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Why are the continents just so…?

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ABSTRACT Variations in gravitational potential energy contribute to the intraplate stress field thereby providing the means by which lithospheric density structure is communicated at the plate scale. In this light, the near equivalence in the gravitational potential energy of typical continental lithosphere with the mid-ocean ridges is particularly intriguing. Assuming this equivalence is not simply a chance outcome of continental growth, it then probably involves long-term modulation of the density configuration of the continents via stress regimes that are able to induce significant strains over geological time. Following this notion, this work explores the possibility that the emergence of a chemically, thermally and mechanically structured continental lithosphere reflects a set of thermally sensitive feedback mechanisms in response to Wilson cycle oscillatory forcing about an ambient stress state set by the mid-ocean ridge system. Such a hypothesis requires the continents are weak enough to sustain long-term (10^8 years) strain rates of the order of $\sim 10^{-17}$ s^{-1} as suggested by observations that continental lithosphere is almost everywhere critically stressed, by estimates of seismogenic strain rates in stable continental interiors such as Australia and by the low-temperature thermochronological record of the continents that requires significant relief generation on the 10^8 year time-scale. Furthermore, this notion provides a mechanism that helps explain interpretations of recently published heat flow data that imply the distribution of heat-producing elements within the continents may be tuned to produce a characteristic thermal regime at Moho depths.

Key words: continental crust; gravitational potential energy; heat flow; heat-producing elements; plate tectonics; stress.

INTRODUCTION

Plate tectonics provides an extraordinary framework for understanding the basic workings of our planet. This is best exemplified in the strikingly simple and complete account plate tectonics provides for the creation and destruction of ocean crust. This account links heat flow, bathymetry and crustal age in a compellingly simple way, and our understanding extends to fine detail, including the thickness and bulk composition of oceanic crust (McKenzie & Bickle, 1988). While there is much to learn in the detail of the mass transfer processes that contribute to ocean crust formation, the question of 'why the ocean crust is just so?' is essentially solved. By comparison, our understanding of the continents is far less complete. While it is well understood that the continents represent amalgams of inherited fragments and new crustal additions accumulated over many plate tectonic cycles (e.g. Brown & Rushmer, 2006), there is little consensus on the basic physical processes that give rise to many of the specific, first-order attributes of the continental crust. For example, there is no compelling understanding for why the continents are typically configured with a ~40-km-thick crust, and so occupy approximately one-third of the Earth's surface. A unified, compelling view of 'why the continents are just so?' is yet to be realized.

As has long been understood, the organization of the continental lithosphere into a light, felsic crust above a denser, ultramafic mantle, is crucial to its geodynamical behaviour as it dictates lithospheric buoyancy, and impacts on stress regimes and lithospheric strength. However, there is little understanding of the underlying physical processes that lead to the specific manifestations of this organization, such as the thickness of the crust or the rather more subtle level of organization evident in the distribution of the heat-producing elements (Birch *et al.*, 1968; Lachenbruch, 1968). Continental crust tends to an average thickness of about 40 km, and in doing so leads to a typical elevation of around 0.5–1 km above sea level (Bassin *et al.*, 2000). For a given volume of continental crust, this characteristic thickness is directly related to the areal extent of the continents, with the continents presently occupying approximately one-third of the surface of the planet. Why, we might ask, are the continents configured this way, and not with a thicker, crust that occupies a smaller fraction of the Earth's surface or, alternatively, a thinner crust that occupies a larger fraction of the Earth's surface?

At time-scales of hundreds of millions of years, the elevation of the continents is clearly modulated by surface processes and, at continental scales, sea level provides the ultimate attractor for both erosional and depositional processes. As such, the thickness and areal proportion of the continents may simply reflect the long-term effects of surface processing. However, the ratio of the surface area of continents and oceans also impacts crucially on a number of important geodynamic processes, such as heat loss from the earth (Lenardic *et al.*, 2005) and the distribution of stress within the plates (Coblentz *et al.*, 1994), and so it would seem unlikely that the ratio is simply an accident of erosional base level. Moreover, the sea level control is dependent on the amount of water in, and the depth of, the oceans basins, and hence on the way water is partitioned between mantle and surface reservoirs and the rates of sea floor spreading and hence ultimately on questions of geodynamics. Any compelling account of 'why the continents are just so?' should link such threads more cogently than is presently the case.

GRAVITATIONAL POTENTIAL ENERGY

An important insight suggesting a more deterministic control on continental structure is provided by the distribution of lithospheric gravitational potential energy across plates. The close correspondence between the mean gravitational potential energy of the continents ($\bar{U}_{\mathrm{cc}}$) and the gravitational potential of the mid-ocean ridges (U_{MOR}) has long been recognized (Coblentz *et al.*, 1994; Doin *et al.*, 1996). As mid-ocean ridges inherently have little strength they provide a useful reference frame for the neutral stress state within plates, and the near equivalence of $\bar{U}_{\mathrm{cc}}$ and U_{MOR} suggests that under ambient conditions the *in situ* stress state in the continents is also close to neutral (following Dahlen, 1981; Coblentz & Sandiford, 1994, the term 'ambient' has been used to refer to the stress state that applies in the absence of any other forces acting on a lithospheric plate, apart from the buoyancy forces due to variations in gravitational potential energy). That this is the case is strongly supported by the world stress map data (e.g. Heidbach *et al.*, 2006) from continental interiors that show stress regimes across the continents vary from mildly compressional (especially in continents in fast-moving plates such as Australia with an asymmetric distribution of plate boundaries) to mildly extensional (especially in continents in slow-moving plates with symmetric disposition of plate boundary such as Africa). In the ambient state, parts of a plate with gravitational potential energy lower than the mean plate potential energy ($\bar{U}_{\mathrm{p}}$) will experience compression, while those with higher potential energy will experience extension. Models of the stress regime in plates, which most approximate ambient conditions such as the African plate, show that the stress regime along the mid-ocean ridges does indeed closely approximate the neutral ambient stress state (Coblentz & Sandiford, 1994). In the light of the discussion above, it would seem surprisingly fortuitous that this near equivalence of and U_{MOR} was simply an 'accident' of a continental structure tuned by the continental erosional base level. Rather, it suggests that the continents may be, at least in part, configured by processes that effectively communicate variations in density and hence gravitational potential energy at the plate scale.

As variations in gravitational potential energy provide a significant source of intraplate stress (e.g. Fleitout & Froidevaux, 1983; Coblentz *et al.*, 1994; Heidbach *et al.*, 2006) it is easy to conceptualize how a neutral ambient stress state could provide a natural attractor state for continents. Consider the case in which the continents were configured with thicker, and hence more elevated, crust. Such a configuration implies an increase in $\bar{U}_{\mathrm{cc}}$ necessarily be greater than both U_{MOR} and $\bar{U}_{\mathrm{p}}$ (mean plate potential energy) and would favour more extensional stress regimes within the continental interiors. If such stress regimes were large enough to accumulate significant strain then they would engender a crustal thinning with a consequent reduction in $\bar{U}_{\mathrm{cc}}$. On the other hand, thinner crust, with $\bar{U}_{\mathrm{cc}} \ll U_{\mathrm{MOR}}$, would promote compressional stress regimes, crustal thickening and an increase in $\bar{U}_{\mathrm{cc}}$. In other words, any long-term structuring of the continents in response to significant departures of the gravitational potential energy of the continents from the neutral ambient plate stress regime will have the tendency to drive the continents towards the neutral ambient stress state. Thus, at the plate scale, the neutral ambient stress state which closely corresponds to U_{MOR} provides an attractor for continental structure.

However, for continents to be naturally structured close to the ambient state requires intraplate processes play a rather more significant role in the long-term evolution of the continents than is currently generally envisaged. The object of this paper is to outline a number of ideas and observations that seem to support the notion that continents might be fundamentally configured by intraplate processes, and to explore some ramifications in terms of several presently unaccounted for, or poorly understood, observations. In doing so, I explore three connected ideas that provide a basis for postulating that a thermo-tectonic feedback process provides an attractor state for the long-term evolution of continental crust. These ideas relate to the *in situ* stress state, deformation rates and thermal structure of continental interiors.

The case of an ambient stress state at the plate scale

Neglecting local flexural effects, the distribution of stress within continents is a function of plate boundary forcing, including tractions imposed at the base of the plates, and variations in gravitational potential energy due to variations in density within the lithosphere (Coblentz *et al.*, 1994; Heidbach *et al.*, 2006). It is well established that variations in gravitational potential energy across the continents, and between continents and adjacent ocean basins provide a significant source of intraplate stress, in the same way that age-related potential energy distributions around mid-ocean ridges sources the so-called ridge-push force (Dahlen, 1981). Of critical importance to understanding the way density distributions contribute to stress state is the variations in the geoid. At wavelengths greater than a few hundred kilometres, appropriate to the limit of complete isostatic compensation, variations in lithospheric gravitational potential energy, ΔU_l, can be directly related to the lithospheric geoid anomaly, ΔN_l:

$$\Delta U_l = \frac{g^2}{2\pi G}\Delta N_l$$

where

$$\Delta N_l = \frac{2\pi G}{g}\int_0^{z_l} z\Delta\rho(z)\mathrm{d}z,$$

G is Newton's gravitational constant, g the gravitational acceleration and $\Delta\rho(z)$ the difference in density from the reference lithosphere, and the integration is taken from the Earth's surface to the depth of compensation (Haxby & Turcotte, 1978).

While the lithospheric geoid anomaly cannot be uniquely distinguished from deeper geoid sources within the convective mantle, a useful approximation to the lithospheric contribution is provided by a high-pass filter (e.g. Chase *et al*., 2002; Coblentz *et al*., 2007). Such filtering reveals weak positive anomalies associated with the ocean–continent transitions consistent with continents supporting around 500 m elevation having the equivalent potential as typical mid-ocean ridge (see also Sandiford & Coblentz, 1994; Doin *et al*., 1996). For example, compared with the mid-ocean ridge geoid anomaly of ~12 m (filtered between degrees 7/11 and 355/360), the continental Australian lithospheric geoid anomaly is ~10 m (D. Coblentz, personal communication). Similar results are shown by density modelling (England & Houseman, 1989; Lachenbruch & Morgan, 1990; Zhou & Sandiford, 1992; Coblentz *et al*., 1994; Jones *et al*., 1996, 1998; Sonder & Jones, 1999). With the exception of the Congo and Brazilian cratons, the general absence of large negative lithospheric geoid anomalies associated with cratons (Doin *et al*., 1996) is particularly important as it implies that there is little secular variation in the gravitational potential energy of stable continental lithosphere. As further discussed in Zoback & Mooney (2003) it also points to the fact that density variations in the upper most mantle lithosphere are important in controlling the buoyancy and stress state of the cratonic lithosphere. As pointed out by Coblentz & Sandiford (1994) and Doin *et al*. (1996), and alluded to in the Introduction, such a distribution of gravitational potential energy implies that the mean ambient stress state in the continents is tuned to the stress state at the mid-ocean ridges. Much of the argument developed below follows from the premise that the similarity in gravitational potential energy of typical continental lithosphere and the mid-ocean ridges reflects a fundamental plate scale organization, rather than an accident of crustal growth.

While the distribution of gravitational potential energy is an important factor in setting the stress state within the continents, so too is the configuration of plate boundaries that surround a continent. This is clearly evident by the contrasting *in situ* stress state in the present-day continents. Antarctica and Africa are both slow-moving continents, largely surrounded by mid-ocean ridges, and are characterized by continental extensional stress fields and/or extensional tectonic regimes (Coblentz & Sandiford, 1994). By contrast, fast-moving continents with asymmetric distribution of plate boundaries, such as Australia, tend to be characterized by compressional continental stress fields (Coblentz *et al*., 1998, 1995). That gravitational potential energy variations provide a first-order control on the *in situ* stress field is well exemplified by North America, where a transition from compressional to extensional stress regimes across the continent can be related to increases in the excess gravitational potential energy of the Colorado Plateau and Basin and Range Province (Jones *et al*., 1998; Sonder & Jones, 1999). Similarly in the African plate, the restricted occurrence of reverse fault earthquakes mechanisms to the Congo Basin (Delvaux & Barth, 2010) testifies to a profound role played by gravitational potential energy in controlling stress regimes at the sub-continental scale. The Congo Basin has the lowest lithospheric gravitational potential energy of any parts of the continents, comparable with that of old ocean lithosphere. The reason for the anomalously low gravitational potential energy in the Congo Basin is not fully understood; however, Downey & Gurnis (2009) have suggested the persistent subsidence and low elevation of this region reflects a dynamic response to anomalously high-density material within the deep lithosphere.

As the plate boundary configurations change on time-scales appropriate to the Wilson cycle, the intraplate stress state within continents should be expected to vary on similar time-scales. The analysis of the *in situ* stress field in the modern-day continents suggests that we should expect a natural oscillation from mildly compressional in fast-moving asymmetric plate settings (such as modern-day Australia) to mildly extensional in slower moving more symmetric plates (such as modern-day Africa, or Australia prior to the onset of fast spreading at *c*. 45 Ma). Moreover, large-scale convective flow processes in the mantle producing dynamic topographic effects impact on the gravitational potential energy of the overriding plate and thus impact on the stress state, providing another source of long-term stress variation within continental interiors. Any such natural oscillation in stress state will be about the neutral ambient state and occur on time-scales equivalent to the Wilson cycle (i.e. in the order of 10^8 years). In this sense, plate tectonics can be viewed as the mechanism that provides for an oscillatory forcing of the stress regime within continental interiors, even those far from plate boundaries. Intraplate stress magnitudes are bounded, with regimes varying from mildly compressional to mildly extensional. On the modern-day earth the likely end-member intraplate scenarios are well represented by India and Australia with relatively high levels of intraplate compression, on the one hand, and Africa with relatively high levels of intraplate extension, on the other hand.

The case of critically stressed continents

The occurrence of widely distributed, low-level seismicity within stable continental regions (Fig. 1a), the widespread phenomenon of induced seismicity and the *in situ* stress measurements in deep boreholes, which are consistently approximate to those predicted by Mohr-Coulomb frictional failure theory (e.g. Townend & Zoback, 2000) all suggest that continental crust is typically critically stressed, and almost everywhere are close to, or at, failure (Scholz, 2002) or what Zoback *et al.* (2002) termed steady-state failure equilibrium. The associated rates of deformation are difficult to quantify, in part because recurrence intervals of the large earthquakes that are responsible for any accumulation of the strain on geological time-scales are much longer than historic seismic records. Moreover, there is uncertainty about how the moments of those earthquakes sum. However, available best estimates of the seismogenic rates of deformation for so-called stable continental regions such as Australia based on historical seismic records (Fig. 1b) are of the order of $\sim 10^{-17}$ s^{-1} (Johnston *et al.*, 1994; Zoback *et al.*, 2002; Leonard, 2008; Braun *et al.*, 2009). Local regions within the stable continental regions are deforming almost one order of magnitude faster (Zoback *et al.*, 2002; Sandiford *et al.*, 2004a; Celerier *et al.*, 2005; Sandiford & Egholm, 2008; Sandiford & Quigley, 2009). Similar rates have been inferred in a number of other relatively stable continental regions such as India, China and North America (Johnston *et al.*, 1994), and suggest crustal strains may accrue at a rate of ~3% per hundred million years at the continental scale. The magnitude of intraplate stresses predicted by numerical modelling studies (up to 50 MPa averaged over a 100-km-thick lithosphere) suggests that the forces driving this deformation are around 5×10^{12} Nm^{-1}, consistent with an important role played by plate scale variations in gravitational potential energy (Coblentz *et al.*, 1994).

Such distributed, low strain rate deformation in continental interiors may provide an insight into the significance of the surprisingly young, and somewhat puzzling, low-temperature thermochronological record of most continental interiors. For example, across the Precambrian continental interior of Australia, apatite fission tracks ages are typically *c.* 300 Ma (Gleadow *et al.*, 2002; Kohn *et al.*, 2002). Considering the local geothermal gradient is typically less than 25 °C km^{-1}, this implies some 3–6 km of erosional denudation since the resetting of apatite fission tracks ages. The notion that such erosion is part of the ongoing denudation of originally thicker crust is difficult to countenance, as it would imply surface elevations being at least 1 km higher prior to the mid-Phanerozoic denudation. To achieve such a denudation as part of an ongoing cycle more likely requires isostatically supported relief generation. If such relief generation reflects distributed crustal thickening, then the required thickening of ~10% over 300 Myr equates to a long-term strain rate of $\sim 10^{-17}$ s^{-1}. Remarkably, this is essentially indistinguishable from the inferred modern-day seismogenic strain rate in Australia as discussed above.

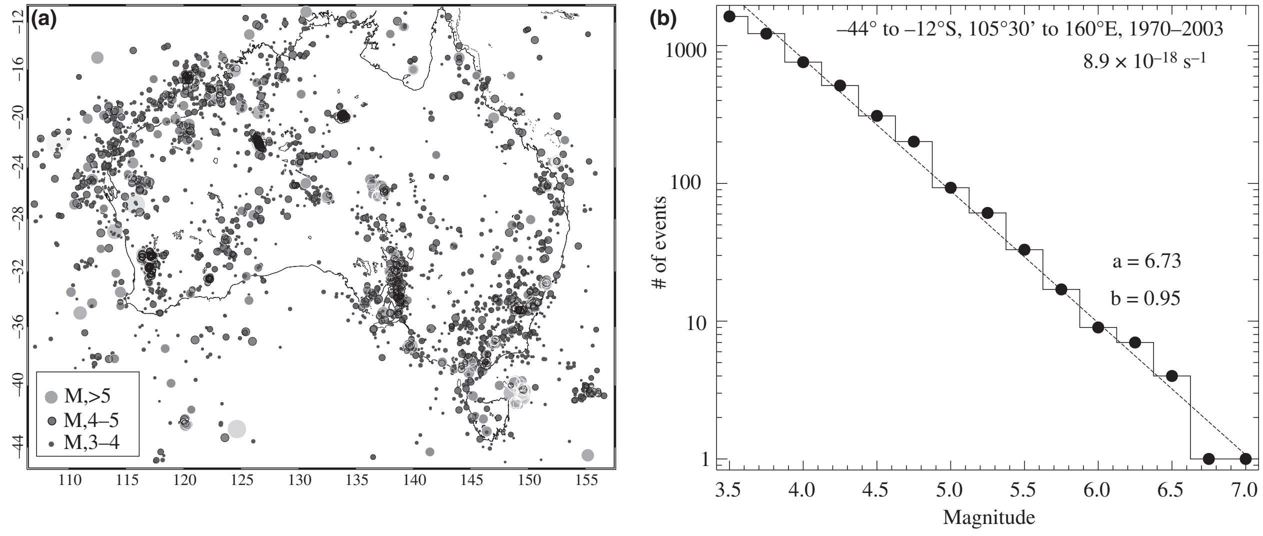

Fig. 1. (a) Distribution of $M > 3$ Australian earthquakes. (b) Gutenberg–Richter relations for Australian earthquakes (1970–2003) which yield a notional seismogenic strain rate of $\sim 10^{-17}$ s^{-1} for the continent as a whole, assuming that the moments of the individual earthquakes sum and the maximum magnitude earthquake is $M_w = 7$ noting that the largest recorded quake is $M_w = 6.8$. For further discussion, see Johnston *et al.* (1994), Sandiford *et al.* (2004a,b), Braun *et al.* (2009) and Sandiford & Quigley (2009).

The case of thermally structured continents

The continental lithosphere shows various levels of geochemical organization that impact on its mechanical behaviour. The most obvious and familiar is the differentiation of the crust and mantle that impacts on both the buoyancy and mechanical strength of the lithosphere. A second level of geochemical organization relates to the distribution of the heat-producing elements within the lithosphere (Birch *et al.*, 1968; Lachenbruch, 1968; Jaupart, 1983; Sandiford & McLaren, 2002) that impacts on its thermal structure and hence its mechanical strength. A variety of observations indicate that heat production accounts for about two-thirds of the surface continental heat flow (typically about 65 mW m^{-2}) and that this heat production is largely concentrated in the upper 10–15 km of the crust. Surprisingly, the reasons why the heat production distribution is organized this way have not been well understood, neither in terms of the absolute amount nor in terms of the degree of differentiation (Oxburgh, 1980). The prevailing contemporary view is that the degree of differentiation is a simple consequence of the lithophile nature of the heat-producing elements, in which case the extent of differentiation might be expected to correlate with the nature of the primary crustal growth processes. The argument is straightforward. As the heat-producing elements preferentially partition into crustal melts they should concentrate in the mid-upper crustal inflationary zone where large granitic bodies congregate, during periods of crustal growth and tectonic reworking. As the nature of crustal growth has changed over time, especially between the Archean and Proterozoic, if this were the case we might expect a correlation between the degree of differentiation and age of crust-forming events.

Sandiford & McLaren (2002) have argued for a more deterministic mechanism recognizing that the details of the distribution of heat-producing elements is crucial to the thermal and mechanical structure of the lithosphere. They showed how small changes in the distribution of heat-producing elements, as might be caused by the long-term accrual of strain implied by modern rates of intraplate seismicity, can significantly impact on the mechanical response of the lithosphere. This is because the thermal structure of the deep crust and upper mantle is influenced by both the amount and the depth distribution of the heat production in the continental crust. Neglecting the second-order effects of temperature-dependent thermal conductivity, the contribution of crustal heat production to the temperature of the deeper crust and upper mantle can be expressed in terms of a very simple relationship between two parameters, h and q_c, representing the distribution of heat sources in terms of depth and absolute amount and the thermal conductivity, k:

$$\Delta T_{q_c} = \frac{h\,q_c}{k}$$

where

$$q_c = \int_0^{z_c} H(z)\mathrm{d}z$$

is the contribution of heat production to surface heat flow (integrated heat production) and

$$h = 1/q_c \int_0^{z_c} H(z)z\ \mathrm{d}z$$

is the effective depth of the heat production. A simple, testable prediction of the Sandiford & McLaren (2002) hypothesis is that q_c and h should be inversely correlated, i.e. crust more enriched in heat production (high q_c) should be more differentiated (low h).

This is precisely what has been demonstrated in a recent analysis of Canadian heat flow data by Perry *et al.* (2006) as shown in (Fig. 2a). Figure 2b shows the Perry data recast in terms of the Sandiford & McLaren (2002) h–q$_c$ parameterization, and indicates that there is strong case to be made that the heat production distribution for Canadian terranes is organized so that it contributes around the same effective Moho heating independently of the absolute amount of heat production, i.e. there is an inverse correlation between h and q_c that maps to the same effective Moho heating. This provides a remarkable insight into the nature of the continental crust, and one of fundamental significance, as it hints at a profound crustal scale thermal organization that potentially links the thermal structure of the continents to their mechanical evolution.

Few other continental regions are so well characterized for heat flow and heat production as Canada; so, it is not yet possible to show whether the 'Perry' relation holds across all continents. Moreover, the absence of very high heat flow provinces in the Perry *et al.* (2006) analysis precludes testing whether the relation holds to high-q_c realms of Fig. 2b. A province that is amenable to such testing is the Australian Proterozoic where very high heat flows (averaging around 85 mW m^{-2}) have long been known to relate to excessive enrichments of high heat-producing rocks in the shallow crust in what is one of the World's premier Uranium provinces (Sandiford *et al.*, 1998; Neumann *et al.*, 2000; McLaren *et al.*, 2003). Figure 2 shows the summary of data compiled by McLaren *et al.* (2003) plotted along with the Canadian data. While the Australian Proterozoic heat flow provinces are far less well characterized than the Canadian heat flow provinces, the data compiled by McLaren *et al.* (2003) imply the Australian high heat production terranes are significantly more differentiated than their similar aged, lower heat flow, counterparts in Canada (i.e. lower h values). These highly differentiated Australian high heat production terranes are now understood to have evolved due to repeated tectonic processing continuing for many hundreds of million years after initial crustal growth (e.g. McLaren & Sandiford, 2001; Sandiford *et al.*, 2001; McLaren *et al.*, 2005), including the relatively youthful Phanerozoic denudation that is

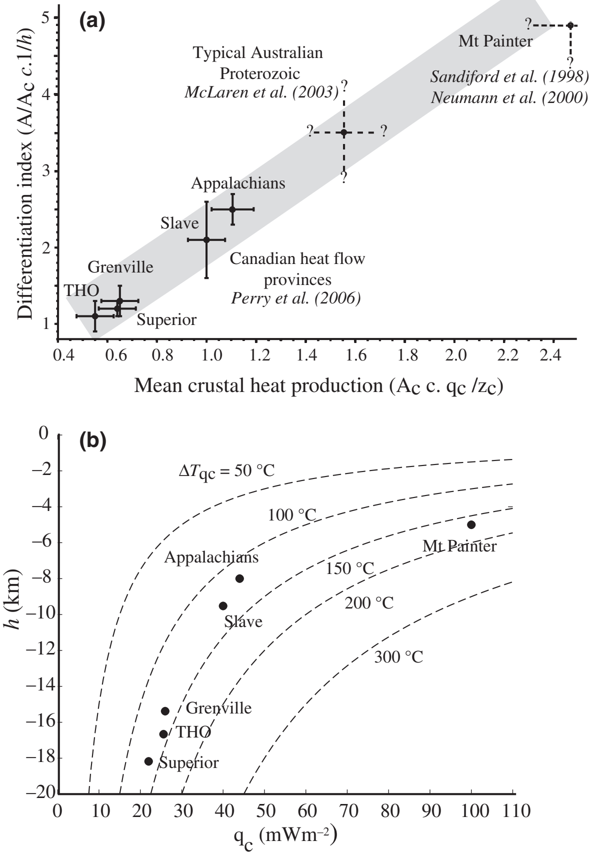

Fig. 2. (a) Crustal heat flow parameterization used by Perry *et al.* (2006) to show that Canadian heat flow provinces exhibit a positive correlation between the degree of differentiation and total abundance of crustal heat production, consistent with predictions by Sandiford & McLaren (2002). Several Australian data sets have been added, although it is noted that these data are not nearly as robust as the Canadian data and should be used with caution (Sandiford *et al.*, 1998; Neumann *et al.*, 2000; McLaren *et al.*, 2003). (b) The Perry *et al.* (2006) data recast in terms of the h–q_c parameterization of Sandiford & McLaren (2002), showing that heat production is configured to produce an effective Moho heating of around 125–150 °C, assuming a temperature-independent thermal conductivity of 3 W m^{-1} K^{-1}. As discussed in the main text, for more typical temperature-dependent conductivities, the contribution of heat production to Moho temperature will be significantly higher.

recorded in the apatite fission track ages alluded to earlier (Gleadow *et al.*, 2002).

Precisely how a given heat production distribution impacts on the Moho temperature depends on the thermal conductivity structure of the crust. Figure 2a is contoured for Moho temperature contributions assuming a constant thermal conductivity of around 3 W m^{-1} K^{-1}. For such a thermal conductivity, the heat production distributions in the Canadian provinces contributes between 125 and 150 °C to Moho temperatures. In fact, the contribution is likely to be higher than this because temperature dependency tends to significantly reduce conductivity significantly at temperatures up to 500–600 °C, and the more likely contribution of heat production is around 200 °C. Moho temperatures are important because the temperature state of the upper mantle is likely to be one the most critical parameters controlling the bulk mechanical strength of the upper mantle (e.g. Zhou & Sandiford, 1992). For example, Brace–Goetze models of lithospheric rheology typically show that changes in Moho temperature of less than 100 °C are needed to change lithospheric strength by a factor of two at a constant strain rate, or change bulk strain rate by one order of magnitude at constant strength (e.g. Sonder & England, 1986; Zhou & Sandiford, 1992). The implication is that processes that modify the distribution of heat-producing elements within the lithosphere, such as deformation and erosion, impact on the long-term strength of the continental lithosphere, and hence the propensity for further activity. This connection has been described in detail by Sandiford & McLaren (2002, 2006) who coined the term ‘tectonic feedback’ to describe it, and interested readers are referred to those papers for a more in-depth discussion of how slow strain rate reworking of the continental lithosphere can contribute to the thermal and geochemical structuring of the continental crust.

DISCUSSION

All three ideas presented above seem to connect the stress distribution and strength (and hence thermal regime) of the lithosphere, and suggest that it is more than just fortuitous that:

1. the mean continental gravitational potential energy is approximately equivalent to the gravitational potential energy of the mid-ocean ridges;
2. the continental crust is just about everywhere in a seismogenically critical state and
3. the distribution of heat production with in the continental crust is organized to produce a characteristic Moho heating of ~200 °C.

The view proposed here is that the emergence of a geochemically, thermally and mechanically structured continental lithosphere reflects the existence of an attractor state for the continental crust. In the introduction it was hinted at how such an attractor state might effect itself, by considering the response of different states. Thinner continental crust, spread over a larger part of the globe, would result in significantly lower $\overline{U}_{cc}$ and hence the time-averaged (ambient) stress state in these thinner continents would be (more) compressional. Accumulation of strain, even at the slow rates associated with critical state continental interior seismicity, would lead to time-averaged crustal thickening, and in doing so reduce the areal extent of the continents and increase $\overline{U}_{cc}$. Increases in $\overline{U}_{cc}$ would reduce the compression leading to lower time-averaged rates of deformation, etc. Conversely, a thicker continental average continental crust, with

$$\overline{U}_{cc} \gg U_{MOR}$$

would be subject to time-averaged extensional stress regimes leading to long-term thinning and a reduction in

$$\bar{U}_{\mathrm{cc}}.$$

Thus, the attractor state is tuned to the neutral ambient stress level, or equivalently the mean plate gravitational potential energy, is communicated via the intraplate stress field and effected by the ability of the continents to accumulate significant strains over long geological time-scales. Of course, changes in plate boundary forcing associated with evolving plate palaegoegraphy cause fluctuations in the stress levels around the ambient state, locally forcing intraplate deformation and ancillary surface process responses. Such plate tectonic forcing can locally accelerate the response time of the continental lithosphere (Fig. 3).

Thus, a corollary of an ambient stress state, in tune with the gravitational potential energy of the mid-ocean ridges, is a crustal evolutionary system attracted towards this state. In a physical sense the attractor can only work effectively if the continental is capable of straining at finite rates. Clearly, low levels of seismicity imply continental interiors are relatively stable. However, as discussed above they are not seismically inert, and seem almost everywhere to be in a near critical stress state. Furthermore, at least in part the distribution of intraplate seismicity in the modern continents can be correlated with variations in thermal regime (e.g. Liu & Zoback, 1997; Perry *et al.*, 2004; Celerier *et al.*, 2005; Sandiford & Egholm, 2008; Sandiford & Quigley, 2009).

It is well appreciated that the ability of continents to respond to imposed stress depends in part on the thermal state and therefore the distribution of heat-producing elements. As shown by Sandiford & McLaren (2002) repeated processing of the continental crust through the coupling of small strain increments at intraplate strain rates ($<10^{-16}$ s^{-1}) and surface processing (erosion/deposition) has the capability to order heat-producing elements in the crust, with the proviso that heat-producing elements show some primary differentiation. Such an ordering impacts the thermal regime and the mechanical response of the lithosphere. It provides an intriguing insight that connects the emergence of long-term geochemically, thermally and mechanically structured lithosphere, as shown conceptually in Fig. 3. The main new additional insight contributed here is that if such a process is driven by forcing in response to time-dependent fluctuation in the stress field, then it would also be tuned to produce continental crust that has the gravitational potential energy close to that of the mid-ocean ridges, and hence about 40 km thick, just as the modern continents appear to be.

Finally, for the ideas presented here to have any validity, there must be a significant role played by intraplate activity in shaping continental interiors, and this may be seen as a problem for many geologists who have been imbued with the notion that all tectonics occurs at plate margins. As articulated above, there is evidence that significant regions with the continents are, and have been, deforming at rates of the order of 10^{-17} s^{-1} (see also Zoback *et al.*, 2002). Moreover,

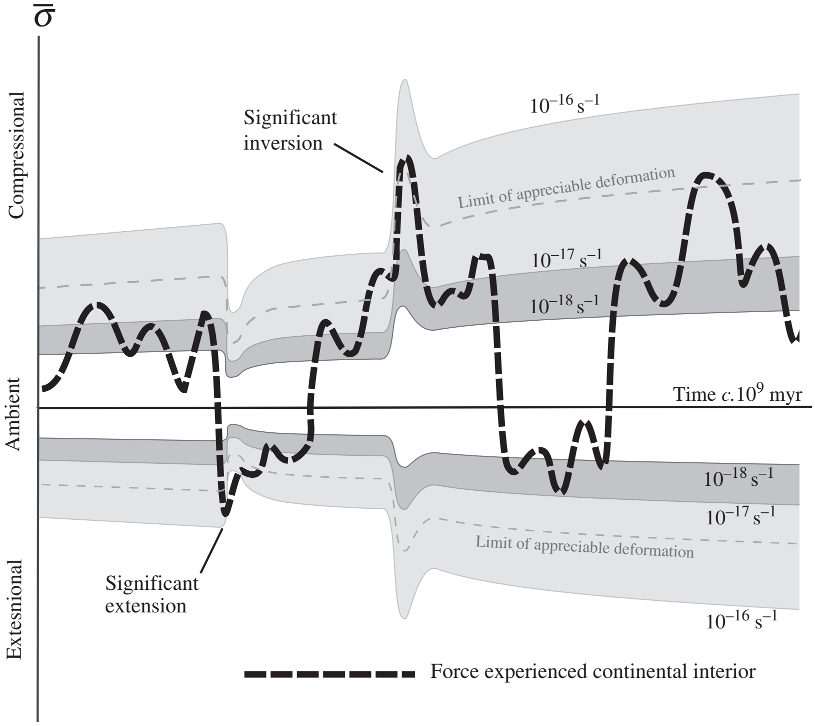

Fig. 3. Schematic illustration of the response of a continental interior to oscillatory forcing of the *in situ* stress state driven by changes in distant plate boundary activity on long geological time-scales. Straining, and associated surface processing, lead to associated changes in the thermal and mechanical state of the lithosphere through the redistribution of heat-producing elements. In turn these changes effect changes in the response of the lithosphere to future forcing (e.g. Sandiford & McLaren, 2002). A gradual increase in lithospheric strength is implied by the secular decrease in heat-producing elements within the lithosphere that induces a significant cooling on the billion-year time-scale.

intraplate deformation is likely to have been even more prevalent early in earth history, when heat production rates were even greater than today (e.g. Sandiford *et al*., 2004b; Bodorkos & Sandiford, 2006). The relevant point is the incredible lengths of time available to accrue intraplate strains; so, even such very slow strain rate deformation can potentially impact on the structure of the continents, especially when coupled to surface processes. Indeed without such impact and coupling, it would be very difficult to account for observations such as the anomalously young low-temperature thermochronological record of the continents.

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