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How long can diamonds remain stable in the continental lithosphere?

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Abstract

Do Archean ages obtained for diamonds from many of the world's cratons constitute a strong constraint on the thermal state of the Archean continental lithosphere? The apparent longevity of diamonds obtained from cratonic kimberlites [Boyd et al., Nature 315 (1985) 387–389; Richardson et al., Nature 310 (1984) 198–202] has been used to infer the physical and chemical isolation of cratonic roots from the convecting mantle since 3 Ga. This would also provide an extremely strong constraint on the thermal history of the lithospheric mantle – requiring low temperatures at depth for its entire history. Recent evidence suggests, however, that the published 'diamond' ages may not represent the ages of the diamonds themselves, but significantly pre-date them [Shimizu and Sobolev, Nature 375 (1995) 308–311; Spetsius et al., Earth Planet. Sci. Lett. 199 (2002) 111–126]. We use a particle-in-cell finite element code to model the thermal stability of the continental lithosphere in a convecting mantle. The continental crust modulates the thermal conditions of the underlying mantle lithosphere, increasing the depth of the thermal boundary layer beneath the continent and providing a mechanism for stabilizing the sub-continental thermal field. If diamonds have survived in cratonic roots since the Archean, the conditions necessary for diamond stability must have existed in the Archean continental lithosphere, and those conditions must have remained relatively unperturbed for ∼3 Gyr [Boyd et al., Nature 315 (1985) 387–389]. Here, the longevity of the diamond stability field is explored for systems with chemically distinct continental crust and a strongly temperature-dependent mantle viscosity. Such models frequently produce the temperature conditions needed to form diamonds within the Archean lithosphere, but the temperature fluctuations experienced within the modeled mantle lithosphere are generally able to destroy these diamonds within 1 Gyr. Increasing the distance to active margins has only a marginal effect on the longevity of the diamond stability field. Convectively stable cratonic roots extend the lifetime of the diamond stability field in those regions. However, while the residence time of diamonds approaches the order of magnitude required (284–852 Myr), extremely fortuitous mantle conditions are required to explain Archean diamonds.

Keywords: Archean; diamond; mantle convection; geotherm; lithosphere

1. Introduction

Archean ages have been reported for diamonds recovered from Phanerozoic kimberlites [1,2].

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This has two major implications: that the conditions for diamond stability existed in the Archean lithospheric mantle, and that the root has remained mechanically and thermally stable over its entire lifetime. However, this has recently been challenged by workers suggesting that the radiometric ages of diamond inclusions may significantly pre-date the ages of the diamonds themselves [3,4].

Navon [5] has pointed out that when Re–Os isotopes are used to date sulfide inclusions, it should be shown that the diamond formation event affected the Re–Os system. If this is not the case, the Re–Os ages of the inclusions may not reflect the age of the host diamond, but pre-date it. The same argument applies for isotopic systems in minerals such as garnet. Non-uniform trace element distributions in some garnet inclusions in diamonds [3] suggest that some South African peridotitic diamonds may be comparatively young (∼360 Ma). Shimizu and Sobolev [3] conclude these diamonds grew shortly before kimberlite eruption. Spetsius et al. [4] have shown that the growth of zircon, and by inference diamond, does not reset the Re–Os system in the sulfide inclusions. This means the sulfide protoliths may significantly pre-date diamond formation.

The purpose of this paper is to explore how long diamonds can survive in continental roots under various conditions. Given the current debate concerning their ages, we would like to know if the conditions for diamond stability could exist under Archean mantle conditions. Similarly, are the conditions for diamond stability strongly sensitive to their position in the continent? Does having a stable continental root provide sufficient thermal stability so that the geotherms pass through the diamond stability field for the lifetime of a continent?

Independent observations suggest that cratonic roots have been mechanically stable since their formation. Re–Os ages have been obtained for xenolith suites for many of the world's cratons [6–8]. These results show the lithosphere is Archean in age, and formed at approximately the same time as the crust. A major focus of modeling to date has been to explain the survival of continental roots in a convecting mantle over billions of years, which has often been assumed to be due to the material properties of the roots themselves [9–11]. Some of the properties suggested include chemical buoyancy, and high root viscosity due to dehydration. The former, first proposed in the form of the tectosphere hypothesis by Jordan [9], invokes the chemical buoyancy of the depleted mantle residuum beneath cratons as a means of stabilizing cratonic roots. Further support for this comes from more recent xenolith studies [12], which show a distinct variation in major element composition of the sub-continental mantle lithosphere from the Archean to the present. Alternatively, dehydration of the cratonic roots, e.g. [13], can provide a viscosity contrast between the roots and the surrounding mantle which can stabilize the roots. Pollack [13] argues that as a consequence of the inverted topography at the base of the sub-continental lithosphere, hot material will be advected away from root zones into adjacent terrains. However, Lenardic and Moresi [11] have argued from numerical experiments that chemical buoyancy alone cannot explain root longevity, and that while an increase in root viscosity of 100–500 due to dehydration can stabilize cratonic roots under the present-day convective regime, it cannot explain root stability under Archean conditions. Similarly, evidence from the Sino-Korean craton [14] suggests that cratons are not universally indestructible. This has led Lenardic et al. [15], to propose that the longevity of cratons may, in part, be dynamic, and arise as a result of the low relative yield stress of surrounding mobile belts.

If they exist, Archean diamonds also place a strong constraint on Archean geotherms. While previous modeling [16] has shown that the buffering effect of continents in a convecting system can explain mild Archean continental crustal geotherms [17–19] in the face of higher upper mantle temperatures [19–22], such models have not satisfied the longevity constraint Archean diamonds place on lower lithospheric geotherms.

The question of the thermal stability of cratonic roots is of direct consequence to their longevity. Irrespective of the survival mechanism, the temperature dependence of silicate rheology [23] im-

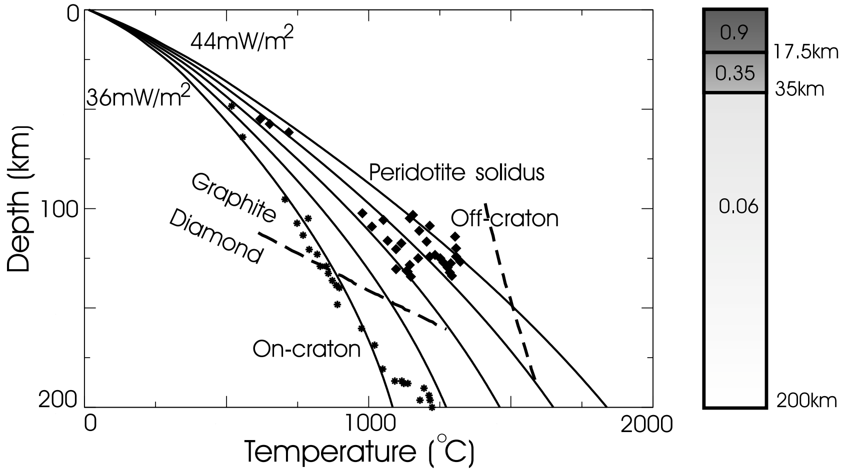

Fig. 1. Illustrative example of a range of typical continental geotherms for the lithospheric column shown (right), for various surface heat flux values (left to right: 36, 38, 40, 42, 44 mW/m^2). Based on the solution to the one-dimensional heat flux equation for a three-layered conductive medium (right bar, heat production in μW/m^3). Xenolith PT estimates from Kopylova et al. ([26], circles) and Franz et al. ([27], diamonds). Graphite–diamond transition and peridotite solidus from Boyd et al. [1] and Takahashi [35]. Geotherms corresponding to low surface heat values (36–38 mW/m^2) pass into the diamond stability field (DSF) within the lower lithosphere.

plies that the survival of cratonic roots depends strongly on the thermal field of the continental lithosphere. That is, low lithospheric temperatures imply strength, but greater negative buoyancy. Higher temperatures require less compositional buoyancy, but an additional source of strength, such as dehydration.

Here we explore the thermal evolution of continents for realistic convection models, and examine the characteristics of the sub-continental thermal field. While the material properties of the cratonic lithosphere no doubt play a role in governing the thermal conditions of cratonic roots, it is important to distinguish between competing mechanisms. Thus, for a large part, we will be considering the effect a chemically distinct continental crust and a strongly temperature-dependent mantle viscosity has in regulating the continental thermal field, and later including the effects of thermochemically stabilized roots.

2. Diamond stability constraints

Fig. 1 shows typical conductive continental geotherms against a range of thermal constraints. Present-day xenolith pressure–temperature estimates can give an indication of the conditions in the deep lithosphere, despite the ambiguity of having been brought to the surface by volcanic events [24]. The majority of Archean thermal constraints come from the crust, and as a result are strongly dependent on the distribution and magnitude of heat production in the Archean continental crust. While it is generally agreed that heat production should have been around three to four times greater in the Archean, the absolute magnitude, its distribution, and its dependence on lithology are not well constrained [25]. The thermal field of the deep lithosphere depends on the thermal coupling of the crust and mantle, and so increased crustal heat production will have some effect on the structure of the deep lithospheric geotherms. However, this effect is largely obscured by the strong relation between lithospheric geotherms and the planform of mantle convection (see Fig. 4b).

The diamond–graphite transition is a well-defined phase transition at depths comparable to the lower lithosphere, and is often used as collaborative evidence with xenolith suites and garnet geotherms in constraining the deep continental

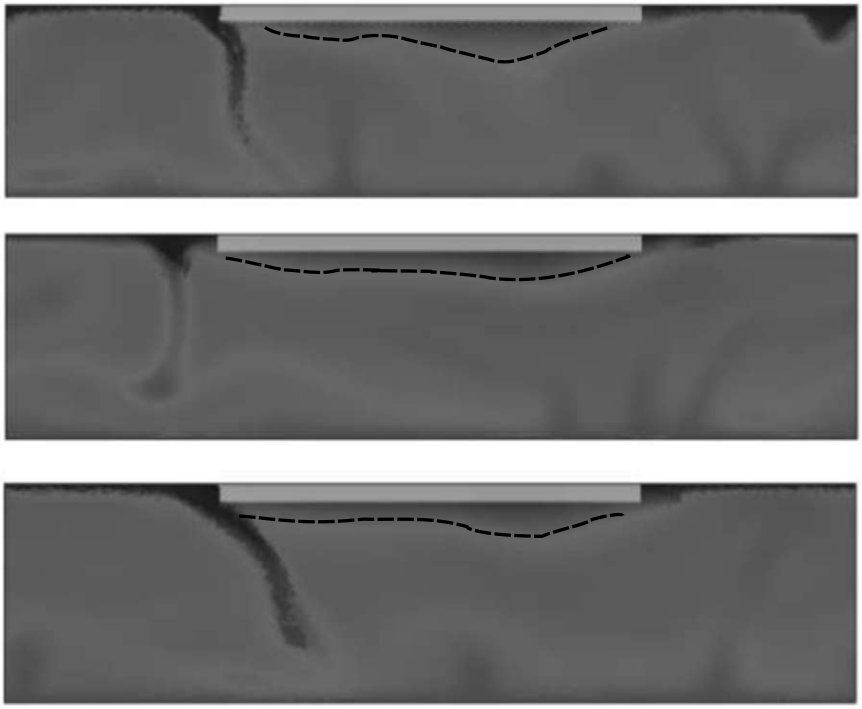

Fig. 2. Development and evolution of a sub-continental thermal boundary layer for a 4 by 1 cell with a basal Rayleigh number of 10^7. The continental extent is 50%. Shown is temperature field (cool material is dark) and strain (light, near-surface localized zones) and chemically distinct continent. Dotted line represents the depth of the TBL.

thermal field (e.g. [26,27]). In regions which possess cool deep continental root zones, such as Archean cratons, geotherms pass into the diamond stability field at depths less than the depth of the lithosphere (see Fig. 1). In these regions, diamonds may be the stable form of carbon for the lower 30–40 km of the lithosphere. However, if the lithosphere is significantly thinner and the geotherms elevated, the geotherms may not pass into the stability field within the depth of the lithosphere. This has led to a well-known empirical relationship, known as Clifford's rule [28], where kimberlites found on-craton have sampled the deep continental root zones in these regions, and as a result are diamondiferous, while those found off-craton, where the lithosphere is significantly thinner, are barren. This relationship holds broadly true for much of southern Africa, but in other places (e.g. Australia) it is of limited use [28,29]. Here, for simplicity, we define the base of the lithosphere as where the geotherms pass the 1300°C isotherm. The stability of diamonds is used as a constraint on the thermal state of the lower lithosphere, and is used to explore the longevity of the continental thermal field over geological timescales.

3. Models

Figs. 2 and 3 illustrate the general convective configuration for the systems discussed here. The upper and lower surfaces are free-slip and isothermal, and periodic (wrap-around) boundary conditions are employed for the side-walls. Two materials are included, the bulk mantle and a chemically distinct continental crust. Since here we are not modeling continental tectonics or deformation, the continents have an intrinsically high buoyancy and viscosity to allow them to re-

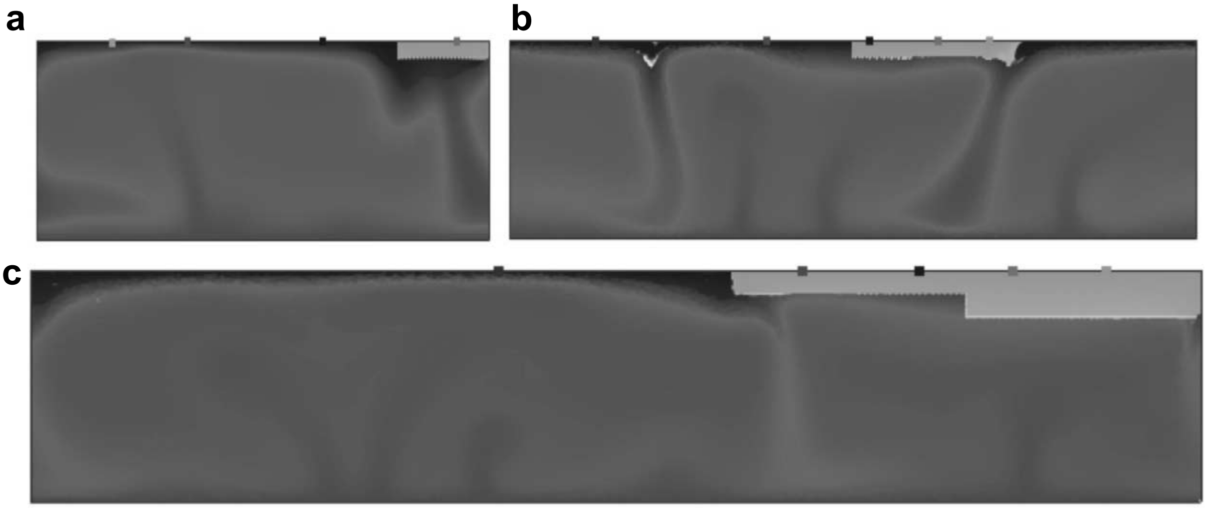

Fig. 3. Temperature field of various convecting systems with basal Rayleigh number of 10^7, cool material is dark, light near-surface lineations represent highly strained material. Continents are near surface light blocks. Side boundary conditions are periodic. (a) Simplest scenario, in a 3 by 1 cell. (b) 4 by 1 system with a larger continent. (c) Heterogeneous continent with chemically distinct root zone.

sist convective entrainment. The initial thermal field is obtained by running analogous simulations for several convective overturn times.

A viscoplastic rheology is employed for each material. For stresses below a specified yield stress, the flow law is that of a temperature-dependent viscosity, and is approximated by an exponential function [30]. The flow switches to a depth-dependent plastic branch above a specified yield stress, based on a continuum representation of Byerlee's frictional law [31]. A strain-dependent weakening has also been included to simulate damage, the effect of which is to stabilize localized zones of failure through time [15].

Stoke's equation for incompressible flow is solved using a particle-in-a-cell finite element code Ellipsis [32]. This employs a multigrid solver for the equation of motion, which is coupled to the continuity equation via a multigrid Uzawa iteration. At each multigrid level of the Uzawa iteration, the non-linear viscosity is determined by repeated substitution. The energy equation is solved using explicit timestepping of a Petrov–Galerkin upwind method [33].

The physical parameters in the simulations are non-dimensionalized in the manner of Moresi and Solomatov [33]. The real values assumed are a temperature of 2200 K at 670 km, at the base of the upper mantle [23], and a viscosity contrast of five orders of magnitude. This scaling predicts variable melting of mantle material at regions with substantially elevated geotherms, and high temperatures at the lower thermal boundary layer.

4. Results

Fig. 2 illustrates the development of a convecting system through time. The temperature field of the convecting system is shown, the light near-surface block is a chemically distinct continent. Highly strained material is shown as white lineations. The basal Rayleigh number is 10^7. The continent has a higher heat production than the surrounding mantle. The lithosphere in our models consists of two parts: a convectively stable chemical boundary layer (CBL), and a thermal boundary layer (TBL) which extends beneath it. In our models, the CBL is either the continental crust (as in Fig. 2), or extended to include convectively stable roots (Fig. 3c). The heat flux constraint imposed by the CBL [34] extends the TBL to greater depths beneath the continent than in the adjacent oceanic domains. This thermal boundary

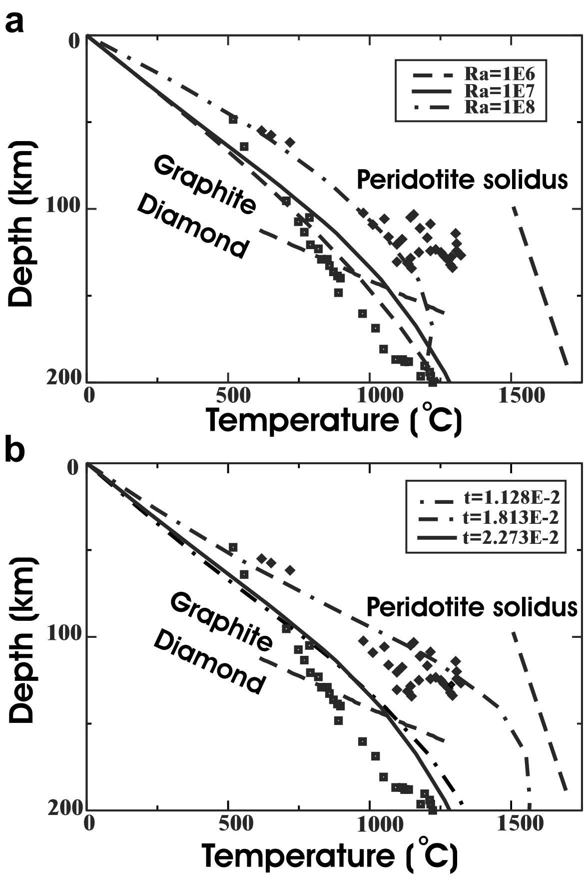

Fig. 4. (a) Average geotherms for the system shown in Fig. 3a, for a variety of Rayleigh numbers. Also shown are present-day xenolith data sets (Kopylova et al. [26], squares; Franz et al. [27], diamonds), the peridotite solidus [35] and the graphite–diamond transition [1]. (b) Geotherms at different times for the system shown in Fig. 3a, for a Rayleigh number of 10^7. The deep geotherms show a large amount of variability pending the thermal structure of the immediately subjacent mantle.

layer is not prescribed, it develops as a consequence of mantle dynamics, yet exhibits a high degree of stability throughout the length of the simulation.

Fig. 4a shows geotherms for a convecting system with an aspect ratio of three (shown in Fig. 3a) for various Rayleigh numbers. Also plotted are present-day xenolith data sets [26,27], the graphite–diamond phase transition [1] and the peridotite solidus [35]. It can be seen that while the geotherms show a considerable amount of variability which is dependent on the thermal state of the mantle in the immediate vicinity of the continent (Fig. 4b), the average geothermal gradient changes little for a wide range of Rayleigh numbers. Thus the most pressing problem is not how could the conditions for diamond stability exist under the Archean thermal regime, in dynamic models these conditions naturally (if sporadically) occur. A more important consideration is how the thermal conditions required for the stability of diamonds have existed, relatively unperturbed, in cratonic mantle lithosphere since 3 Ga. The problem is highlighted in Fig. 4b, which shows the continental geotherms at various times for a convecting system with a Rayleigh number of 10^7. The deeper parts of the geotherm depend strongly on the planform of mantle convection around the continent, and may pass in and out of the diamond stability field depending on the thermal structure of the local mantle.

The survival of diamonds is intimately tied to

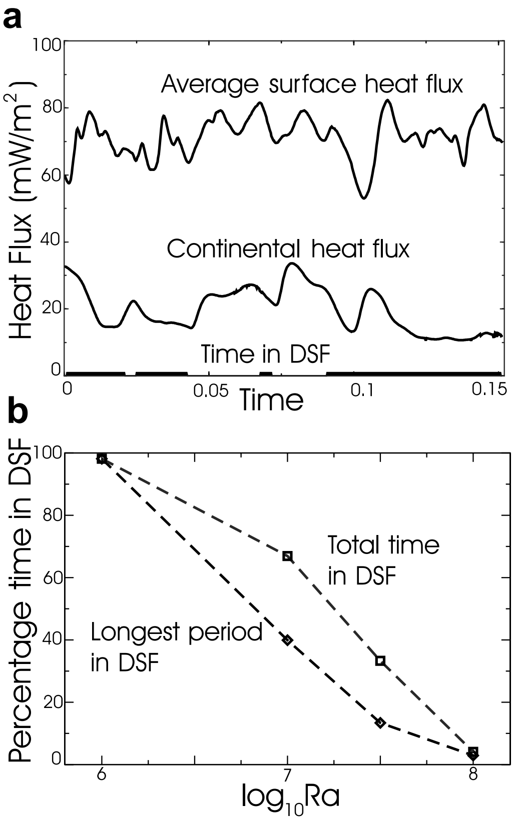

Fig. 5. (a) The average surface heat flux, continental heat flux (heat flux into the CBL), and the time the continental geotherms spent in the diamond stability field (DSF) for the convecting system shown in Fig. 4a, with a Rayleigh number of 10^7. (b) The percentage time of a simulation the continental geotherms spend in the diamond stability field (DSF) against the log of the Rayleigh number, for configuration shown in Fig. 4a.

the survival of the cratonic roots themselves. However, it is useful to isolate the mechanisms responsible for the thermal stability of cratonic roots in order to assess their individual efficacy. To clarify this, the time the continental geotherms spend in the diamond stability field, together with average and continental heat flux, are shown in Fig. 5a for a simple convecting system. The time spent by the geotherms in the diamond stability field is directly correlated to the thermal configuration of the mantle beneath the continent, and by association also broadly related to the continental heat flux. The relationship between the time spent by the geotherms in the diamond stability field and the Rayleigh number is shown in Fig. 5b. For more vigorous convection, the time the geotherms spend in the diamond stability field decreases dramatically. This illustrates the main unresolved issue of the Archean thermal record, namely, the difficulty in explaining the longevity of the thermal conditions in the cratonic roots over a timescale of ~3 Gyr.

4.1. *Influence of mobile belts*

It has been suggested that the survival of cra-

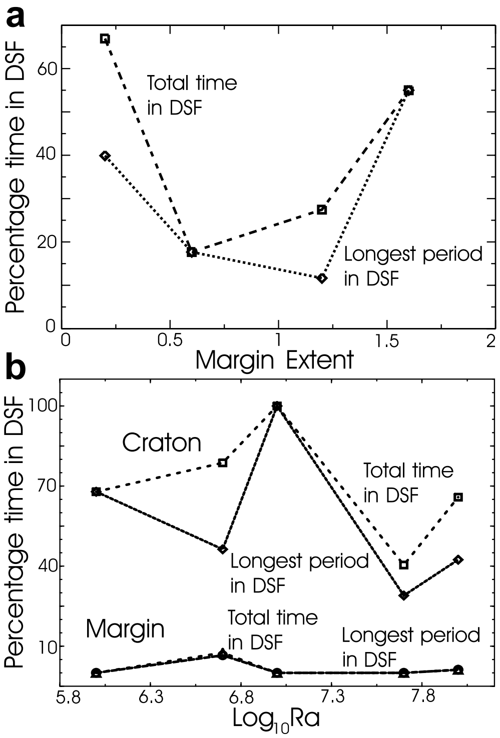

Fig. 6. (a) The relative size of the continental margins with respect to the central portion of a continent plotted against the percentage time of a simulation the continental geotherms spend in the diamond stability field (DSF, y-axis). Shown are both the longest single period and the total time the geotherms spent in the diamond stability field. (b) The log of the Rayleigh number, plotted against the percentage time of a simulation the continental geotherms spend in the diamond stability field (DSF). The percentage times are shown for both cratonic geotherms (regions with thermochemically stabilized roots, see Fig. 3c), and for adjacent margins. The longest single period and total time the geotherms spent in the diamond stability field are shown.

tonic regions may be largely due to the low relative yield stress of surrounding mobile belts [15]. In this way, cratonic regions may be buffered from the dynamics of active margins by the deformation of off-cratonic regions. In this vein, one potential mechanism for providing a dynamic stability to a continental region is by preferentially distancing from active margins. Fig. 6a plots the time the continental geotherms spend in the diamond stability field against increasing margin extent. This effect does provide some degree of stabilization for extremely large continental margins. However, the effect is mild, and its efficacy is undermined by the stability of the geotherms for an extremely small continent, which itself is largely due to the presence of a long-lived stable downwelling underneath the continent. Hence, this effect alone cannot provide the stability required to explain the longevity of the diamond stability field beneath many cratons.

4.2. Anomalous strength of continental lithosphere

It has been long postulated that the survival of cratonic roots requires a chemical or rheological distinction of such roots from both the bulk mantle and non-cratonic lithosphere (e.g. [9]). The chemical distinction of Archean cratonic roots has been observed from xenolith geochemistry [6,12,36]. While the competing mechanisms which provide mechanical stability to cratonic roots is still an active area of research [11,15], in the present context it is useful to see the effect thermochemically stabilized roots have on the subcontinental thermal field. Fig. 3c illustrates the configuration of a convecting system with chemically distinct cratonic roots. The ability of the roots to avoid convective recycling enables the thermal boundary layer in these areas to extend to greater depths than in adjacent non-cratonic regions. Fig. 6b illustrates the relationship of the lifetime of the diamond stability field and Rayleigh number for different regions of the continent in Fig. 3c. The longevity of the diamond stability field is largely independent of Rayleigh number. The geotherms in regions with thermochemically stable roots spend significantly more time in the diamond stability field than do their adjacent (non-cratonic) counterparts. However, the cratonic geotherms are generally not exclusively within the diamond stability field for the length of the simulations. The residence time for diamonds in models with a cratonic root varies between 284 and 852 Myr. This range is dependent on the dynamics of the mantle around the continent over the time of the simulation.

5. Discussion and conclusions

The well-defined nature of the graphite–diamond transition make the diamond stability field a useful indicator in exploring the long-term thermal stability of the continental lithosphere. Here we have shown that the conditions for diamond stability can certainly exist in continents under Archean mantle conditions, provided that the cratonic roots themselves can resist convective recycling. Independent geochemical constraints [12,36] suggest that cratonic roots are geochemically distinct from both Proterozoic and Phanerozoic mantle lithosphere, and have survived since their formation in the Archean. However, the fact that the conditions for diamond stability can exist does not mean that this is a stable state. The survival of the cratonic root does not necessarily imply the survival of the diamonds within it; in our models the convecting mantle can perturb the thermal state of a stable root to a degree that the geotherms no longer pass through the diamond stability field within the root zone.

The nature of continental geotherms depends strongly in these models on the thermal state of the surrounding mantle. The magnitude of this effect is certainly related to the prescribed depth of the CBL and the distribution of heat production with depth within it. The depth extent of continental roots has been a subject of debate, as heat-flow [37], xenolith [38] and electrical conductivity data [39] all indicate the continental lithosphere is at most 200–250 km thick. However, many seismic tomographic models indicate extremely thick (up to 400 km) roots in cratonic regions [40]. Gung et al. [41] have recently shown that the discrepancy can be reconciled by considering the differences in velocity between horizontally and vertically polarized shear waves, and that the seismic lithosphere beneath old continents is at most 200–250 km thick. We assume a conservative estimate of the thickness of the CBL in our models of less than 150 km (cf. [42]). This results in a TBL (the thermal lithosphere) in these regions of up to 200–250 km.

Heat production in the Archean crust and mantle are generally accepted as having been three to four times greater than today. For the mantle, this implies a Rayleigh number in the Archean two to three orders of magnitude larger than at present [11]. Previous work [16,29] has shown that the mantle contribution to the continental heat flux may not have been significantly greater in the Archean. We have shown here that under Archean mantle conditions, some portions of the continental lithosphere may be cool enough for the equilibrium geotherms to pass through the diamond stability field. Enhanced crustal heat production in the Archean means that the crustal geotherms may have been significantly elevated above present values. This would have a large effect on observed deformation styles in Archean terrains. However, O'Neill et al. [29] have shown that heat production in the crust is anti-correlated to mantle heat flow into its base. In these models, the effect of crustal heat production on deep continental geotherms is small compared to the effect of the local mantle thermal state. Heat production in the depleted cratonic mantle roots is a far more important consideration; however, this is not well constrained for the present continental lithosphere, and even less so for Archean lithosphere [38].

The Archean ages obtained for diamonds from many cratonic regions placed strong constraints on both Archean thermal conditions in the continental lithosphere, and on the mechanical stability of cratonic roots. While debate continues over what these ages represent, alternative evidence still supports comparatively mild continental geotherms in the Archean [19], and synchronous formation of Archean crust and root zones [6]. Our modeling suggests that the conditions for diamond stability could have existed in the Archean lithosphere. However, temperature fluctuations in the mantle lithosphere result in strong time dependence in the modeled continental geotherms, and thus cannot explain the longevity of Archean diamonds. The size of the continent and the position of the geotherms within it have a mild effect on the longevity of the diamond stability field. Stable cratonic roots result in more mild, less time-dependent geotherms. However, even in our models with stable cratonic roots, the maximum residence time of diamonds in the lithosphere is around 284–852 Myr. While this approaches the order of magnitude required (~3.5 Gyr), extremely fortuitous local mantle temperatures are required throughout the evolution of a continent to explain the longevity of Archean diamonds.***[SK]***

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