Geochemical Perspectives Letters



# Fluid-present melting of early Archean crust: Stable Sr isotopes from the Kaapvaal Craton

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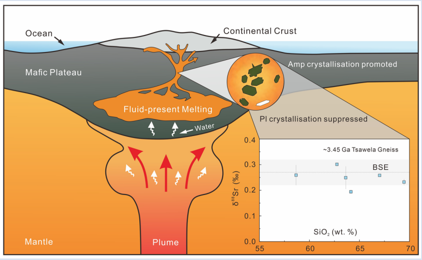
OPEN ACCESS
https://doi.org/10.7185/geochemlet.2634

## Abstract


Stable Sr isotopes ($\delta^{88}Sr$) provide a process specific tracer of plagioclase behaviour in magmatic systems. Because plagioclase liquidus is sensitive to the water content of melt, $\delta^{88}Sr$ can be applied as a tool to discriminate fluid-present from fluid-absent melting to form early continental crust. Here, we present high precision $\delta^{88}Sr$ data for the ~3.45 Ga Tsawela gneiss (TG) of the Kaapvaal Craton. The samples display a narrow, mantle-like $\delta^{88}Sr$ range (0.19–0.30 ‰, average 0.25 ± 0.07 ‰) and low initial $^{87}Sr/^{86}Sr$ that shows no correlation with $SiO_2$, Sr content and Eu anomaly. Plagioclase fractional crystallisation would produce melts with lighter $\delta^{88}Sr$ values and lower Sr content. The results indicate suppressed plagioclase crystallisation during melt evolution, providing direct isotopic evidence for fluid-present melting. This interpretation aligns with the calc-alkaline trends and the low pressure TTG trace element signature of the TG suite. Phase equilibria modelling also indicates that a progressive increase in melt $H_2O$ content lowers the plagioclase liquidus from >1200 °C to ~750 °C. Given that the TG samples were formed in an Archean mafic plateau setting, this indicates that the early felsic crust can be efficiently generated under water-rich conditions without requiring modern style subduction.


Received 25 April 2026 | Accepted 25 August 2026 | Published 17 September 2026

## Introduction

Earth is the only terrestrial planet with voluminous felsic continental crust. The formation of early Archean crust is a fundamental issue for understanding planetary differentiation and habitability. Water is widely regarded as a decisive factor during the generation and evolution of silicic rocks (*e.g.*, tonalite-trondhjemite-granodiorite, TTG). Water significantly lowers rock solidus temperature, reduces melt viscosity, enhances melt volume, thereby influencing the composition of residual mineral assemblages, melt compositions and differentiation pathways (Collins *et al.*, 2020). Based on the mode of water involvement during melting, previous studies have proposed two fundamental end member models with significant tectonic implications: fluid-present and fluid-absent melting (Beard and Lofgren, 1991; Pourteau *et al.*, 2020; Tamblyn *et al.*, 2023). The former typically involves the influx of external free fluids, enabling melting at relatively low temperatures and is commonly invoked to support subduction or water-rich tectonic environments. In contrast, the latter primarily occurs in the absence of a free fluid phase and is driven by heating or decompression that induces the breakdown of hydrous minerals, typically associated with thickened lower crust or a mafic plateau setting. It is suggested that hydrous mantle plateaus occurred occasionally in the Phanerozoic (Liu *et al.*, 2017). Distinguishing between those two melting mechanisms is not only a fundamental petrological issue but also central to evaluate whether water-rich conditions within mafic plateaus existed in the Archean (Roman and Arndt, 2020; Smithies *et al.*, 2021).

However, precisely identifying the specific mechanisms of partial melting remains challenging. On the one hand, traditional thermobarometry highly depends on pressure, melt composition, water activity, and equilibrium state, making it difficult to serve as a direct indicator for fluid-present melting (Schwindinger *et al.*, 2019). On the other hand, Archean felsic terranes commonly underwent amphibolite to granulite facies metamorphic overprinting, obscuring primary magmatic signatures. Because the stability of plagioclase is highly sensitive to the water content of melts, fluid-present melting suppresses plagioclase stability, whereas fluid-absent melting stabilises plagioclase (Beard and Lofgren, 1991; Müntener and Ulmer, 2018). Plagioclase is the primary reservoir of Sr in magmatic systems and preferentially incorporates heavy Sr isotopes relative to the bulk rock, such that its fractionation or residue produces resolvable stable Sr isotope fractionation (Charlier *et al.*, 2012; Klaver *et al.*, 2020; Chen *et al.*, 2025b). This highlights stable Sr isotope ($\delta^{88}Sr$) as a potentially powerful tracer of plagioclase behaviour and melting mechanism.

The Kaapvaal Craton is one of the classic regions for studying the formation of Archean continental crust. The ~3.45 Ga Tsawela Gneiss (TG) from the Ancient Gneiss Complex (AGC) (Fig. S-1) is mainly composed of tonalite to trondhjemite (Fig. S-2a), providing a critical window into the debate over fluid-present *versus* fluid-absent melting. The TG exhibits calc-alkaline trends (Fig. S-2b), moderate Sr contents, and low Sr/Y ratios, consistent with a low pressure TTG origin (Fig. S-3). The TG displays weak deformation, lack

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migmatisation features, and has low loss on ignition (LOI) values, indicating relatively limited later modification (Hoffmann *et al.*, 2016). The source of TG is close to depleted mantle and lacks clear evidence for the involvement of ancient continental crustal materials (Hoffmann *et al.*, 2016). Based on rock assemblages, geochemistry and palaeomagnetic detection, these rocks are commonly interpreted to have formed in a mafic plateau tectonic setting during the early Archean (Hoffmann *et al.*, 2016; Brenner *et al.*, 2026).

Here, we investigate the ~3.45 Ga TG exposed in the Kaapvaal Craton for high precision stable Sr isotopic analysis to distinguish the melting mechanisms. By integrating whole rock geochemistry and modelling, we aim to (1) evaluate plagioclase behaviour during TG petrogenesis, and (2) test the reliability of stable Sr isotopes in distinguishing fluid-present *versus* fluid-absent melting during ~3.45 Ga TG formation.

## Geological Background

***Background***. The Kaapvaal Craton preserves some of Earth's representative Archean crustal fragments, comprising the AGC in Eswatini and the 3.6–3.2 Ga Barberton granitoid-greenstone terrane (BGGT) in South Africa (Hoffmann *et al.*, 2016). The AGC is primarily composed of the 3.66–3.2 Ga Ngwane Gneiss (NG), the 3.47–3.42 Ga TG and ~3.46 Ga Dwalile Supracrustal Suite (DSS) (Hoffmann *et al.*, 2016). The NG exhibits a bimodal character with interlayered felsic and mafic components. It is intensely deformed and experienced upper amphibolite to granulite facies metamorphism, and represents the oldest basement component of the AGC. The TG is a weakly to well foliated TTG suite (Fig. S-2a) and intruded the older NG and Dwalile Greenstone remnants (Hoffmann *et al.*, 2016). Within the TG, $SiO_2$ contents range from 58.67 to 71.48 wt. %. They originated from a juvenile source supported by Nd and Hf isotopic compositions (Zeh *et al.*, 2011; Hoffmann *et al.*, 2016). Importantly, the low initial $^{87}Sr/^{86}Sr$ ratios reported for the AGC (Davies and Allsopp, 1976) suggest negligible involvement of pre-existing siliceous crust. Interpretation of major and trace element proxies is complicated by source heterogeneity, fractional crystallisation, and melting depth (Kendrick and Yakymchuk, 2020). We integrate stable Sr isotopes with modelling to constrain the petrogenetic regime of the TG suite.

***Samples and methods***. Six TG and one NG samples were analysed; sample location (Fig. S-1), petrography, major and trace element data, U-Pb zircon ages, and Hf-Nd isotopes were reported in Hoffmann *et al.* (2016). TG samples are medium to coarse grained tonalitic gneisses with weak deformation; sample AGC502T exhibits more pronounced fabric development. The studied NG sample (AGC470) is a strongly deformed migmatitic orthogneiss.

Stable and radiogenic Sr isotope measurements were performed at the State Key Laboratory of Lithospheric and Environmental Coevolution, University of Science and Technology of China, following the protocol of Chen *et al.* (2022). Long term external reproducibility was 0.03 ‰ (2 s.d.) for $\delta^{88}Sr$ and 0.000025 (2 s.d.) for $^{87}Sr/^{86}Sr$. Procedural blanks were <0.18 ng Sr. Initial $^{87}Sr/^{86}Sr$ ratios were calculated at 3.45 Ga. Results for international standards and replicate analyses (Table S-1) are in agreement with certified values, ensuring data robustness. For the TG samples, replicate analyses show differences of $^{87}Sr/^{86}Sr$ but a consistent $\delta^{88}Sr$ value, which were attributed to the slight heterogeneity of the Rb/Sr ratio among the different mineral phases within the bulk rock powders, while $\delta^{88}Sr$ remains homogeneous at the hand specimen scale (Chen *et al.*, 2025b).

## Results

The $\delta^{88}Sr$ and $^{87}Sr/^{86}Sr$ ratios for the AGC gneisses are summarised in Table S-1. TG samples exhibit $^{87}Sr/^{86}Sr$ ratios of 0.723139–0.773669 and initial $(^{87}Sr/^{86}Sr)_t$ values of 0.69799–0.71722. Their $\delta^{88}Sr$ values range from 0.19 ‰ to 0.30 ‰ (2 s.d. < 0.04 ‰), with a mean of 0.25 ± 0.07 ‰ (2 s.d.) (Figs. 1, S-4), largely overlapping with the reported Bulk Silicate Earth (BSE) values (0.27 ± 0.05 ‰, Moynier *et al.*, 2010; 0.29 ± 0.07 ‰, Charlier *et al.*, 2012; 0.30 ± 0.02 ‰, Amsellem *et al.*, 2018). Compared with the wide range for granitoids $\delta^{88}Sr$ (−1.51 ‰ to 0.54 ‰) (Chen *et al.*, 2025a, 2025b) (Fig. S-4), the stable Sr isotope fractionation in the TG sample is negligible (Fig. 1).

The NG sample shows $\delta^{88}Sr$ = 0.10 ± 0.02 ‰, significantly lighter than both TG samples and BSE. Its $^{87}Sr/^{86}Sr$ ratio is 0.758083, with a calculated initial $(^{87}Sr/^{86}Sr)_t$ value of 0.70597.

## Discussion

***What controls $\delta^{88}Sr$ in the early Archean felsic magmas?*** Available data for Archean mantle derived rocks indicate that the stable Sr isotopic composition of the convecting mantle has remained constant since the Paleoarchean (Amsellem *et al.*, 2018). Importantly, mafic igneous processes have limited effect on stable Sr isotope fractionation (Amsellem *et al.*, 2018). Stable Sr isotopes in felsic magmas are primarily governed by feldspar and apatite, either through crystallisation or as residual phase. Plagioclase and apatite preferentially incorporate heavy Sr isotopes, while K feldspar favours light isotopes (Charlier *et al.*, 2012; Andrews and Jacobson, 2018; Klaver *et al.*, 2020; Chen *et al.*, 2025b). In this study, the TG exhibits an average $\delta^{88}Sr$ of 0.25 ± 0.07 ‰, consistent with the mantle/BSE composition (Moynier *et al.*, 2010), suggesting that plagioclase was a negligible residual phase in the melting source. The lack of correlations between $\delta^{88}Sr$ and $SiO_2$, Sr contents, Eu/Eu* (Fig. 1) suggests negligible plagioclase, K feldspar and apatite fractionation. In addition, Rayleigh fractionation modelling (Fig. 2) suggests that 10 wt. % plagioclase fractionation would decrease the $\delta^{88}Sr$ value of whole rock to 0.14 ‰ (for plagioclase-melt fractionation factor $\alpha_{Pl\text{-}Melt}$ = 1.0003 from Chen *et al.*, 2025b) and 0.00 ‰ (for $\alpha_{Pl\text{-}Melt}$ = 1.0007 from Charlier *et al.*, 2012). This demonstrates that $\delta^{88}Sr$ is sufficiently sensitive to detect even a small amount of plagioclase crystallisation. However, this deviation is not observed in the TG suite. Also, the coarse grained texture of the TG precludes rapid cooling as a potential mechanism for suppressed plagioclase fractionation.

Secondary processes are unlikely to account for the restricted $\delta^{88}Sr$ values observed in the TG samples. First, the TG samples are fresh, as indicated by low LOI values, and no correlation exists between LOI and $\delta^{88}Sr$ (Fig. S-5). Second, the major Sr hosting minerals (feldspar, apatite) are relatively stable during amphibolite facies metamorphism. The narrow $\delta^{88}Sr$ range despite variable initial Sr isotopes (Fig. S-5b) and bulk compositions argue against substantial metamorphic resetting or crustal contamination. Previous hybridisation models require mixing between mafic and felsic end members (Hoffmann *et al.*, 2016); however, reproducing the observed Sr concentrations through such a process would require the mafic component to contain an extremely high Sr content (800 ppm), which is inconsistent with typical mafic melts (Fig. S-10b). Moreover, magma mixing between isotopically distinct end members would be expected to generate resolvable $\delta^{88}Sr$ heterogeneity (Fig. S-10a), which is not observed. Therefore, the narrow $\delta^{88}Sr$ range of the TG samples likely reflects their primary

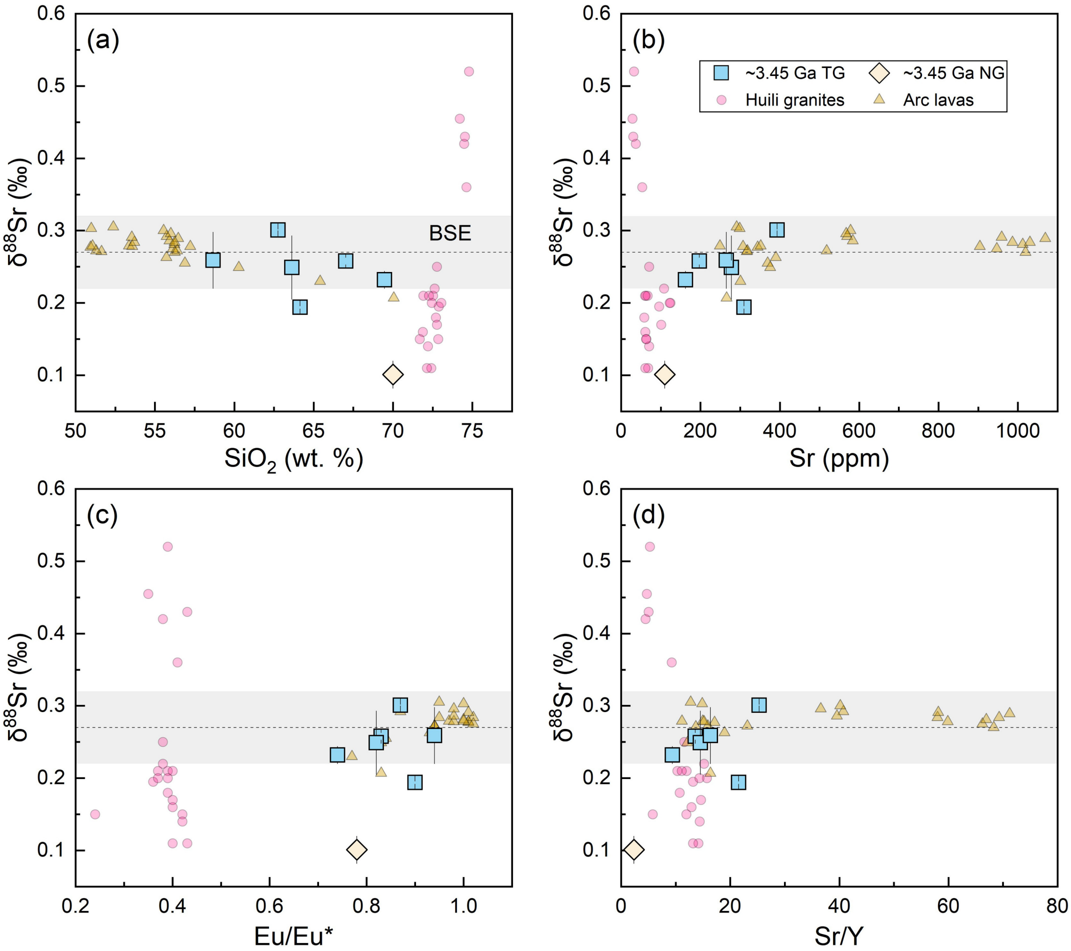


**Figure 1** The $\delta^{88}Sr$ *versus* **(a)** $SiO_2$, **(b)** Sr, **(c)** Eu/Eu*, and **(d)** Sr/Y for the ~3.45 Ga TG and NG samples. The BSE value is from Moynier *et al.* (2010). The $\delta^{88}Sr$ values of Huili granites and arc lavas (Aegean and Mariana arc) are derived from Chen *et al.* (2025b) and Klaver *et al.* (2020), respectively.

magmatic compositions, consistent with the preservation of their relatively low initial Sr isotope compositions (Davies and Allsopp, 1976; this study).

However, the Sr content of TG samples decreases with increasing $SiO_2$ (Fig. S-5a) (Hoffmann *et al.*, 2016). This trend may indicate heterogeneous Sr contents in their mafic precursors, consistent with the observed heterogeneity in whole rock Hf-Nd and initial $(^{87}Sr/^{86}Sr)_t$ values (Davies and Allsopp, 1976; Fig. S-6) (Hoffmann *et al.*, 2016). This interpretation is further supported by the wide variation in Sr contents (~25–250 ppm), Sr/Y (1.2–9.8), and Eu/Eu* (0.78–1.02) of the ~3.46 Ga DSS greenstone remnants (Fig. S-7) (Hoffmann *et al.*, 2020).

*Fluid-present melting and tectonic implications.* A mafic plateau setting has been proposed as a viable tectonic environment for the formation of voluminous felsic crust during the early Archean (Johnson *et al.*, 2017). However, this view has been challenged by the argument that the lower crust of thick mafic plateaus is predominantly dry, thereby limiting the production of large volumes of silicic melt (Roman and Arndt, 2020). Resolving the presence or absence of fluids in mafic plateaus is therefore critical for understanding the mechanisms of early continental crust formation and differentiation.

Thermochemically, magmatic water reduces melt polymerisation by breaking Si-O-Si bonds (Stolper, 1982), which significantly depresses the plagioclase liquidus while expanding the stability field of amphibole (Beard and Lofgren, 1991; Pichavant

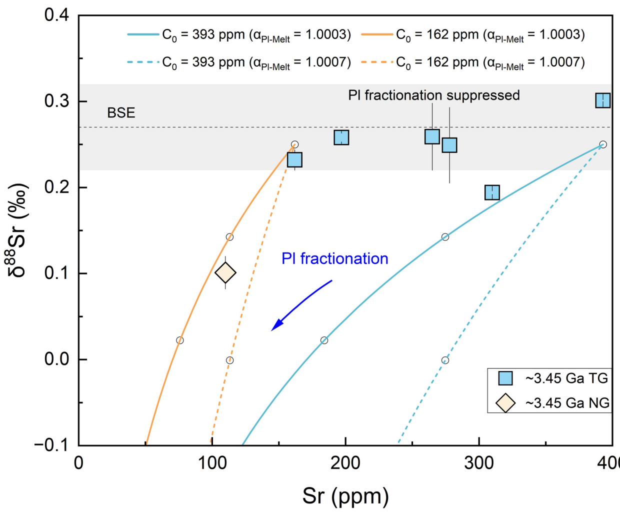


**Figure 2** Rayleigh fractionation models for stable Sr isotope evolution of residual melt during fractional crystallisation of sodium rich magma. Bulk fractionation factors ($\alpha_{Pl\text{-}Melt}$) between plagioclase and melt of 1.0003 and 1.0007 are assumed according to Chen *et al.* (2025b) and Charlier *et al.* (2012), respectively. $C_0$ is the initial Sr content in primary melt, with values of 162 and 393 ppm corresponding to the observed range of the TG samples. Circular markers on each curve represent 10 wt. % increments of plagioclase fractionation.

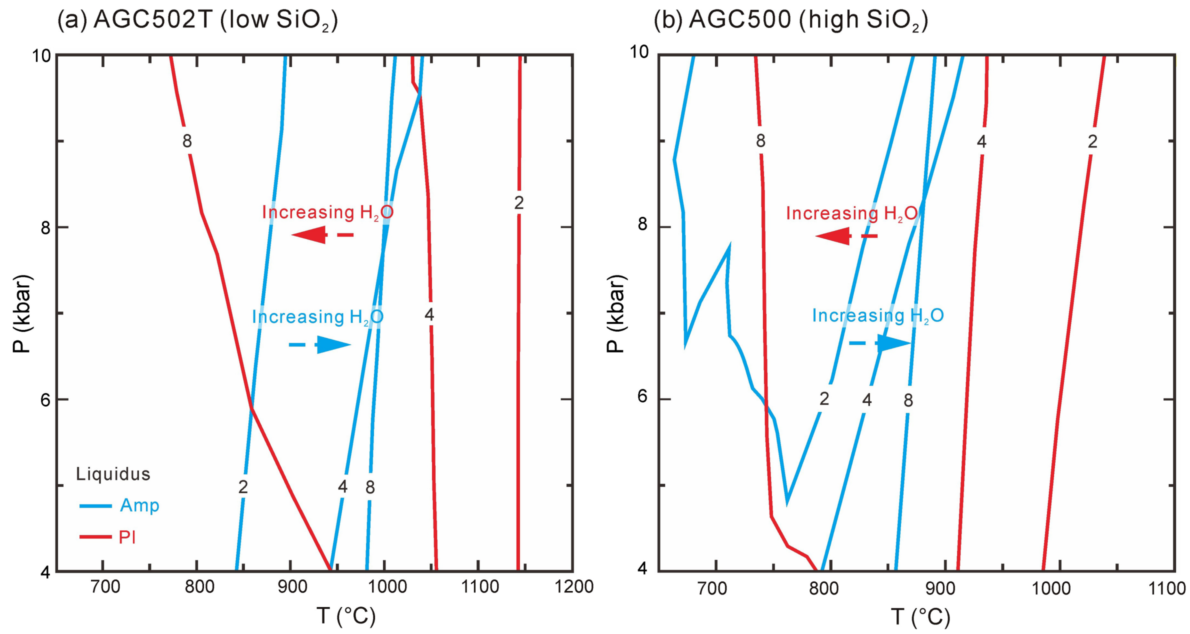


**Figure 3** Pseudosections illustrating the suppression of plagioclase (Pl) liquidus relative to amphibole (Amp) liquidus during magmatic cooling at 4–10 kbar, with labels indicating $H_2O$ contents (in wt. %). Calculations using samples **(a)** AGC502T (primitive melt proxy) and **(b)** AGC500 (evolved), demonstrate that the suppression of plagioclase by high melt $H_2O$ content is consistent regardless of bulk $SiO_2$ variations.

and Macdonald, 2007; Müntener and Ulmer, 2018). The resulting melts are consequently enriched in $Al_2O_3$, follow calc-alkaline differentiation trends, exhibit low Sr/Y ratios (Beard and Lofgren, 1991; Pichavant and Macdonald, 2007; Müntener and Ulmer, 2018) and most importantly, preserve $\delta^{88}$Sr values indistinguishable from mantle compositions because plagioclase, the primary Sr-rich phase that preferentially incorporates heavy Sr, is largely absent from the fractional crystallisation assemblages. The restricted, mantle-like $\delta^{88}$Sr values of the TG samples require minimal isotopic fractionation, which in turn demands suppression of plagioclase crystallisation. While high pressure (>1.5 GPa) can also destabilise plagioclase, the TG samples are characterised by low pressure TTG signatures (Fig. S-3), ruling out a deep origin. We therefore ascribe the suppression of plagioclase crystallisation to fluid-present melting. This interpretation is independently supported by their calc-alkaline differentiation trend (Hoffmann *et al.*, 2016), low pressure TTG affinity (Fig. S-3; Pourteau *et al.*, 2020) and no obvious Eu anomaly (Hoffmann *et al.*, 2016). In contrast, fluid-absent melting favours plagioclase crystallisation, producing melts with lighter $\delta^{88}$Sr and tholeiitic differentiation trends (Müntener and Ulmer, 2018).

To quantitatively evaluate the impact of magmatic $H_2O$ content on mineral crystallisation sequences during magma cooling, we performed thermodynamic forward modelling at 4–10 kbar using the bulk compositions of sample AGC502T (primitive proxy) and AGC500 (evolved). Phase equilibrium modelling (Figs. 3, S-8) quantitatively confirms these experimental relationships linking water content to the stability fields of plagioclase and amphibole (Beard and Lofgren, 1991; Müntener and Ulmer, 2018). A progressive increase in melt $H_2O$ content lowers the plagioclase liquidus from >1200 °C to ~750 °C while simultaneously extending the stability field of amphibole to ~1050 °C (Figs. 3, S-8). Crucially, the effect of water activity on depressing the plagioclase liquidus far exceeds that of temperature and pressure variations in the upper to lower crustal regime, serving as the principal control on plagioclase stability, independent of the bulk composition (Fig. 3a,b).

Plagioclase fractionation may be suspended due to insufficient gravitational settling in a viscous magma chamber, which would drive magma to higher Sr contents, $\delta^{88}$Sr values and positive Eu anomalies in the cumulate portions. However, those features are absent in the TG suite (Figs. 1, S-5). Thus, plagioclase was neither a significant fractionating nor a cumulate-forming phase, consistent with suppressed plagioclase crystallisation under water-rich conditions.

These findings challenge the prevailing assumption that the lower crust of mafic plateaus is inherently water-poor (Roman and Arndt, 2020). Their "wet" geochemical signature suggests that fluid activity was pivotal in non-plate tectonic regimes. Water not only enhances melt productivity by depressing the solidus but also promotes calc-alkaline differentiation, facilitating rapid generation of voluminous felsic crust. Consequently, early continental growth may not require modern style subduction; instead, it could have occurred within hydrated mafic plateaus (Fig. 4).

The ultimate source of these fluids remains uncertain, but can be constrained. Seawater hydrothermal alteration is a potential source (Vezinet *et al.*, 2018); however, intensely altered oceanic crust is characterised by elevated $\delta^{88}$Sr values (0.27–0.34 ‰), higher $^{87}Sr/^{86}Sr$, and correlated enrichments in fluid mobile element ratios such as K/La and K/Th ratios (Klaver *et al.*, 2020; Liu and He, 2021). In contrast, the TG samples display mantle-like stable Sr isotopic compositions and lack systematic correlations with K/La and K/Th ratios (Fig. S-9), suggesting that the involvement of hydrothermal alteration fluids was likely minimal. Altered komatiites within oceanic plateaus represent another potential fluid source through dehydration (Tamblyn *et al.*, 2023). Although Barberton komatiites exhibit relatively heavy $\delta^{88}$Sr values (0.16–0.97 ‰) (Amsellem *et al.*, 2018), the isotopic composition of the fluids released remains poorly constrained. By comparison, the low Sr content of komatiites (average Sr contents = 23 ppm; Chavagnac, 2004) limits their ability to significantly modify the bulk Sr isotopic compositions of the mafic source. On the other hand, natural observations reveal that low temperature, slab derived fluids are enriched

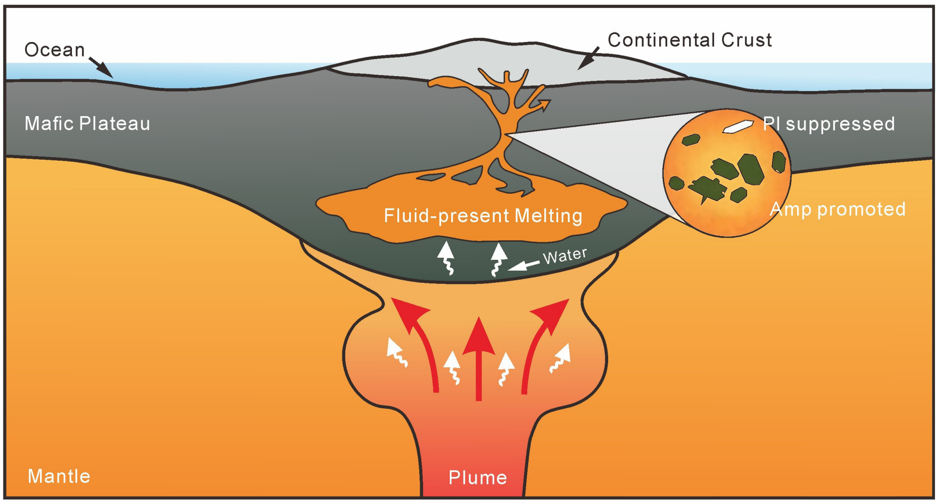


**Figure 4** Schematic model for fluid-present melting of mafic crust in a Paleoarchean plateau setting, producing the ∼3.45 Ga Tsawela Gneiss in Kaapvaal Craton. The source of fluid is discussed in the main text.

in light Sr isotopes ($\delta^{88}$Sr = 0.122–0.157 ‰) (Kani *et al.*, 2023), whereas high temperature fluids (>700 °C) tend to equilibrate with their source rocks, preserving a mantle-like isotopic signature (Klaver *et al.*, 2020). Therefore, the mantle-like $\delta^{88}$Sr values exclude shallow, fractionated fluids but are consistent with high temperature fluid-rock equilibrium. Collectively, these observations suggest that the TG magmas were influenced by deep seated, high temperature fluids, partially derived from hydrated komatiites from the middle-lower crust (Tamblyn *et al.*, 2023) and possibly from mantle plumes underplating the oldest continental fragments (Liu *et al.*, 2017; Pourteau *et al.*, 2020; Smithies *et al.*, 2021), facilitating efficient crustal differentiation without the prerequisite of modern style plate subduction, although these sources cannot be uniquely distinguished.

## Conclusions

Stable Sr isotopes demonstrate that the ∼3.45 Ga Tsawela Gneiss formed through fluid-present melting of mafic crust. The mantle-like $\delta^{88}$Sr values, consistency with calc-alkaline trends and phase equilibrium modelling provide direct Sr isotopic evidence for water-rich conditions in a Paleoarchean mafic plateau setting. Voluminous felsic crust can be generated efficiently under hydrous conditions without modern style subduction. Water is a critical driver of early continental growth, enabling differentiation of mafic plateaus and shaping the thermal volatile evolution of the early Earth.

## Acknowledgements

This study was supported by the National Natural Science Foundation of China (Grant No. 42403002). JEH thanks the German Research Foundation (DFG) for grants HO 4697/1-1 and HO 4697/1-2. We thank Chun-Hui Li (from Chengdu University of Technology) for helpful discussion. We thank editor Helen Williams and Ambre Luguet for patient handling of the manuscript. We are also grateful to Renée Tamblyn and one anonymous reviewer for their constructive comments and suggestions that greatly improved the manuscript.

*Editor: Helen Williams and Ambre Luguet*

## Additional Information

**Supplementary Information** accompanies this letter at https://www.geochemicalperspectivesletters.org/article2634.



**Cite this letter as:** Zhang, C.-W., Hoffmann, J.E., Ding, X., Chen, X.-Q., Huang, F. (2026) Fluid-present melting of early Archean crust: Stable Sr isotopes from the Kaapvaal Craton. *Geochem. Persp. Let.* 42, 1–6. https://doi.org/10.7185/geochemlet.2634

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