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The thermal structure of stable continental lithosphere within a dynamic mantle

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Abstract

The thermal structure of stable continental lithosphere is determined by (1) the concentration and distribution of heat sources within the crust and (2) the amount of heat input from the convecting mantle. The self-consistent coupling of these two factors has not been included in thermal models of stable lithosphere to date. We conducted two suites of numerical simulations (one with variable crustal heat production and the other with a chemically distinct cratonic root) to explore the thermal coupling between stable continental lithosphere and the convecting mantle. The distribution of heat producing elements within the crustal column was found to play a significant role in determining the local thermal structure of the continental lithosphere. Concentrating heat producing elements in the lower crust lead to a thinner thermal lithosphere. Mantle heat flux into the base of stable continents was low relative to surface heat flux and did not vary significantly within the simulations regardless of the presence or absence of a thick cratonic root. A suite of simulations with variable root thickness indicated that although cratonic roots have a weak effect on surface heat flow patterns, relative to crustal heat source variations, they do have a pronounced effect on deeper thermal structure. Roots stabilized temporal variations of deep continental geotherms and were required to generate a thick thermal lithosphere. The ratio of thermal to chemical lithospheric thickness was found to decrease toward unity with increasing root thickness and thick cratonic roots limited small-scale mantle convection beneath themselves.

Keywords: thermal structure; continental lithosphere; mantle convection

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1. Introduction

Thermal modeling studies, constrained principally by heat flow data, have played a key role in assessing the present day thermal structure and chemical make up of stable continental lithosphere (e.g., [1–6]). The long and rich history of such studies has lead to significant advances in our understanding of stable continental thermal structure. There is, however, still a key missing element in completing this understanding: the connection between the heat from the convecting mantle and the heat generated within the continental lithosphere.

The thermal structure of stable continental lithosphere depends on crustal and mantle chemistry, which determine thermal conductivity and the dis-

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tribution of heat producing elements within the lithosphere. It also depends on the amount of heat coming from the convecting mantle. The majority of continental thermal models to date have not treated convective mantle heat flux as a dependent parameter. Rather, they have been based on solutions to the one-dimensional heat conduction equation in a layered medium meant to represent the lithosphere. Although much has been learned [7], this approach hits a fundamental impasse; a variety of models with different proportions of internal heat sources and mantle heat flow can be consistent with heat flow observations [6]. Added constraints, when available in the form of deep xenoliths, can bridle this problem to a degree, but such constraints are restricted to small areas. In addition, the degree to which xenolith data represent equilibrium conditions is not always known. Thus, one cannot discriminate between fundamentally different models even if xenolith data is available [6].

The standard thermal modeling approach hits this impasse because it inherently assumes that the concentration of lithospheric heat sources and the component of heat from the convecting mantle are decoupled (e.g., mantle heat flow can take on a range of values for the same distribution of crustal heat sources within such an approach). This is why a variety of models can be made to match heat flow data. If, however, local mantle heat flux depends on the amount of heat produced within a continent, then the range of allowable models becomes more tightly constrained. Local mantle heat flux must depend on the amount of heat produced within a continent as this heat influences the local surface conditions that the convecting mantle experiences. Mantle convection models have already shown that continents can have significant effects on mantle flow (e.g., [8–12]). Mantle convection models to date have not incorporated continents with variable distributions of heat producing elements, but there is no reason they could not. Doing so leads to an approach that treats conduction and internal heat generation in stable continental lithosphere and convection in the mantle below in a self-consistent manner.

The purpose of this study is to use this self-consistent approach to elucidate the relationship between mantle heat flux and the thermal properties of stable continental lithosphere. We conducted two sets of numerical simulations, one with variable crustal heat production and the other with a chemically distinct cratonic (or tectospheric) root [13] of variable thickness. The two suites of simulations allowed us to isolate the effects of each potential contribution. The observed range of crustal heat production on the Earth is 57 to 371 times a reference mantle heat production of 0.007 $\mu W/m^3$ [14–16]. We chose to extend the range from 1 to 500 times the reference mantle heat production in our numerical simulations to encompass the extreme cases possibly not sampled or potentially representative of past crustal heat production values. Within the variable crustal heat production simulations, we also explored the role of variable distributions of heat producing elements within the crustal column. For the variable cratonic root thickness simulations, we varied the chemical lithospheric thickness from 40 to 200 km, placing the range within the limits for maximum thickness (< 250 km) as determined by xenolith thermobarometry [15,17]. For comparison, we note that seismic studies have estimated thermal lithosphere thicknesses in stable continental regions to be up 300 km [18–20]. The thermal thickness of the lithosphere within our simulations is not preset, but is solved for within the simulations themselves.

2. Modeling approach, assumptions and methods

In order to obtain a self-consistent thermal model, the heat transfer in stable continental lithosphere (via conduction and internal heat production) must be coupled with the heat transfer in the mantle (via convection). This is achieved within the numerical simulations of this study by emplacing a chemically distinct, layered, and stable (non-deforming) continent within the upper thermal boundary layer of a convecting mantle layer. Fig. 1 illustrates the model setup. The continental layers possess unique heat production values. Variations in thermal conductivity with depth have been neglected to maintain focus on the effects of heat production. The combined thickness of the upper and lower continental crustal layers is set at a constant value that is 6% of the total system thickness. An additional layer representing a chemically distinct mantle root of variable thickness was also included in a suite of simulations. Convection within the simulations is limited to the upper mantle with the lower model boundary representing the 660-km phase transition boundary. Wrap-around side boundary conditions are used so as to minimize artificial edge effects and to allow model continents to drift freely across the modeling domain over time (Fig. 1b). The top and bottom boundaries are free slip and isothermal. The bottom heating Rayleigh number, Ra, was set at 2×10^7. This Rayleigh number is defined as

$$Ra = \frac{\rho_0 g \alpha \Delta T d^3}{\mu \kappa} \tag{1}$$

where ρ_0 is the average mantle density, α is the coefficient of thermal expansion, ΔT is the temperature drop across convecting layer, d is the convecting layer depth, μ is the mantle viscosity at the system base, and κ is the thermal diffusivity.

The internal heating Rayleigh number, Ra_{H}, is defined as

$$Ra_{\mathrm{H}} = \frac{\alpha \rho_0^2 g H d^5}{k \mu \kappa} \tag{2}$$

where H is the rate of internal heat generation per unit mass and k is thermal conductivity. The ratio of internal to bottom heating Rayleigh numbers was set to one. This ratio parameterizes the degree of internal relative to basal heating within the mantle. Variations of this ratio and of the Rayleigh number have not been addressed in this study. Continental lateral extent is fixed at ~40% of the bulk system: approximately the present day value.

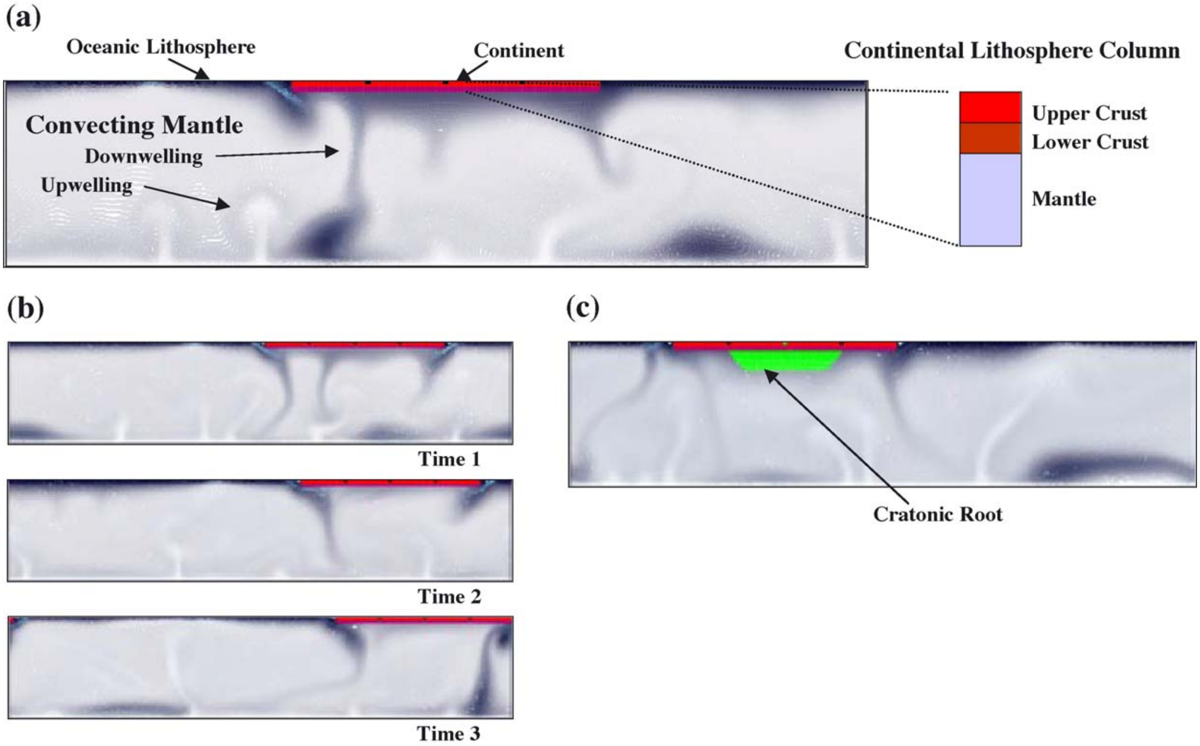
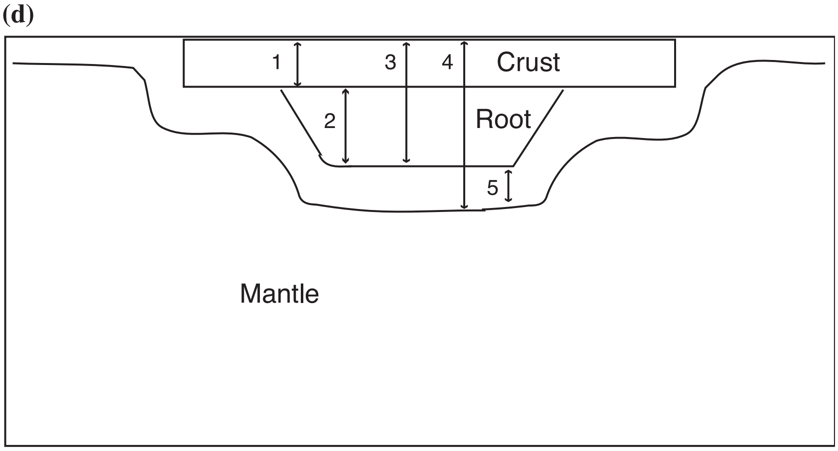


Fig. 1. Numerical simulation setup. (a) A chemically distinct, stable continent with two layers is emplaced in a convecting mantle. Dark gray regions represent cold downwellings and light gray areas are warm upwellings. Bright white features indicate areas of high localized stress and are akin to model faults. The model continent is allowed to drift freely within the simulations (b). Continental crust is 40 km thick. Convection is limited to the upper mantle (660 km). A cratonic root is excluded initially, but is included in later simulations (c). (d) Cartoon illustrating different definitions of lithospheric thicknesses used in paper.



1 - Crustal Thickness (fixed at 40 km; two layer crust used)

2 - Cratonic Root Thickness - varied from 50 to 150 km; angle of side walls fixed

3 - Chemical Lithosphere Thickness - defined by thickness of crust and root combined

4 - Thermal Lithosphere Thickness - defined by depth at which temperature reaches 1% of the average internal temperature within the mantle

5 - Mantle Sublayer Thickness - thermal boundary layer

Fig. 1 (*continued*).

All parameters within the numerical simulations are non-dimensionalized with respect to the assigned Rayleigh number. To compare against observed continental lithosphere thermal structure in stable regions, we scaled the system using reference values (see Table 1). The scaled dimensional results produce surface heat flow values consistent with present Earth conditions for stable continental lithosphere, 24–65 mW/m^2 [7]. It is important to note that although the absolute magnitude of simulation results depends on our reference values, which have uncertainty associated with them, changing these reference values does not change the parameter trends determined from the simulations.

Table 1
Table showing values used to redimensionalize model parameters

Layer	ρ (kg m^{-3})	d (km)	H$_c$ (mW m^{-3})
Upper crust	2700	20	0.007–3.5
Lower crust	2700	20	0.007–3.5
Cratonic root	3200	40–200	0.0007, 0.007
Mantle	3300	660	0.007

The thermal conductivity for all layers is 2 Wm^{-1}°C^{-1}.

Plate tectonic-like behavior is incorporated via a viscoplastic rheology similar to that used by [21], but with an added component of strain dependent weakening along the plastic deformation branch [22]. The viscoplastic formulation maintains a temperature-dependent viscosity when stresses remain below a specified yield stress. However, when this yield stress is exceeded, then deformation is described by a plastic deformation branch based on a continuum representation of Byerlee's law [23,21]. The temperature-dependent viscosity is defined as

$$\eta(T) = A\exp(-\theta T) \tag{3}$$

$$\theta = Q\Delta T/T_i^2 \tag{4}$$

where T is the temperature, A is a prefactor, Q is an activation energy, ΔT is the temperature drop across the system and T_{i} is the temperature of the hot interior of the convecting system. For stresses above the yield stress, the flow law switches to a plastic branch. The nonlinear, effective viscosity along the plastic deformation branch is given by

$$\eta_{\mathrm{yield}}(D) = \frac{\tau_{\mathrm{yield}}}{D} \tag{5}$$

where τ_{yield} is the yield stress determined from Byerlee's frictional law [23] and D is the second invariant of the strain rate tensor. A more detailed description of this rheology can be found in [21]. In our simulations, this rheology leads to a mode of mantle convection that allows for temperature-dependent viscosity and the creation and recycling of oceanic lithosphere. Continents were defined as rigid blocks that drift freely while resisting deformation and subduction (Fig. 1b). In the Lagrangian Integration Point FEM, the entire domain is filled with tracers, which carry material property information during fluid deformation. Model continents are represented by blocks of tracers. These tracers have different material properties to the background (mantle) fluid: in this case density, viscosity, and concentration of radioactive heat producing elements. The material properties at each individual tracer particle contribute directly to the stiffness matrix of the element in which it happens to lie at a given time as described in [24]. The deformation, heat transfer and movements of the continents are, therefore, solved as an integral part of the solution on the entire domain. All simulations were allowed to run for multiple mantle overturns in order to achieve a statistical steady state.

Temperature versus depth profiles are sampled throughout the simulations at the center of the model continents. These geotherms represent the local thermal conditions at specific times during the simulation and may record transient features such as secondary downwellings or upwellings. Therefore, a temporally averaged geotherm was also calculated to describe the mean thermal structure of the continent. Mean mantle and surface heat flows were then calculated from the gradient of the average geotherm at the base and surface of the crust, respectively. Geotherm envelopes illustrate the maximum thermal variations for a complete simulation and are used to calculate the associated variations in heat flow values, temperatures, and thermal thicknesses (Fig. 2). The depth at which the temperature reaches within 1% of the mantle's average internal temperature is chosen as the thermal lithosphere thickness. Chemical lithosphere thickness is prescribed within the simulations by fixing the crustal thickness or the crustal and chemically distinct mantle root thickness. The difference between the thermal and chemical lithosphere thickness defines the thickness of the thermal mantle sublayer that forms at the base of the chemical lithosphere (Fig. 1d).

3. Simulations with variable crustal heat production

For the first set of simulations, we isolated the effects of variable crustal heat production on the thermal structure of stable continental lithosphere. The total heat concentration of the upper or lower crustal layer was varied from the reference mantle value to an extreme value 500 times that value, while the other crustal layer is held at a constant value of 50 times the reference mantle value (see Table 1 for scaled values). Again, the typical range of crustal heat production is 57 to 371 times a reference mantle heat production of 0.007 $\mu\mathrm{W/m^3}$ [14–16], but we chose to extend that range to account for extreme end-member cases. A chemically distinct cratonic root was not included in this set of simulations.

Fig. 3a shows the surface and mantle heat flow variations at the center of the continental lithosphere for varying crustal heat production values. As expected, surface heat flow variations are highly dependent on crustal heat production values. However, the mantle heat flow into the base of the crust remains relatively constant when enriching either the upper or lower crust. Within the typical range of crustal heat production, mantle heat flow variations are limited to 10–15 $\mathrm{mW/m^2}$. As these simulations model only the upper and lower crustal layers, relatively low and constant mantle flow values can be achieved without the presence of an insulating cratonic root.

Heat source distribution influences the local thermal structure of continents (Fig. 3a–c). Differing heat

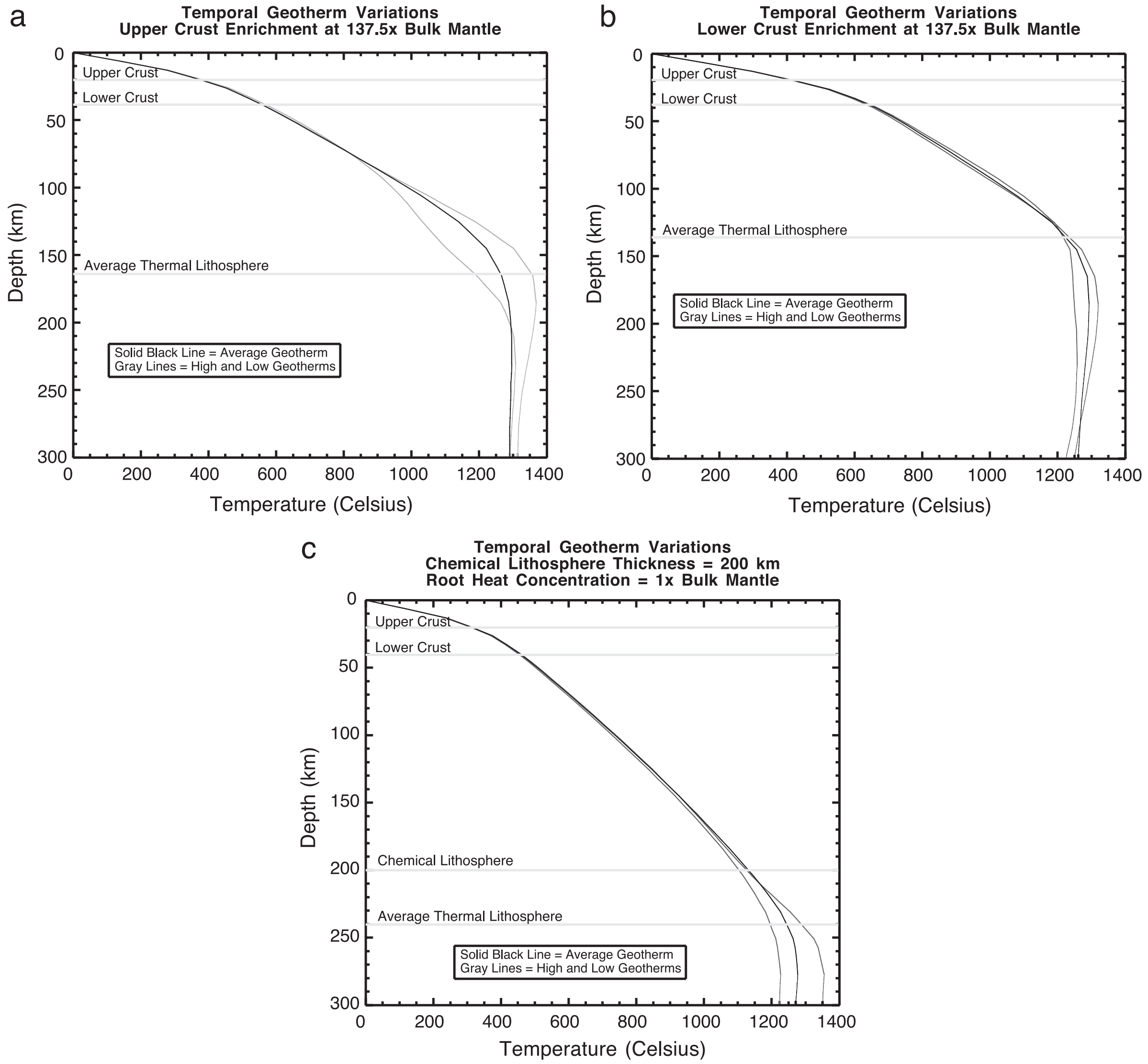


Fig. 2. Geotherm envelopes for (a) a simulation with an enriched upper crust (137.5 times the mantle's heat production), (b) a simulation with an enriched lower crust (137.5 times the mantle's heat production), and (c) a simulation with thick cratonic root (chemical lithosphere thickness 200 km). The geotherm envelopes show the temporal variations (light gray curves) about the mean geotherm (solid black curve) throughout the course of the simulation. The depth at which the temperature reached 1% of the average internal mantle temperature defines the thermal lithosphere thickness.

production distributions can yield similar surface heat flow values, yet varying thermal conditions within the deeper lithosphere. For example, consider the simulations that produce surface heat flow values of 70 mW/m^2 (Fig. 3a). Changing the distribution and total amount of heat production can produce equivalent surface heat flow values, yet the corresponding change in temperatures at the base of the crust is 280 °C and the change in thickness of thermal lithosphere is 40 km. As is evident in Fig. 3b, increasing lower crust heat concentration produces higher temperatures at the base of the crust (and thus lower viscosities) than increasing upper crust heat concentration. This suggests that concentrating heat production in the

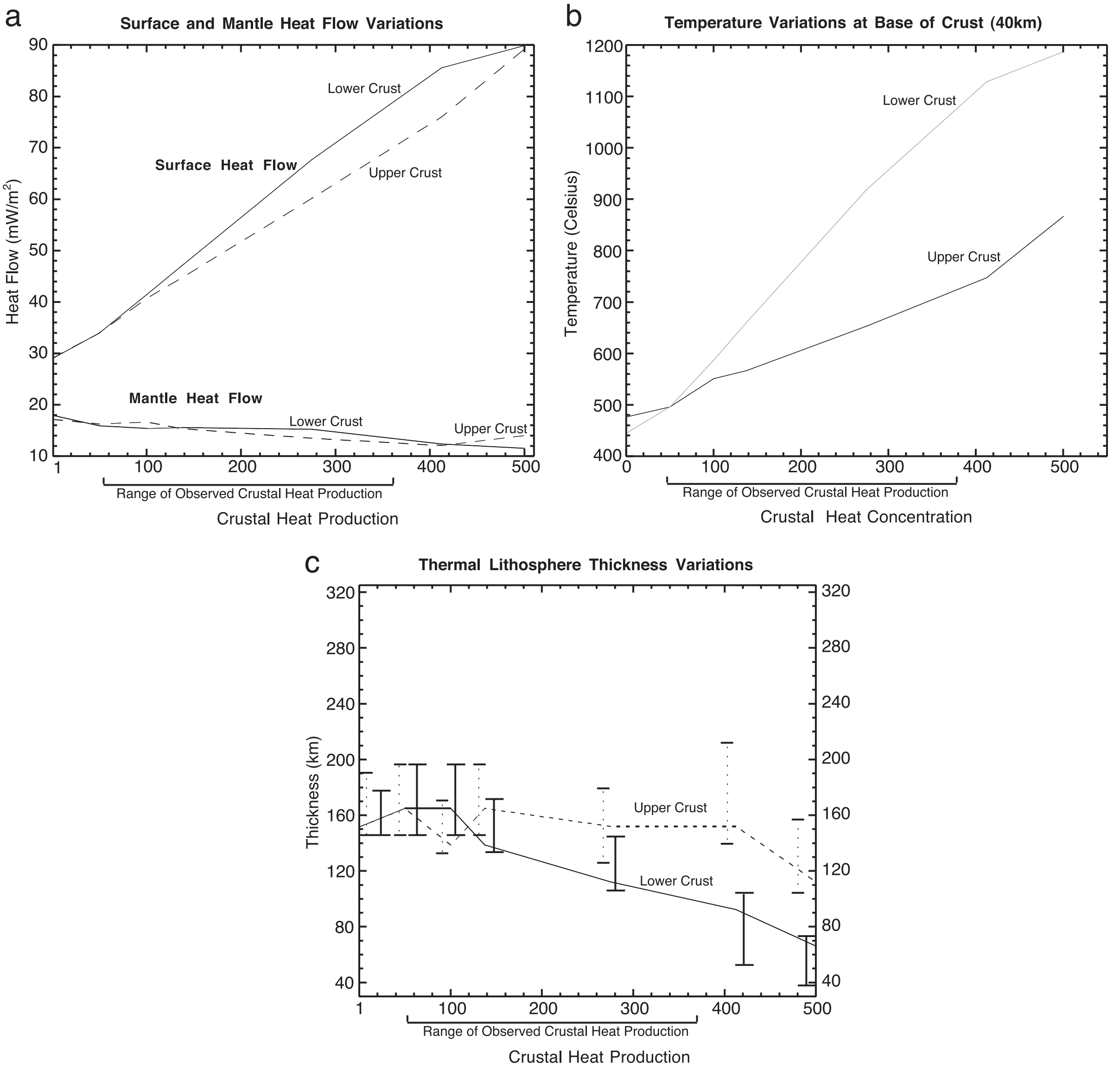


Fig. 3. (a) Surface and mantle heat flow variations with variable heat production for both an enriched upper crust (dashed line) and an enriched lower crust (solid line). Heat production in the enriched layer is varied from 1 to 500 times the mantle value, while the other layer's heat production is kept constant at 50 times the bulk mantle value. (b) Temperature variations at the base of the crust (40 km) with crustal heat concentration for both an enriched upper crust (solid black line) and an enriched lower crust (light gray line). (c) Thermal lithosphere thickness versus crustal heat concentration for both an enriched upper crust (dashed line) and an enriched lower crust (solid line). Brackets show the temporal (and spatial, since the continent drifts freely) variations of thermal lithosphere thickness for the duration of a simulation.

upper crust can potentially increase lithospheric viscous strength as this configuration results in higher viscosities at the base of the crust.

Fig. 3c shows thermal lithosphere thickness variations with increasing heat concentration for both distribution scenarios. The thermal lithosphere thickness remains relatively constant for increasing upper crust heat concentrations, while decreasing for increased lower crust heat concentration. Within the range of typical crustal heat production values, the observed range of thermal lithosphere thicknesses is 100–160 km (Fig. 3c). Also shown in Fig. 3c are the temporal variations in thermal lithosphere thickness during each simulation. Since the continent is free to drift during the simulation, temporal and spatial variations in the thermal structure can be tracked as the continent moves over small-scale secondary convective feature within the mantle. The variance bars in Fig. 3c show that the variations in thermal lithosphere thickness due to secondary convection can be up to ± 20 km for either an enriched upper or lower crust.

4. Simulations with variable chemically defined root thickness

For the second suite of simulations, we explored the effects of variable chemical root thickness on the thermal structure of stable continental lithosphere. Model reference values were used for upper crust and lower crust heat production (137.5 × and 50 × , respectively) to isolate the effects of the variable cratonic root thickness. Again, simulations were allowed to run to a statistical steady state. The entire continental chemical lithosphere, including the cratonic root, remained undeformed to represent a stable craton. Chemical lithosphere (crust + cratonic root) thickness was varied from 40 to 200 km. The geometric configuration used to represent the root is illustrated in Fig. 1c. The lateral extent of the root is greatest at the base of the crust and half the lateral extent of the continental crust. Lateral extent is then decreased with depth maintaining a constant angle along the sides of the root. Root material was depleted in heat producing elements for one scenario (0.1 × reference mantle heat production) and set to the same concentration as the mantle for a second modeling scenario.

Fig. 4a shows the variations in surface and mantle heat flow due to increased chemical lithosphere thickness. The surface heat flow values are sampled on the center on the continent directly over the area of greatest root thickness. Increased root thickness accounts for surface heat flow variations of 5 mW/m^2. The temperatures seen at the base of the crust (40 km) decrease by less than 100 °C over the range of root thicknesses (Fig. 4b). This decrease in temperature results in a slight increase in viscosity at the base of the crust. Thermal lithosphere thickness increases with the chemically defined lithosphere thickness; however, the ratio of thermal to chemical lithospheric thickness decreases with root thickness (Fig. 4c, d). The variance bars in Fig. 4c illustrate the range of thermal lithospheric thickness sampled throughout the course of the simulation (showing both temporal and spatial variations, as the continent is free to drift). The range of thermal lithosphere thicknesses variations can be up to ± 35 km throughout the simulation.

5. Discussion

5.1. Influence of variations in crustal heat production on thermal regime

Thermal modeling of continental lithosphere using one-dimensional heat conduction approach treats mantle heat flux as a free parameter. The full convection simulations of this paper can provide an added constraint as they directly solve for mantle heat flux as a function of crustal heat concentration and the degree of convective vigor within the mantle. The simulations suggest that in stable continental regions mantle heat flux does not vary greatly with values typically between 10 and 20 mW/m^2. This limit is consistent with values obtained based on direct heat flow and heat production measurements [5,6,14,25] and suggests that mantle heat flux remains relatively low in stable, continental regions.

Furthermore, the small variations in the mantle heat input (10–20 mW/m^2) to the crust observed within the simulations imply a near constant flux boundary condition at the base of the crust. Maintaining a constant mantle heat flux at the base of the crust does not mean that temperature is also held constant. Therefore, while mantle heat flux may be limited to values < 20 mW/m^2, significant temperature variations at the base of the crust may be present, in addition to the corresponding variations in the thickness of the thermal lithosphere. With the constant heat flux boundary condition, larger basal temperature variations would produce larger variations in thermal lithosphere thickness (Fig. 3b, c).

The simulations also show that the distribution of heat producing elements within the continental crust

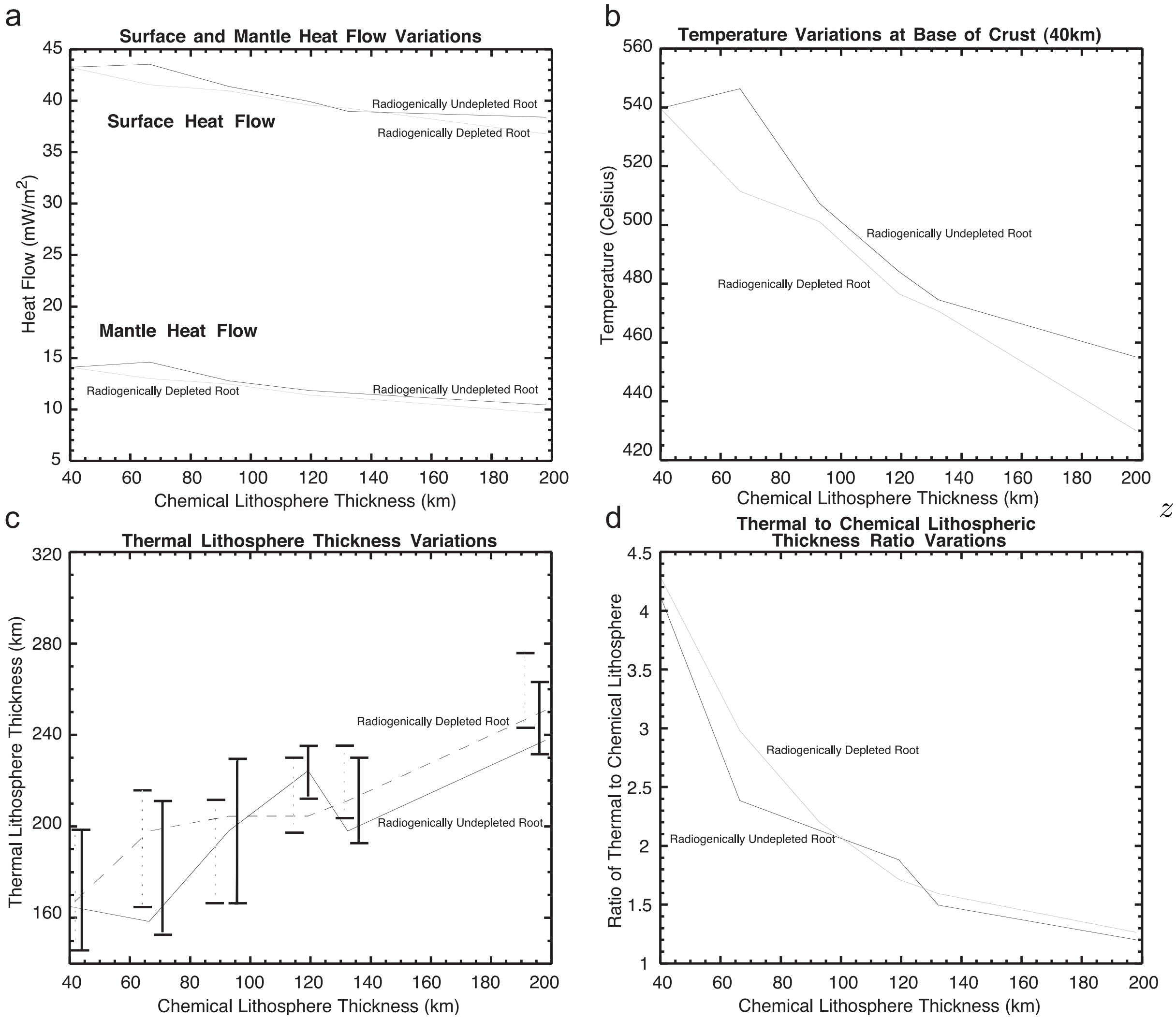


Fig. 4. (a) Surface and mantle heat flow variations with variable chemical lithosphere thickness for both a radiogenically undepleted (solid black line) and depleted (light gray line) cratonic root. (b) Temperature variations at the base of the crust with variable chemical lithosphere thickness for both a radiogenically undepleted (solid black line) and depleted (light gray line) cratonic root. (c) Thermal lithosphere thickness versus chemical lithosphere thickness for both radiogenically undepleted (solid black line) and depleted (dashed line) cratonic root. Brackets show the temporal (and spatial, since the continent drifts freely) variations of thermal lithosphere thickness for the duration of a simulation. (d) The ratio of thermal to chemical lithosphere thickness versus chemical lithosphere thickness for both a radiogenically undepleted (solid black line) and depleted (light gray line) cratonic root.

can play a key role in determining the local thermal structure of the continental lithosphere. Placing additional heat producing elements into the lower, as opposed to the upper, crust causes the thermal lithosphere to thin more dramatically, basal temperatures to increase more dramatically, and viscosity to decrease more dramatically.

5.2. Influence of variations in chemically defined root thickness on thermal regime

There has been a long-standing debate as to whether continental surface heat flow variations are primarily caused by heat production variations in the crust or by insulating effects of a cratonic root

[6,7,22,26,27]. Our simulations showed a strong dependence between surface heat flux and crustal heat production. A much weaker relationship was found between surface heat flux and chemical lithosphere thickness. A thick chemical lithosphere lowers the surface heat flow by 4 mW/m^2, a value that falls within the uncertainty in surface heat flow measurements [5]. Compared against the 60 mW/m^2 variation due to the increased crustal heat production in our first set of simulations (Fig. 3a), the insulating effect of a cratonic root seems to be less important in determining the observed surface heat flow variations in stable continental regions. The cratonic root may be more influential in determining deeper thermal structure. The presence of a chemically distinct cratonic root might be required to produce a thick thermal lithosphere. The simulations with variable crustal heat production and no cratonic root did not produce as thick of a thermal lithosphere as observed in some areas [18–20].

An increased chemical lithosphere also causes a reduction in the thermal sublayer thickness (Fig. 4d). The size and strength of any dynamic mantle downwellings below a craton will depend directly on this sublayer thickness. Thus, a thick cratonic root is not predicted to have an associated large, cool mantle downwelling at its base, contrary to a common assumption [28]. This is consistent with the lack of topography in the 410-km discontinuity beneath the North American craton [29]. The 410-km would be elevated in response to cold material traveling through the boundary and the fact that it is not elevated suggests that either such a downflow does not exist or that it is very weak.

The variable ratio of thermal to chemical lithosphere thicknesses observed in our simulations (Fig. 4d) may also explain discrepancies between lithospheric thicknesses determined from seismic and geochemical data [6,20,30]. Seismic data images the depth of the thermal lithosphere, whereas geochemical data determines a chemical lithosphere thickness. As the ratio does not remain constant for increasing root thickness, a seismically derived thermal lithospheric thickness cannot be used to extrapolate a chemical lithospheric thickness and vice versa. Our simulations predict that seismic and geochemically determined lithospheric thicknesses should only become comparable in regions having thick chemical roots.

6. Conclusions

Numerical simulations of coupled continental heat transfer and mantle convection indicate that subcontinental mantle heat flux remains relatively low (<20 mW/m^2) and constant within stable continental regions regardless of variable crustal heat production or variable cratonic root thickness. The distribution of heat producing elements within the crust plays a key role in determining local thermal structure as differing distributions can result in similar surface heat flow expressions and varying thermal thicknesses. Cratonic roots play a minor role in determining surface heat flow variations, but may be required to produce a thick thermal lithosphere. A thick cratonic root reduces the strength of small-scale mantle convection beneath cratons, limiting the size and negative thermal buoyancy of local downwellings. Thermal lithospheric thickness cannot be used to extrapolate a chemical lithospheric thickness (and vice versa, a geochemically derived chemical lithospheric thickness cannot be used to determine a thermal lithosphere thickness) as the ratio of thermal to chemical lithospheric thicknesses does not remain constant for increased cratonic root thickness.

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