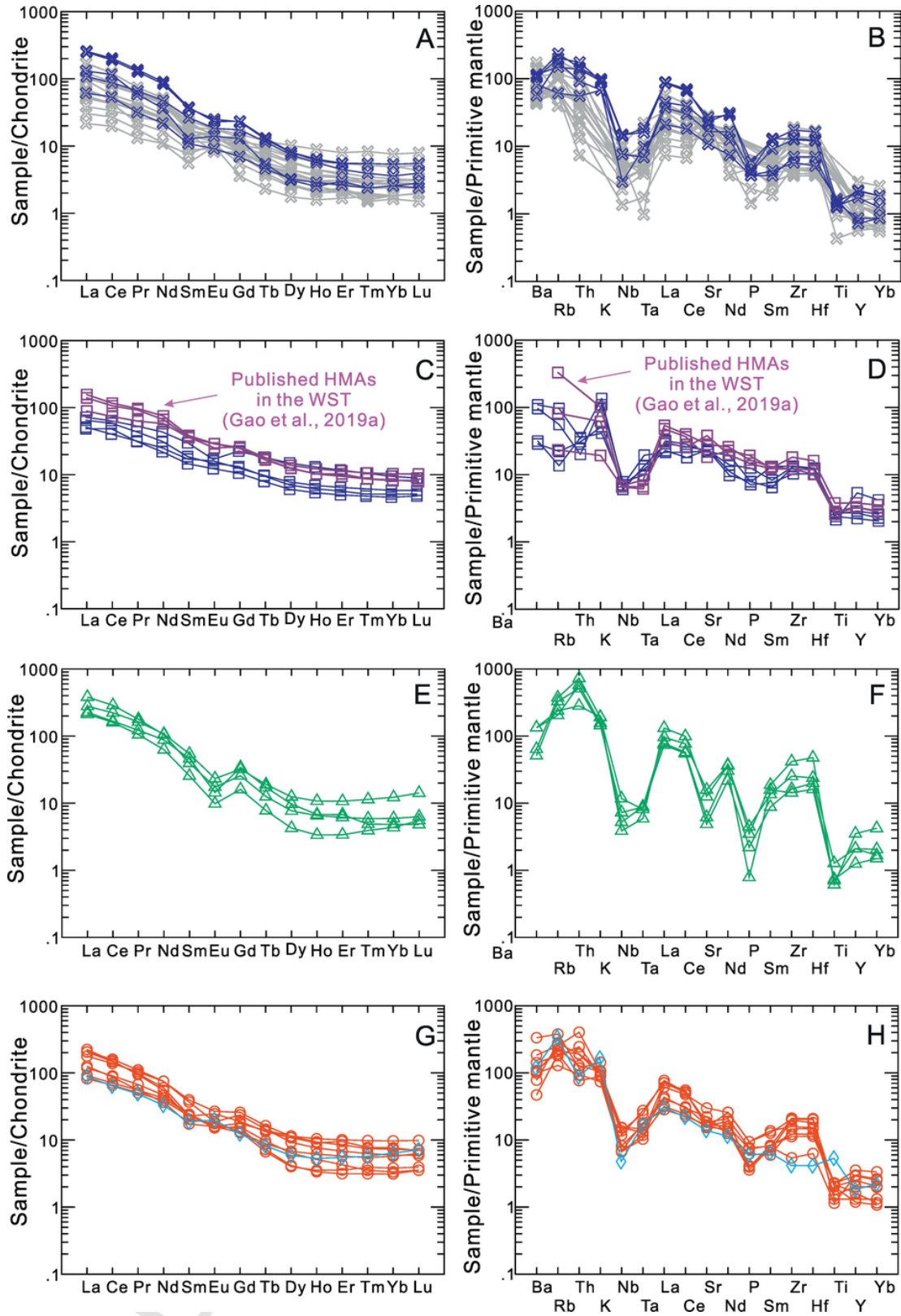


Fig. 4. Chondrite-normalized REE and primitive-mantle-normalized multi-element variation diagrams for analytic samples: (A-B) ~2.7 Ga TTG gneisses; (C-D) ~2.6 Ga tonalitic gneisses; (E-F) ~2.6 Ga monzogranitic gneisses; (G-H) ~2.6 Ga granodioritic gneisses and MME. Abbreviations: HMAs, high magnesian andesites. Symbols are the same as Fig. 3. Data for chondrite and primitive mantle values after Sun and McDonough (1989). Data for the published HMAs after Gao et al. 2019a.



Fig. 5. Cathodoluminescence images of representative samples showing internal structures, analysed spot locations and calculated apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages. (A) Tonalitic gneiss sample 16SD157-3; (B) Trondhjemitic gneiss sample 16SD189-1; (C) Tonalitic gneiss sample 17SD22-1; (D) Granodioritic gneiss sample 16SD169-1; (E) Monzogranitic gneiss sample 16SD200-1; (F) Monzogranitic gneiss sample 16SD208-1. Numbers show analysed spot orders in Table 3.

inset). Therefore, the concordia age of 2581 ± 15 Ma is considered the crystallization age of this sample, and the 3644 Ma and 2756 Ma signatures are considered inherited zircon ages.

Eight spots were measured for the Lu-Hf isotopes. The analyses in the second age group show a $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratio of 0.281278, with a positive $\varepsilon\text{Hf}(t_2)$ and a $T_{\text{DM}}(\text{Hf})$ age of +8.1 and 2725 Ma, respectively (Table 4). The other spots give $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of

0.281241–0.281314, with $\varepsilon\text{Hf}(t_2)$ and $T_{\text{DM}}(\text{Hf})$ values of +2.0–+5.2 and 2685–2806 Ma, respectively (Table 4).

5.2.6. Sample 16SD208-1

Twenty-nine U-Pb isotopes were analysed on twenty-six zircons of monzogranitic gneiss sample 16SD208-1, displaying Th/U ratios mostly >0.1 (0.20–1.13; except for #19 at 0.05; Table 3) and yielding apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1439 ± 99 Ma to 2619 ± 16 Ma. Some spots are excluded from the age calculation due

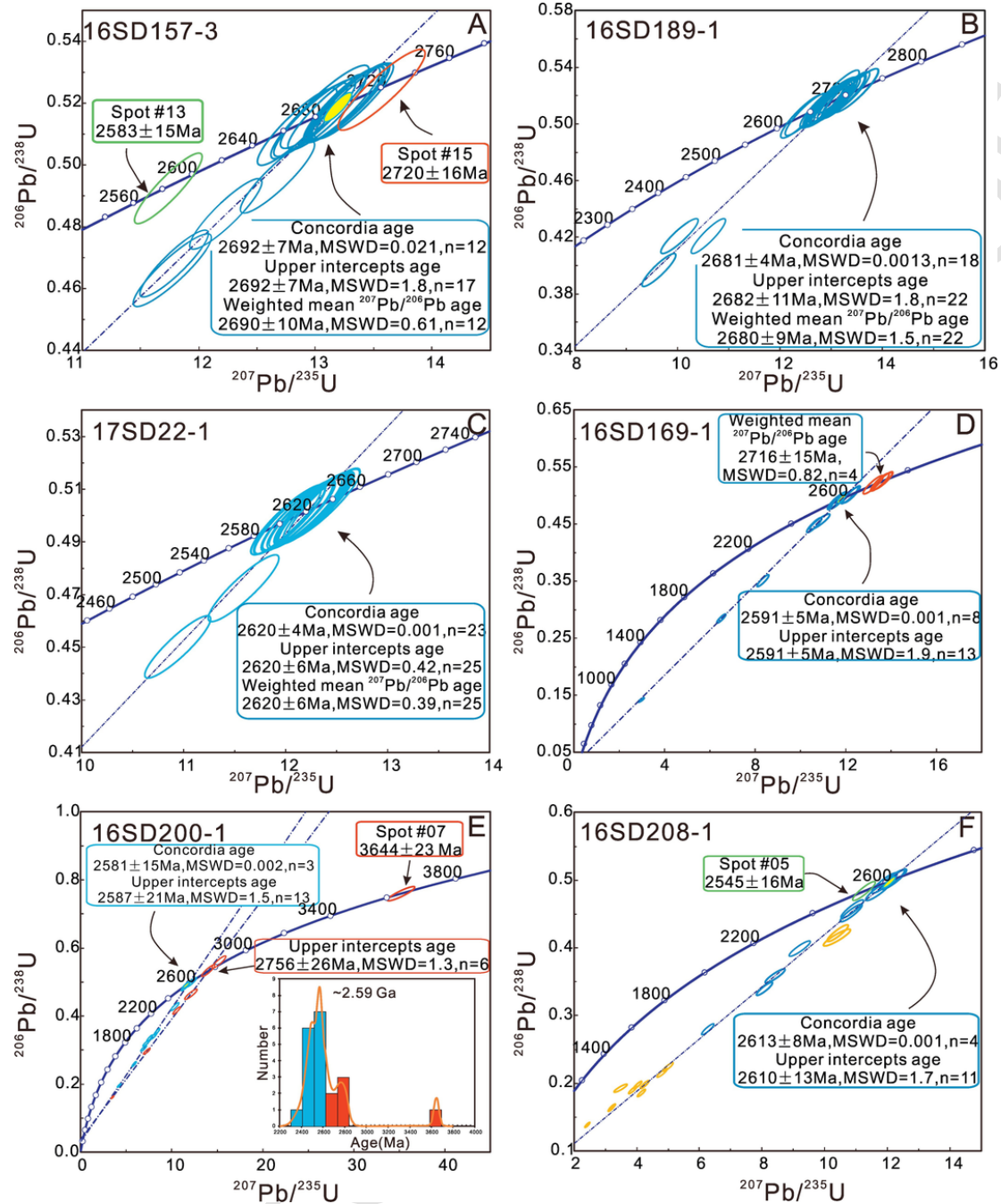


Fig. 6. Concordia diagram for all the analysed zircon spots, showing upper intercept ages, concordia ages and weighted mean ages. (A) Granodioritic gneiss sample 16SD157-3; (B) Trondhjemitic gneiss sample 16SD189-1; (C) Tonalitic gneiss sample 17SD22-1; (D) Granodioritic gneiss sample 16SD169-1; (E) Monzogranitic gneiss sample 16SD200-1; (F) Monzogranitic gneiss sample 16SD208-1. The insets in Figure. 6 (E) are histograms of apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages, with the probability curve.

to their large error and severe Pb-loss resulting from strong alteration (spots with extremely young ages, e.g. #19). Only sixteen analyses remain to calculate the apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages, and they can be divided into two groups (Fig. 6F).

The older age group consists of eleven analyses, defining a discordant upper intercept age of 2610 ± 13 Ma (MSWD=1.7; Fig. 6F). Four analyses plot on the concordia curve and yield a concordia age of 2613 ± 8 Ma (MSWD=0.00050; Fig. 6F), which is consistent with the upper intercept age and therefore considered the crystallization age of this sample. The remaining spot #05 was measured on a

blurred zoning domain and shows an apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2545 ± 16 Ma (Fig. 6F). It is a single young age, which may be an age record of a late thermal event (Corfu et al., 2003; Liu et al., 2017, 2018a; Zeh et al., 2009).

Eight spots were used for the Lu-Hf analyses and display consistent $^{176}\text{Hf}/^{177}\text{Hf}(t_1)$ ratios of 0.2812928–0.2813576 within error (Table 4). When corrected to the crystallization age (2613 , t_2), they show positive $\epsilon\text{Hf}(t_2)$ values of $+4.9$ – $+6.6$ and $T_{\text{DM}}(\text{Hf})$ values of 2658–2723 Ma.

6. Discussion

6.1. Assessment of element mobility

A lower amphibolite facies metamorphism and various degrees of deformation may have triggered variable element mobilities in the Neoproterozoic intrusive rocks of the WST (Cao, 1996; Gao et al., 2018; Sun et al., 2019a); thus, evaluating the element mobility is crucial. All the samples in this study show low LOI values (0.21–2.15 wt%) and no significant Ce anomalies ($\delta\text{Ce} = \text{Ce}_N / \text{Sqrt}(\text{La}_N \times \text{Pr}_N) = 0.97\text{--}1.11$), indicating that the elements are generally immobile (Polat and Hofmann, 2003). The linear relationships between an alteration-insensitive index such as the $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio and major oxides reveal the immobility of SiO_2 , MgO , TFe_2O_3 and Na_2O (Guo et al., 2015). However, the weak correlations between K_2O and the $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio from the monzogranitic gneisses suggest that K_2O is mobile. In addition, the correlations between Zr and the REEs, high field strength elements (HFSEs), transition metals and large ion lithophile elements (LILEs) indicate the immobility of these elements, which is further supported by the consistent trace element patterns (Fig. 4; Pearce et al., 1992).

6.2. Petrogenesis

6.2.1. The ~2.7 Ga TTG gneisses

The TTG gneisses show high SiO_2 and Na_2O contents but low K_2O and MgO contents and low Mg# values and MgO contents, all of which exclude contributions from mantle materials (Fig. 3E–F). On the $\text{CaO}/(\text{FeO}_{\text{tot}} + \text{MgO} + \text{TiO}_2)$ versus $\text{CaO} + \text{FeO}_{\text{tot}} + \text{MgO} + \text{TiO}_2$ diagram, the TTG gneisses plot in the range of partial melts derived from amphibolites (Fig. 7A). Therefore, the TTG gneisses may have originated from the partial melting of mafic rocks. The dated samples show concentrated $\varepsilon\text{Hf}(t_2)$ values ranging from +4.8 to +7.4 and slightly older $T_{\text{DM}}(\text{Hf})$ values than their crystallization age (2694–2775 Ma of sample 16SD157-3; 2757–2839 Ma of sample 16SD189-1), indicating a juvenile crustal source (Fig. 8A). On the $\text{Al}_2\text{O}_3/(\text{FeO}_{\text{tot}} + \text{MgO}) - 3 \times \text{CaO} - 5 \times (\text{K}_2\text{O}/\text{Na}_2\text{O})$ diagram (Fig. 7B), these rocks plot in the domain of melts derived from low-K mafic rocks, indicating that low-K mafic rocks are most likely the source of the TTG gneisses (Laurent et al., 2014). In addition, the TTG gneisses have low Y and Yb contents (2.59–13.6 ppm and 0.31–1.28 ppm, respectively) and high $(\text{La}/\text{Yb})_N$ and Sr/Y ratios (7.84–93 and 21–204, respectively), plotting in the adakite fields on the $(\text{La}/\text{Yb})_N - \text{Yb}_N$ and Sr/Y–Y diagrams (Fig. 7C–D; Defant and Drummond, 1990). These samples are characterized by differentiated REE patterns with slightly negative to positive Eu anomalies ($\delta\text{Eu} = 0.78\text{--}1.38$, except 1.66 for sample 16SD160-1 and 2.22 for 6LB03-1), indicating that their magmas were sourced from low-K mafic rocks in the stability region of garnet (Fig. 4A).

6.2.2. The ~2.62 Ga tonalitic gneisses

The tonalitic gneisses feature high Na_2O , MgO and Sr but relatively low K_2O , Y and Yb contents, showing high $(\text{La}/\text{Yb})_N$ and Sr/Y ratios, and fall into the range between adakites and classic island arc-related volcanic suites on $(\text{La}/\text{Yb})_N - \text{Yb}_N$ and Sr/Y–Y diagrams (Table 2; Fig. 7C–D). These samples plot in the HSA and adakite ranges on the $\text{MgO}-\text{SiO}_2$ and $\text{Mg\#}-\text{SiO}_2$ diagrams, respectively (Fig. 3E–F). All these features indicate that they are similar to Phanerozoic adakites in their geochemical characters (Defant and Drummond, 1990; Martin et al., 2005). These samples define a line with a positive slope and a curve on the Ta/Sm–Ta and 1/Yb–Hf/Yb diagrams, re-

spectively, indicating petrogenetic models of partial melting (Fig. 7E–F). The dated sample 17SD22-1 displays positive $\varepsilon\text{Hf}(t_2)$ values ranging from +2.7 to +7.4 (Fig. 8A), indicating a juvenile crust source derived from the depleted mantle (DM) or a direct DM source. Integrating these data with their low SiO_2 but high MgO contents and Mg# values, petrogenesis from the reworking of pure crustal materials may be excluded for these tonalitic gneisses. These samples show high MgO , Cr and Ni contents, and trace element patterns similar to those of the high-magnesian andesites (HMAs) from the Yishui area in the WST, which are restricted to arc-related settings (Fig. 4C–D; Gao et al., 2019a). Combining this information with their low TiO_2 contents (0.41–0.50 wt%), the petrogenetic model of partial melting from enriched mantle may also be excluded (Bai et al., 2014; Martin et al., 2010). Accordingly, the tonalitic gneisses were produced by the partial melting of subducting slabs, and their high MgO contents resulted from contamination by the mantle wedge during the melt ascent.

6.2.3. The ~2.61–2.58 Ga monzogranitic gneisses

Together with one sample from Ren et al., 2017, the five monzogranitic samples exhibit high SiO_2 , K_2O and Al_2O_3 concentrations, but low MgO and transition metal (Cr, V and Ni) contents, implying a crustal source. These rocks have no Al-rich minerals and the P_2O_5 contents are negatively related to the SiO_2 contents, defining a trend similar to that of I-type granites, which indicates that the magma may have been derived from metamorphic igneous rocks instead of mature sedimentary rocks (Chappell, 1999). On the $\text{MgO}-\text{SiO}_2$ diagram, these samples plot in the PMB area (Fig. 3E); however, they plot in the field of partial melts from greywackes on the $\text{CaO}/(\text{FeO}_{\text{tot}} + \text{MgO} + \text{TiO}_2)$ versus $\text{CaO} + \text{FeO}_{\text{tot}} + \text{MgO} + \text{TiO}_2$ diagram (Fig. 7A). In addition, they plot in the fields of tonalities and metasediments on the $\text{Al}_2\text{O}_3/(\text{FeO}_{\text{tot}} + \text{MgO}) - 3 \times \text{CaO} - 5 \times (\text{K}_2\text{O}/\text{Na}_2\text{O})$ diagram, indicating a complex source (Fig. 7B; Laurent et al., 2014). Therefore, the monzogranitic gneisses most plausibly originated from the partial melting of greywackes. Combined with the positive $\varepsilon\text{Hf}(t_2)$ values of the dated samples (+2.0–+6.6; Fig. 8A), the source greywackes came from juvenile materials consisting predominantly of mafic volcanic rocks, with lesser tonalitic gneiss or other sediment contributions. All these samples display strongly differentiated chondrite-normalized REE patterns with negative Sr and Eu anomalies (Fig. 4E–F), implying that they were produced by the partial melting of juvenile greywackes in the stability region of plagioclase.

6.2.4. The ~2.59 Ga granodioritic gneisses and their enclosed MMEs

The granodioritic gneisses have higher MgO contents (1.39–3.51 wt%) than crust-derived magmas ($\text{MgO} = 0.84 \pm 0.44$ wt% on average; Martin et al., 2005; Zamora, 2000), suggesting a contribution of mantle components and excluding a derivation from purely crustal materials. On genetic discrimination diagrams, they plot along a magma mixing trend, further proving that they originated from a magmatic mixing process between mafic and felsic melts (Fig. 7E–F; Schiano et al., 2010). Isotopically, the wide range of $\varepsilon\text{Hf}(t_2)$ values of the dated sample 16SD169-1 from –0.2 to +5.3 and the variable T_{DM} values from 2688 to 2899 Ma (Table 4; Fig. 8A) also support the involvement of both the mantle and ancient crustal materials. Integrating the geological, geochemical and isotopic characteristics, we propose that these granodioritic gneisses originated from a mixing process between crust- and mantle- sourced magmas. However, several mechanisms could cause the mixing of magmas, including (1) the underplating of mantle-derived melts at various crustal levels, providing sufficient heat to generate crustal magma and cause the

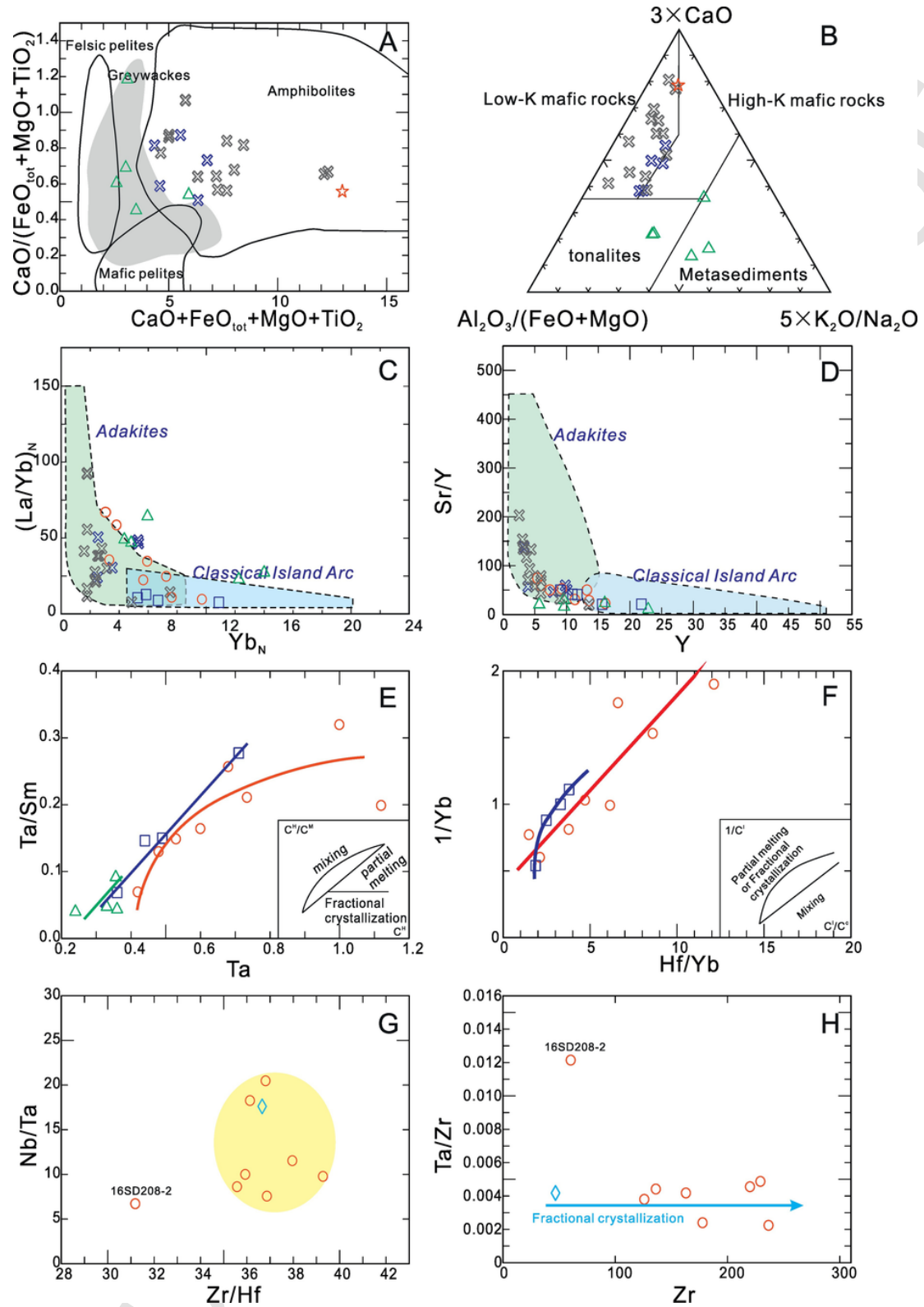


Fig. 7. Petrogenetic discrimination diagrams for the Neoproterozoic granitoid rocks in the WST. (A) $\text{CaO}/(\text{FeO}_{\text{tot}} + \text{MgO} + \text{TiO}_2)$ versus $\text{CaO} + \text{FeO}_{\text{tot}} + \text{MgO} + \text{TiO}_2$ diagram. The fields represent compositions of melts produced by experimental dehydration-melting of various lithologies (amphibolites, greywackes, mafic pelites and felsic pelites), modified from Patiño-Douce (1999); (B) Ternary diagram of $\text{Al}_2\text{O}_3/(\text{FeO} + \text{MgO})$, $3 \times \text{CaO}$, and $5 \times (\text{K}_2\text{O}/\text{Na}_2\text{O})$. The fields represent the composition of melts derived from a range of potential sources: tonalites, metasediments, low- and high-K mafic rocks (Laurent et al., 2014); (C) Chondrite-normalized $(\text{La}/\text{Yb})_N$ versus Yb_N diagram (Defant and Drummond, 1990); (D) Sr/Y versus Y diagram (Defant and Drummond, 1990); (E) Ta/Sm versus Ta diagram (Defant and Drummond, 1990); (F) $1/\text{Yb}$ versus Hf/Yb diagram (Defant and Drummond, 1990); (G) Nb/Ta versus Zr/Hf diagram (Defant and Drummond, 1990); (H) Ta/Zr versus Zr diagram (Defant and Drummond, 1990).

1990); (D) Sr/Y versus Y diagram (Moyen, 2011); (E) Ta/Sm versus Ta diagram; (F) 1/Yb versus Hf/Yb diagram; (G) Nb-Ta-Zr/Hf diagram; (H) Ta/Zr-Zr diagram. Symbols are the same as Fig. 3.

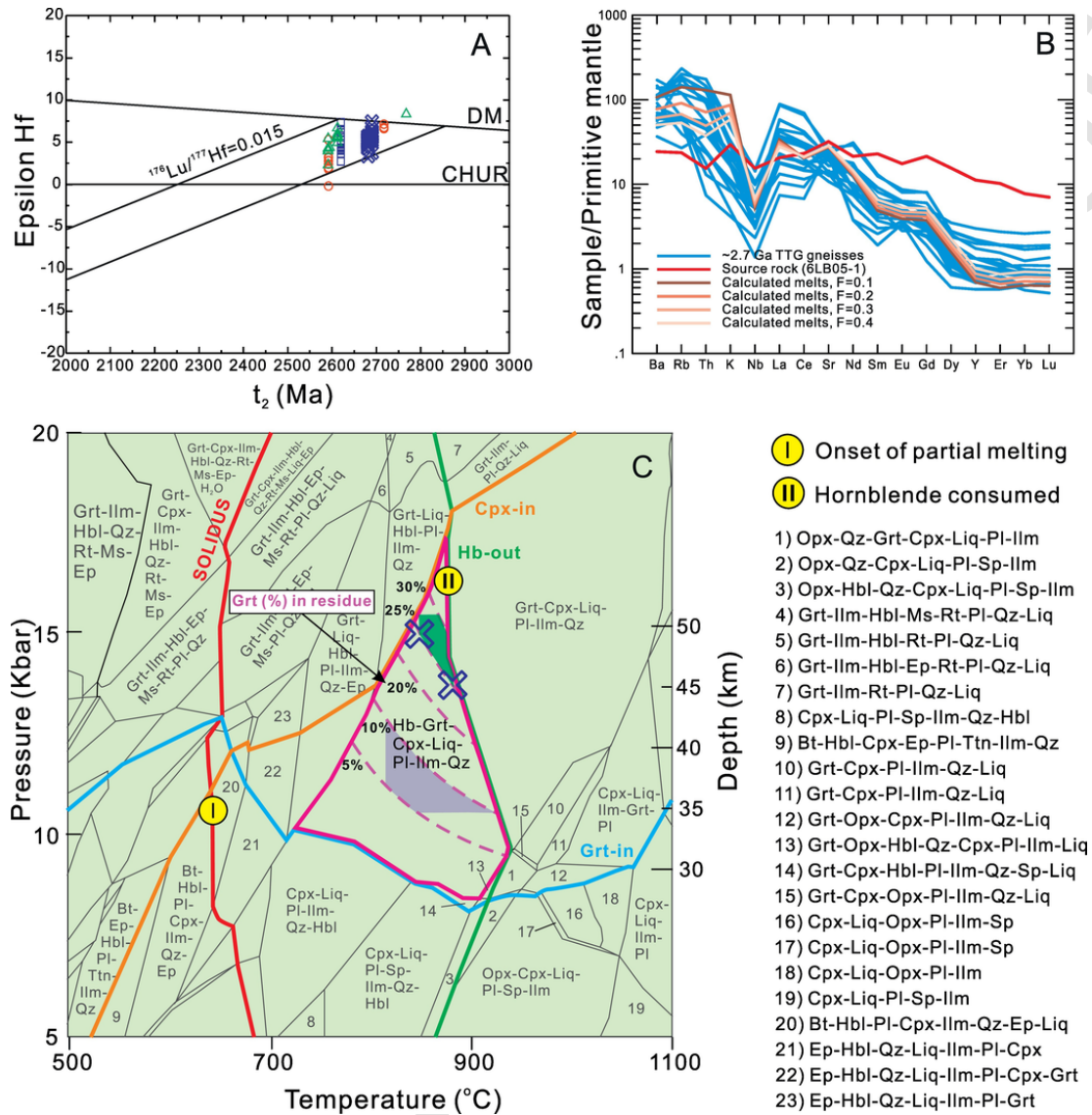


Fig. 8. (A) Zircon $\epsilon_{\text{Hf}}(t_2)$ values versus crystallization ages (t_2) for the supracrustal and granitoid rocks. (B) Trace element modeling for the petrogenesis of the ~2.7 Ga TTG gneisses. (C) P-T pseudosections to represent the TTG-source of early Archean metabasalt (Sun et al., 2019b). P-T pseudosections of equilibrium mineral assemblages were computed with the Gibbs free-energy minimization software PerpleX for the average C-F2 metabasalt in the model system $\text{Na}_2\text{O}-\text{CaO}-\text{K}_2\text{O}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}-\text{TiO}_2-\text{Fe}_2\text{O}_3$ (Modified from Wiemer et al., 2018). The purple dashed lines show the garnet proportion in the residue of an amphibolite (Zhang et al., 2013). The Green shadow shows the P-T conditions of the TTG gneisses in this study. The purple shadow shows the P-T conditions of the ~2.7 Ga and ~2.55 Ga TTG gneisses from Sun et al., 2019b. The legends are the same as those in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mixing of crustal and mantle magmas (Gao et al., 2018; Sun et al., 2019a), and (2) the partial melting of delaminated lower-crustal materials, followed by the melts ascending and interacting with the sub-crustal mantle (Wang et al., 2004, 2006; Xu et al., 2002).

Despite the similarities between the magmas produced by the two mechanisms described above, some distinctions between the resultant geochemical features should be noted. First, magmas derived from delaminated lower-crustal materials are generally produced at relatively deep crustal levels such as the stability region of garnet, whereas those formed by the mantle-derived magma upwelling model are produced at shallower crustal levels. The granodioritic gneisses show strongly differentiated chondrite-normalized REE patterns with

no significant Sr or Eu anomalies, indicating that the residual minerals were mainly garnets rather than plagioclase; hence, these granodiorite magmas were formed at deep crustal levels. Furthermore, magmas formed by mantle-derived magma upwelling processes generally show mixed geochemical compositions, especially Mg# values, due to the participation of the two end member magmas (mantle- and crust-derived magmas; e.g., Gao et al., 2018; Sun et al., 2019a). Magmas formed by delamination processes generally show relatively uniform compositions (e.g., Wang et al., 2004, 2006; Xu et al., 2002) due to the relatively homogeneous lower crust, which mainly consists of mafic rocks with minor metasediments and plutonic intrusions. The granodioritic samples exhibit consistent chondrite-normalized

REE patterns and major element compositions, with relatively high MgO concentrations of 1.39–3.51 wt% and concentrated Mg# values from 48 to 53, suggesting that the lower-crustal material delamination is the appropriate petrogenetic model for these samples (Fig. 4G–H).

The granodioritic gneisses contain some MMEs in outcrops, and the content ratios of two trace elements with similar geochemical characteristics such as Nb/Ta and Zr/Hf can be used to constrain the petrogenesis of the MMEs. On the Nb/Ta–Zr/Hf diagram, the MME (sample 16SD169-8) plots into the range of the host granodioritic gneisses, suggesting that the MME is a cognate enclave within the host rocks, granodioritic gneisses (Fig. 7G; Rollinson, 1993; Wang et al., 2016a). The consistent REE and multi-trace element patterns also support this point (Fig. 4G–H). Moreover, the ratio of the incompatible elements Zr and Ta may be used to distinguish the fractional crystallization process (Rollinson, 1993). On the Ta/Zr–Zr diagram, the MME sample and the host granodioritic gneisses define a horizontal line, indicating that they were produced by the fractionation crystallization of cogenetic magmatic evolution.

In summary, the best petrogenetic model for the granodioritic gneisses involves the delamination of lower crustal materials that melted in the subcrustal mantle. As the primary granodioritic magmas ascended and passed through the mantle, the pristine melts interacted with the mantle materials, leading to increases to some extent in the MgO, V and Ni concentrations of these samples. The enclosed MMEs originated as cumulates from the cogenetic magma of the granodioritic gneisses.

6.3. Neoproterozoic variations in crustal thickness in the WST

Recently, two episodes of ~2.71–2.68 Ga and ~2.56–2.52 Ga crust-derived TTG gneisses were recognized in the WST (Hu et al., unpublished data; Sun et al., 2019b). In this study, we use the plagioclase amphibolite 6LB05–1 as a source rock to model the partial melts and residual minerals after the melting of three early Neoproterozoic TTG gneiss samples. The residual mineral assemblages are referenced from partial melting experiments and the partition coefficients (K_d) of the minerals are derived from <http://earthref.org/GERM/> (Supplementary Table S3; Qian and Hermann, 2013). As shown in Fig. 8B, the trace element modeling results reveal that the residual minerals of the ~2.70 Ga TTG gneisses in this study consist of 25% amphibole, 25% clinopyroxene, 25% garnet, 20% plagioclase and 5% ilmenite, which is generally consistent with results for the ~2.70 Ga TTG gneisses obtained in previous research (Sun et al., 2019b).

A new method has been proposed to quantitatively calculate the Neoproterozoic crust thickness: (1) select granitoid rocks produced by the partial melting of the lower crust; (2) determine the proportion of garnet in the residual mineral assemblage and the lowest temperature of partial melting; and (3) estimate the pressures (depths) by the experimental phase relationships and pseudosection phase relations (Fig. 8C; Sun et al., 2019b; Wiemer et al., 2018; Zhang et al., 2013). Combining the calculated Ti-in-zircon temperatures of the ~2.70 Ga TTG melts in the WST (841–876 °C; Sun et al., 2019b) with the P–T range in the pseudosections indicates that the partial melting temperature of the ~2.70 Ga TTG gneisses was 841–890 °C. This result is employed to approximately represent the partial melting temperature of ~2.70 Ga TTG gneisses in this study. Considering the proportion of garnet in the residual phases (~25%), these ~2.70 Ga TTG gneisses formed at 13.5–15.5 kbar, and the corresponding early Neoproterozoic crustal thickness was at least 45–51 km (Fig. 8C), which is consistent with the results of a previous study (44–51 km, Sun et al., 2019b). That study also determined that the ~2.55 Ga thickness of the conti-

nenental crust in the WST was approximately 35–43 km, indicating that the crustal thickness may have been reduced by ~10 km from ~2.70 to 2.55 Ga in the WST (Sun et al., 2019b).

6.4. Crust–mantle interactions derived from the subduction–delamination regime of the WST

The available chronological data for the early–middle Neoproterozoic supracrustal rocks and intrusive rocks in the WST are briefly summarized in Table 5. They suggest that the early–middle Neoproterozoic magmatism in the WST can be divided into three episodes.

- (1) Formation of the TTG gneisses at ~2.71–2.68 Ga (Hu et al., unpublished data; Jahn et al., 1988; Jiang et al., 2010; Sun et al., 2019b; Wan et al., 2011). A previous study proposed an intraoceanic arc magmatic system prior to ~2.71 Ga, based on the well-preserved ~2.78–2.71 Ga island arc tholeiites (IATs), calc-alkaline basalts (CABs) and descending slab-derived adakites, the concomitant progressive NE–SW-oriented compressional deformation, and the relatively low early Neoproterozoic continental geothermal gradient (~17–20 °C/km; Gao et al., 2019b; Sun et al., 2019b). The mantle-derived magmas may have underplated the crustal roots to generate the ~2.71–2.68 Ga TTG melts, given that chemical modeling indicates that the TTG gneisses were derived from the partial melting of lower crustal materials with compositions similar to those of the pre-existing supracrustal rocks (Sun et al., 2019b).
- (2) Eruption of the calc-alkaline volcanic rocks and emplacement of associated TT gneisses at ~2.68–2.62 Ga, which mainly correspond to magmas generated in an island arc tectonic setting (Dong et al., 2017; Gao et al., 2019a; Lu et al., 2008; Ren et al., 2016; Wan et al., 2014; Wang et al., 2016c). The geodynamic setting of the WST transformed from an intraoceanic arc to an active continental margin between ~2.68 and 2.62 Ga, based on occurrence of CABs, high-magnesian andesites (HMAs), adakites, TT gneisses and the inherited ancient zircons in the HMAs (Fig. 9A; Gao et al., 2019a). The ~2.64 Ga HMAs display differentiated chondrite-normalized REE patterns, negative Nb, Ta and Ti anomalies, inherited ancient zircons and enrichments in typical continental crustal trace elements such as LILEs, Zr, Hf and Pb, suggesting that these rocks were derived from the partial melting of a depleted mantle wedge metasomatized by fluids or melts of subducted materials in a continental arc system. The ~2.64 Ga fine-grained amphibolites have CAB compositions, less differentiated chondrite-normalized REE patterns than the coeval HMAs and negative Nb, Ta and Ti anomalies, and were derived from an enriched mantle wedge at shallow levels in the upper mantle (Gao et al., 2019a). Concomitantly, the dehydration melting of the subducted slab led to the generation of the magmatic precursors of the ~2.68–2.62 Ga TT gneisses.
- (3) Formation of tholeiitic basalts and associated plutonic gabbro–diorites and emplacement of high-Mg granodioritic, monzogranitic and trondhjemitic gneisses at ~2.61–2.58 Ga. These rocks are more diverse than those formed during the early Neoproterozoic, indicating changes in petrogenetic processes and magma sources (Gao et al., 2019b; Wan et al., 2014; Yang and Santosh, 2017). The ~2.59–2.58 Ga tholeiitic basalts and associated gabbro–diorites display slightly differentiated REE patterns and significant depletions in Nb and Ta, suggesting that their primitive magma originated from an enriched mantle source and was erupted or emplaced at shallow crustal levels, allowing for intense crust–mantle interactions (Gao et al., unpublished data; Yang and Santosh, 2017). The mantle-derived magma may

Table 5

Summarized zircon U-Pb age data of the early-middle Neoproterozoic supracrustal rocks and intrusive rocks in the Western Shandong Terrane.

Sample	Lithology	Location	Magmatic age	References
~2.71–2.68 Ga				
S0503	Tonalitic gneiss	Northwest of Taishan	2714 ± 13 Ma	Wan et al., 2011
S0741	Granodiorite	East of Taishan	2712 ± 7 Ma	Wan et al., 2011 Wan et al., 2014
SY0336	Gneissic trondhjemite	Northwest of Taishan	2711 ± 10 Ma	Wan et al., 2011
S0732	Gneissic trondhjemite	West of Duoquhuang	2707 ± 9 Ma	Wan et al., 2011
CF84	Grey gneiss	Wangfushan	2700 ± 35 Ma	Jahn et al., 1988
JN0742	Tonalitic gneiss	Taishan	2691 ± 7 Ma	Jiang et al., 2010
16SD157-3	Tonalitic gneiss	North Pingyi	2690 ± 10 Ma	This study
17SD33-1	Tonalitic gneiss	South Qixingtai	2682 ± 15 Ma	Sun et al., 2019b
16SD189-1	Trondhjemitic gneiss	South Pingyi	2680 ± 9 Ma	This study
~2.68–2.62 Ga				
Supracrustal rocks				
SD0601	Amphibolite	Caishixi, Taishan	2678 ± 27 Ma	Lu et al., 2008
16SD30-1	Amphibolite	Yangzhuangzhen	2641 ± 8 Ma	Gao et al. 2019
Intrusive rocks				
CY002-TM1	Gneissic trondhjemite	Qixingtai	2667 ± 10 Ma	Wan et al., 2014
S1027	Tonalite gneiss	Yishan	2666 ± 9 Ma	Dong et al., 2017
SY0301	Gneissic trondhjemite	Yanlingguan	2663 ± 11 Ma	Wan et al., 2014
S1028	Gneissic tonalite	Yishan	2662 ± 9 Ma	Wan et al., 2014
TS1106	Trondhjemitic dike	Qixingtai	2660 ± 18 Ma	Wang et al., 2016a
SD0602	Felsic vein	Caishixi, Taishan	2660 ± 32 Ma	Lu et al., 2008
TS1112	Trondhjemitic dike	Qixingtai	2653 ± 17 Ma	Wang et al., 2016c
TS1104	Trondhjemite	Qixingtai	2653 ± 16 Ma	Wang et al., 2016b
TS1204	Gneissic trondhjemite	Xintai	2650 ± 10 Ma	Wan et al., 2014
TS09111	Gneissic quartz diorite	Southeast of Mengjiatun	2645 ± 9 Ma	Ren et al., 2016
SY0335A	Gneissic trondhjemite	Taishan	2642 ± 12 Ma	Wan et al., 2014
TS09109	Gneissic trondhjemite	South of Mengjiatun	2642 ± 7 Ma	Ren et al., 2016
S1314	Gneissic trondhjemite	West of Culaishan	2641 ± 12 Ma	Ren et al., 2016
SD0604	Gneissic tonalite	Taishan	2637 ± 22 Ma	Lu et al., 2008
TS1111	Trondhjemitic dike	Qixingtai	2631 ± 13 Ma	Wang et al., 2016a
S1305	Tonalite	Taishan	2630 ± 10 Ma	Ren et al., 2016
S1306	Trondhjemitic vein	Taishan	2628 ± 8 Ma	Ren et al., 2016
SD0502	Gneissic tonalite	Liuhan, Taishan	2627 ± 18 Ma	Lu et al., 2008
S0726	Gneissic trondhjemite	Qixingtai	2623 ± 9 Ma	Wan et al., 2014
17SD22-1	Tonalitic gneiss	North of Taian	2620 ± 4 Ma	This study
SD0503	Gneissic trondhjemite	Taishan	2620 ± 16 Ma	Lu et al., 2008
S0722	Mylonitized tonalite	Panchegou	2615 ± 8 Ma	Wan et al., 2014
~2.61–2.58 Ga				
Supracrustal rocks				
17SD11-5	Plagioclase amphibolite	Shipengshan	2591 ± 9 Ma	Gao et al., unpublished data
16SD157-7	Plagioclase amphibolite	Majiayu	2585 ± 5 Ma	Gao et al., unpublished data
17SD49-9	Plagioclase amphibolite	Laohuling	2577 ± 32 Ma	Gao et al., unpublished data
Intrusive rocks				
16SD51-1	Monzogranitic gneiss	Youfangcun	2615 ± 6 Ma	Gao et al. 2019
TS09110	Meta-gabbro	Southeast of Mengjiatun	2614 ± 11 Ma	Ren et al., 2016
16SD208-1	Monzogranitic gneiss	East of Xintai	2613 ± 8 Ma	This study
TS1107-2	Trondhjemite	Qixingtai	2611 ± 31 Ma	Wang et al., 2016a, 2016b, 2016c
S1324	Biotite monzogranite gneiss	Xintai	2611 ± 9 Ma	Dong et al., 2017
SD0512	Felsic vein	Lihang, Taishan	2607 ± 50 Ma	Lu et al., 2008
S0834	Mylonitized trondhjemite	Yanlingguan	2605 ± 12 Ma	Wan et al., 2014
S1136	Gneissic granite	Panchegou	2600 ± 15 Ma	Wan et al., 2014
S1144	Hornblende (Meta-cumulate gabbro)	Qixingtai	2597 ± 19 Ma	Wan et al., 2014
S0772	Banded granitic gneiss	Sishui	2597 ± 40 Ma	Dong et al., 2017
S0714	Trondhjemitic gneiss	Pingyi	2592 ± 25 Ma	Dong et al., 2017
16SD169-1	Granodioritic gneiss	East of Menglianggu	2591 ± 5 Ma	This study
YS-2A	Diorite	Yishui	2587 ± 15 Ma	Yang and Santosh, 2017
S0513	Banded tonalite gneiss	Menglianggu	2585 ± 19 Ma	Dong et al., 2017
YS-6C	Monzogranite	Luojiazhuang	2581 ± 21 Ma	Li et al., 2016
16SD200-1	Monzogranitic gneiss	South of Yanlingguan	2581 ± 15 Ma	This study
16SD31-1	Monzogranitic gneiss	Yangzhuangzhen	2578 ± 9 Ma	Gao et al. 2019
16SD50-1	Monzogranitic gneiss	Yishui	2575 ± 8 Ma	Gao et al., 2019a, 2019b

have underplated at various crustal levels, causing the diversity of the crust-derived granitoids in this period. The extensive ~2.61–2.58 Ga trondhjemitic gneisses and monzogranitic gneisses were derived mainly from pure crustal melts (Dong et al., 2017; Wan et al., 2014; Wang et al., 2016c; Wu et al., 2013). The ~2.61–2.58 Ga K-rich monzogranitic gneisses represent the oldest

potassic granitoid magmatism in the WST, marking a transformation of the continental granitoid composition from Na-rich to K-rich (Arndt et al., 2002; Bédard, 2006; Gao et al., 1998; Nelson, 1991; Rudnick and Fountain, 1995). In contrast, the magmas of the ~2.59 Ga high-Mg granodioritic gneisses in this study were derived from the delamination of lower crust material.

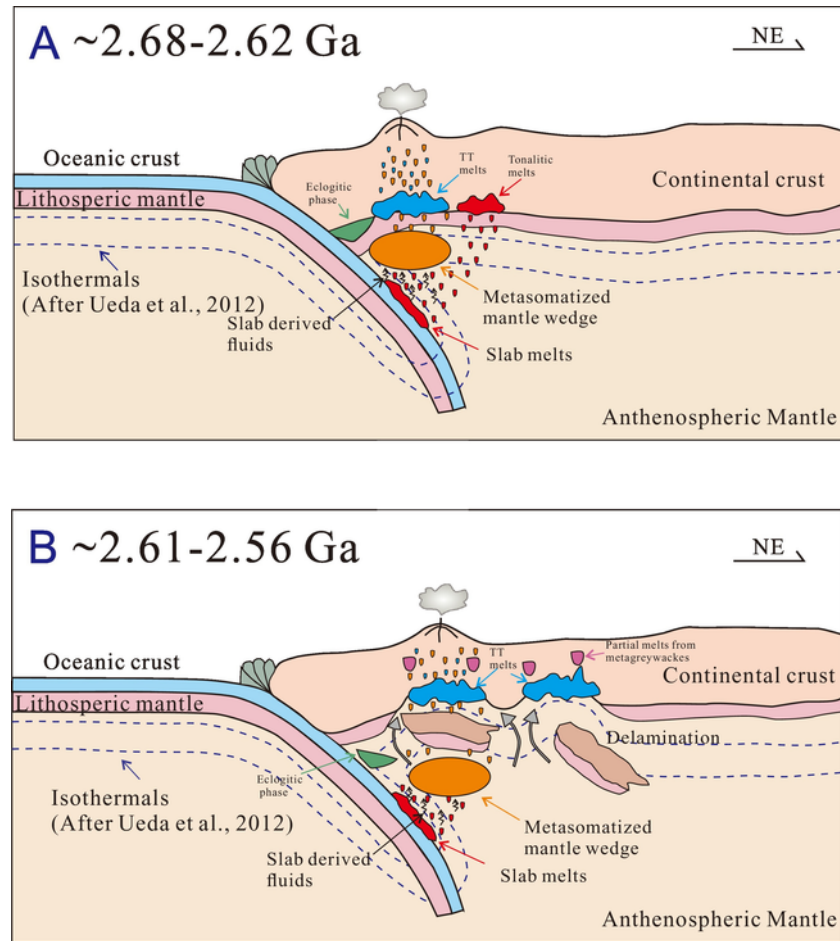


Fig. 9. Schematic tectonic model illustrating the early-middle Neoproterozoic subduction-delamination geodynamic regime in the WST. (A) An active continental arc system, which is identified by eruptions of CABs, HMAs, adakites and inherited ancient zircons in the HMAs, is operated during ~2.68–2.62 Ga. Some mantle-derived magma underplated at various crustal levels, generating the magmatic precursors of the ~2.66–2.62 Ga TT gneisses. Simultaneously, the lithosphere was thickened resulted from long-term lateral accretion. (B) The thickened lithosphere lost its stability and delaminated, leading to the rising of the mantle materials and forming magmatic precursors of the ~2.61–2.58 Ga tholeiitic basalts and gneisses. The delaminated lower crust materials melted in the subcrustal mantle, generating the pristine magma of the ~2.59 Ga high-Mg granodioritic gneisses. The rising mantle magma underplated and developed the magmatic precursors of the ~2.61–2.58 Ga TT and monzogranitic gneisses.

As discussed in Section 6.3, the Neoproterozoic continental crust of the WST experienced an ~10 km thinning process in a relatively short period (~2.70–2.55 Ga), which is appropriately explained by the delamination of the thickened lower crust at ~2.61–2.58 Ga.

Given the distinct characteristics of the lithological associations among the ~2.71–2.68 Ga, ~2.68–2.62 Ga and ~2.61–2.58 Ga rocks, the geodynamic process obviously transformed from subduction to delamination; accordingly, we propose a subduction-delamination geodynamic model for the early-middle Neoproterozoic crustal evolution (Fig. 9).

In summary, a plate tectonic regime operated before ~2.71 Ga in the WST (Gao et al., 2019b). With the continuous subduction, the crust gradually thickened resulting in a crustal thickness of ~44–51 km at ~2.69 Ga and was uplifted, and the formation of the continental crust in the WST further evolved with the active continental margin during ~2.68–2.62 Ga (Fig. 9A; Sun et al., 2019b). The long-term lateral accretion from ~2.7 Ga in the WST may have caused the lithosphere to thicken, lose its stability and finally break off during ~2.61–2.58 Ga, leading to the upwelling of mantle materials and intense crust-mantle interactions and generating the diverse granitoids (Fig. 9B; Gao et al., 1998; Jull and Kelemen, 2001; Nelson, 1991).

Furthermore, the delamination of the lower crust may have contributed to the compositional evolution of the Neoproterozoic continental crust from basaltic to andesitic, leading to the uplift of the continental crust in the WST.

7. Conclusions

- (1) The middle Neoproterozoic intrusive granitoids in the WST are mainly composed of ~2620 Ma tonalitic gneisses, ~2591 Ma high-Mg granodioritic gneisses and ~2613–2581 Ma monzogranitic gneisses. They generally intruded into ~2681–2692 Ga TTG gneisses.
- (2) The early Neoproterozoic TTG gneisses originated from the partial melting of low-K mafic rocks in the lower crust. The middle Neoproterozoic tonalitic gneisses were derived from the dehydration melting of descending slabs. The magmatic precursor of the middle Neoproterozoic monzogranitic gneisses originated from juvenile greywackes in the stability region of plagioclase. The pristine magma of the middle Neoproterozoic high-Mg granodioritic gneisses was derived from delaminated lower crustal materials that melted in the subcrustal mantle.

- (3) Three episodes of geological events have been identified at ~2.71–2.68 Ga, ~2.68–2.62 Ga and ~2.61–2.58 Ga. The first episode was characterized by extensive crust-derived TTG gneisses. The second episode produced arc-related calc-alkaline volcanic or intrusive rocks. The rock assemblages in the third episode exhibit diversity, consisting of abundant delaminated granodioritic gneisses, crust-derived monzogranitic gneisses and trondhjemitic gneisses and contemporaneous mantle-derived tholeiitic basalts and diorites.
- (4) A middle Neoproterozoic subduction–delamination model is proposed in the WST, in which a long-term lateral accretion from ~2.7 Ga may have caused the lithosphere to thicken, lose stability and finally break off during ~2.61–2.58 Ga, leading to mantle uplift and intense crust–mantle interactions, forming the diverse granitoids.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lithos.2019.105178>.

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