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Diversion of heat by Archean cratons: a model for southern Africa

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The surface heat flow in the interior of Archean cratons is typically about 40 mW m^{-2} while that in Proterozoic and younger terrains surrounding them is generally considerably higher. The eighty-four heat flow observations from southern Africa provide an excellent example of this contrast in surface heat flow, showing a difference of some 25 mW m^{-2} between the Archean craton and younger peripheral units. We investigate two possible contributions to this contrast: (1) a shallow mechanism, essentially geochemical, comprising a difference in crustal heat production between the two terrains, and (2) a deeper mechanism, essentially geodynamical, arising from the existence of a lithospheric root beneath the Archean craton which diverts heat away from the craton into the thinner surrounding lithosphere. A finite element numerical model which explores the interplay between these two mechanisms suggests that a range of combinations of differences in crustal heat production and lithospheric thickness can lead to the contrast in surface heat flow observed in southern Africa. Additional constraints derived from seismological observations of cratonic roots, the correlation of surface heat flow and surface heat production, petrological estimates of the mean heat production in continental crust and constraints on upper mantle temperatures help narrow the range of acceptable models. Successful models suggest that a cratonic root beneath southern Africa extends to depths of 200–400 km. A root in this thickness range can divert enough heat to account for 50–100% of the observed contrast in surface heat flow, the remainder being due to a difference in crustal heat production between the craton and the surrounding mobile belts in the range of zero to 0.35 μW m^{-3}.

1. Introduction

One of the most consistent characterizations to emerge from the many measurements of the terrestrial heat flux is that the heat flow from Archean cratons is generally lower than that from younger Precambrian and Phanerozoic terrains. This characterization holds true individually for the Archean terrains of North America, western Australia, India and southern Africa, and collectively when viewed as a global ensemble [1,2].

Recent heat flow measurement programs in southern Africa [3,4] have greatly expanded the data set in that region, in both Archean and younger terrains. In this paper we briefly describe the contrast in heat flow between Archean and other terrains in southern Africa, and present results from numerical models that attempt to assess the relative contributions of crustal geochemical differences and deeper geodynamical causes to the observed heat flow contrast.

2. Heat flow data

Terrestrial heat flow measurements have been made at 84 sites in southern Africa (Fig. 1) [3,4,7–12]. Of these measurements, 39 are located on the Archean Kaapvaal-Limpopo-Zimbabwe Craton and 45 are located in the Proterozoic and Pan-African mobile belts which surround the craton. While these mobile belts have experienced tectonothermal events of different character at widely different post-Archean times, they exhibit similar heat flow in the context of their proximity to the Archean craton. Fig. 2 shows the heat flow at individual sites as a function of distance from the cratonic margin. The heat flow in the interior of the Kaapvaal-Limpopo-Zimbabwe Craton is typically about 40 mW m^{-2} but increases to about 60 mW m^{-2} at the boundary between the craton and the surrounding Proterozoic and Pan-African mobile belts. Within the mobile belts, the heat flow increases from about 60 mW m^{-2} at the edge

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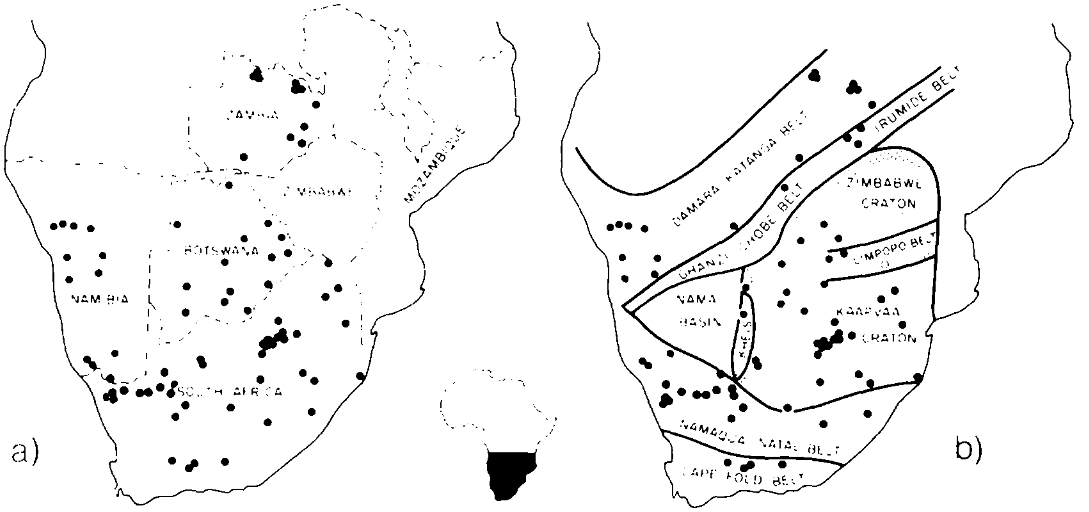

Fig. 1. Maps of southern Africa showing the locations of the currently available terrestrial heat flow sites: (a) shows international boundaries and (b) shows the major tectonic elements [5,6]. The shaded region in (b) is the Archean Kaapvaal-Limpopo-Zimbabwe Craton.

of the craton to about 70 mW m^{-2} several hundred kilometers away. This represents a contrast of about 25 mW m^{-2} between the heat flow at the center of the craton and the characteristic values of the mobile belts.

In 1977, when Chapman and Pollack [11] reported their measurements in Zambia, the data from Botswana and Namibia [3] as well as many data from South Africa [4,12] were not yet available, and the Zambian results were geographically isolated from the data that were available in South Africa at that time. Chapman and Pollack observed a mean heat flow of 66 mW m^{-2} in the Proterozoic mobile belts of Zambia, a value which we now identify as the characteristic heat flow of all the mobile belts of southern Africa. Chapman and Pollack recognized that the heat flow was unusually high for a Precambrian terrain, and they proposed that it was a result of incipient rifting associated with the extension of the East African Rift System into south-central Africa. That hypothesis was supported by diffuse seismicity [13] and recent normal faulting [14] which extends from southern Tanzania, southwest through Zaire and Zambia and into northern Botswana. We now observe that the relatively high heat flow is characteristic not only of Zambia but of all the circum-cratonic mobile belts, most of which do not display neo-tectonic activity. We therefore believe that the elevated heat flow in the mobile belts derives from other mechanisms. An incipient rift may indeed be propagating southwest across the central African plateau, but much of the high heat flow likely preceded the rifting rather than resulting from it.

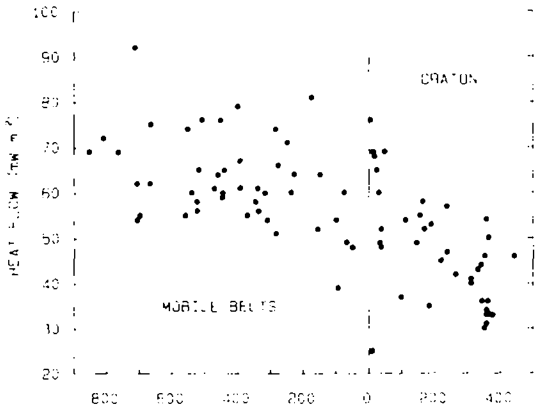

Fig. 2. Heat flow vs. distance from the margin of the Archean Craton.

In the remainder of this paper we examine two mechanisms, one shallow and geochemical, the other deeper and geodynamical, that may contribute to the contrast in surface heat flow between the Archean craton and the younger surrounding mobile belts: (1) differences in crustal heat production between the two terrains, and (2) the existence of a lithospheric root beneath the Archean craton which diverts heat away from the craton into the surrounding mobile belts. Broad regional differences in crustal heat production obviously must be considered as a possible component of the heat flow contrast, just as local variations in heat production have been positively correlated with local heat flow. However, the effect that a cratonic root may have on the diversion of mantle heat is, we believe, less widely recognized. We therefore describe briefly below some aspects of root development that bear on heat transfer characteristics.

3. Conductive roots beneath Archean cratons

Petrological, geothermal and seismological investigations have led several workers to suggest that cratons have lithospheric roots that may extend to depths as great as 400 km [15–21]. Grand and Helmberger [19] recognized a contrast in shear wave velocities between the Canadian Shield and tectonically active western North America that extends to 400 km depth. Grand [20] used seismic tomography to define the three-dimensional shape of the region of relatively fast shear waves and found that it correlates quite well with the shield and stable platform of North America. The general configuration of the high velocity zone is roughly that of a broad inverted cone with its apex extending to 400 km depth beneath the Superior Province of Canada. Jordan [15–17] has argued that buoyant stabilization of the cratons derives from petrological differentiation during partial melting within the upper mantle, early in their history. Pollack [21] has suggested that devolatilization of segments of the Archean upper mantle during partial melting episodes has contributed significantly to the long-term stability of Archean cratons. Volatile depletion elevates the solidus and imparts a higher effective viscosity to the affected region of the upper mantle thereby rendering it more resistant to subsequent melting and isolating it from entrainment in mantle convection. Because the depth range of partial melting and volatile depletion associated with continental crust formation was probably greatest in the Archean, the Archean lithosphere is likely thicker than that of the younger surrounding terrains. The consequence for later thermal structure and evolution is that conduction, the characteristic mode of heat transfer in the lithosphere, will extend to greater depths within the cratonic root than beneath the mobile belts. Since convection is a more efficient mechanism of heat transfer than conduction, and continues to higher levels beneath the mobile belts than beneath the craton, heat rising from deep within the mantle will be diverted laterally away from the thicker Archean lithosphere into the surrounding terrains, thus creating a contrast in surface heat flow between the Archean craton and the peripheral mobile belts. Davies [22] explored some general aspects of this heat transfer system via one-dimensional considerations.

4. Numerical model

To investigate the interplay between differences in crustal heat production and the diversion of heat by a lithospheric root, we have constructed a two-dimensional, axisymmetric, finite element model. The region over which the heat transfer problem is being solved is illustrated in Fig. 3. The use of cylindrical symmetry means that the two-dimensional model simulates a three-dimensional

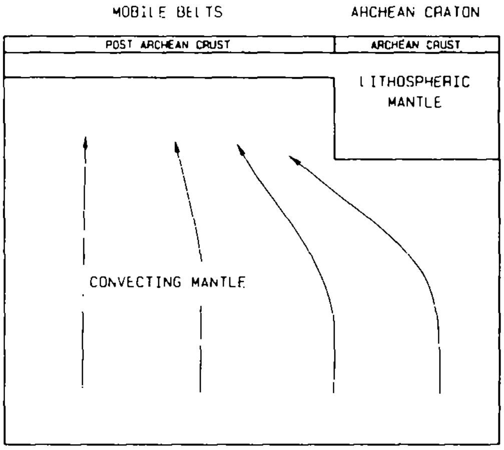

Fig. 3. The four regions incorporated in the finite element model (see text for discussion). The cratonic and mobile belt crusts are each 40 km thick but have independently variable heat productions. The Archean craton is 400 km in radius and of variable thickness; it is surrounded by an 800 km wide annulus of mobile belt lithosphere.

region which can be visualized by rotating Fig. 3 about the right-hand edge of the figure. The model consists of four sub-regions each with different thermal properties. The cratonic and mobile belt crusts, both considered a part of the lithosphere, have uniform thickness and thermal conductivity but the mean heat production and the contrast in heat production between them vary from model to model. The mean crustal heat production is the average heat production of both the Archean and post-Archean crusts, weighted by their respective areas. It is the integral of crustal heat production over crustal thickness which is of importance in the models rather than the respective values separately. In the absence of any evidence to the contrary we have assumed a uniform crustal thickness and attribute all variations in the integral to variations in crustal heat production alone.

The mantle is also divided into two sub-regions. Within the lithospheric portion of the mantle, which varies in thickness between the craton and the mobile belts, heat is transferred only by conduction, with the thermal conductivity varying with depth and temperature [23]. Since the heat production of the rocks in the subcrustal lithosphere is about two orders of magnitude less than that of the crust, any contrasts in subcrustal heat production between the cratonic and mobile belts lithosphere would have virtually no effect on the pattern of surface heat flow. Accordingly, no contrast in subcrustal lithospheric heat production has been incorporated in the models. In the sublithospheric convecting portion of the mantle we have employed a parameterized convection scheme which utilizes an enhanced heat transfer coefficient [24,25], adjusted to yield an adiabatic temperature gradient in the sublithospheric mantle. While this scheme for simulating convection will not accurately represent the complex temperature distribution in the convecting mantle at a given instant in time, it yields a reasonably good representation, in a time-averaged sense, of the thermal conditions within the convecting sub-lithospheric mantle, as well as in the overlying conductive lithosphere.

We have elected to model the combined craton-mobile belt terrains and subjacent mantle as a single multi-dimensional system, rather than construct independent one-dimensional models of each terrain separately. It is true that separate one-dimensional models involving only vertical heat transport would likely point to a contrast in crustal heat production and to differences in heat flow into the bases of cratonic and mobile belt lithospheric columns as important contributors to the contrast in surface heat flow between the two terrains. However, the heterogeneity implied by the geographic extent and the depth range over which these "one-dimensional" differences exist leads inevitably to significant horizontal as well as vertical heat transfer. Our multi-dimensional models acknowledge this heterogeneity as an essential characteristic of the system, and accommodate to it with both vertical and horizontal heat transfer. Moreover, because the heterogeneity is also rheological, the heat transfer comprises both conduction and convection, each dominant in different regions of the model. The significance of this difference is far from trivial; the convective diversion of heat away from the conductive cratonic root into the base of the adjacent mobile belt lithosphere provides a single mechanism that physically regulates the heat flow into the base of both the craton and the mobile belts. In separate one-dimensional models the respective basal heat flows are independent quantities, unrelated by the geodynamics of the heat transfer process.

5. Model behavior

The contrast in surface heat flow between the craton and the mobile belts predicted by the models varies principally in response to variations of four parameters. In addition to the thickness of the craton and the difference in crustal heat production between the craton and the mobile belts, the models are also sensitive to the thickness of the mobile belt lithosphere which surrounds the craton (it is the difference in thickness between the craton and the mobile belts that defines the cratonic root), and to the ratio of heat produced within the crust to that which arises at greater depth. This latter ratio is important because when it is small, most of the heat arises at depth and can be affected by the presence of the cratonic root. When the ratio is large, much of the heat flow arises at crustal levels and the contrast in surface heat flow is less sensitive to root thickness.

Figure 4 is a sensitivity diagram which illustrates how a reference model responds to

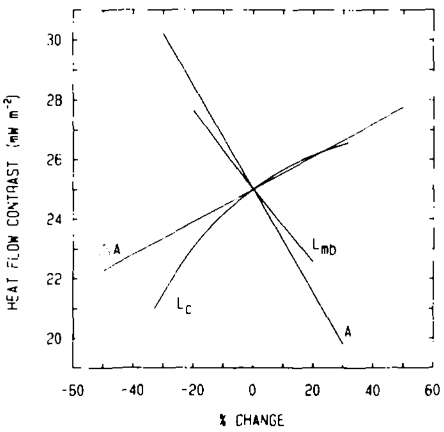

Fig. 4. Sensitivity diagram illustrating the effect on the contrast in surface heat flow of varying each model parameter one at a time. Parameter variations are shown as a percentage departure from a reference value at the common intersection of the curves. L_c is the thickness of the cratonic root, ΔA the difference in crustal heat production between the craton and the mobile belts, $\bar{A}$ the mean crustal heat production and L_{mb} the thickness of the mobile belt lithosphere. Reference values for these parameters are 300 km, 0.16 μW m^{-3}, 0.72 μW m^{-3} and 100 km, respectively.

changes in any of the four model parameters. Each curve in Fig. 4 represents the change in contrast in surface heat flow that results when one of the four parameters is allowed to vary over a geologically reasonable range while all other parameters remain constant. We have chosen as a reference model one with the following characteristics: a 300 km thick craton, a 100 km thick mobile belt, a mean crustal heat production of 0.72 μW m^{-3} and a difference in crustal heat production between the craton and the surrounding mobile belts of 0.16 μW m^{-3}. These values, represented by the point of intersection in Fig. 4, will later be shown to be central values in a range of observationally constrained parameter space. The reference model yields 40 mW m^{-2} of surface heat flow in the craton and 65 mW m^{-2} in the mobile belts, thus yielding a contrast of 25 mW m^{-2}, the contrast observed in southern Africa.

Two curves, those for variation in cratonic thickness and the difference in crustal heat production show positive slopes. As the cratonic lithosphere increases in thickness from 200 to 400 km, the contrast in surface heat flow also increases, but the effect is non-linear. Much of the diversion of heat is accomplished by cratonic thickness less than the reference value; further thickening of the craton beyond the reference value provides progressively smaller increases in the surface heat flow contrast, i.e. the diversion mechanism becomes increasingly insensitive to increasing cratonic thickness. As the contrast in crustal heat production ranges ± 50% from the reference model, the contrast in surface heat flow also increases linearly from about 22 to 28 mW m^{-2}, a change of ± 12% relative to the reference model.

The other two parameters, the mean crustal heat production and the thickness of the mobile belt lithosphere affect the contrast in surface heat flow inversely. As mentioned above, less mean crustal heat production implies more heat coming from depth, which in turn means that more heat is available to be diverted by the cratonic root, thereby leading to an amplification of the diversion effect and an increase in the contrast in surface heat flow. And, the thicker the mobile belt lithosphere surrounding the craton, the more thermal resistance it offers, resulting in less diversion and less contrast in surface heat flow.

6. Trade-offs between model parameters

It is clear from Fig. 4 that any single departure from the reference values will yield a contrast in surface heat flow greater or less than 25 mW m^{-2}. However, suitable variations of two or more parameters can maintain 25 mW m^{-2} of contrast. We now hold the thickness of the mobile belt lithosphere at the reference value of 100 km and examine more closely the relationship between the remaining three variables which influence the contrast in surface heat flow. In Fig. 5, every point on and between the curves represents conditions which will yield 40 mW m^{-2} of heat flow in the center of the craton and 65 mW m^{-2} in the mobile belts. The average surface heat flow is the average heat flow of the Archean and post-Archean terrains, weighted by their respective areas. Each curve represents, for a given mean crustal heat production, the relationship between cratonic thickness and contrasts in crustal heat production which will yield the observed 25 mW m^{-2} contrast in surface heat flow.

If the mean crustal heat production is greater than about 0.6 μW m^{-3} then it is impossible to

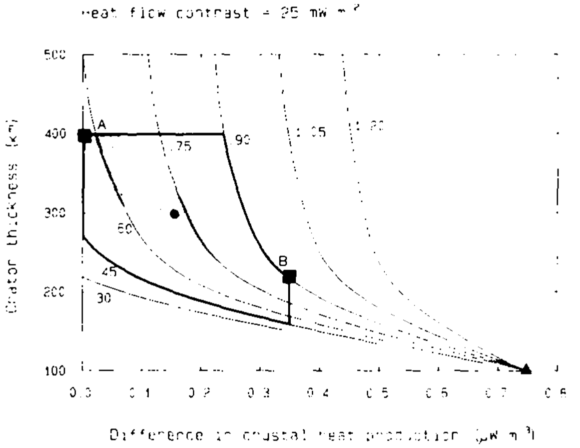

Fig. 5. The relationship between cratonic thickness, mean crustal heat production and difference in crustal heat production between the Archean craton and younger surrounding terrains, which yield a surface heat flow of 40 mW m^{-2} at the center of the Archean craton and 65 mW m^{-2} in the mobile belts. Numbers on curves are the mean crustal heat production in μW m^{-3}. From the lowest (0.3 μW m^{-3}) to the highest (1.20 μW m^{-3}) values, the curves respectively represent approximately 20, 30, 40, 50, 60, 70 and 80% of the average surface heat flow produced in the crust. The heavy line encloses the region in the solution space indicated by various independent estimates of the model parameters. The shaded region includes all of the models which satisfy the additional constraint that the temperature at 150 km depth at the center of the Archean craton falls in the range 1000–1100 ° C. The point in the shaded region represents the parameters of the reference model used in Fig. 4. The triangle represents the parameters of an unsatisfactory "end member" model described in the text. The squares labelled *A* and *B* represent the parameters of the characteristic models shown in Fig. 6.

account for all of the contrast in surface heat flow by cratonic root diversion alone because there is insufficient heat coming from depth to be diverted by the root. Curves representing these levels of mean crustal heat production become asymptotic to some amount of difference in crustal heat production, indicating the minimum amount of difference in crustal heat production required to produce the heat flow contrast no matter how deep the root may extend. Conversely, if the average crustal heat production is less than 0.6 μW m^{-3}, the contrast in heat flow can be accounted for entirely by diversion around a cratonic root, and cannot be explained solely by a difference in crustal heat production because there is not enough heat production in the crust to permit a sufficiently large difference.

While all points on and between the curves in Fig. 5 represent conditions for which both the average surface heat flow and the contrast in surface heat flow observed in southern Africa are satisfied, not all are equally probable or reasonable geologically. The range of the solution space can be considerably narrowed with constraints provided by independent estimates of each of the relevant parameters. We consider in turn estimates of the cratonic thickness, the mean crustal heat production and the contrast in crustal heat production.

7. Model constraints

7.1. Cratonic roots

While several investigators have proposed that cratons have lithospheric roots, Grand [20] offered persuasive evidence that such a root exists beneath North America, extending to depths of up to 400 km beneath the Superior Province of Canada. By analogy, a similar root may exist beneath the Archean craton in southern Africa, but the necessary seismological investigations have not yet been carried out. Boyd and Gurney [26], on the basis of thermobarometry studies of mantle xenoliths in Cretaceous kimberlites, have suggested that the lithosphere beneath the Kaapvaal Craton in southern Africa extends to depths of at least 180 km.

7.2. Mean crustal heat production

Several workers have estimated the concentrations of the heat producing radioelements U, Th and K in the continental crust and used these concentrations to estimate mean crustal heat production and the contribution of crustal heat production to surface heat flow. The latter two estimates however, depend on assumed values of crustal density and thickness. While the mean crustal density is probably about 2.87 g cm^{-3} [27], most of the published estimates of crustal heat production have assumed a crustal density of 2.67 g cm^{-3}. In the interest of maximizing comparability, we have used the estimated radioelement concentrations, a crustal density of 2.67 g cm^{-3}, the relationship between radioelement concentrations and heat production of Birch [28] and a 40 km thick crust. While different estimates of crustal density and thickness yield somewhat different estimates of mean crustal heat production, the differences have little effect on our conclusions.

The only estimate of the full crustal heat production specifically in southern Africa is that of Nicolaysen et al. [29], who measured the heat production in rocks of the Vredefort structure, which they interpret to expose a 15 km section of the upper and middle Archean crust of the Kaapvaal Craton. They conclude that crustal heat production in the Archean crust contributes between 29 and 34 mW m^{-2} to the surface heat flow, which implies a mean crustal heat production of about 0.8 μW m^{-3} in the craton. Since the characteristic surface heat flow in the interior of the Kaapvaal Craton is only about 40 mW m^{-2}, this study suggests that crustal heat production in the craton contributes about 80% of the cratonic heat flow. This fraction considerably exceeds most other estimates of the crustal contribution to surface heat flow, and may be linked to the interpretation that the Vredefort structure exposes a vertical section of the upper and middle crust.

Several estimates of the heat production of "average" continental crust have also been made. Haack [30] proposed an upper crustal model with a different exponential decrease of heat production with depth for each of the principal heat-producing radioisotopes, and a lower crust comprising granulites. His model yields an estimate of the mean crustal heat production of 0.69 μW m^{-3}. Taylor and McLennan [31] estimated the concentrations of the principal heat-producing radioelements in post-Archean crust based on an "andesite" model of crustal genesis and on rare earth element patterns observed in sediments eroded from large continental areas. Their model yields a mean crustal heat production of 0.78 μW m^{-3}. Weaver and Tarney [32] adopted Taylor and McLennan's upper crustal heat production estimate, but assumed the lower crust consists of granulites. Their model yields an average crustal heat production of 0.89 μW m^{-3}. Allègre [33], on the basis of a geodynamical model of trace element distributions in the Earth, estimated the concentrations of U, Th and K in the continental crust from which we have calculated a mean crustal heat production of 0.46 μW m^{-3}.

Pollack and Chapman [18] noted that for several heat flow provinces of the world the reduced heat flow comprises approximately 0.6 of the mean surface heat flow of the province. The level within the crust at which the reduced heat flow occurs is model dependent, but as a limiting case it can be considered the heat flow at the base of the crust, and its complement, 0.4 of the mean surface heat flow, as being produced within the crust. Assuming a mean continental surface heat flow of 60 mW m^{-2} [34] and a 40 km thick crust, this implies a mean crustal heat production of at least 0.6 μW m^{-3}.

7.3. Difference in crustal heat production

Several measurements of surface heat production in southern Africa have been made on samples from both the Archean craton [3,12,35] and the younger mobile belts [3,4,11,36]. However, these measurements cannot be used to make a robust case for or against a contrast in crustal heat production, because simple arithmetic averages of cratonic and mobile belt measurements without weighting by the relative area of each sampled unit cannot be considered representative estimates, and even if a significant difference in surface heat production could be demonstrated, additional arguments would be required to show that the surficial contrast persists throughout the crust.

Taylor and McLennan [31], comparing the composition of Archean and post-Archean crust, suggested a difference in heat production between the two crustal types of aproximately 0.31 μW m^{-3}. Morgan [2] arrived at a similar estimate based on an analysis of data from the global ensemble of heat flow provinces. However, the surface heat flow–heat production data from southern Africa [3,4,11,12] allow an interpretation in which there is no difference in crustal heat production between the Archean craton and the surrounding mobile belts [3].

All of these estimates of the distribution of heat production in the continental crust, with the exception of that of Allègre [33], rely to varying degrees on the empirical linear relationship between surface heat flow and surface heat production [37], in which the slope of the regression line is interpreted as a length scale for the crustal heat source distribution and the intercept yields the heat flow from below the zone of crustal enrichment. Recent studies [38–42] have called into question this interpretation, noting that lateral variations of thermal conductivity and heat production, the latter of which makes the correlation between surface heat flow and surface heat production possible in the first place, also lead to three-dimensional heat transfer. In multi-dimensional heat flow neither the slope nor the intercept of the linear relationship can be interpreted simply, as in the traditional, one-dimensional case. Because of these questions, we believe that estimates of crustal heat production which rely on the traditional interpretation of the heat flow–heat production relationship must be considered with caution.

To summarize, seismological, geochemical and geothermal studies enable us to narrow the range of models which satisfy the contrast in surface heat flow between Archean cratons and younger surrounding terrains. The constrained subset of models is bounded by a cratonic root extending to between 180 and 400 km depth, a mean crustal heat production between 0.45 and 0.90 μW m^{-3}, and a contrast in crustal heat production between the Archean craton and younger surrounding terrains less than about 0.35 μW m^{-3}. The region enclosed by the heavy line in Fig. 5 encompasses all of these estimates of the critical model parameters.

7.4. Temperature constraints

We have thus far discussed only direct constraints on the model parameters, but indirect constraints can also be called upon to narrow the range of acceptable models still further. Each set of model parameters also defines a unique lithospheric and sub-lithospheric temperature field within the upper mantle, and therefore estimates of upper mantle temperature may also be relevant constraints. Boyd and Gurney [26] have suggested, on the basis of thermobarometry studies of mantle xenoliths in kimberlite pipes in southern Africa, that the temperature at a depth of 150 km beneath the Archean craton was probably in the range of 1000–1100 °C at the time of kimberlite eruption in the Cretaceous. Assuming that thermal conditions in the root have not changed significantly since that time, these data can be used to constrain present-day models for the thermal structure of the cratonic root. Models that yield temperatures consistent with this constraint fall within the shaded region in Fig. 5.

8. Characteristic models

We now examine two models representative of the full range of parameters consistent with the constraints on heat flow, heat production, lithospheric thickness and subsurface temperatures described above. The parameters of these two models are shown by the squares labeled *A* and *B* in Fig. 5; model A incorporates a 400 km thick craton and no contrast in crustal heat production, whereas model B features a 220 km thick craton and a significant contrast in crustal heat production. The parameters of the reference model for the earlier sensitivity analysis presented in Fig. 4 are represented by the circle in Fig. 5 and can be seen as central values in the constrained range of parameter space.

Model A is an "end member" model in the sense that it meets all constraints without requiring any contrast in crustal heat production between the craton and mobile belts; all of the contrast in surface heat flow arises from the diversion mechanism. The mean crustal heat production of this model is 0.57 μW m^{-3}, which yields nearly 40% of the surface heat flow. (One can envision another "end member" case, shown by the triangle in Fig. 5, in which the cratonic and mobile belt lithospheres are of equal thickness and therefore a root does not exist. In such a model all of the contrast in surface heat flow would arise from differences in crustal heat production. However, such a model would require an unreasonably large contrast in crustal heat production and in addition cannot meet the subsurface temperature constraints within the craton.) Model B, the second characteristic model drawn from the constrained range of parameter space, derives the contrast in surface heat approximately equally from differences in crustal heat production and diversion by the cratonic root.

The surface heat flows resulting from the characteristic models A and B are shown in Fig. 6a and d. As noted earlier, every point on and between the curves in Fig. 5 will yield 40 mW m^{-2} of heat flow in the craton and 65 mW m^{-2} in the mobile belts. The surface heat flow predicted by the various models represented in Fig. 5 differs in

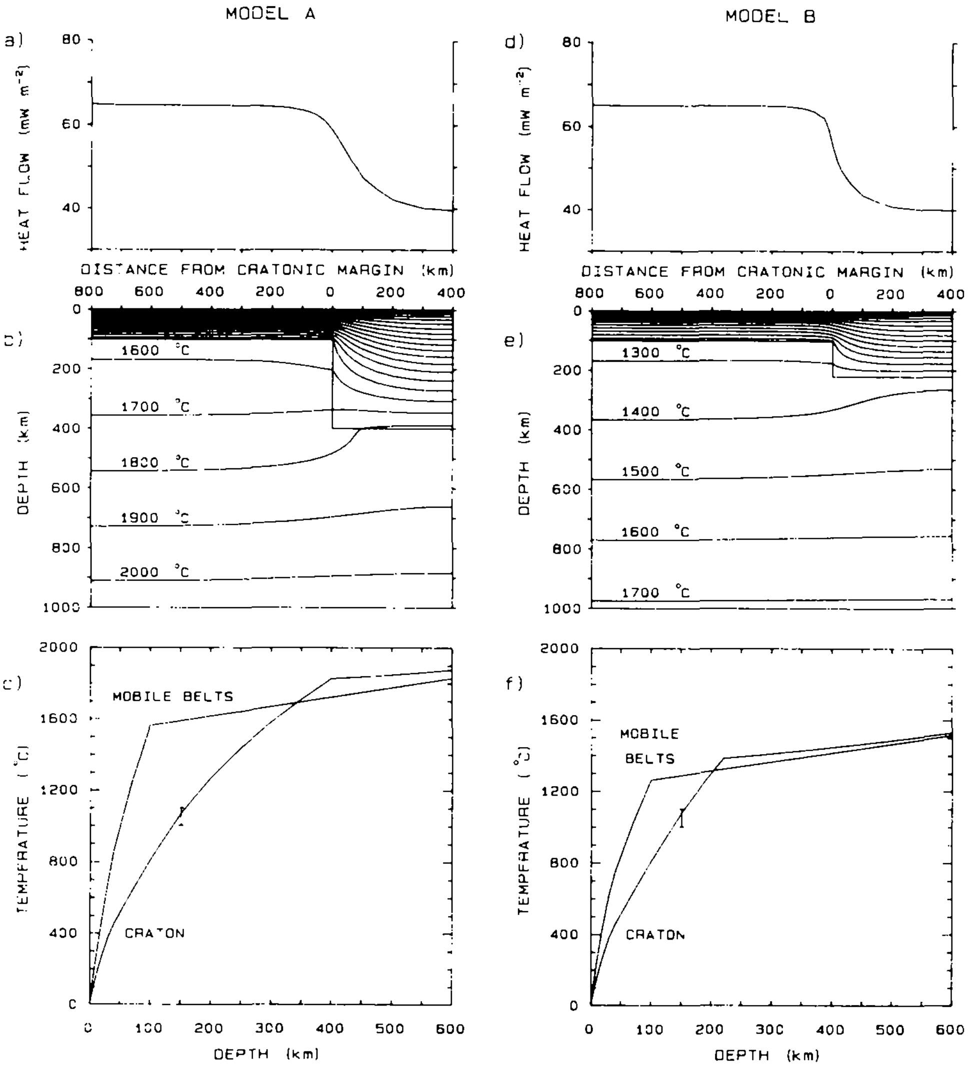

Fig. 6. Two characteristic models with thermal parameters represented by the squares labelled *A* and *B* in Fig. 5. (a), (d) Surface heat flows and (b), (e) temperature fields resulting from the models, and (c), (f) two geotherms (vertical temperature profiles), one at the center of the Archean craton and the second in the mobile belts at the periphery of the model region. The vertical bars in (c) and (f) indicate xenolith thermobarometry constraints.

the transition from cratonic to mobile belt heat flow; models with both high crustal heat production and strong crustal contrasts yield sharp transitions, whereas models with more diverted heat and less crustal contrast show a broader transition zone. The simple geometry of the model cratonic root precludes a closer match with the actual observed transition in heat flow shown in Fig. 2. A more tapered root configuration would also influence the transition zone of surface heat flow, but no independent evidence has yet been presented that provides constraints on root shape in southern Africa.

The temperature fields of the characteristic models are shown in Fig. 6b and e. In both models the temperature gradients in the cratonic and mobile belt lithospheres are superadiabatic, with the more closely spaced isotherms in the mobile belt lithospheres reflecting the higher heat flow there. Approximately adiabatic temperature gradients exist within the sub-lithospheric convecting mantle. The upward bowing of the isotherms in the sub-lithospheric mantle beneath the Archean craton arises from the diversion of deep mantle heat away from the base of the cratonic root toward the thinner surrounding mobile belts. The more pronounced warping of the sublithospheric isotherms in model A reflects the fact that more heat is diverted by the thicker root in that model compared to model B where part of the contrast in surface heat flow results from a contrast in crustal heat production between the craton and mobile belts. Note that in each model a range of temperatures can be found that exists in both the conducting root and in the adjacent convective mantle, a clear reflection that the rheological structure controlling the mode of heat transfer is not exclusively temperature dependent, but likely a function also of other variables such as volatile content. The cratonic root is stiff and conductive in this temperature range whereas the adjacent upper mantle beneath the mobile belts remains convective.

Fig. 6c and f each show two vertical geotherms from the two models, one at the center of the Archean craton and another in the mobile belts, 1200 km from the center of the craton. Each of the cratonic geotherms satisfies the xenolith thermobarometry constraint indicated by the vertical bars. To a depth of about 350 km in model A the lithosphere within the cratonic root is cooler than at comparable depths beneath the mobile belts, but at greater depths, temperatures beneath the craton are warmer than those at similar depths beneath the mobile belts. Even though heat is being diverted away from the cratonic root and its surface heat flow is low, the base of the root experiences relatively high temperatures because conduction and superadiabatic gradients extend to greater depths within the craton than within the mobile belts. At a depth of about 800 km the temperatures beneath the craton and the mobile belts are again approximately equal and their respective geotherms merge. The base of the root in model B is also warmer than the surrounding mantle, but the difference in temperature between these two regions is less than in model A because in model B, with a significant contrast in crustal heat generation contributing to the contrast in surface heat flow, the root need divert only about half as much heat as the root in model A.

Another difference between the two characteristic models is that model B yields lower temperatures in the sublithospheric mantle than does model A. This difference arises because more of the surface heat flow of model B is generated within the crust, and less comes from depth; subcrustal temperature gradients therefore are smaller and lower temperatures are developed within the lithosphere and sublithospheric mantle.

9. Conclusion

These models provide insight into the interplay of various parameters that influence the contrast in surface heat flow between Archean cratons and younger surrounding terrains: a lithospheric root beneath the Archean craton which diverts heat into the surrounding mobile belts, a contrast in crustal heat production between the craton and the surrounding mobile belts, the relative contribution of heat produced in the crust as compared to that which comes from greater depths, and the thickness of the mobile belt lithosphere. Independent estimates of these model parameters as well as petrologic constraints on upper mantle temperatures help to narrow the range of acceptable models.

The acceptable models indicate that the contrast in surface heat flow in southern Africa between about 40 mW m^{-2} in the Archean Kaapvaal-Limpopo-Zimbabwe Craton and 65 mW m^{-2} in the surrounding mobile belts, is consistent with a contrast in crustal heat production between zero and 0.35 μW m^{-3} and the diversion of heat by a cratonic root that extends to depths in the range of 200–400 km. If the difference in crustal heat production between the craton and the mobile belts is at the low end of the suggested range then a relatively thick cratonic root would be called for to satisfy the heat flow data and a relatively low mean crustal heat production to satisfy the temperature constraint in the cratonic root. Conversely, if the difference in crustal heat production is at the high end of the suggested range then a thinner root and higher mean crustal heat production would be indicated. The models suggest that half or more of the contrast in surface heat flow between the craton and the surrounding mobile belts observed in southern Africa may result from the diversion of heat by the thick cratonic lithosphere.

This diversion model also has relevance to and interesting implications for two other tectonic settings: the more energetic thermal regime in the Archean and, through scale effects, the regime beneath supercontinental assemblages. In the Archean, heat production was 2–3 times greater than the present day, and Archean continental nuclei were surrounded by thin oceanic lithosphere, rather than the younger continental mobile belts accreted later. That much of the additional heat available in the Archean was lost through the Archean oceans was suggested by Burke and Kidd [43] and modeled one-dimensionally by Davies [22] and Bickle [44]. Our preliminary multi-dimensional models [45] indicate that even with a relatively high surface heat flow in the craton resulting from the augmented heat production within the cratonic crust, diversion of deep mantle heat away from the craton in the Archean can maintain a relatively cool cratonic geotherm at that time, a condition advocated by Boyd et al. [46]. Multi-dimensional diversion models of the Archean thermal regime are developed more fully by us in a subsequent paper now in preparation.

The application of this model to understanding the heat flow in and around other cratons introduces the question of horizontal scale, since the Archean craton in southern Africa is relatively small compared to some other Archean terrains such as the Superior Province of Canada. Preliminary modeling suggests that as the cratonic size increases, a smaller proportion of the deep mantle heat rising beneath it can escape peripherally because the edge of the craton becomes more remote. This results in progressively more heat entering the base of the craton thereby raising the temperatures within it and making it more susceptible to disruption. The implication that there may be a critical size of continental assemblages which when exceeded renders them thermally unstable and vulnerable to breakup is an intriguing possibility.

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References

1 D.S. Chapman and K. Furlong, Continental heat flow-age relationships (abstract), EOS, Trans. Am. Geophys. Union 58, 1240, 1977.

2 P. Morgan, Crustal radiogenic heat production and the selective survival of ancient continental crust, J. Geophys. Res. 90, C561–C570, 1985.

3 S. Ballard, H.N. Pollack and N.J. Skinner, Terrestrial heat flow in Botswana and Namibia, J. Geophys. Res. 92, in press, 1987.

4 M.Q.W. Jones, Heat flow and heat production in the Namaqua Mobile Belt, South Africa, J. Geophys. Res. 92, in press, 1987.

5 H.M. Meixner and R.J. Peart, The Kalahari drilling project: a report on the geophysical and geological results of follow-up drilling to the aeromagnetic survey of Botswana, Botswana Geol. Surv. Bull. 27, 224 pp., 1984.

6 C. Hartnady, P. Joubert and C. Stowe, Proterozoic evolution in southwestern Africa, Episodes 8, 236–244, 1985.

7 E.C. Bullard, Heat flow in South Africa, Proc. R. Soc. London, Ser. A 173, 474–502, 1939.

8 A.E. Carte, Heat flow in the Transvaal and Orange Free State, Proc. Phys. Soc., Sect. B 67, 664–672, 1954.

9 D.I. Gough, Heat flow in the southern Karroo, Proc. R. Soc. London, Ser. A 272, 207–230, 1963.

10 A.E. Carte and A.I.M. van Rooyen, Further measurements of heat flow in South Africa, J. Mine Vent. Soc. S. Afr., pp. 94–98, 1969.

11 D.S. Chapman and H.N. Pollack, Heat flow and heat production in Zambia: evidence for lithospheric thinning in central Africa, Tectonophysics 41, 79–100, 1977.

12 M.Q.W. Jones, Heat flow and heat production studies in the Namaqua Mobile Belt and Kaapvaal Craton, 319 pp., Ph.D. Thesis, University of the Witwatersrand, Johannesburg, 1981.

13 J.D. Fairhead and R.W. Girdler, The seismicity of Africa, Geophys. J. R. Astron. Soc. 24, 271–301, 1971.

14 C.H. Scholz, T.A. Koczynski and D.G. Hutchins, Evidence for incipient rifting in southern Africa, Geophys. J. R. Astron. Soc. 44, 135–144, 1976.

15 T.H. Jordan, The continental tectosphere, Rev. Geophys. Space Phys. 13, 1–12, 1975.

16 T.H. Jordan, Composition and development of the continental tectosphere, Nature 274, 544–548, 1978.

17 T.H. Jordan, Continents as a chemical boundary layer, Philos. Trans. R. Soc. London, Ser. A 301, 359–373, 1981.

18 H.N. Pollack and D.S. Chapman, On the regional variation of heat flow, geotherms, and lithospheric thickness, Tectonophysics 38, 279–296, 1977.

19 S.P. Grand and D.V. Helmberger, Upper mantle shear structure of North America, Geophys. J.R. Astron. Soc. 76, 399–438, 1984.

20 S.P. Grand, Shear velocity structure of the mantle beneath the North American plate, 228 pp., Ph.D. Thesis, California Institute of Technology, Pasedena, Calif., 1986.

21 H.N. Pollack, Cratonization and thermal evolution of the mantle, Earth Planet. Sci. Lett. 80, 175–182, 1986.

22 G.F. Davies, Thickness and thermal history of continental crust and root zones, Earth Planet. Sci. Lett. 44, 231–238, 1979.

23 J.F. Schatz and G. Simmons, Thermal conductivity of Earth materials at high temperatures, J. Geophys. Res. 77, 6966–6983, 1972.

24 H.N. Sharp and W.R. Peltier, Parameterized mantle convection and the Earth's thermal history, Geophys. Res. Lett. 5, 737–740, 1978.

25 H.N. Sharpe and W.R. Peltier, A thermal history model for the Earth with parameterized convection, Geophys. J.R. Astron. Soc. 59, 171–205, 1979.

26 F.R. Boyd and J.J. Gurney, Diamonds and the African lithosphere, Science 232, 472–477, 1986.

27 R.G. Allis, A heat production model for stable continental crust, Tectonophysics 57, 151–165, 1979.

28 F. Birch, Heat from radioactivity, in: Nuclear Geology, H.F. Faul, ed., p. 148, John Wiley and Sons, New York, N.Y., 1954.

29 L.O. Nicolaysen, R.J. Hart and N.H. Hart, The Vredefort radioelement profile extended to supracrustal strata at Carletonville, with implications for continental heat flow, J. Geophys. Res. 86, 10653–10661, 1981.

30 U. Haack, On the content and vertical distribution of K, Th, and U in the continental crust, Earth Planet. Sci. Lett. 62, 360–366, 1983.

31 S.R. Taylor and S.M. McLennan, The composition and evolution of the continental crust: rare earth element evidence from sedimentary rocks, Philos. Trans. R. Soc. London, Ser. A 301, 381–399, 1981.

32 B.L. Weaver and J. Tarney, Major and trace element composition of the continental crust, in: Structure and Evolution of the Continental Lithosphere, Physics and Chemistry of the Earth, 15, H.N. Pollack and V.R. Murthy, eds., pp. 39–68, Pergamon, New York, N.Y., 1984.

33 C.J. Allègre, Chemical geodynamics, Tectonophysics 81, 109–132, 1983.

34 H.N. Pollack, The heat flow from the Earth: a review, in: Mechanisms of Continental Drift and Plate Tectonics, P.A. Davies and S.K. Runcorn, eds., pp. 183–192, Academic Press, London, 1980.

35 R.J. Hart, L.O. Nicolaysen and N.H. Gale, Radioelement concentrations in the deep profile through Precambrian basement of the Vredefort structure, J. Geophys. Res. 86, 10639–10652, 1981.

36 U. Haack, E. Gohn and O. Hartmann, Radiogenic heat generation in Damaran rocks, Spec. Pub. Geol. Soc. S. Afr. 11, 225–231, 1983.

37 R.F. Roy, E.R. Decker, D.D. Blackwell and F. Birch, Heat generation of plutonic rocks and continental heat flow provinces, Earth Planet. Sci. Lett. 5, 1–12, 1968.

38 P.C. England, E.R. Oxburgh and S.W. Richardson, Heat refraction around granite plutons in north-east England, Geophys. J. R. Astron. Soc., 62, 439–455, 1980.

39 C. Jaupart, Horizontal heat transfer due to radioactivity contrasts: causes and consequences of the linear heat flow relation, Geophys. J.R. Astron. Soc. 75, 411–435, 1983.

40 S.B. Nielsen, Steady state heat flow in a random medium and the linear heat flow-heat production relationship, Geophys. Res. Lett. 14, 318–321, 1987.

41 K.P. Furlong and D.S. Chapman, Crustal heterogeneities and the thermal structure of the continental crust, Geophys. Res. Lett. 14, 314–317, 1987.

42 G. Vasseur and R.N. Singh, Effects of random horizontal variations in the radiogenic heat source distribution on its relationship with heat flow, J. Geophys. Res. 91, 10397–10404, 1986.

43 K. Burke and W.S.F. Kidd, Were Archean continental geothermal gradients much steeper than those of today?, Nature 272, 240–241, 1978.

44 M.J. Bickle, Heat loss from the Earth: a constraint on Archean tectonics from the relation between geothermal gradients and the rate of plate production, Earth Planet. Sci. Lett. 40, 301–315, 1978.

45 S. Ballard and H.N. Pollack, Present-day heat flow and thermobarometry of ancient diamonds: implications for the diversion of heat by Archean cratons, EOS, Trans. Am. Geophys. Union 67, 1183, 1986.

46 F.R. Boyd, J.J. Gurney and S.H. Richardson, Evidence for a 150–200 km thick Archean lithosphere from diamond inclusion thermobarometry, Nature 315, 387–389, 1985.