Modelling partial melting in sinking greenstone belts with implications for Archaean continental crust formation

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Key Points:

- Partial melting of komatiitic basalt can produce high Mg$^{\#}$ trondhjemitic melts.
- Hybridization of melts produced by tholeiitic and komatiitic basalts would generate TTG-like magma.
- Partial melting of komatiitic basalt cannot generate sanukitoid suites.

Abstract

Tonalite–trondhjemite–granodiorite (TTG) gneisses are the dominant component of Archaean continental crust, with their parent magmas generally thought to have formed due to the partial melting of hydrated basalts; however, this process typically produces melts with a notably lower $Mg^{\#}$ than most natural TTGs. By contrast, ultramafic volcanic rocks commonly preserved in Archaean greenstone belts may represent an alternative source of TTG magma that has been largely overlooked. Here, we use petrological modelling to investigate anatexis of komatiites and komatiitic basalts from the Warrawoona Group of the Pilbara craton. In all cases, komatiite is refractory and generates no melt within the pressure-temperature range considered. Komatiitic basalts, however, could produce 20–25 vol. % of MgO-rich melts during greenstone belt sinking and hot subduction. Anatexis of komatiitic basalts generates melt fractions too depleted in large ion lithophile elements to represent natural TTGs; however, hybridization of melts produced by partial melting of tholeiitic basalts and komatiitic basalts during crustal overturn would generate magma that resembles natural TTGs. All calculated melts are felsic in composition, and TTGs with high $Mg^{\#}$ could have been generated entirely within the crust, with no requirement for the assimilation of mantle materials. By contrast, Archaean sanukitoids require some assimilation of mantle materials with crustal melts, indicating that the oldest sanukitoids preserved in each Archaean craton may record temporary and localized subduction on the early earth. The ubiquitous occurrence of sanukitoids worldwide by *c*. 2.7 Ga may provide a minimum age for the onset of global plate tectonics.

Plain Language Summary

Tonalite–trondhjemite–granodiorite (TTG) gneisses, the major component of the ancient nuclei of continents, have been broadly accepted to be formed by partial melting of hydrated tholeiitic basalt. However, experimental studies show this process can only produce magma with lower magnesium than natural TTGs. As a result, researchers proposed that the assimilation of mantle materials during subduction is necessary for the generation of high-MgO magma resemble natural TTGs. This proposal neglects the contribution of high-MgO rocks in the Archaean greenstone belts as an alternative source of TTGs. In this study, we use petrological modelling to investigate partial melting of some high-MgO rocks. The results show that partial melting of high-MgO basalts can produce some high-MgO melts. Magma mixing of melts produced by partial melting of high-MgO basalts and tholeiitic basalts can generate TTG-like magma. Natural TTGs with high magnesium contents can be formed totally in the crustal level, and the assimilation of mantle materials driven by subduction is not necessary. By contrast, the production of high-MgO diorite in the ancient continental crust should involve assimilation of mantle materials. The widespread *c*. 2.7 Ga high-MgO diorite might indicate the onset of global plate tectonics.

1 Introduction

Archaean continental crust is mainly composed of felsic orthogneisses and metamorphosed supracrustal rocks dominated by basalt (greenstones) (Condie, 1993). As the dominant Archaean lithology, TTGs may occur as intrusions in linear tectonic belts, such as those in the Nuvvuagittuq in Québec, Canada and Isua, west Greenland (O'Neil et al., 2012; Windley & Garde, 2009), or as circular-to-elliptical domes surrounded by trough-shaped greenstone belts (keels). Such dome-and-keel structures, which are particularly well-preserved in the Pilbara, Kaapvaal, and Zimbabwe cratons (Fig. 1a; Anhaeusser & Wilson, 1981; Van Kranendonk, 2004, 2014), are notably different from linear features, such as arcs and strike-slip shear zones that form due to horizontal deformation in a plate tectonic regime, which have dominated the rock record since the Neoarchaean (Herzberg et al., 1983; Wells et al., 1980). They are typically interpreted to have resulted from relative vertical motions in the crust, with magmatic over-accretion causing downward advection (i.e., drip, sagduction, delamination) (Van Kranendonk, 2007; Smithies et al., 2021), although some researchers also suggested that such dome-and-keel structures could also have formed via plate tectonic processes (Kusky et al., 2021; Whitney et al., 2004; Windley et al., 2021).

Most Archaean TTG magmatic rocks have been metamorphosed after emplacement and occur as grey gneisses dominated by plagioclase, quartz, and biotite, with minor K-feldspar and hornblende. They are characterized by low K_2O/Na_2O (<0.6), with an average $Mg^{\#}$ of 43 (Moyen, 2011; Moyen & Martin, 2012). Based on several geochemical proxies (e.g., Sr/Y and La_N/Yb_N), TTGs have historically been classified into high pressure (HP), medium pressure (MP), and low pressure (LP) types. Given the geochemical similarities between some HP TTGs and modern adakites (Moyen & Martin, 2012; Smithies et al., 2019), hot subduction zones have been proposed as possible geodynamic environments for the generation of felsic crust during the Archaean (Arndt, 2013). Alternatively, Archaean oceanic crust has been suggested to be much thicker and hotter than Phanerozoic oceanic crust (Bickle, 1986; Windley & Davis, 1978). Consequently, crustal anatexis at the lower levels of thickened oceanic crust or within crustal drips into the underlying mantle have been proposed as magmatic settings for generating dome-structured TTGs, especially in the early Archaean (Bédard, 2006; Johnson et al., 2017).

Changing tectonic styles and geodynamic regimes documented throughout the Archaean, recorded either by structure, metamorphism, or geochemistry, have been linked to secular cooling of the mantle (Brown & Johnson, 2018; Herzberg, 2022; Herzberg et al., 2010; Mitchell & Ganne, 2022; Johnson et al., 2019). Inferred high mantle potential temperatures (T_P) during the middle Archaean (up to ~1,600 °C) caused higher degrees of partial melting of the primitive mantle (Herzberg et al., 2010), generating melt fractions up to 30–50% (Arndt et al., 2003). Higher mantle T_P associated with mantle plumes also led to the production of komatiites (MgO >18 wt. %), which are common in Archaean greenstone belts, but rare in Proterozoic and Phanerozoic terranes (Arndt, 2008). Komatiites usually occur in the lower tectono-stratigraphic portions of major greenstone belts, interlayered with basaltic and komatiitic basaltic rocks (Furnes et al., 2015) (Fig. 1b).

Several petrological modelling studies have investigated partial melting of enriched tholeiitic basalt from greenstone belts (Ge et al., 2018; Kendrick et al., 2022; Palin et al., 2016), including the Coucal basalt from the Warrawoona Group of eastern Pilbara craton (Johnson et al., 2017). A common feature of all these previous results is that calculated melt compositions have MgO contents and $Mg^{\#}$ (molar $MgO/(MgO+FeO_t)$) lower than natural TTGs (Huang et al., 2020, 2022), consistent with experimental results (e.g. Laurie & Stevens, 2014; Patiño-Douce & Beard, 1995; Winther & Newton, 1990). The assimilation of mantle materials into natural TTGs during ascent towards Earth's surface has been proposed to explain this disparity, which is expected to have been common in Archaean subduction zone settings (e.g. Smithies & Champion, 2000). Nonetheless, the assimilation of mantle materials would also enrich TTGs in compatible elements (e.g. Cr and Ni), which is often not the case. Indeed, previous studies have shown that modelled melt compositions produced from tholeiitic basalts have lower $Mg^{\#}$, but higher Ni contents than natural TTGs (Huang et al., 2022).

The early Archaean rock record indicates that very few terranes record peak metamorphic pressures >1.5 GPa at geothermal gradients lower than 500 °C/GPa, suggesting that convergent margin processes were relatively rare before *c*. 3.0 Ga (Brown & Johnson, 2018). In addition, the intracrustal melting model neglects the potential contribution of MgO-rich rocks in greenstone belts that may be a possible source of TTG magma. The partial melting of interlayered ultramafic volcanic rocks (komatiite or komatiitic basalt), which should have experienced the same metamorphic evolution as the mafic components of the Archaean crust, potentially has significant implications for understanding TTG generation. Recent modelling of komatiite and komatiitic basalts mainly focuses on their dehydration process at subsodius conditions (Hartnady et al., 2022; Tamblyn et al., 2022). Here, we performed petrological modelling on mafic and ultramafic rocks from the Paleoarchaean Warrawoona Group of the eastern Pilbara craton, Western Australia, which is a dome and keel structure-dominated greenstone belt that likely formed in an intraplate environment. Modelled melt compositions were then compared with natural TTGs, and our results are discussed within the context of the role of various Archaean greenstone belt components in generating Earth's earliest continental crust.

2 Pressure–temperature (*P*–*T*) paths of vertical motion

Greenstone belts vary in thickness from <2 km (the Taishan greenstone belt of North China craton) to >12 km (Warrawoona Group) (Furnes et al., 2015; Polat et al., 2006; Van Kranendonk et al., 2007), although the Pilbara Supergroup has been suggested to reach >15 km in some areas (Fig. 1b; Van Kranendonk et al., 2007). As most greenstone belts have thicknesses <10 km (Furnes et al., 2015), sinking of their lower portions through the middle and lower crust should promote partial melting (Sizova et al., 2018). Study of the *P–T* evolution of metasedimentary and mafic rocks in the interior of greenstone keels, close to dome margins and enclaves in granite domes in the Pilbara craton, suggests that metamorphic rocks in the interior of the greenstone belts only experienced up to greenschist facies metamorphism (~500 °C). Rocks close to the dome margins record a peak pressure of 0.9 GPa at ~600 °C and enclaves in the domes reached peak metamorphic conditions of ~700 °C (François et al., 2014). Similar peak temperatures have been obtained from the Barberton greenstone belt of the Kaapvaal craton (Moyen et al., 2006). In the late Archaean (*c.* 2.5 Ga), supracrustal rocks in the TTG dome from East Hebei, North China craton are suggested to have reached ultra-high temperature (UHT) conditions (Liu et al., 2024). However, synchronous subduction has also been reported in this area (Ning et al., 2022). Coexisting greenstone belt sinking and subduction renders it difficult to decipher the high Mg# of TTGs. Besides, UHT metamorphism was scarce in the early Archaean (Brown & Johnson, 2018; Jiao et al., 2023). Thus, UHT metamorphic *P–T* evolution will not be explored in this study.

By using 2-D geodynamic modelling, Sizova et al. (2015) proposed three tectonic processes in the absence of plate convergence for generating TTG magma: crustal overturn, local thickening of the crust, and lower crustal delamination (Fig. 1c). In the crustal overturn model, Sizova et al. (2018) reproduced typical *P–T* paths for greenstone keels and enclaves in felsic domes, with simulated peak temperatures being close to or slightly higher than those preserved in Archaean cratons worldwide (Fig. 2a). In this numerical model, metamorphic rocks in the interior of the greenstone keels recorded heating and compression from the surface to 500 °C at 0.45 GPa. Rocks close to the dome at 15 km depth recorded compressional heating from 550 °C at 0.55 GPa to 700 °C at 1.0 GPa, then experienced a thermal relaxation to 800 °C at 0.7 GPa owing to the underplating of dry basaltic melts. Exhumed keel enclaves within domes recorded heating during burial from 200 °C near to the surface to 700 °C at 1.0 GPa, and subsequently experienced conditions of <900 °C at 0.6 GPa before exhumation to the middle crust.

In local thickened crust model, partially hydrated to anhydrous lower crust would experience heating along high geothermal gradients identical to the crustal overturn model (900–1300 °C/GPa) (Sizova et al., 2015). The main difference is that crustal overturn mainly experiences melting during heating and decompression but crustal thickening experiences melting during heating and compression (Fig. 2). In the lower crustal delamination model, partially hydrated to anhydrous lower crust could sink into the mantle and reach depths of ~100 km before melting along geothermal gradients similar to those of hot subduction (400–500 °C/GPa) (Hartnady et al., 2022; Martin, 1986; Sizova et al., 2015). Sizova et al. (2010) and Perchuk et al. (2019) also produced *P*–*T* paths documenting the transition from Precambrian hot subduction to modern cold subduction (~250 °C/GPa) and Precambrian intraoceanic subduction (<200 °C/GPa) (Fig. 2b). These geothermal gradients are too low to induce significant partial melting of the subducted slab, and so are not considered further here.

In the crustal overturn model, *P*–*T* paths of sinking greenstone belts show that keels close to the dome and enclaves in the granite domes should partially melt (Fig. 2a), with the majority of anatexis occurring during decompression. Predicted *P*–*T* paths for both lithologies are similar during this decompression process, with peak metamorphic conditions of ~700 °C at 1.0 GPa and thermal relaxation to peak temperatures, although enclaves in the domes are expected to reach temperatures ~100 °C higher than keels close to the dome. In such a case, melts produced by partial melting of the keels close to the domes and enclaves in the domes will be identical for temperatures <800 °C. To fully constrain the partial melting of sinking greenstones during crustal overturn, modelling partial melting of the enclaves in the granite domes should therefore be sufficient. Here, we used the modelled *P*–*T* path of enclaves in domes to explore the partial melting behavior of a sinking greenstone belt. For comparison with local crustal thickening, lower crustal delamination and hot subduction, *P*–*T* paths along 900°C/GPa, 500 °C/GPa (partially hydrated bulk composition) and 500 °C/GPa (fully hydrated bulk composition) were also explored (Fig. 2b). Model setup conditions are provided in the supplementary materials.

3 *P*–*T* conditions of komatiite metamorphism

Most TTGs in the East Pilbara craton were emplaced after 3.47 Ga (Johnson et al., 2019; Vandenburg et al., 2023; Hickman, 2021), indicating that their source lithologies are older. Thus, our petrological modelling considered mafic and ultramafic volcanic rocks from the Warrawoona Group, the lowermost sequence of the Pilbara Supergroup that record crystallization ages of 3.53–3.43 Ga (Van Kranendonk et al., 2007; Hickman, 2021). Komatiites in the Warrawoona group have an average SiO_2 content of 49.2 wt. % and MgO content of 23.9 wt.%. The $K_2O + Na_2O$ contents of komatiites are <2 wt. %, and the TiO_2 contents are <1 wt. % (Sossi et al., 2016). Compared with basaltic compositions in the Warrawoona Group, the komatiites are poor in large ion lithophile elements (LILEs) and high field strength elements (HFSEs), but rich in compatible elements (e.g., Cr and Ni; Table S1) (Kato & Nakamura, 2003; Johnson et al., 2017).

Metamorphic phase equilibria are controlled by bulk-rock composition, including H_2O content, hence individual *P*–*T* pseudosections were constructed for Warrawoona komatiite with different H_2O contents in case of different tectonic environments (Fig. 3a and b). Although it is suggested that some Proterozoic TTGs in the Pilbara craton can be produced by fluid-fluxed melting in the crust (Pourteau et al., 2020), introducing of aqueous fluid into the lower crust in an intraplate setting might be local (Brown, 2013). Besides, adding H_2O content into basaltic compositions will shrink the stability field to lower pressure, leading to the production of TTG melts with high Sr/Y (Pourteau et al., 2020), which is not characteristic of Paleoarchaean TTGs in the east Pilbara craton; thus, we used 3.5 wt.% H_2O in our modelling as a threshold for minimum saturation during crustal thickening and dripping (shows in grey phase diagrams in Fig. 3a and b). We used a H_2O content of 7.5 wt.% for TTG formation in a subduction zone setting to allow for all the calculated melts to be produced from fluid-present melting, since fluid is abundant in such an environment and basaltic oceanic crust can be readily hydrated at ridge systems and during plate bending prior to the onset of subduction (shown in blue in the phase diagram in Fig. 3b). Although the topologies of the phase diagrams are distinct, neither wet solidus occurs below <1,000 °C (Fig. 3a and b). Given UHT metamorphism recording temperatures >900°C are scarce in the early Archaean until c. 3.0 Ga (Jiao et al., 2023), partial melting of komatiite is only expected to make a minor contribution to TTG magma generation. The water content of the protolith strongly affects the stabilities of garnet and pyroxene. When the protolith is minimally fluid-saturated, garnet is stable at P > 0.6–1.0 GPa and clinopyroxene is stable at *P*–*T* conditions of >0.8–0.9 GPa and >800 °C. Orthopyroxene is stable throughout the considered *P*–*T* range (Fig. 3a). Under fluid-saturated conditions, the stability of garnet and clinopyroxene reduces up-pressure, while orthopyroxene stability field reduces at temperatures >700 °C (Fig. 3b); instead, talc and quartz would form below 650 °C in such lithologies.

4 Partial melting of komatiitic basalts and basalts

4.1. Partial melting of komatiitic basalts

Komatiitic basalts from the Warrawoona Group, Pilbara craton have an average SiO_2 content of 51.4 wt.% and MgO content of 12.5 wt.% (Kato & Nakamura, 2003). They are very low in K_2O (0.06 wt.%), prohibiting the stabilization of K-bearing minerals like biotite. Partial melting of the komatiitic basaltic compositions is expected to occur at a minimum temperature of 700 °C at 1.1–1.2 GPa. Olivine is unstable in the studied *P*–*T* range. At suprasolidus condition, garnet is stable at P > 1.0 GPa, plagioclase is stable at pressure < 1.0 GPa, and rutile is expected to occur at P > 1.3 GPa for all considered protolith H_2O contents (Fig. 3c and d).

During crustal overturn, nearly 20 vol.% melt is expected to be produced per unit volume of protolith up to 900°C (Fig. 3c), with this melt having a trondhjemitic composition (cf. Ab–An–Or diagram, Fig. 4a). These melts have very low K_2O/Na_2O (Fig. 5a), although their $Mg^{\#}$ and MgO content can be as high as 39 and 1.7 wt.%, respectively (Fig. 5b). Calculated trace elements of the melts are depleted in LILEs and HFSEs, with positive Sr and Zr anomalies, but distinct from those of natural TTGs (Fig. 6a and b). The lack of K_2O and other LILEs in melts produced by komatiitic basalt anatexis is consistent with experimental work by Hastie et al. (2016 & 2023). The Sr/Y and $(La/Yb)_N$ are relatively lower than those of natural TTGs (Fig. 5c and d).

During crustal thickening, 18 vol.% melt is produced up to 900°C (Fig. 3d). Identical to those produced during crustal overturn, all the melts have low K_2O/Na_2O, and plot in the trondhjemite field (Fig. 4b and 5e), although the melt composition tends to be tonalitic at temperature >900 °C (c.f. Hastie et al., 2016). The MgO contents of the calculated melts are always lower than 1.0 wt.%, despite that the $Mg^{\#}$ can be as high as 35 (Fig. 5f). Trace elements of the melts are similar with those produced during crustal overturn (i.e., depleted in LILEs and HFSEs, low Sr/Y and $(La/Yb)_N$; Fig. 6c; 5g and h).

During lower crustal delamination, 20 vol.% melt would be generated up to 900 °C (Fig. 3c). All the melts are also trondhjemitic (Fig. 4c), and are depleted in K_2O (Fig. 7a). The $Mg^{\#}$ of the calculated melts can be as high as 42, but MgO contents are always lower than 0.7 wt.% (Fig. 7b). The trace elements of the calculated melts are characterized by higher Sr/Y and $(La/Yb)_N$ than those produced at crustal overturn and crustal thickening (Fig. 7c and d), although the HREEs, LILEs and HFSEs of the calculated melts are depleted (Figs. 6e and 7c).

Given fluids are expected to have been abundant in hot subduction systems, a higher proportion of melt (25 vol.%) would have been produced than for fluid-absent melting at a similar thermal gradient (Fig. 3d), although all melt compositions are still trondhjemitic (Fig. 4d), with low K_2O/Na_2O (Fig. 7e). The $Mg^{\#}$ and MgO contents of calculated melts can be up to 41 and 1.5 wt.%, respectively (Fig. 7f). The calculated melts produced at hot subduction zone also have high Sr/Y and $(La/Yb)_N$, but the HREEs, LILEs and HFSEs of the calculated melts are still depleted (Figs. 6g and 7g).

4.2. Partial melting of tholeiitic basalts

In the Warrawoona Group, tholeiitic basalts from different formations show a wide range of MgO contents, from 2.6 wt. % in the Coucal Formation to 12.5 wt. % in the Apex Formation (Johnson et al., 2017; Kato & Nakamura, 2003). We modelled the evolution of pillow structured Apex tholeiitic basalts and averaged low-MgO Coucal basalts.

4.2.1. Apex tholeiitic basalts

In the *P*–*T* diagram of the Apex tholeiitic basalts, garnet stability is both temperature and pressure dependent, and it is expected to be consumed at pressures <0.9 GPa (Fig. 3e and f). The rutile–ilmenite transition is expected to occur at pressures >1.0 GPa above the solidus, although the addition of fluid will shrink the stability of rutile to higher pressure (>1.2–1.7 GPa; Fig. 3e and f). When fluid is limited in the protolith, the plagioclase stability field is both temperature and pressure dependent, which is unstable >0.8 GPa at the solidus condition (~750℃) and >1.8 GPa at 900℃ (Fig. 3e). However, plagioclase is always unstable at pressures >1.2 GPa when fluid is sufficient (Fig. 3f). Partial melting is expected to occur at 700 ℃ above 1.0 GPa, but should occur at higher temperature (up to 800℃) when pressure is <1.0 GPa (Fig. 3e and f).

Partial melting during crustal overturn could produce 30 vol.% of melts (Fig. 3e). In the Ab–An–Or diagram, the melt compositions evolve from granodioritic to tonalitic, with slightly higher K_2O/Na_2O up to 0.7 (Figs. 4a and 5a). The calculated melts have a lower $Mg^{\#}$ and MgO contents than those produced by komatiitic basalt (Fig. 5b). The $(La/Yb)_N$ and Sr/Y of the calculated melts are slightly lower than those of natural TTGs (Figs. 5c and d). Compared with melts produced through the partial melting of komatiitic basalts, melts produced by tholeiitic basalts are richer in LILEs (Fig. 6a).

Crustal thickening could induce 12 vol.% of melt production (Fig. 3f). The melt compositions evolve from granodioritic to tonalitic (Fig. 4b), with K_2O/Na_2O always in TTG range (Fig. 5e). The $Mg^{\#}$ and MgO contents of the calculated melts are always lower than 30 and 1 wt.%, respectively (Fig. 5f). Compared with melts produced for crustal overturn, the $(La/Yb)_N$ and Sr/Y of the melts produced for crustal thickening occur in a similar but more narrow range (Figs. 5g and 5h). LILEs are also enriched in melts produced by crustal thickening (Fig. 6c).

During lower crustal delamination, 19 vol.% melt could be produced up to 900℃ (Fig. 3e), all of which plot in the trondhjemite field (Fig. 4c). The K_2O/Na_2O is always lower than 0.6 (Fig. 7a). The MgO contents of the calculated melts are extremely low (<0.24 wt.%), although the $Mg^{\#}$ are identical to natural TTGs (Fig. 7b). The $(La/Yb)_N$ and Sr/Y of the melts are obviously higher than those produced at high geothermal gradients (Figs. 7c and 7d). LILEs are still enriched in melts produced by lower crustal delamination (Fig. 6e).

The melts volume proportion produced in a hot subduction setting could be as high as 51 vol.% (Fig. 3f), with compositions evolving from trondhjemitic to tonalitic (Fig. 4d). The K_2O/Na_2O of the melts are always in the TTG range (Fig. 7e). The $Mg^{\#}$ are similar with natural TTGs, whereas the MgO contents are still <1 wt.% (Fig. 7f). The $(La/Yb)_N$ and Sr/Y of the melts are similar with natural TTGs, but the HREE are obviously depleted (Figs. 7g and 7h). LILEs are also enriched in the melts, essentially identical to natural TTGs (Fig. 6g).

4.2.2. Coucal low-MgO tholeiitic basalts

The *P–T* diagram and partial melting of averaged Coucal basalts has been described in several studies (Huang et al., 2020; Johnson et al., 2017), thus is not described in detail here again, but is provided in Figures 4–7 and S1. Given that the K_2O contents of the Coucal basalts (avg. 0.5 wt.%) are relatively higher than other possible aforementioned sources, the stability field of biotite extends to the suprasolidus condition (Fig. S1a), leading to an increase of K_2O/Na_2O of calculated melts during biotite dehydration melting, which could be found in intraplate settings (Figs. 5a, 5e and 7a). Thus, the melts initially produced are usually granitic (Fig. 4a and b). After biotite is completely consumed, incongruent melting of hornblende will generate TTG-like melts. The $Mg^{\#}$ of the calculated melts are always <30, no matter the geological setting (Figs 5b, 5f, 7b and 7f). Higher geothermal gradients would produce melts containing higher MgO contents (>1 wt.%; Fig. 5b and f). All the calculated melts are rich in LILEs and HFSEs (Fig. 6), although Nb and Ta negative anomalies are obvious in the melts produced at low thermal gradients (Fig. 6e and g). Melts produced at low geothermal gradients (i.e., lower crustal delamination and hot subduction) have low HREEs, distinct from natural TTGs (Fig. 7c and g). Melts produced for crustal overturn and crustal thickening are usually characterized by lower $(La/Yb)_N$, Sr/Y, and Nb/Ta (Figs. 5c, 5d, 5g, 5h and 6), whereas melts produced at lower crustal delamination and hot subduction settings have lower $(La/Yb)_N$, Sr/Y, and Nb/Ta (Figs. 6, 7c, 7d, 7g and 7h).

5 Magma mixing

As described, melts generated from enriched tholeiitic basalts have lower $Mg^{\#}$ and higher K_2O/Na_2O than natural TTGs, but their trace elements are enriched in LILEs and HFSEs that are broadly consistent with natural TTGs. Melts produced from komatiitic basalts are poor in K_2O and LILEs and HFSEs, but their $Mg^{\#}$ match natural TTGs. Since the melts produced by the partial melting of basalts and komatiitic basalts are complementary, natural TTGs might be generated by mixing melts produced from different protoliths. For simplicity, we assume both that komatiitic basalts and tholeiitic basalts are evenly distributed in the greenstone belts considered, and that the Apex tholeiitic basalts and the Coucal low-MgO tholeiitic basalts have the same proportion during partial melting. Given a specific protolith composition, the volume of melt produced during anatexis is a strong function of temperature (Fig. 3). Thus, we used a temperature interval of 25 °C to explore the magma mixing results.

Since the Coucal low-MgO basalts were the most fertile protolith we investigated, mixed melts produced by initial anatexis of the Coucal low-MgO basalts, Apex tholeiitic basalts, and komatiitic basalts will be identical to the melts generated by low-MgO tholeiitic basalts. At higher temperatures, the melts produced by the Apex tholeiitic basalts and komatiitic basalts start to make a greater contribution to the mixed magma. During crustal overturn, the mixed melts evolve from the trondhjemite field to the tonalite field rising above 900 °C (Fig. 4a), while all the mixed melts produced during other tectonic processes plot in the trondhjemite field, distinct from natural TTGs, of which nearly half are tonalitic. In a K_2O/Na_2O vs. SiO_2 diagram, the natural TTGs in the Pilbara craton can be divided into two groups, with one group plotting along the melts evolution produced from low-MgO basalts and the other along the mixed melts evolution produced at high geothermal gradient (i.e., crustal overturn and crustal thickening) (Fig. 5a and e). Mixed melts produced at low geothermal gradient would have SiO_2 contents too high (>70 wt.%) to match natural TTGs (Fig. 7a and e). During crustal overturn, the $Mg^\#$ and MgO contents of mixed melts can as high as 31 and 1.37 wt.%, respectively (Fig. 5b). Mixed melts produced during crustal thickening would have slightly lower $Mg^\#$ up to 29 (Fig. 5f). The $Mg^\#$ of calculated melts produced at low thermal gradients would have higher $Mg^\#$, but the MgO contents are <1 wt.% for lower crustal delamination (Fig. 7b and f). The trace elements of mixed melts produced at higher thermal gradients are identical to natural TTGs (Fig. 6b and d). In contrast, the HREEs and Nb/Ta of mixed melts produced at low thermal gradients are too low to match natural TTGs in the east Pilbara (Fig. 6f and h).

6 Discussion

6.1. Partial melting of komatiite and high-MgO basalt

Partial melting experiments investigating Archaean TTG formation performed on komatiite were first attempted by Foley et al. (2003), followed by similar partial melting experiments performed on high-MgO basaltic compositions (Adam et al.,2012; Ziaja et al., 2014; Hastie et al. 2016, 2023). All of these experiments focused on UHT partial melting >900 °C, whereas low-temperature anatexis has not been explored experimentally. Nonetheless, metamorphic conditions recording temperatures <900 °C dominate Archaean greenstone belts. Exploring partial melting at amphibolite to granulite facies metamorphism is thus necessary for potentially emulating the generation of most TTG magmas. In many of these previous works, the water contents in the starting compositions were quite low for water saturation (e.g., Foley et al., 2003; Ziaja et al., 2014). The water contents in the source rock play an important role on the solidus temperature. Based on recent thermodynamic modelling, hydrous minerals, especially chlorite and serpentine, are relatively abundant in high-MgO source rock (Hartnady et al., 2022), consistent with natural rocks that could be found in greenstone belts, such as Belingwe, Zimbabwe (Bohar, 2003) and Isua, West Greenland (Furnes et al., 2009). Komatiite could preserve as much as twice the amount of crystal-bound H_2O (6 wt. %) than low-MgO basalts at subsolidus conditions (Hartnady et al., 2022; Tamblyn et al., 2023). Aqueous fluids released by dehydration of these nearby komatiites during greenbelt sinking would then introduce to the komatiitic basalt and basalt, and promote partial melting (Hartnady et al., 2022; ; Smithies et al., 2021; Tamblyn et al., 2023). If water contents in the protolith were adjusted so that minimal free H_2O occurred at the intersection of the solidus and the *P*–*T* path, then the fertility of mafic-ultramafic rocks would be primarily controlled by the MgO and SiO_2 contents in their protoliths (Fig. 3).

Figure S2 shows *T*–*X* pseudosections constructed at 1.1, 0.9, and 0.7 GPa for bulk compositions ranging from average Archaean basalt (SiO_2 = 51 wt.% and MgO = 7 wt.%, Ge et al., 2018) to Archaean high-MgO basaltic composition (SiO_2 = 49 wt.% and MgO = 16 wt.%, sample 02MB256 from Kato & Nakamura (2003)). Comparatively, the average Archaean basaltic composition would have higher SiO_2, Al_2O_3, Na_2O, and TiO_2 contents, but lower MgO and CaO contents than high-MgO basalt (picrite). For the H_2O contents in protolith compositions that ensure fluid-present melting at the solidus, the wet solidus would shift from about 650 °C to about 800 °C with starting compositions evolved from basaltic to picritic (increasing MgO, but decreasing SiO_2). Even so, such a temperature difference (ΔT up to 150 °C) would be sufficient to ensure partial melting of high-MgO basalt during dripping of an Archaean greenstone belt. The melt compositions generated through partial melting of basalt at <900 °C evolve from granodiorite to tonalite at <1.0 GPa, and from trondhjemite to tonalite at 1.1 GPa. Those produced by partial melting of high-MgO basalt evolve from trondhjemite to tonalite. In a $Mg^{\#}$ vs. MgO diagram, MgO contents in the melts are a function of temperature and residual bulk composition (Fig. S2). All melts produced below 800 °C will have MgO contents <0.5 wt. %, but will be higher at 900 °C, especially those produced from komatiitic basalts (>1.5 wt. %). By contrast, the $Mg^{\#}$ of melts mostly depend on the bulk compositions, with komatiitic basalts producing higher- $Mg^{\#}$ melts (up to 37) but basalts produce lower $Mg^{\#}$ (<30) melts. When compared with natural TTGs of the Pilbara craton, the high $Mg^{\#}$ of the modelled TTGs indicate that komatiitic basalts must make a measurable contribution to the generation of TTG magmas.

6.2. Comparison between magma mixing and natural TTGs

During tectonic processes that may have been prevalent in the early Archaean—crustal overturn and lower crustal delamination—interlayered volcanic rocks in the lowermost parts of greenstone belts would experience a similar *P*–*T* path, although their peak temperature would vary depending on the maximum depth reached (Sizova et al., 2018). As described, melts produced during the metamorphism of basalts and komatiitic basalts are complementary; the generation of melt fractions that resemble those of natural TTGs requires either the mixing of melts produced from different protoliths, or assimilation-fractional crystallization processes.

In the Pilbara craton, natural TTGs are mostly tonalitic and trondhjemitic, with minor granodiorite bodies. Mixed melts produced during crustal overturn are both trondhjemitic and tonalitic, while those produced through other tectonic processes at temperature <900 °C are always Na_2O rich (i.e., trondhjemitic). Previous studies suggest that partial melts of high-MgO basalts are tonalitic (Hastie et al., 2016, 2023), with such melts produced at UHT conditions. As described above, however, metamorphism recording temperatures >900°C was likely scarce before 3.0 Ga (Brown & Johnson, 2018). The addition of cumulus hornblende could be used to explain how magma compositions could evolve from being trondhjemitic to tonalitic (Rollinson, 2021); however, hornblende is rare in natural TTGs of the Pilbara (Smithies et al., 2021), rendering hornblende accumulation less likely.

Mixed melts produced at low thermal gradients usually have low MgO contents, although their $Mg^{\#}$ are higher than those produced at high thermal gradients. Even those produced during crustal thickening also have lower MgO contents than those produced during crustal overturn, indicating that decompression heating is necessary to produce high MgO melts identical to natural TTGs. Trace elements of the melts are broadly controlled by the thermal gradient. Mixed melts produced at high geothermal gradient have lower Sr/Y, $(La/Yb)_N$ and Nb/Ta and higher HREEs, identical to natural TTGs in the east Pilbara. However, tectonic processes yielding low geothermal gradients (e.g., lower crustal delamination and hot subduction) could only produce low-HREE melts, no matter the protolith, thus the mixed melts could not match the natural TTGs.

6.3. Implications of generating TTGs through partial melting of sinking greenstone belts

The genesis of Archaean TTG gneiss has been studied for over half a century (Jahn et al., 1981). The most popular models for TTG generation are fractional crystallization of basaltic magma (e.g., Arth, 1979; Barker, 1979) and a two-stage melting model (e.g., Arth & Hanson, 1975; Baker, 1979). The fractional crystallization model requires removal of hornblende from a crystallizing basaltic magma to generate felsic magma. The degree of fractional crystallization would be >75%, and thus should produce a significant amount of cumulates (Martin et al., 2005). Recent studies proposed that up to 27% of hornblende fractional crystallization from high-MgO dioritic magma (sanukitoid) could produce TTGs (Liou & Guo, 2019; Smithies et al., 2019), which means that a large amount of high-MgO parental magma should be produced prior to TTG. However, sanukitoids with formation ages older than 3 Ga are too scarce to produce large volumes of Archaean continental crust (Heilimo et al., 2010, Laurent et al., 2014).

By contrast, the two-stage melting model requires partial melting of the mantle to generate tholeiitic basalt, then partial melting of basalt to generate TTG. However, melt compositions produced by partial melting of tholeiitic basalts usually have too low MgO contents and $Mg^{\#}$ to match natural TTGs. This feature can be accounted for by the assimilation of peridotite during ascent through the mantle, which would be expected if partial melts were generated during subduction (Smithies & Champion, 2000). However, thermodynamic modelling results indicate that the compatible elements (e.g., Ni) of melt compositions produced by partial melting of averaged tholeiitic basalts are higher than natural TTGs, indicating limited assimilation of mantle materials (Huang et al., 2022). By process of elimination then, the partial melting of komatiitic basalts, which are also ubiquitous in greenstone belts, might make a notable contribution to the generation of TTG-like magma. In this study, the mixed melts produced by komatiitic basalts and tholeiitic basalts during crustal overturn most closely resemble the natural TTGs of the Pilbara craton. We thus suggest that the partial melting of komatiitic basalts and tholeiitic basalts followed by magma mixing provides the most plausible recipe for generating TTG-like magmas. In geodynamic modelling, crustal delamination occurs prior to crustal overturn, and produces some TTG magmas (Sizova et al., 2018). Based on our study, these melts are usually trondhjemitic, and are characterized by high Sr/Y and La_N/Yb_N ratios. However, such melts are rare in the east Pilbara craton, indicating that the TTGs produced through crustal delamination might be small in volume or difficult to be preserved, although crustal delamination might trigger crustal overturn, which would produce significant amount of TTGs.

The partial melting of komatiitic basalts can only generate felsic magma (SiO_2 >66 wt. %) with K_2O/Na_2O always <0.5 (Figs. 5a, 5e, 7a and 7e), although Archaean sanukitoids, with SiO_2 <62 wt. % (down to 50 wt. %) and average K_2O/Na_2O of 0.72, would thus not be expected to be generated by the partial melting of komatiitic basalts (Martin et al., 2009). Furthermore, sanukitoids are rich in LILEs (Sr and Ba >1,000 ppm), and thus are inconsistent with melts generated by the partial melting of komatiitic basalts that are poor in LILEs. In such a case, the generation of sanukitoids would still require the partial melting of metasomatised mantle rock. Our calculation results further support the proposal that the petrogenesis of sanukitoids involves the partial melting of a TTG-melt-metasomatised mantle wedge (Martin et al., 2009; Oliveira et al., 2011; Laurent et al., 2014; Moyen and Laurent, 2018). Phase equilibrium modelling even suggests that 50/50 vol.% to 70/30 vol.% of TTG melt-mantle mixture is needed to produce sanukitoid (Semprich et al., 2015), which would, if true, indicate that sanukitoids are a proxy for subduction.

Given that *c*. 2.7 Ga sanukitoids are globally widespread, plate tectonics might have been nearly globally operational by this age. Some even older sanukitoids occur within some older cratons, such as the Pilbara and Amazonia cratons (Heilimo et al., 2010; Laurent et al., 2014), which is consistent with a recent argument using the Ba contents in TTG as a proxy for subduction that the onset of plate tectonics was globally diachronous (Huang et al., 2022). As the global propagation of subduction was such a protracted and localized process, a possible transition from bottom-up to top-down geodynamics over time as suggested on the basis of changing mantle melts (Mitchell et al., 2022) would gain support from our study of TTG genesis that demonstrates that uniquely vertical-driven intracrustal melting (i.e., anatexis) of Archaean basaltic-to-komatiitic crust is required to melt the proper compositions and necessary volumes of observed TTGs.

7 Conclusion

Both experiments and thermodynamic modelling of Archaean basalts has been previously unable to produce melts with $Mg^{\#}$ identical to natural TTGs. Our petrological modelling explores the partial melting of komatiites and high-MgO basalts according to different tectonic processes. Our results suggest that SiO_2 and MgO contents of the protolith would significantly influence the fertility of rocks. Komatiites from the Warrawoona greenstone belt of Pilbara craton are refractory and could not produce any melts. Komatiitic basalts would produce high $Mg^{\#}$ and trondhjemitic melts depleted in LILEs and HFSEs, distinct from natural TTGs, no matter the tectonic processes. However, our modelling shows that mixed melts produced from tholeiitic basalts and komatiitic basalts during crustal overturn could produce an appreciable amount of TTG melts, with compositions similar to natural TTGs. We therefore suggest that komatiitic basalts as well as tholeiitic basalts should most accurately reflect the protoliths of TTG in the early Earth. The assimilation of mantle materials, which mainly occurs in a subduction setting, is not necessary for the generation of TTG. We further suggest that only the partial melting of all the rocks in the greenstone belt could generate felsic magma. The generation of the Archaean sanukitoids, with SiO_2 down to 50 wt. %, should be produced through partial melting of a TTG-melt-metasomatised mantle wedge in a subduction setting. The globally distributed *c*. 2.7 Ga sanukitoids might therefore indicate a minimum constraint on the age of widespread subduction, with vertically-dominated tectonics predominating on Earth before this.

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Open Research

The software and datafiles used to phase equilibrium modelling can be downloaded at https://hpxeosandthermocalc.org/. Data are available through Mendeley Data at https://data.mendeley.com/datasets/c3kng92tmf/1

References

Adam, J., Rushmer, T., O'Neil, J., & Francis, D. (2012). Hadean greenstones from the Nuvvuagittuq fold belt and the origin of the Earth's early continental crust. *Geology*, 40, 363–366. https://doi.org/10.1130/G32623.1

Anhaeusser, C.R., & Wilson, J.F. (1981). Chapter 8 The Granitic-Gneiss Greenstone Shield. In D. R. Hunter (Eds.), *Precambrian of the southern hemisphere* (pp. 423–499). Amsterdam: Elsevier. https://doi.org/10.1016/s0166-2635(08)70202-0

Arndt, N. (1986). Differentiation of komatiite flows. *Journal of Petrology*, 27, 279–303. https://doi.org/10.1093/petrology/27.2.279

Arndt, N.T., Lesher, C.M. & Barnes, S.J. (2008). Komatiite. Cambridge University Press, 488 pp.

Arndt, N. (2013). The formation and evolution of the continental crust. *Geochemical Perspectives*, 2(3), 405–533.

Arth, J.G. (1979). Chapter 3 - Some trace elements in trondhjemites, their implication to magma genesis and paleotectonic setting. In Barker, F. (Eds.), *Trondhjemites*, *Dacites and Related Rocks* (pp. 123–132). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-444-41765-7.50008-3

Arth, J.G., & Hanson, G.N. (1975). Geochemistry and origin of the Early Precambrian crust of north-eastern Minnesota. *Geochimica et Cosmochimica Acta*, 39, 325–362. https://doi.org/10.1016/0016-7037(75)90200-8

Barker, F. (1979). Trondhjemites: definition, environment and hypothesis of origin. In Barker, F. (Eds.), *Trondhjemites*, *Dacites and Related Rocks* (pp. 1–12.). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-444-41765-7.50006-X

Bédard, J. H. (2006). A catalytic delamination-driven model for coupled genesis of Archaean crust and sub-continental lithospheric mantle. *Geochimica et Cosmochimica Acta*,70, 1188–1214. https://doi.org/10.1016/j.gca.2005.11.008

Berry, A.J., Danyushevsky, L.V., O'Neil, H.S.C., Newville, M.,& Sutton, S.R. (2008). Oxidation state of iron in komatiitic melt inclusions indicates hot Archaean mantle. *Nature*, 455, 960–963. https://doi.org/10.1038/nature07377

Bickle, M.J. (1986). Implications of melting for stabilization of the lithosphere and heat loss in the Archean. *Earth and Planetary Science Letters*, 80, 314–324. https://doi.org/10.1016/0012-821X(86)90113-5

Boehnke, P., Watson, E.B., Trail, D., Harrison, T.M., & Schmitt, A.K. (2013). Zircon saturation re-revisited. *Chemical Geology*, 351, 324–334. https://doi.org/10.1016/j.chemgeo.2013.05.028

Bohar, R., Woodhead, J.D., & Hergt, J.M. (2003). Continental setting inferred for emplacement of the 2.9–2.7 Ga Belingwe Greenstone Belt, Zimbabwe. *Geology*, 31, 295–298. https://doi.org/10.1130/0091-7613(2003)031<0295:CSIFEO>2.0.CO;2

Brown, M. (2013). Granite: From genesis to emplacement. *GSA Bulletin*, 125, 1079–1113. https://doi.org/10.1130/B30877.1

Brown, M. (2014). The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics. *Geoscience Frontiers*, 5, 553–569. https://doi.org/10.1016/j.gsf.2014.02.005

Brown, M. & Johnson, T. (2018). Secular change in metamorphism and the onset of global plate tectonics. *American Mineralogist*, 103, 181–196.

Condie, K.C. (1993). Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. *Chemical Geology*, 104, 1–37. https://doi.org/10.1016/0009-2541(93)90140-E

Foley, S.F., Buhre, S., & Jacob, D.E. (2003). Evolution of the Archaean crust by delamination and shallow subduction. *Nature*, 421, 249–252. https://doi.org/10.1038/nature01319

François, C., Philippot, P., Rey, P., & Rubatto, D. (2014). Burial and exhumation during Archean sagduction in the east Pilbara Granite-Greenstone Terrane. *Earth and Planetary Science Letters*, 396, 235–251.

Furnes, H., Rosing, M., Dilek, Y., & de Wit, M. (2009). Isua supracrustal belt (Greenland)-a vestige of a 3.8 Ga suprasubduction zone ophiolite, and the implications for Archean geology. *Lithos*, 113, 115–132. https://doi.org/10.1016/j.lithos.2009.03.043

Furnes, H., Dilek, Y., & de Wit, M. (2015). Precambrian greenstone sequences represent different ophiolite types. *Gondawana Research*, 27, 649–685. https://doi.org/10.1016/j.gr.2013.06.004

Ge, R.F., Zhu, W.B., Wilde, S.A., & Wu, H.L. (2018). Remnants of Eoarchean continental crust derived from a subducted proto-arc. *Science Advances*, 4, eaao31559. DOI: 10.1126/sciadv.aao3159

Green, E.C.R., White, R.W., Diener, J.F.A., Powell, R., Holland, T.J.B., & Palin, R.M. (2016). Activity–composition relations for the calculation of partial melting equilibria in metabasic rocks. *Journal of Metamorphic Geology*, 34, 845–869. https://doi.org/10.1111/jmg.12211

Harrison, T.M., & Watson, E.B. (1984). The behavior of apatite during crustal anatexis: equilibrium and kinetic considerations. *Geochimica et Cosmochimica Acta*, 48,1467–1477. https://doi.org/10.1016/0016-7037(84)90403-4

Hartnady, M.I.H., Johnson, T.E., Schorn, S., Smithies, R.H., Kirkland, C.L., & Richardson, S.H. (2022). Fluid processes in the early Earth and the growth of continents. *Earth and Planetary Science Letters*, 594, 117695. https://doi.org/10.1016/j.epsl.2022.117695

Hastie, A.R., Fitton, J.G., Bronmiley, G.D., Butler, I.B., & Odling, N.W.A. (2016). The origin of Earth's first continents and the onset of plate tectonics. *Geology*, 44, 855–858. https://doi.org/10.1130/G38226.1

Hastie, A.R., Law, S., Bromiley, G.D., Fitton, J.D., Harley, S.L., & Muir, D.D. (2023). Deep formation of Earth's earliest continental crust consistent with subduction. *Nature Geoscience*, 16, 816–821. https://doi.org/10.1038/s41561-023-01249-5

Herzberg, C.T., Fyfe, W.S., & Carr, M.J. (1983). Density Constraints on the Formation of the Continental Moho and Crust. *Contributions to Mineralogy and Petrology*, 84, 1–5. https://doi.org/10.1007/BF01132324

Herzberg, C., Condie, K.C., & Korenaga, J. (2010). Thermal history of the Earth and its petrological expression. *Earth and Planetary Science Letters*, 292, 79–88. https://doi.org/10.1016/j.epsl.2010.01.022

Herzberg, C. (2022). Understanding the Paleoproterozoic Circum-Superior Large Igneous Province constrains the thermal properties of Earth's mantle through time. *Precambrian Research*, 375, 106671. https://doi.org/10.1016/j.precamres.2022.106671

Heilimo, E., Halla, J., & Holtta, P. (2010). Discrimination and origin of the sanukitoid series: Geochemical constraints from the Neoarchean western Karelian Province (Finland). *Lithos*, 115, 27–39. https://doi.org/10.1016/j.lithos.2009.11.001

Hickman, A.H. (2021). East Pilbara Craton: a record of one billion years in the growth of Archean continental crust: Geological Survey of Western Australia, Report 143, 187pp.

Holland, T.J.B., & Powell, R. (2011). An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *Journal of Metamorphic Geology*, 29, 333–383. https://doi.org/10.1111/j.1525-1314.2010.00923.x

Holland, T.J.B., & Powell, R. (2003). Activity–composition relations for phases in petrological calculations: An asymmetric multicomponent formulation. *Contributions to Mineralogy and Petrology*, 145, 492–501. https://doi.org/10.1007/s00410-003-0464-z

Huang, G.Y., Palin, R., Wang, D. Guo, J.H., 2020. Open-system fractional melting of Archean basalts: implications for tonalite–trondhjemite–granodiorite (TTG) magma genesis. *Contributions to Mineralogy and Petrology*, 175, 102. https://doi.org/10.1007/s00410-020-01742-9

Huang, G.Y., Mitchell, R.M., Palin, R.M., Spencer, C.J., & Guo, J.H. (2022). Barium content of Archaean continental crust reveals the onset of subduction was not global. *Nature Communications*, 13, 6553. https://doi.org/10.1038/s41467-022-34343-0

Jahn, B., Glikson, A.Y., Peucat, J.J., & Hickman, A.H. (1981). REE geochemistry and isotopic data of Archean silicic volcanics and granitoids from the Pilbara block, western Australia: implications for early crustal evolution. *Geochimica et Cosmochimica Acta*, 45, 1633–1652. https://doi.org/10.1016/S0016-7037(81)80002-6

Jiao, S.J., Brown, M., Mitchell, R.N., Chowdhury, P., Clark, C., Chen, L., et al. (2023). Mechanisms to generate ultrahigh-temperature metamorphism. *Nature Reviews Earth & Environment*, 4, 298–318. https://doi.org/10.1038/s43017-023-00403-2

Johnson, T., Brown, M., Gardinier, N.J., Kirkland, C.L., & Smithies, R.H. (2017). Earth's first stable continents did not form by subduction. *Nature*, 543, 239–242. https://doi.org/10.1038/nature21383

Kato, Y., & Nakamura, K. (2003). Origin and global tectonic significance of Early Archean cherts from the Marble Bar greenstone belt, Pilbara Craton, Western Australia. *Precambrian Research*, 125, 191–243. https://doi.org/10.1016/S0301-9268(03)00043-3

Kelsey, D.E., Clark, C., Hand, M. (2008). Thermobarometric modelling of zircon and monazite growth in melt-bearing systems: examples using model metapelitic and metapsammitic granulites. *Journal of Metamorphic Geology*, 26, 199–212. https://doi.org/10.1111/j.1525-1314.2007.00757.x

Kubota, Y., Matsu'ura, F., Shimizu, K., Ishikwa, A., & Ueno, Y. (2022). Sulfur in Archean komatiite implies early subduction of oceanic lithosphere. *Earth and Planetary Science Letters*, 598, 117826. https://doi.org/10.1016/j.epsl.2022.117826

Kusky, T., Windley, B.F., Polat, A., Wang, L., Ning, W., & Zhong, Y. (2021). Archean dome and basin style structures form during growth and death of intraoceanic and continental margin arcs in accretionary orogens. *Earth-Science Review*, 220, 103725. https://doi.org/10.1016/j.earscirev.2021.103725

Laurent, O., Martin, H., Moyen, J.F., & Doucelance, R. (2014). The diversity and evolution of late-Archean granitoids: Evidence for the onset of “modern-style” plate tectonics between 3.0 and 2.5 Ga. *Lithos*, 205, 208–235. http://dx.doi.org/10.1016/j.lithos.2014.06.012

Liou, P., & Guo, J. H. (2019). Generation of Archaean TTG gneisses through amphibole-dominated fractionation. *Journal of Geophysical Research: Solid Earth*, 124, 3605–3619. https://doi.org/10.1029/2018JB017024

Liu, T., Wei, C.J. & Johnson, T.E. (2024). Archean UHT metamorphism with counterclockwise P–T path: Insights from pelitic granulites from East Hebei, North China Craton. Gondwana Research, 133, 108–128. https://doi.org/10.1016/j.gr.2024.06.007

Martin, H. (1986). Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas. *Geology*, 14, 753–756. https://doi.org/10.1130/0091-7613(1986)14<753:EOSAGG>2.0.CO;2

Martin, H., Smithies, R.H., Rapp, R.P., Moyen, J.-F., & Champion, D.C. (2005). An overview of adakite, tonalite–trondhjemite–granodiorite (TTG) and sanukitoid: relationships and some implications for crustal evolution. *Lithos*, 79, 1–24. https://doi.org/10.1016/j.lithos.2004.04.048

Martin, H., Moyen, J.F., & Rapp, R. (2009). The sanukitoid series: magmatism at the Archaean–Proterozoic transition. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 100, 15–33. https://doi.org/10.1130/2010.2472(02)

Martin et al., 2019

McKenzie, D., & O’Nions, R.K. (1991). Partial melt distributions from inversion of rare earth element concentrations. *Journal of Petrology*, 32, 1021–1091. https://doi.org/10.1093/petrology/32.5.1021

Mitchell, R.N., Brown, M., Gernon, T.M., & Spencer, C.J. (2022). Evolving mantle convection from bottom up to top down. *The Innovation*, 3, 100309. https://doi.org/10.1016/j.xinn.2022.100309

Mitchell., R.N., & Ganne, J. (2022). Less is not always more: A more inclusive data-filtering approach to secular mantle cooling. *Precambrian Research*, 379, 106787.

Moyen, J.F., Stevens, G., & Kisters, A.F.M. (2006). Record of mid-Archean subduction from metamorphism in the Barberton terrain, South Africa. *Nature*, 442, 559–562. https://doi.org/10.1016/j.precamres.2022.106787

Moyen, J.F. (2011). The composite Archaean grey gneisses: Petrological significance, and evidence for a non-unique tectonic setting for Archaean crustal growth. *Lithos*, 123, 21–36. https://doi.org/10.1016/j.lithos.2010.09.015

Moyen, J.F., & Martin, H. (2012). Forty years of TTG research. *Lithos*, 148, 312–336. https://doi.org/10.1016/j.lithos.2012.06.010

Moyen, J.F., & Laurent, O. (2018). Archaean tectonic systems: A view from igneous rocks. *Lithos*, 302–303, 99–125. https://doi.org/10.1016/j.lithos.2017.11.038

Ning, W.B., Kusky, T., Wang, L., & Huang, B. (2022). Archean eclogite-facies oceanic crust indicates modern-style plate tectonics. The Proceedings of National Academy of Sciences. 119 (15), e2117529119. https://doi.org/10.1073/pnas.2117529119

Oliveira, M.A., Dall'Agnol, R., & Almeida, J.A.C. (2011). Petrology of the Mesoarchean Rio Maria suite and the discrimination of sanukitoid series. *Lithos*, 127, 192-209. https://doi.org/10.1016/j.lithos.2011.08.017

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

Patiño-Douce, A.E., & Beard, J. S. (1995). Dehydration-melting of Bt gneiss and Qtz amphibolite from 3 to 15 kb. *Journal of Petrology*, 36, 707–738. https://doi.org/10.1093/petrology/36.3.707

Perchuk, A.L., Zakharov, V.S., Gerya, T.V., & Brown M. (2019). Hotter mantle but colder subduction in the Precambrian: What are the implications?. *Precambrian Research*, 330, 20–34. https://doi.org/10.1016/j.precamres.2019.04.023

Polat, A., Li, J., Fryer, B., Kusky, T., Gagnon, J., Zhang, S., 2006. Geochemical characteristics of the Neoarchean (2800–2700 Ma) Taishan greenstone belt, North China Craton: evidence for plume-craton interaction. *Chemical Geology*, 230, 60–87. https://doi.org/10.1016/j.chemgeo.2005.11.012

Pourteau, A., Doucet, L.S., Blereau, E.R., Volante, S., Johnson, T.E., Collins, W.J., Li, Z.X. & Champion, D.C. (2020). TTG generation by fluid-fluxed crustal melting: Direct evidence from the Proterozoic Georgetown Inlier, NE Australia. *Earth and Planetary Science Letters*, 550, 116548. https://doi.org/10.1016/j.epsl.2020.116548

Powell, R., & Holland, T.J.B. (1988). An internally consistent dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program. *Journal of Metamorphic Geology*, 6, 173–204. https://doi.org/10.1111/j.1525-1314.1988.tb00415.x

Rollison, H. (2021). Do all Archaean TTG rock compositions represent former melts. Precambrian Research, 367, 106448. https://doi.org/10.1016/j.precamres.2021.106448

Semprich, J., Moreno, J.A., & Oliveira, E.P. (2015). Phase equilibria and trace element modeling of Archean sanukitoid melts. *Precambrian Research*, 269, 122-138. https://doi.org/10.1016/j.lithos.2011.08.017

Shaw, D.M. (1970). Trace element fractionation during anatexis. Geochimica et Cosmochimica Acta, 34, 237–243. https://doi.org/10.1016/0016-7037(70)90009-8

Sizova, E., Gerya, T., Brown, M., & Perchuk, L.L., 2010. Subduction styles in the Precambrian: Insight from numerical experiments. *Lithos*, 116, 209–229. https://doi.org/10.1016/j.lithos.2009.05.028

Sizova, E., Gerya, T., Stüwe, K., & Brown, M., 2015. Generation of felsic crust in the Archean: A geodynamic modeling perspective. *Precambrian Research*, 271, 198–224. https://doi.org/10.1016/j.precamres.2015.10.005

Sizova, E., Gerya, T., Brown M., & Stüwe, K., 2018. What Drives metamorphism in early Archean greenstone belts? Insights from numerical modeling. *Tectonophysics*, 746, 587–601. https://doi.org/10.1016/j.tecto.2017.07.020

Smithies, R.H., Lu, Y.J., Johnson, T.E., Kirkland, C.L., Cassidy, K.F., Champion, D.C., et al. (2019). No evidence for high-pressure melting of Earth's crust in the Archean. *Nature Communicaitons*, 10, 5559. https://doi.org/10.1038/s41467-019-13547-x

Smithies, R.H., Lu, Y.J., Kirkland, C.L., Johnson, T.E., Mole, D.R., Champion, D.C., et al. (2021). Oxygen isotopes trace the origins of Earth's earliest continental crust. *Nature*, 592, 70–75. https://doi.org/10.1038/s41586-021-03337-1

Smithies, R.H., & Champion, D.C. (2000). The Archaean high-mg diorite suite: links to tonalite-trondhjemite-granodiorite magmatism and implications for early Archaean crustal growth. *Journal of Petrology*, 41, 1653–1671. https://doi.org/10.1093/petrology/41.12.1653

Sossi P.A., Eggins, S.M., Nesbitt, R.W., Nebel, O., Hergt, J.M., Campbell, I.H., et al. (2016). Petrogenesis and Geochemistry of Archean Komatiites. *Journal of Petrology*, 57, 147–184. https://doi.org/10.1093/petrology/egw004

Sun, S.s., & McDonough, W.F. (1989). Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and process. *Geological Society*, *London*, *Special Publications*, 42, 313–345. https://doi.org/10.1144/gsl.sp.1989.042.01.19

Tamblyn, R., Hermann, J., Hasterok, D., Sossi, P., Pettke, T., & Chatterjee, S. (2023). Hydrated komatiites as a source of water of TTG formation in the Archean. *Earth and Planetary Science Letters*, 603, 117982. https://doi.org/10.1016/j.epsl.2022.117982

Vandenburg, E.D., Nebel, O., Smithies, R.H., Capitnio, F.A., Miller, L., Cawood, P.A., Millet, M.A., Bruand, E., Moyen, J.F., Wang, X.Y., & Neble-Jacobsen, Y. (2023). Spatial and temporal control of Archean tectonomagmatic regimes. *Earth-Science Reviews*, 241, 104417. https://doi.org/10.1016/j.earscirev.2023.104417

Van Kranendonk, M.J., Collins, W.J., Hickman, A., & Pawley, M.J., (2004). Critical tests of vertical vs. horizontal tectonic models for the Archaean East Pilbara Granite-Greenstone Terrane, Pilbara Craton, Western Australia. *Precambrian Research*, 131(3), 173–211. https://doi.org/10.1016/j.precamres.2003.12.015

Van Kranendonk, M.J., Kröner, A., Hoffman, J.E., Nagel, T., & Anhaeusser, C.R. (2014). Just another drip: Re-analysis of a proposed Mesoarchean suture from the Barberton Mountain Land, South Africa. *Precambrian Research*, 254, 19–35. https://doi.org/10.1016/j.precamres.2014.07.022

Van Kranendonk, M.J., Smithies, R.H., Hickman, A.H., & Champion, D.C. (2007). Review: secular tectonic evolution of Archean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia. *Terra Nova*, 19, 1–38. https://doi.org/10.1111/j.1365-3121.2006.00723.x

Webster, J.D., & Piccoli, P.M. (2015). Magmatic apatite: a powerful, yet deceptive, mineral. *Elements*, 11, 177–182. https://doi.org/10.2113/gselements.11.3.177

Wells, P.R.A. (1980). Thermal models for the magmatic accretion and subsequent metamorphism of continental crust. *Earth and Planetary Science Letters*, 46, 253–265. https://doi.org/10.1016/0012-821X(80)90011-4

White, R.W., & Powell, R. (2002). Melt loss and the preservation of granulite facies mineral assemblages. *Journal of Metamorphic Geology*, 20, 621–632. https://doi.org/10.1046/j.1525-1314.2002.00206_20_7.x

White, R.W., Powell, R., Holland, T.J.B., & Johnson, T.E. (2014). The effect of Mn on mineral stability in metapelites revisted: new a-x relations for manganese-bearing minerals. *Journal of Metamorphic Geology*, 32, 809–828. https://doi.org/10.1111/jmg.12095

White, R.W., Powell, R., Holland, T.J.B, & Worley, B.A. (2000). The effect of TiO_2 and Fe_2O_3 on metapelitic assemblage at greenschist and amphibolite facies conditions: Mineral equilibria calculations in the system $K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2–Fe_2O_3$. *Journal of Metamorphic Geology*, 18, 497–511. https://doi.org/10.1111/jmg.12095

Whitney, D.L., Teyssier, C., & Siddoway, C.S. 2004. Gneiss domes in orogeny: Boulder, Colorado, Geological Society of America, Special Paper 380, ISBN: 9780813723808. https://dx.doi.org/10.1130/SPE380.

Windley, B.F., & Davies, F.B. (1978). Volcano spacings and lithospheric/crustal thickness in the Archaean. *Earth Planetary Science Letters*, 231, 53–72. https://doi.org/10.1016/0012-821X(78)90102-4

Windley, B.F., & Garde, A.A. (2009). Arc-generated blocks with crustal sections in the North Atlantic craton of West Greenland: Crustal growth in the Archean with modern analogues. *Earth-Science Reviews*, 93, 1–30. https://doi.org/10.1016/j.earscirev.2008.12.001

Windley, B.F., Kusky, T., & Polat, A. 2021. Onset of plate tectonics by the Eoarchean. *Precambrian Research*, 352, 105980. https://doi.org/10.1016/j.precamres.2020.105980

Winther, K.T., & Newton, R.C. 1991. Experimental melting of hydrous low-K tholeiite: evidence on the origin of Archaean cratons. *Bulletin Geological Society of Denmark*, 39, 213–228. https://doi.org/10.37570/bgsd-1991-39-10

Xiong, X., Keppler, H., Audétat, A., Ni, H.W., Sun, W.D., & Li, Y. (2011). Partitioning of Nb and Ta between rutile and felsic melt and the fractionation of Nb/Ta during partial melting of hydrous metabasalt. *Geochimica et Cosmochimica Acta*, 75, 1673–1692. https://doi.org/10.1016/j.gca.2010.06.039

Yakymchuk, C., & Brown, M. (2014). Behaviour of zircon and monazite during crustal melting. *Journal of the Geological Society*, 171, 465–479. https://doi.org/10.1144/jgs2013-115

Yakymchuk, C. (2017). Behaviour of apatite during partial melting of metapelites and consequences for prograde suprasolidus monazite growth. *Lithos*, 274–275, 412–426. https://doi.org/10.1016/j.lithos.2017.01.009

Yakymchuk, C., Kirkland, C.L., & Clark, C. (2018). Th/U ratios in metamorphic zircon. Journal of Metamorphic Geology, 36, 715–737. https://doi.org/10.1111/jmg.12307

Ziaja, K., Foley, S.F., White, R.W., & Buhre, S. (2014). Metamorphism and melting of picritic crust in the early Earth. *Lithos*, 189, 173–184. https://doi.org/10.1016/j.lithos.2013.07.001

Figure 1. (a) Geologic map of east Pilbara craton, showing distribution of granitoids and greenstone (Van Kranendonk et al., 2014); (b) Stratigraphic columns of the Pilbara Supergroup, east Pilbara craton (Van Kranendonk et al., 2007). (c) Simplified geodynamic sketches showing vertical tectonic regimes for generating TTG magma in Pilbara craton (Sizova et al., 2015; 2018).

Figure 2. Summarized *P–T* paths of different Precambrian tectonic processes. (a) *P–T* paths comparison between modelled results of crustal overturn (Sizova et al., 2018) and *P–T* calculations of metamorphic rocks within greenstone belt from east Pilbara craton (François et al., 2014). The bold orange line represents a simplified enclave-type *P–T* path. The pink polygon represents the calculated *P–T* conditions of natural samples. (b) *P–T* paths of local crustal thickening (bold orange line), lower crustal delamination (bold yellow line) and hot subduction (bold yellow line). *P–T* paths of initial cold subduction and intraoceanic subduction are from Sizova et al. (2010) and Perchuk et al. (2018). Metamorphic facies boundaries and abbreviations follow Brown (2014). Wet solidus of tholeiitic basalt is based on the calculation in this study (Fig. S1).

Figure 3. Pseudosections of different source rocks. (a) and (b) komatiite from the Warrawoona Group. (c) and (d) komatiitic basalts. (e) and (f) tholeiitic basalts. Phase diagrams calculated with limited fluids are shown in grey and with sufficient fluids are shown in blue.

Figure 4. Ab-An-Or classification diagrams showing the modelled melts composition evolution. Dividing lines for different rock types are after O'Connor (1965). (a) melt composition evolution of partial melting of different protoliths during crustal overturn in the Pilbara craton. (b) melt composition evolution during crustal thickening. (c) melt composition evolution during lower crustal delamination. (d) melt composition evolution during hot subduction . Small grey circles show natural TTGs in Pilbara craton (Johnson et al., 2017).

Figure 5. Modelled melts compositions, compared to the natural TTGs from Pilbara craton. (a)–(d) show K_2O/Na_2O vs SiO_2, $Mg^{\#}$ vs MgO, $(La/Yb)_N$ vs Yb and Sr/Y vs Y during crustal overturn; (e)–(h) show K_2O/Na_2O vs SiO_2, $Mg^{\#}$ vs MgO, $(La/Yb)_N$ vs Yb and Sr/Y vs Y during crustal thickening; Small grey circles show natural TTGs.

Figure 6. Trace element trends of model melt compositions, compared to the natural TTGs. (a) model melt compositions during crustal overturn. (b) Mixed melt compositions during crustal overturn. (c) model melt compositions during crustal thickening. (d) Mixed melt compositions during crustal overturn. (e) model melt compositions during lower crustal delamination. (f) Mixed melt compositions during lower crustal delamination. (g) model melt compositions during hot subduction. (h) Mixed melt compositions during hot subduction. Grey lines represent natural TTGs in Pilbara craton (Johnson et al., 2017). Primitive mantle normalizing values from Sun and McDonough (1989).

Figure 7. Modelled melts compositions, compared to the natural TTGs from Pilbara craton. (a)–(d) show K_2O/Na_2O vs SiO_2, $Mg^{\#}$ vs MgO, $(La/Yb)_N$ vs Yb and Sr/Y vs Y during lower crustal delamination;. (e)–(h) show K_2O/Na_2O vs SiO_2, $Mg^{\#}$ vs MgO, $(La/Yb)_N$ vs Yb and Sr/Y vs Y during hot subduction; Small grey circles show natural TTGs.