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A global look at cratons and the thermal properties that define their roots

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Because cratons are perhaps the largest source of Earth's mineral wealth, defining the term "craton" is important for understanding how this mineral endowment arises and thus for discovering more of it. Via integration of seismology and geology, we apply a consistent craton definition that encompasses a greater proportion of the Earth's crust than many older definitions (see Pearson et al., 2021). This definition is consistent with the temporal evolution of Earth's thermal history and is neither age nor process dependent. We will present an up-dated map of cratonic nuclei and cratonic regions that defines >60 Archean nuclei, plus varieties of composite, modified and supercratons.

To better constrain the early evolution of cratonic lithosphere we examine a range of thermal evolution models relevant to the early part of craton histories, under different conditions of formation. Our goal is to evaluate the models against the thermal conditions recorded by inclusions in diamonds extracted from Earth's mantle in the Meso- to Neoarchean, which preserve snapsots of the early thermal evolution of cratonic roots (Stachel et al., 2006; Miller et al., 2012; Timmerman et al., 2022; Pezzera et al., 2024; Changleng et al, 2024). Such samples offer the only available "real-time" data on the thermal conditions existing in the lower portions of cratonic lithosphere in Archean times.

Lithospheric Thermal Evolution Models – Model parameters

Our thermal models build on the approach of Jaupart & co-workers (e.g., Maraschal & Jaupart, 2006) for modelling non-steady state geotherms. The one-dimensional thermal models solve the conductive heat equation numerically to explore how the temperature within the lithosphere evolves over 3 Ga from an initial state, exploring the thermal consequences of both slab-stacking and mantle plume end-member scenarios of Archean craton formation. In the slab-stacking models (2 and 3 stacked slabs), we assume the oceanic slabs have Mg-rich oceanic crust with time corrected crustal heat generation and negligible heat production in the mantle (McIntyre et al., 2021). The slabs are in thermal equilibrium prior to subduction/ stacking and heat is transferred conductively after the 'stacking event'. Mantle plumes are modelled as a temporary thermal perturbation below oceanic lithosphere initially in thermal equilibrium, with hot plume residues accreting lithosphere from below by cooling, in a "static" situation. Mantle plume temperatures are set at 1750 °C, and cool to mantle potential temperatures in 15 Myr. Both end-member scenarios are also tested using an initial T_p of 1600 °C or 1470 °C that cools to a present-day T_p = 1350 °C.

Lithospheric Thermal Evolution Models – General Results

Example model results are given in Fig 1 with summary data for all models given in Fig. 2. Our plume accretion models (e.g., Fig 1A) are characterised by rapidly evolving curved geotherms and require 500 Myr to cool to a point where the lithosphere is within the diamond stability field. After that point, geotherms are relatively linear with little heat conducted from the relatively low heat producing crust. These models do not reproduce the cool P-T conditions recorded by inclusions within Meso- to Neoarchean diamonds (e.g., Timmerman et al., 2022; Pezzera et al., 2024, Changleng et al., 2024).

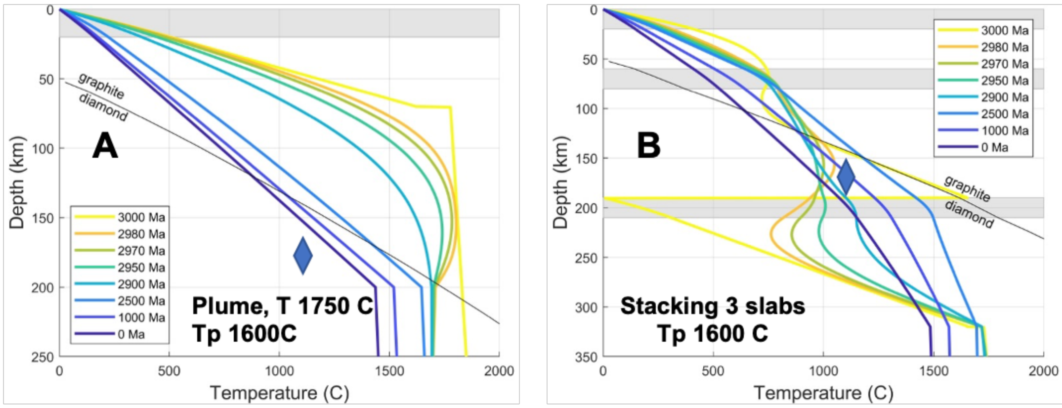

Figure 1: **A:** Thermal model of the thermal evolution of plume residues instantly accreted beneath a 70 km thick oceanic lithosphere in approximate thermal equilibrium. The oceanic crust is Mg-rich basalt with appropriate heat production at 3 Ga. Mantle potential temperature cools by 50 °C/Gyr. Blue diamond marks P-T condition of olivine inclusion in Mesoarchean diamond from Timmerman et al (2022). Grey fields are the slab crusts. **B:** Thermal model of the stacking of 3 slabs initially in thermal equilibrium. Upper slab is a thin 60 km thick slab with 20 km thick Mg-rich crust; 2 lower slabs are 130km thick, each with 20 km thick Mg-rich crust. Stacking of third slab occurs 20 Myr after the first stacking event. Oceanic crust assumes present-day heat production at 0.15 μW/m^3, corrected to 3 Ga, whereas no heat production is added in the lithospheric mantle portions (following McIntyre et al., 2021). Blue diamond same as in A. In both models Tp decreases with time, through the model.

Slab stacking models are characterised by very complex geotherm evolution, depending on the number of slabs modeled. In all cases, emplacement of a lower cool slab immediately creates a diamond stability "window" from quite shallow depths within the root through to the base (See Fig. 2 for the temporal evolution of this window). Consequently P-T conditions equivalent to those recorded by Meso- to Neoarchean diamonds are readily attained early in the evolution of the craton, and remain in the diamond stability field unless otherwise thermally disturbed. Interestingly, the complex transient geotherms evident in these models remain "transient" until present day. Even though these "evolved geotherms become more linear, they remain far from "steady-state" equilbrium.

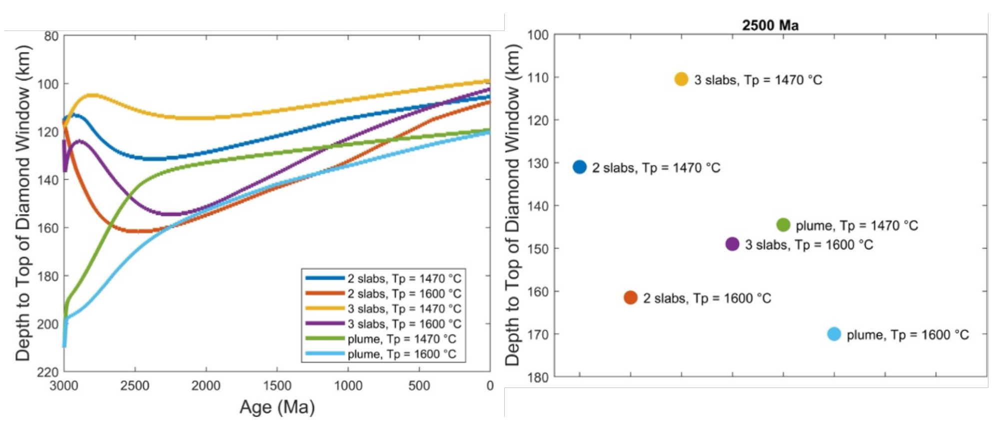

Figure 2: Summary of thermal modelling results showing (left) the temporal evolution, since 3 Ga, of the depth (in km) to the top of the diamond window and (right) the depth (in km) to the top of the diamond window at 2500 Ma,

500 Myr after model initiation (slab stacking or plume impingement), for a variaty of slab stacking and plume models initiated over a range of ambient mantle potential temperatures at 3 Ga, from 1470 to 1600 °C.

Summary

The thermal evolution of Archean and Paleoproterozoic lithospheric mantle roots are a strong function of their mode of formation and initial architecture for a period of between 1 and 3 Ga after craton formation as shown by Maraschel & Jaupart (2006). Our models confirm and expand on the finding that cratonic geotherms are transients for much of their evolution. Cratonic geotherms should not be modeled as "steady-state" geotherms in the first 2 Ga of their evolution. In thick cratonic roots, the thermal response time of the lithosphere is similar to the half-life of crustal heat production so that temperatures in the mantle root cannot adjust to time-dependent radiogenic heat production, especially in high heat production thick continental crust (Maraschel & Jaupart, 2006). The thermally transient nature of such lithosphere, in which temperatures remain lower than in steady state calculations (e.g., Hoare et al., 2022), lead to shallower roots than those predicted by instantaneous steady state models and likely more uniform in cratonic root thickness through time. A further consequence of the transient nature of the evolving geotherms is that there is no *apriori* reason to expect P/T conditions documented by inclusions in Archean and Proterozoic diamonds to reflect or define steady-state geothermal conditions. The dispersed nature of P-T conditions defined by some diamond inclusion suites may be less a function of some "artifact" of the thermobarometry, as often assumed, but instead could represent snap-shots of strongly evolving thermal conditions in the mantle root. The thermal conditions recorded by diamonds erupted in the Archean, sampling the early stages of cratonic root evolution, record cool thermal conditions and eclogite-facies metamorphism. From the thermal condition modelled here, these geological observations are best interpreted in terms of the thermal evolution of lithospheric slabs "stacked" due to collision of lithospheric blocks and subduction. The geochemical signatures of these Archean diamonds are consistent with subducted crustal material and for all of the Meso- to Neoarchean diamond locations found so far, the thermal and geochemical data are most consistent with slab stacking (e.g., Timmerman et al., 2022), although other mechanisms are possible.

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