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A comparative study of parameterized and full thermal-convection models in the interpretation of heat flow from cratons and mobile belts

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SUMMARY

Heat flow from Archean cratons worldwide is typically lower than from younger mobile belts surrounding them. The contrast in heat flow between cratons and mobile belts has been attributed in previous studies to the greater thermal resistance of thicker lithosphere beneath the cratons which impedes the flow of mantle heat through the cratons and forces more mantle heat to escape through thinner mobile belt lithosphere. This interpretation is based on thermal models which employ a parameterized convection algorithm to calculate heat transfer in the sublithospheric mantle. We test this interpretation by comparing thermal models constructed using the parameterized convection scheme with models developed using an algorithm for full thermal convection. We show that thermal models constructed using the two different convection algorithms yield similar surface heat flow and thermal structure to moderate depths within the lithosphere. Therefore, we conclude that the interpretation of the heat-flow observations in terms of thicker lithosphere under Archean cratons than under mobile belts is robust in the sense that surface heat flow is not sensitive to the details of heat transfer within the convecting mantle and how deep mantle heat is delivered to the base of the lithosphere.

Key words: convection, cratons, heat flow, mobile belts.

INTRODUCTION

A marked contrast in heat flow between Archean cratons and younger pre-Cambrian and Phanerozoic mobile belts is observed in many shield areas around the world (e.g. Morgan 1985; Chapman & Furlong 1977). For example, in southern Africa heat flow in the Kalahari Craton is 40–50 $\mathrm{mW\,m^{-2}}$ and increases to 60–70 $\mathrm{mW\,m^{-2}}$ in the mobile belts surrounding the craton (Nyblade *et al.* 1990; Ballard, Pollack & Skinner 1987).

Over the past two decades there has been a growing number of geophysical and petrological observations which support the hypothesis that the lithosphere extends to depths of several hundred kilometers beneath Archean cratons (see Jordan 1988, for a review). Ballard & Pollack (1987) interpreted the contrast in heat flow between the Kalahari Craton and its surrounding mobile belts within the context of this hypothesis, and by analogy, their interpretation can be applied to other pre-Cambrian shield areas. Through numerical models, they showed that the lower heat flow in the craton could result entirely from the diversion of deep mantle heat from beneath 400 km thick cratonic lithosphere laterally to thinner mobile belt lithosphere, or alternatively that if some of the difference in heat flow between the craton and mobile belt arises from differences in crustal heat production between the craton and mobile belt, then less heat need be diverted by the cratonic root. In the latter case the cratonic lithosphere then need extend only to some 200 km depth. In constructing their thermal models, Ballard & Pollack used a parameterized convection algorithm to calculate heat transfer in the sublithospheric mantle. They assumed that this approach yields, in a time-averaged sense, a reasonably good representation of the thermal conditions in the convecting mantle and of the delivery of heat to the overlying lithosphere; however, the parameterized convection algorithm does not embody a full description of mantle convection, and a more complete representation can be obtained from full thermal convection models. In this paper we test the Ballard & Pollack interpretation by comparing thermal models using the parameterized convection

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algorithm with models using a full thermal convection algorithm to determine if surface heat flow is sensitive to the details of how mantle heat is delivered to the base of the lithosphere. Our comparative study has three parts. We first describe the models, then compare them, and finally discuss implications of the comparison for the Ballard & Pollack interpretation of heat flow from Archean cratons and mobile belts.

MODELS

Finite element analysis is used to solve the governing equations in both modelling approaches on a 64×50 element mesh. The models are heated internally, and heat transfer in the lithosphere is by conduction only. The two approaches differ in how heat transfer is calculated in the sublithospheric mantle. In the parameterized convection models, the steady-state heat conduction equation is solved with an enhanced thermal conductivity, adjusted to yield an adiabatic temperature gradient beneath the lithosphere (Sharpe & Peltier 1979). For the full convection models, the coupled thermo-mechanical equations which govern thermal convection in an incompressible fluid with an infinite Prandtl number are solved. These equations and their numerical solutions are described by King, Raefsky & Hager (1990).

In the full convection models, the lithosphere is rigid, the mantle viscosity is constant, free-slip boundary conditions exist on the sides and base of the model, and there is no heat or mass transfer across the sides or base of the model (i.e. reflecting boundary conditions). Because of computational limitations we are restricted to models with Rayleigh numbers no higher than about 10^7, somewhat lower than appropriate for the whole mantle. To accommodate this constraint, one or more of the parameters that comprise the Rayleigh number can be adjusted, and for this study we have elected to limit the depth extent of our models to 1000 km (lithosphere plus convecting mantle). The thermal and rheological parameters used in the models are given in Table 1.

In both the parameterized and full convection models the craton is located in the centre of the model to insure that edge effects do not perturb the thermal regime within it.

Table 1. Thermal and rheological properties

Property	Value
coefficient of thermal expansion	3.0×10^{-5} K^{-1}
gravitational acceleration	9.8 m s^{-2}
sub-lithospheric mantle heat production	3.5×10^{-8} W m^{-3}
lithospheric mantle heat production	1.0×10^{-8} W m^{-3}
crustal heat production	8.0×10^{-7} W m^{-3}
thermal conductivity	3.5 W m^{-1} K^{-1}
thermal diffusivity	1.0×10^{-6} m^2 s^{-1}
kinematic viscosity	3.0×10^{17} m^2 s^{-1}

However, because the models are symmetric about their mid-points, we display only the left half of each model [Figs 1(a) and (d)]. The models also include a uniform 40 km thick crust. In the comparisons to follow, we use a simplified version of the models constructed by Ballard & Pollack. In the first comparison, the craton is 1000 km wide, the cratonic lithosphere is 400 km thick, and the mobile belt lithosphere is 100 km thick. In the second comparison the cratonic lithosphere extends only to 200 km, letting us examine how variations in the thickness of cratonic lithosphere affect results.

COMPARISON OF RESULTS

Isotherms from the parameterized and full thermal convection models are shown in Figs 1(a) and (d). Shallow lithospheric isotherms in the models are generally similar, but at greater depths they become noticeably different. This is evident from the more closely spaced isotherms in the lower half of the cratonic lithosphere in the full convection model (Fig. 1d) as compared to the parameterized convection model (Fig. 1a). In the sublithospheric mantle, the two models show greater differences. Isotherms in the full convection model show an area of cold downwelling, and near the base of the mobile belt lithosphere the convecting mantle has super-adiabatic temperature gradients. 'Steady-state' mantle isotherms in the parameterized convection model are characterized by a bowing-up under the craton and approximately adiabatic temperature gradients beneath the base of the mobile belt lithosphere.

Surface heat flow for each model is given in Figs 1(b) and (e). The full convection model is time-dependent, and thus a sampling of heat flow at different times is shown in Fig. 1(e). We averaged the curves in Fig. 1(e) to produce a single time-averaged heat-flow curve for this model which, together with heat flow for the parameterized convection model, is shown in Fig. 2(a). The results are in good agreement; both show a pronounced difference in heat flow between the craton and mobile belts. Heat flow is about 46–47 mW m^{-2} over the craton and increases to about 66–67 mW m^{-2} over the mobile belts. Minor differences include (1) a slightly steeper gradient in heat flow over the craton-mobile belt contact in the parameterized convection model, and (2) a slightly larger contrast in heat flow between the craton and mobile belt in the parameterized convection model.

Figs 1(c) and (f) show temperatures at the base of the lithosphere. There is good agreement between temperatures at the base of the mobile belt lithosphere in the two models, but not at the base of the cratonic lithosphere. Temperatures at the base of the mobile belt lithosphere in both models are about 1150 °C, and for the cratonic lithosphere, about 1400 °C on average in the parameterized convection model and about 1600 °C in the full convection model. Additionally, in the full convection model temperatures vary both temporally and spatially by 100–200 K at the base of the mobile belt lithosphere, in contrast to the base of the cratonic lithosphere where temperature variations are very small.

The models in Fig. 1 have a lithospheric root extending to a depth of 400 km beneath the craton. But, Ballard & Pollack suggested that if some of the difference in heat flow

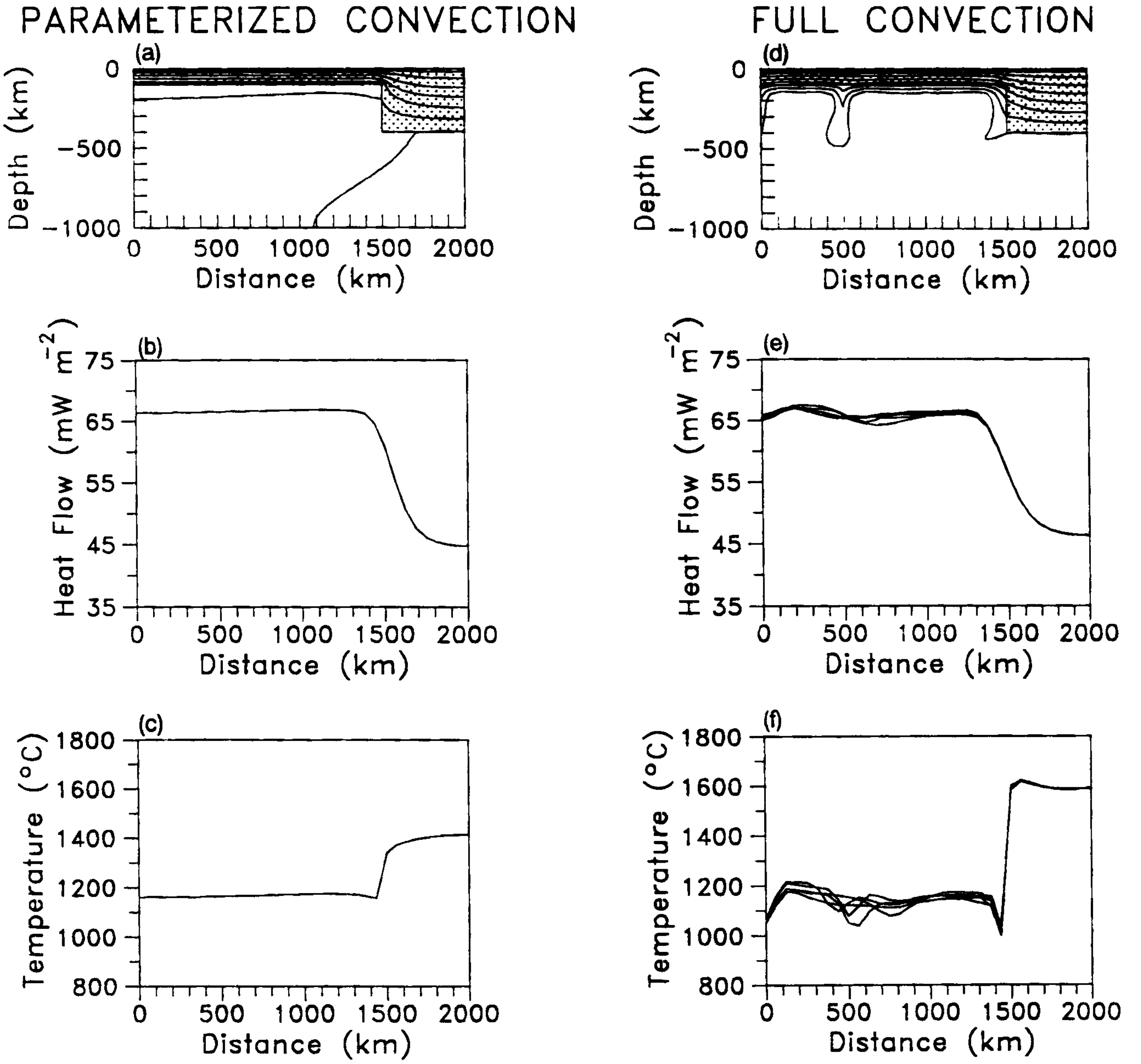

Figure 1. Thermal models. (a–c) and (d–f) show isotherms in a vertical section, surface heat flow, and temperatures at the base of the lithosphere for the parameterized convection model and the full thermal convection model, respectively. In (a) and (d), the surface of the models are at 0 °C, the contour interval is 200°, and the shaded region is the lithosphere. Heat flow and temperatures in (e) and (f) are displayed at 100 Myr intervals.

between the craton and mobile belt arises from a difference in crustal heat production between the craton and mobile belt, then less heat need be diverted by the cratonic root, and the cratonic lithosphere need not extend as deep as 400 km. We have therefore compared parameterized and full convection models that have a 200 km thick cratonic root as well. As with the models with 400 km thick cratonic lithosphere, there is good agreement between surface heat flow in the parameterized and full convection models with 200 km thick cratonic lithosphere (Fig. 2b). However, the contrast in heat flow between the craton and mobile belts is only about 15 mW m^{-2}, illustrating the reduced thermal resistance of the less pronounced cratonic root. For the model with 200 km thick cratonic lithosphere to be fully consistent with the heat flow observations from southern Africa, at least an additional 5 mW m^{-2} contrast would have to come from differences in crustal heat production between the craton and mobile belts, as Ballard & Pollack suggested previously.

DISCUSSION

The principal observation from the comparison of parameterized and full thermal convection models is that surface heat flow in both models is very similar. The difference in heat flow between the two models is less than 1 mW m^{-2} on average over the mobile belt and only 1–2 mW m^{-2} over the craton. This result clearly indicates

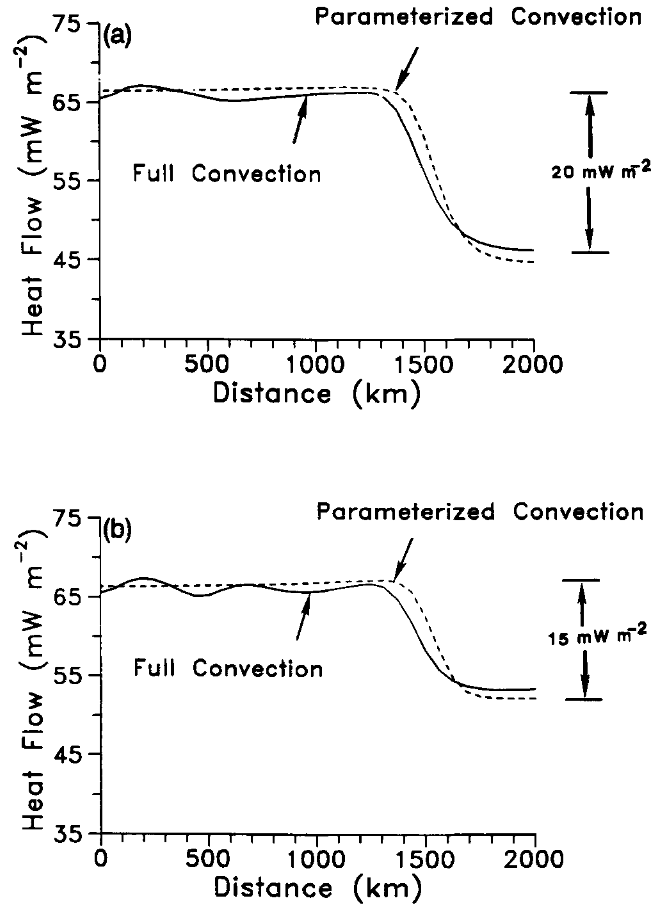

Figure 2. (a) Surface heat flow for the models in Figs 1(a) (dashed curve) and (d) (solid curve). (b) Surface heat flow for models with 200 km thick cratonic lithosphere.

that surface heat flow is not sensitive to the details of how heat is delivered to the base of the lithosphere. The similar contrast in heat flow between the craton and mobile belts in both models demonstrates the effect of the increased thermal resistance of thick lithosphere beneath the craton postulated by Ballard & Pollack: flow of heat from the mantle through the thicker cratonic lithosphere is impeded and therefore more mantle heat must escape through the thinner lithosphere of the mobile belts.

It is instructive to calculate how much mantle heat is diverted in the models from beneath the cratonic lithosphere to the mobile belt lithosphere. Heat flow from the craton and mobile belt in the absence of any heat diversion can be determined by summing the heat produced within rock columns under the craton and mobile belts. This calculation yields a heat flow of 64 mW m^{-2} from the mobile belts and 57 mW m^{-2} from the craton (see Table 1 for heat production values). The models in Fig. 1 show heat flow from the craton (about 47 mW m^{-2}) and mobile belts (about 67 mW m^{-2}) when mantle heat is diverted from beneath the cratonic lithosphere to the mobile belt lithosphere. Thus, heat flow in the craton is lowered by about 10 mW m^{-2} by heat diversion, and heat flow from the mobile belts is increased by about 3 mW m^{-2}. Conservation of energy is maintained because of the greater area of the mobile belts.

There are other observations that also warrant discussion. Although we attribute the contrast in heat flow between the craton and mobile belts to thicker lithosphere beneath the craton, our results (and those of Ballard & Pollack) also show that surface heat flow is not a sensitive indicator of absolute lithospheric thickness. This is evident in Fig. 2, by comparing heat flow for models with 200 km and 400 km thick Archean lithosphere; the thickness in Archean lithosphere varies by 200 km between the models, while the difference in heat flow between the mobile belts and the craton changes by only about 5–6 mW m^{-2}.

As discussed above, temperatures within and at the base of the mobile belt lithosphere are similar in both models, but noticeable temperature differences exist between the lower parts of the cratonic lithosphere and at its base. This is consistent with the small difference in cratonic heat flow between the two models of about 2 mW m^{-2} (Fig. 2a). Given a thermal conductivity of 3.5 W m^{-1} K^{-1} for the lithosphere, an increase in basal (and surface) heat flow of 2 mW m^{-2} will create a 230 K difference in temperature at the base of the 400 km thick lithosphere, and will lead to noticeable variations in isotherms near the base of the lithosphere. For the mobile belts, the smaller differences in surface heat flow (<1 mW m^{-2}) and the lesser thickness of the lithosphere give rise to much smaller temperature variations within the lithosphere and at its base.

Finally, there are two results from the full convection model that may be attributed, at least in part, to the nature of the boundary conditions imposed on the calculations. The first result is that temporal and spatial variations in temperatures at the base of the cratonic lithosphere are negligible and are only between 100–200 K at the base of the mobile belt lithosphere (Fig. 1f). Because of the reflecting boundary conditions used in the model which preclude horizontal mobility of the lithosphere, temperatures at any point along the base of the lithosphere may not vary as much as they would in a convecting system with dynamic feedback between moving plates and convecting mantle (Gurnis 1988). If there are temperature variations at the base of either the mobile belt or cratonic lithosphere which have larger amplitudes or persist for longer periods of time than do the temperature variations in our model, then surface heat flow could be affected to a somewhat greater extent. However, thick lithosphere is a strong low-pass filter, and it is likely that many temperature fluctuations would be damped out within the lithosphere before reaching the surface. Even in a convecting system with larger spatial and temporal temperature variations at the base of the lithosphere, it seems unlikely that the general pattern of surface heat flow would be significantly different from the pattern obtained in this study from the full convection model.

The second result from the full convection model that may be attributed to the boundary conditions is the persistently large difference between temperatures at the base of the mobile belt and cratonic lithosphere (about 450 K). Models with dynamically interacting plates and convection show that plates translate laterally as heat builds up beneath them, and this lateral plate motion could diminish the time-averaged mantle temperature at the base of thick cratonic lithosphere by moving the plate from warmer to colder regions (Gurnis 1988; Gurnis & Zhong 1991). Our model with stationary lithosphere may therefore represent an end-member model which provides an estimate of the maximum likely difference between temperatures at the base of the cratonic and mobile belt lithosphere. However, decreasing the difference in temperature between the base of the mobile belt and cratonic lithosphere somewhat is also unlikely to significantly alter the surface heat-flow pattern; as we showed above, modifying temperatures at the base of thick cratonic lithosphere by a few hundred degrees alters surface heat flow by only a few milliwatts per square metre.

CONCLUSION

Surface heat flow from thermal models employing either parameterized or full thermal convection algorithms is very similar. The contrast in heat flow between the craton and mobile belts in both models is also similar, and demonstrates the effect of the increased thermal resistance of thick lithosphere beneath the craton postulated earlier by Ballard & Pollack (1987). We conclude that the Ballard & Pollack interpretation of heat flow from cratons and mobile belts is robust in the sense that surface heat flow is not sensitive to the details of heat transfer within the convecting mantle and how mantle heat is delivered to the base of the lithosphere.

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