Weaker lithospheric dripduction into Archean TTG crust formation

Prasanna M. Gunawardana[1], Gabriele Morra[2], Priyadarshi Chowdhury[3], and Peter A. Cawood[3]

[1]School of Earth
[2]Department of Physics and School of GeoSciences, University of Louisiana at Lafayette, USA
[3]School of Earth, Atmosphere and Environment, Monash University, Australia

November 23, 2022

Abstract

Lithospheric yield stress is a key parameter in controlling tectonic processes. We calculate yield stress for a range of conditions appropriate to the Archean Earth, including hotter mantle potential temperatures and a range of Moho temperatures using 2D high resolution numerical geodynamic modelling techniques. This range of conditions are evaluated for generating felsic, tonalite-trondhjemite-granodiorite (TTG), crust with the results bench marked against the preserved rock record. The model results indicate that lithospheric yield stress slightly lower than the present-day Earth values (i.e. < 100 MPa) generates TTG melt volumes similar to those preserved in the rock record. In particular, large volumes of TTG melts form in the tails of lithospheric drips. Melting occurs profusely within the thinner portions of the drips as these regions are more efciently heated by the enclosing hotter mantle. In contrast, only limited melting occurs in regions of thickened crust, in part because the weaker lithosphere cannot sustain crustal thickening for long time periods, resulting in its removal through drips. Our models highlight the dominance of non-plate tectonic mechanisms in producing TTGs under the conditions that operated on the hotter Archean Earth.

Weaker lithospheric dripduction into Archean TTG crust formation

Gunawardana, P. M.* ,Morra, G.' , Chowdhury P. *,Cawood, P. A.*

* Monash University, Australia. ' University of Louisiana at Lafayette, USA

PRESENTED AT:

AGU FALL MEETING
Online Everywhere | 1–17 December 2020

INTRODUCTION

- Lithospheric yield stress is a key parameter in controlling tectonic processes, remains poorly constrained for the Archean lithosphere.
- We calculate yield stress for a range of conditions appropriate to the Archean Earth, including hotter mantle potential temperatures and a range of Moho temperatures.
- This range of conditions are evaluated for generating felsic, tonalite-trondhjemite-granodiorite (TTG), crust with the results bench marked against the preserved rock record.
- Expected total TTG volume is 70% of the present continental volume which cast into differentiation index (DI) of 1.7 % and the expected medium presure(MP-) to Low pressure (LP-) TTG ratio is 3:1. Please refer Gunawardana et al., 2020 for further details.

The growth models for continental crust (Reproduced from Cawood and Hawkesworth., 2019)

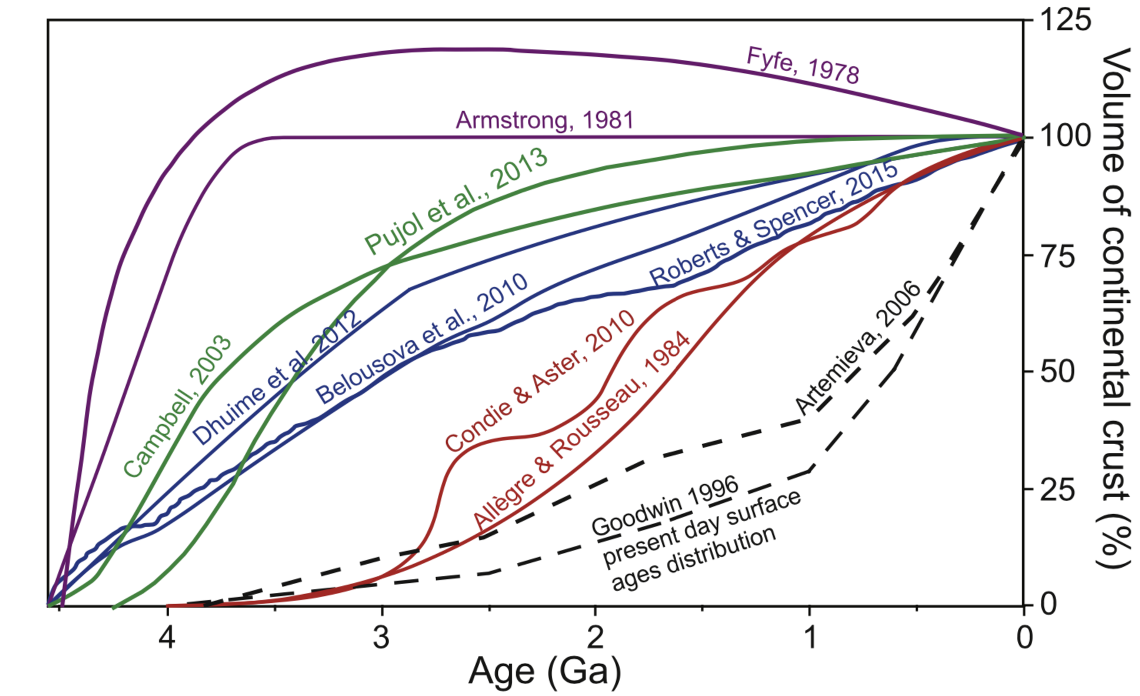

Fig.1 The growth models of the continental crust relative to its present-day volume (Reproduced from Cawood and Hawkesworth (2019))

METHODOLOGY

- 2D high resolution numerical geodynamic modelling techniques are used in Underworld2 software platform.

- Mass, Momentum and Energy equations are solved using particle in cell method.

$$\vec{\nabla}.\vec{u} = 0 \quad (1)$$

$$-\vec{\nabla}.P + \vec{\nabla}.\left[\eta\left(\partial_i u_j + \partial_j u_i\right)\right] = -\rho\vec{g} \quad (2)$$

$$\partial_t T + \vec{u}\,\vec{\nabla}T = \nabla^2 T + H \quad (3)$$

Viscosity

- Arrhenius viscosity and plastic yielding are applied to the model.

$$\eta_T = \eta_o exp\left[\frac{E+d.V}{T+1} - \frac{E}{2}\right] \quad (6)$$

$$\sigma_Y = \sigma_Y^o + d\sigma_Y' \quad (7)$$

Density

- Temperature dependent density is applied following Sizova et al., 2015.

$$\rho = \rho_o[1 - \alpha\Delta T] \quad (8)$$

$$\rho_{eff} = \rho_{solid}(1 - M) + \rho_{melt}M \quad (9)$$

$$\rho_{solid} = \rho_o[1 - \alpha\Delta T](1 + coef_{res} + coef_{phase}) \quad (10)$$

Melt generation and depletion

- Melt fraction and depletion are calculated following Sizova et al., 2015.

$$M_o = \begin{cases} 0, \ T_1 < T_{solidus} \\ \frac{T_1 - T_{solidus}}{T_{liquidus} - T_{solidus}}, \ T_{solidus} < T_1 < T_{liquidus} \\ 1, \ T_1 > T_{liquidus} \end{cases} \quad (4)$$

$$M = M_o - \sum_n M_{ext} \quad (5)$$

Melt classification

- Melt is classified based on the source rock P-T conditions

P-T conditions for various TTG types

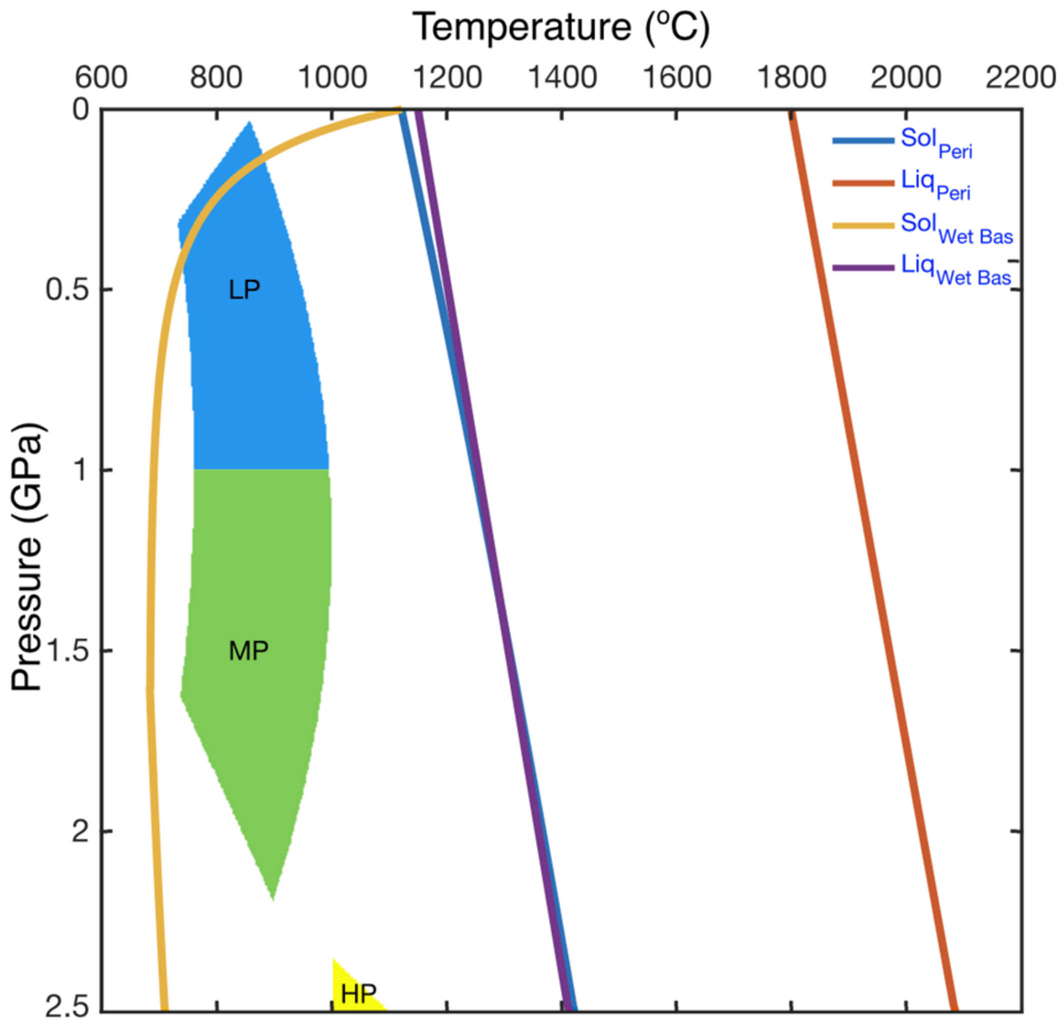

Fig. 2 Pressure and temperature conditions of Low-Pressure (LP), Medium-Pressure (MP) and High-Pressure (HP) tonalite-trondhjemite- granodiorite formation (Reproduced from Moyen (2011) and Jain et al. (2019)

RESULTS

- Lithospheric yield stress slightly lower than the present-day Earth values (i.e. < 100 MPa) generates TTG melt volumes equivalent ~70 % of present continental volume within few hundreds of Ma.

- Furthermore, weaker lithosphere together with the dominance of dripping can also account for the large abundance of MP-TTGs relative to the LP-variant within the early Archean rock record.

Total melt volume and relative proportion of TTGs for 3 dripping stages of a model with Tp = 1600 ^oC, Tmoho = 600 ^oC and Yield stress = 50 MPa.(Reproduced from Gunawardana et al., 2020)

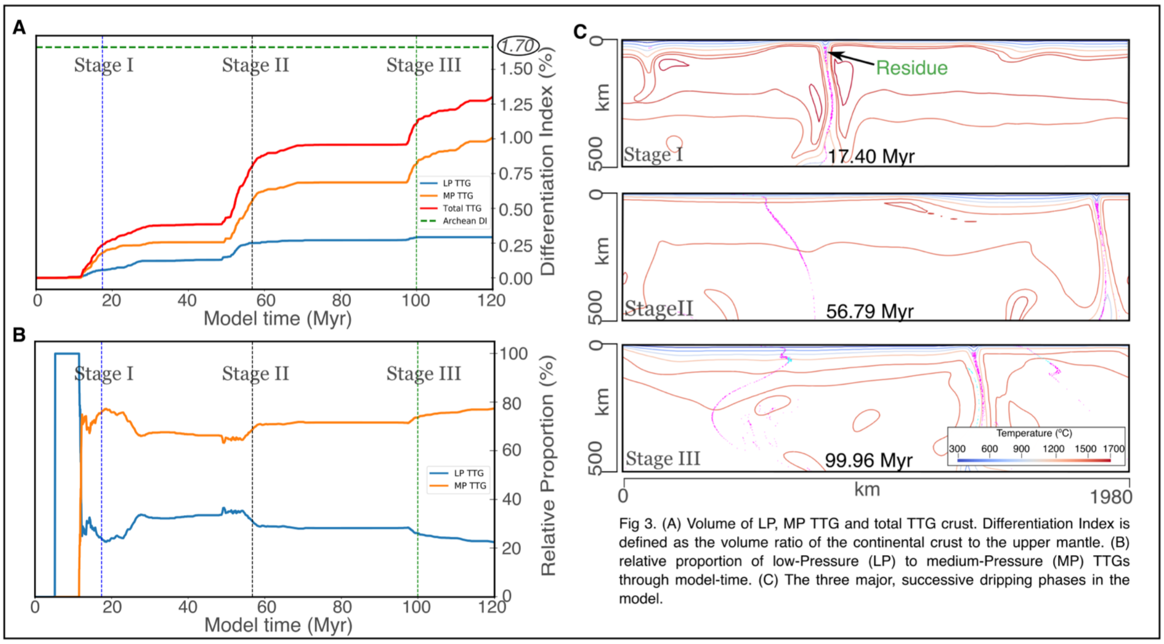

Fig 3. (A) Volume of LP, MP TTG and total TTG crust. Differentiation Index is defined as the volume ratio of the continental crust to the upper mantle. (B) relative proportion of low-Pressure (LP) to medium-Pressure (MP) TTGs through model-time. (C) The three major, successive dripping phases in the model.

- In particular, large volumes of TTG melts form in the tails of lithospheric drips. Melting occurs profusely within the thinner portions of the drips as these regions are more efficiently heated by the enclosing hotter mantle.

- In contrast, only limited melting occurs in regions of thickened crust, in part because the weaker lithosphere cannot sustain crustal thickening for long time periods, resulting in its removal through drips.

TTG formation between basaltic crustal dripping vs thickening phase(Reproduced from Gunawardana et al., 2020)

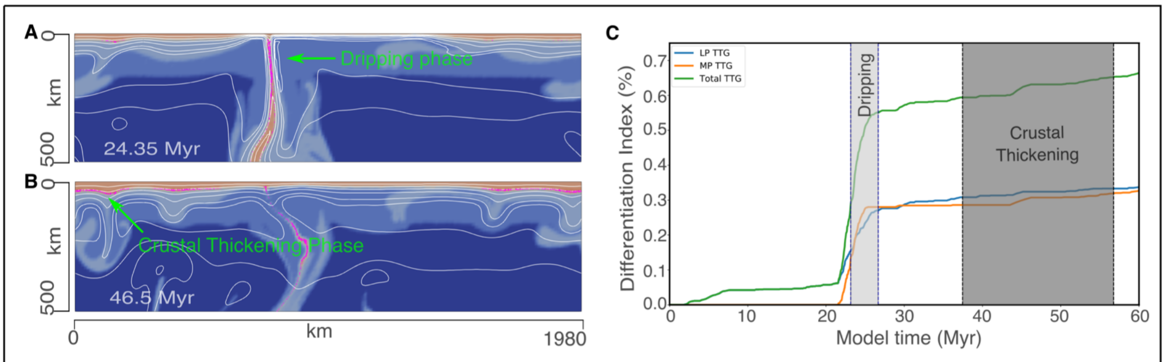

Fig 4. (A) Dripping phase, and (B) crustal thickening phase of a model. (C) Total TTG volume formed at each phase. Note that the dripping phase produce relatively larger TTG volume wrt thickening phase.

RESULTS...

- Furthermore, the model results show that TTG production and the resulting Differentiation Index (DI) values increase with the lowering of lithospheric yield strength for any given mantle and Moho temperature conditions.

Total tonalite-trondhjemite-granodiorite (TTG) crustal volume cast in terms of the Differentiation Index (DI) and proportions of low-pressure (LP-) to medium-pressure (MP-)TTGs as a function of lithospheric yield stress, as obtained from our numerical models with different mantle Tp and Moho-T values.(Reproduced from Gunawardana et al., 2020)

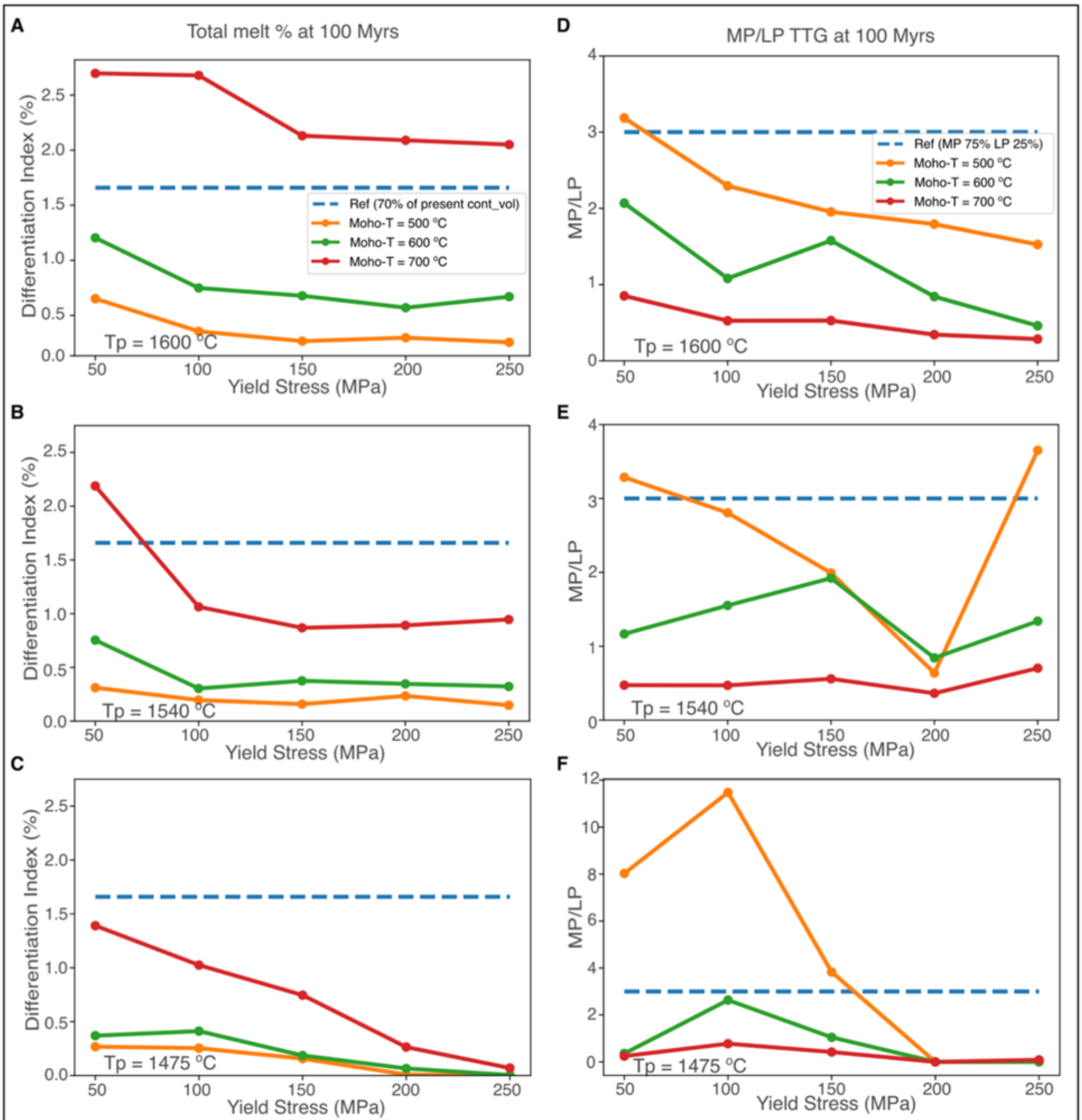

Fig.5 Plots showing (A–C) the total tonalite-trondhjemite-granodiorite (TTG) crustal volume cast in terms of the Differentiation Index (DI) value and (D–F) the proportions of low-pressure (LP-) to medium-pressure (MP-)TTGs as a function of lithospheric yield stress, as obtained from our numerical models with different mantle Tp and Moho-T values. The DI and MP/LP values are computed at the end of the first 100 Myr of the model evolution in each case.

CONCLUSION

- The preserved record of early Archean felsic crust is more consistent with the presence of weaker lithosphere during active tectonism at those times.

- Tectonic activity involving such weaker lithosphere atop hotter mantle would have led to the production of voluminous TTG melt prior to ~3Ga, consistent with the inference of numerous crustal growth models.

- Our study further shows that TTG production may have dominantly occurred within mafic crustal drips, whereas crustal thickening made an only subordinate contribution unless the crust was significantly thicker.

- The low yield stress facilitated the drips to grow in length up to few hundreds of km and keeping them stable over tens of Myr.

- Furthermore, weaker lithosphere together with the dominance of dripping can also account for the large abundance of MP-TTGs relative to the LP-variant within the early Archean rock record.

- Our models highlight the dominance of non-plate tectonic mechanisms in producing TTGs under the conditions that operated on the hotter Archean Earth.

AUTHOR INFORMATION

Prasanna Mahesh Gunawardana (PhD student)

email: prasanna.gunawardana@monash.edu

pmgunawardana@gmail.com

Affiliation:

School of Earth, Atmosphere and Environment

Monash University

Clayton, VIC 3800

Australia

ABSTRACT

Lithospheric yield stress is a key parameter in controlling tectonic processes. We calculate yield stress for a range of conditions appropriate to the Archean Earth, including hotter mantle potential temperatures and a range of Moho temperatures using 2D high resolution numerical geodynamic modelling techniques. This range of conditions are evaluated for generating felsic, tonalite-trondhjemite-granodiorite (TTG), crust with the results bench marked against the preserved rock record. The model results indicate that lithospheric yield stress slightly lower than the present-day Earth values (i.e. < 100 MPa) generates TTG melt volumes similar to those preserved in the rock record. In particular, large volumes of TTG melts form in the tails of lithospheric drips. Melting occurs profusely within the thinner portions of the drips as these regions are more efficiently heated by the enclosing hotter mantle. In contrast, only limited melting occurs in regions of thickened crust, in part because the weaker lithosphere cannot sustain crustal thickening for long time periods, resulting in its removal through drips. Our models highlight the dominance of non-plate tectonic mechanisms in producing TTGs under the conditions that operated on the hotter Archean Earth.

REFERENCES

- Cawood, P. A., and Hawkesworth, C. J. (2019). Continental crustal volume, thickness and area, and their geodynamic implications. Gondwana Res. 66, 116–125. doi:10.1016/j.gr.2018.11.001
- Gunawardana PM, Morra G, Chowdhury P and Cawood PA (2020) Calibrating the Yield Strength of Archean Lithosphere Based on the Volume of Tonalite-Trondhjemite- Granodiorite Crust. Front. Earth Sci. 8:548724. doi: 10.3389/feart.2020.548724
- Jain, C., Rozel, A. B., Tackley, P. J., Sanan, P., and Gerya, T. V. (2019). Growing primordial continents self-consistently in global mantle convection models. Gondwana Res. 73, 96–122. doi:10.1016/j.gr.2019.03.015
- Moyen, J.-F. (2011). The composite Archean grey gneisses: petrological significance, and evidence for a non-unique tectonic setting for Archean crustal growth. Lithos 123, 21–36. doi:10.1016/j.lithos.2010.09.015
- Sizova, E., Gerya, T., Stüwe, K., and Brown, M. (2015). Generation of felsic crust in the Archean: a geodynamic modeling perspective. Precambrian Res. 271, 198–224. doi:10.1016/j.precamres.2015.10.005