Why is the North America Cordillera high? Hot backarcs, thermal isostasy and mountain belts

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ABSTRACT

Global mountain belts are commonly concluded to be a consequence of crustal thickening resulting from continental collision, with high elevations supported by crustal roots. However, accumulating seismic structure data indicate that many mountain belts have no crustal root. Most of the North American Cordillera has 30-35 km crust in contrast to 40-45 km for the lower elevation craton and other stable areas. It has been shown previously that most such mountain belts are in present or recent backarcs that are uniformly hot. From thermal constraints we predict a uniform ~1,600 m elevation support of the Cordillera by thermal expansion compared to stable areas. Over most of the Cordillera the actual elevation difference after correction for variable crustal thickness and density is in excellent agreement. When subduction and shallow backarc convection stop, the lithosphere may cool and the elevation of mountain belts subside over ~300 Ma.

INTRODUCTION

Ocean closing followed by continent collision is a simple elegant explanation for the major global mountain belts. Shortening and crustal thickening result in a crustal root and high

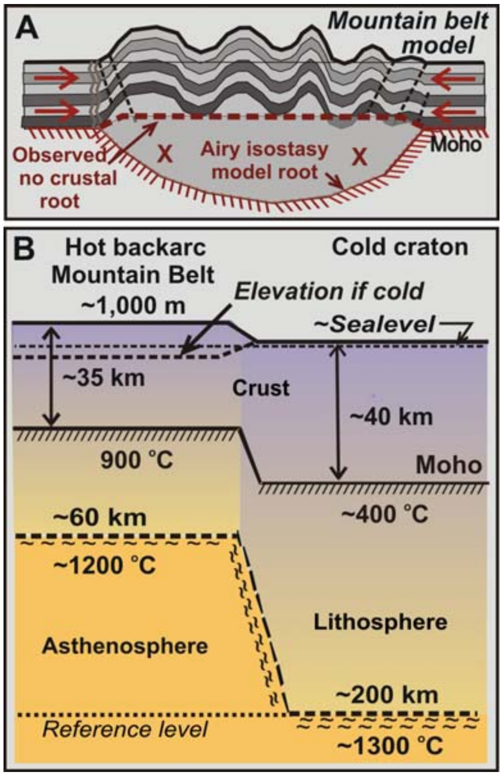
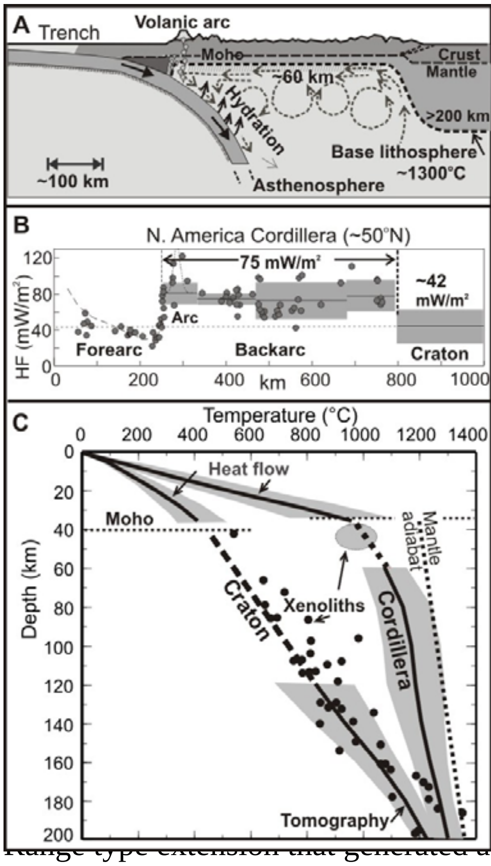


Figure 1. (a) Crustal root Airy isostasy model compared to observed common thin crust. (b) Characteristic elevations and crustal thicknesses for hot backarcs like the North America Cordillera and cool cratons that are in isostatic balance. High elevations are commonly associated with thin crust, in contrast to Airy isostasy predictions.

elevations through Airy isostasy (Figure 1). The type example is the Himalaya-Tibet region of India-Asia collision where the crust reaches ~70 km and elevations ~5 km. Here we address a prediction of the collision model that is commonly not observed for other mountain belts, a thick crust root. It is now evident that the crust is in fact thin in many major mountain belts, including the North America Cordillera, commonly 30-35 km in contrast to 40-45 km for cratons and other stable areas (e.g., Mooney et al., 1998).

The U.S. Basin and Range has long been known to have a thin 30-35 km crust, often ascribed to its ongoing crustal extension. However, it has only recently been recognized that most of the Cordillera has similarly thin crust, ~35 km although 1000-1500 m elevations (e.g., summaries by Clowes et al., 1995; 2005; Perry et al., 2002; Mooney et al., 1998; Bensen et al., 2009). Clearly a thickened crustal root does not support most of the Cordillera. We argue that the majority of mountain belts are in backarcs that are consistently hot and have nearly constant thermal expansion elevation support (Figure 1). Superimposed are local elevation effects due to variations in crustal thickness and crustal density. We deal with the North America Cordillera but suggest that our conclusions apply globally.

A number of authors have discussed the large effect of temperature on elevation (e.g.,



ry et al., 2000 and references therein). In an important

Chapman (2007) showed that elevation is related to the

v data, after correction for crustal thickness and density

ar, there is a considerable scatter likely because of large

from heat flow. An important estimator of upper mantle

aphy, has recently become available that, with other

e quantitative assessment of the relationship between

KARCS; NORTH AMERICAN CORDILLERA

has often been discussed in terms of Cenozoic Basin and Range-type extension that generated a thin high temperature lithosphere. However, Lowry et al. (2000) demonstrated that extension cannot explain the elevations. Hyndman et al. (2005) and Currie and Hyndman (2006) documented that uniformly high upper mantle temperatures and thin ~60 km lithospheres are characteristic of most current and recent subduction zone backarcs globally, including those with no significant recent extension. The Cordillera is a current backarc or recent backarc such that the thermal effects have not significantly decayed. The high temperatures and thin lithosphere are argued to be produced by shallow small-scale convection that results from a reduction in upper mantle viscosity by subducted water (e.g., Dixon et al., 2004; Honda and Saito, 2003) (Figure 2a). Continental thermal regimes are distinctly bimodal, divided mainly into backarcs and stable areas with limited transition areas. The thermal constraints indicate surprisingly small variability in upper mantle temperatures within each region (e.g., Currie and Hyndman, 2006, and references therein). We argue that there is a consequent bimodal distribution of thermally controlled elevations.

There is high heat flow throughout the North America Cordillera backarc (e.g., Blackwell and Richards, 2004), but considerable scatter in part due to variable upper crustal heat generation that has only a small effect on deep temperatures. Correction to a reference heat generation reduces the variability in heat flow and inferred deep temperatures (e.g., Hyndman and Lewis, 1999; Figure 2b**)**. Seismic tomography upper mantle velocities are another important estimator of temperatures (e.g., Goes and van der Lee, 2002; van der Lee and Frederiksen, 2005), although as noted below, caution is needed where partial melt may affect velocities. Tomography-based temperatures have low horizontal resolution but similar to that for crustal thickness data and for lithosphere flexural wavelengths used for isostasy calculations. Xenoliths provide an important additional thermal constraint mainly in cratons.

Figure 2. (a) Schematic cross-section of backarc shallow small-scale convection, (b) Uniform high heat flow across North America Cordillera backarc (see text), (c) Temperature-depth and variability for the northern Cordillera and adjacent Craton (see text).

Figure 2c illustrates average geotherms and variability for the Canadian Cordillera backarc and adjacent craton (Hyndman et al., 2009). Geotherms are similar for most of the U.S. Cordillera and stable areas (e.g., Goes and van der Lee, 2002). There is a dramatic contrast between the Cordillera and stable areas, ~500^{o}C at ~100 km depth. The Cordillera hot backarc excludes the cool present and recent subduction zone forearc, and the eastern foreland belt where the Cordillera upper crust overthrusts the cold cratonic lithosphere (see SOM). The backarc temperatures everywhere below ~60 km are similar and have a small increase with depth, close to a single adiabatic gradient. The stable craton temperatures approach the mantle adiabat deeper than ~200 km at a shallow angle (e.g., Eaton et al., 2009). The top of Cordillera adiabatic temperatures is taken to mark the top of vigorous small-scale convection (e.g., Currie and Hyndman, 2006). Below ~60 km large lateral temperature variations are therefore not expected.

There are small velocity variations in the upper asthenosphere, 60-200 km depth, especially in the United States Cordillera (e.g., Bensen et al., 2009, and references therein). The temperatures inferred from velocity-temperature relations for some low velocity areas appear to be above those for partial melting, and much of the velocity variability may be better explained by the effect of small amounts of melt (e.g., Hammond and Humphreys, 2000) rather than especially high temperatures. We ignore the small density and isostasy effect of such partial melt.

The most significant regional upper mantle velocity variation is slightly lower than average in a region of central and southern U.S. Cordillera (e.g., van der Lee and Frederiksen, 2005; Bensen et al., 2009). There also is smaller scale variability defined in detail by recent US Array data (e.g., Obrebski et al., 2010; Schmandt and Humphreys, 2010, and references therein). Most variations are less than 10-15% of the contrast between the Cordillera and craton so, even if the velocity variations are due to temperature, the range is less than about ±50^{o}C compared to a Cordillera-craton contrast of about 500^{o}C, and therefore the thermal isostasy effect is small (see SOM). Surprisingly the currently extending Basin and Range province exhibits little difference in velocities below ~60 km compared to the Cordillera average (e.g., Goes and van der Lee, 2002; Bensen et al., 2009). Also, most of the Colorado Plateau which had large Cenozoic uplift, exhibits only small differences from the Cordillera average (e.g., Schmandt and Humphreys, 2010; Sine et al., 2008). The Yellowstone Plateau region does have a local low velocity anomaly, especially deeper than 200 km (e.g., Obrebski et al., 2010; Schmandt and Humphreys, 2010)., which may be due to partial melt rather than especially high temperature.

LITHOSPHERE TEMPERATURE AND ELEVATION

If the general association of backarcs with nearly uniform thin hot lithospheres is accepted, we expect that thermal expansion will contribute a nearly constant amount to surface elevation. The average temperature difference between Cordillera and craton from the surface to ~200 km depth where the two geotherms converge, is about 250°C (e.g., Figure 2c). Using these summary temperatures and a coefficient of thermal expansion of 3.2×10^{-5} $^{o}C^{-1}$ (Hasterok and Chapman, 2007) the Cordillera is predicted to be ~1,600 m higher than the craton for the same crustal thickness. Alternatively, for the same elevation, the craton requires a ~12 km thicker crust for isostatic balance. There may be an elevation effect due to systematic mantle composition differences but much smaller than that for temperature (e.g., Kaban et al., 2003). Within the Cordillera backarc, local variations in elevation are then interpreted to be mainly due to variations in crustal thickness (corrected for average density). A similar association of elevation and crustal thickness is expected for stable areas but 1,600 m lower.

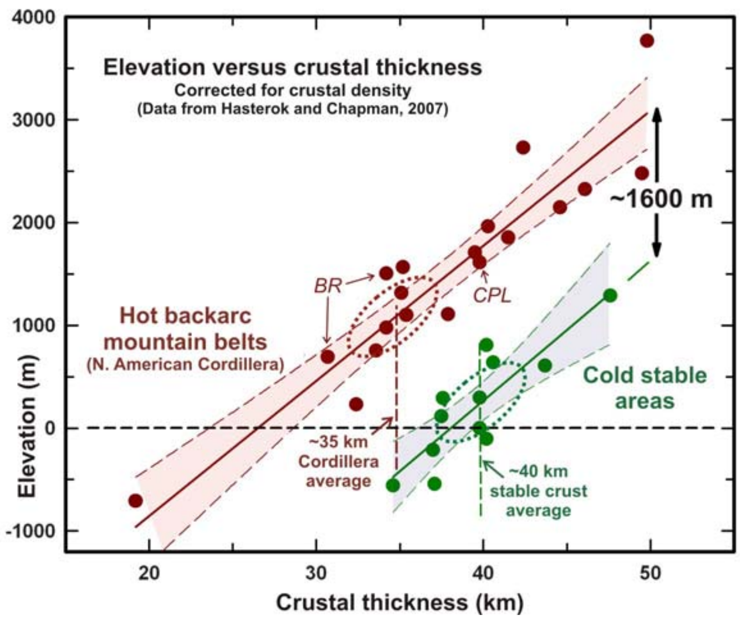
For the Cordillera backarc the thermal elevation is not very sensitive to the crustal temperature gradient (and heat flow), because the geotherm from the base of the lithosphere to ~200 km depth (e.g., Figure 2c) everywhere has nearly the same convectively maintained adiabatic temperatures. A difference of 20% in Cordillera crustal gradient (and lithosphere thickness and heat flow) results in only ~10% change in the thermal elevation compared to the craton (see SOM). For the craton which is conductive to ~200 km, variations in near surface gradient and heat flow directly affect the average temperature to 200 km and therefore the surface elevation.

ELEVATION AND CRUSTAL THICKNESS FOR BACKARCS AND STABLE AREAS

To test the model of uniform backarc high temperatures resulting in a nearly constant contribution to elevation, we have used the broadly spaced compilation of North America crustal thickness and elevation data, corrected for crustal density, by Hasterok and Chapman (2007). They used average crustal velocity (commonly well determined in wide angle seismic studies) and relations between density and velocity by Christensen and Mooney (1995). The reference density is 2850 kg m^{-3}. The density corrections average 120 m so are generally much smaller than the thermal effect. As pointed out by Hasterok and Chapman there is an interesting trend of inferred higher average crustal densities for thick crust and low densities for thin crust (shown in SOM).

Figure 3. Elevation corrected for crustal density versus crustal thickness showing the ~1600 m difference between the Cordillera and stable areas (linear regressions and 95% confidence). The ellipses include most of the North American Cordillera and stable areas; sites covering a wider range were selected to better define the relations. CPL: Colorado Plateau. BR: Basin and Range.

Cordillera sites in the current or recent forearc are excluded because their thermal regime is controlled by subduction effects, and the foreland belt where Cordillera crust overthrusts cold craton lithosphere. The Appalachians region has been excluded as it may have been in a backarc ~300 Ma ago and still have a residual thermal anomaly. Most of the Cordillera has crustal thicknesses of 30-35 km (ellipses in Figure 3) but the sites have been chosen to cover a considerable range of crustal thicknesses in order to define the thickness vs elevation relations.. In the compilation the Cordillera backarc and stable area average crustal thicknesses are 33±5 km and 40±4 km respectively.



We expect and observe the Cordillera to be consistently higher than stable areas with the same crustal thickness (histograms in SOM). The observed quite constant ~1,600 m difference for the same crustal thickness is ascribed to the density reduction by thermal expansion in the backarc, i.e., thermal isostasy. This difference is in good agreement with the ~1,600 m predicted from the average temperature difference calculated above. The slopes between crustal thickness and elevation provide the crust-mantle density contrast, 131±12 m/km for the Cordillera and 141±27 m/km for stable areas. For the reference of Hasterok and Chapman (2007) with a 410 kg/m^3 density contrast (crust 2850 kg/m^3 and mantle 3260 kg/m^3) the slope is 126 m/km. Our slopes imply slightly larger contrasts of 429 kg/m^3 for the Cordillera and 459 kg/m^3 for stable areas, but the differences are not significant. For average crustal density the sealevel crustal thickness is ~27 km for the Cordillera and ~38 km for the craton (Figure 3).

The effect of Cordillera backarc high temperatures on elevation is clearly evident in the transition from thin to thick crust eastward in the southeastern Canadian and southeastern U.S. Rocky Mountains. The crust thickens eastward from 30-35 to 45-50 km over the underlying backarc-craton lithosphere thermal boundary with little change in elevation or Bouguer gravity (e.g., Hyndman and Lewis, 1999; Reiter 2008; Li et al., 2005). The isostasy effect of eastward increased crustal thickness is balanced by the thermal isostasy effect of the decrease in average temperature to ~200 km.

Several Cordillera areas that might be expected to have different crustal thickness-elevation relationships are not significantly anomalous (Figure 3). The Basin and Range is a little high compared to our relation, perhaps due to especially thin lithosphere or small amounts of partial melt, but within the uncertainties. The Colorado Plateau where there has been Cenozoic uplift of up to 2 km (see Flower, 2010, for a discussion) also fits our relation well. The Plateau uplift is approximately that expected from a change from a cool stable thermal regime to that of the Cordillera backarc. The Yellowstone Plateau is not in the compilation but uncorrected for crustal density variations it fits the Cordillera relation well (~47 km and ~2400 m). However, our emphasis is on the overall Cordillera backarc and detailed study is needed for accurate thermal isostasy models for these and other special areas.

DISCUSSION AND CONCLUSIONS

Although there has been a complex tectonic history with crustal shortening and probably thickening, the Cordillera now has a generally thin crust. The high elevations are interpreted to be primarily due to the thermal isostasy effect of nearly constant high temperatures. The effect of the thermal regime on elevation is strongly bimodal. The Cordillera versus stable area elevation difference of ~1,600m (after correction for crustal thickness and density) is explained by the average temperature difference of ~250^{o}C. Only Cordillera areas higher than about 1,600 m above the near-sea level average of stable areas, have thick crustal roots. Our analysis implies that other effects on elevation such as mantle dynamics generally must be small. Much of the scatter in the elevation versus crustal thickness plots can be explained by uncertainties in crustal densities and thicknesses, i.e., about ±200 m due to the 1-2 km uncertainties in crustal thickness and similar from the uncertainties in crustal densities.

Since high temperatures in backarcs like the Cordillera are concluded to be a consequence of shallow convection, we expect backarcs to cool and subside following the termination of subduction and loss of water that maintains low viscosity. Lithosphere cooling and thickening is expected to occur following transient processes such as slab windows that may last a few 10's of Ma. A simple conductive cooling model (Currie and Hyndman, 2006) has a thermal time constant and expected elevation decay of ~300 Ma. The study by Holt et al. (2010) on the thermal subsidence of backarc basins showed a similar decay time of ~300 Ma. Further work involving a careful examination of the elevation-crustal thickness relation for former backarc regions is required to define this cooling subsidence.

A consistent elevation difference between backarc mountain belts and stable areas has not yet been demonstrated for the other continents. However, a number of other continental backarcs have been found to be uniformly hot, similar to the North American Cordillera (Hyndman et al., 2005; Currie and Hyndman, 2006) which should result in a first order constant thermal isostasy. We conclude that many backarc mountain belts including most of the North America Cordillera are high primarily because they are hot, not because of crustal roots, except in the areas of large recent crustal thickening.

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Why is the North America Cordillera High? Hot Backarcs, Thermal Isostasy, and Mountain Belts Supporting Online Material (SOM)

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Area of North America backarc

The area of the North America Cordillera backarc with inferred uniformly hot and thin lithosphere is shown in **Figure A1**. Excluded are the current Cascadia forearc and the recent forearcs of western California and western British Columbia north of Cascadia because they have thermal regimes influenced by cooling subduction effects, and the eastern Cordillera foreland belt where Cordilleran crust overthrusts cold craton lithosphere. The deep Cordillera-Craton thermal boundary is precisely defined only in a few places. Bensen et al. (2009) provide estimates of this boundary based on seismic velocity and crustal thickness data.

Figure A1. The North America Cordillera showing the region of the hot backarc mobile belt.

Histograms of elevations in Cordillera backarc compared to craton

Figure 2A shows histograms of the elevation points of Hasterok and Chapman (2007) for North America Cordillera backarc compared to the craton and other stable areas. The elevations have been corrected for the isostasy effects of crustal thickness and of crustal density (from average seismic velocity) as described by Hasterok and Chapman (2007). There are two distinct populations with no overlap. The average difference in elevation is 1,600m. Although there may be other effects on isostasy, the scatter of points around the two means is approximately that expected for the uncertainties in crustal thicknesses and crustal densities.

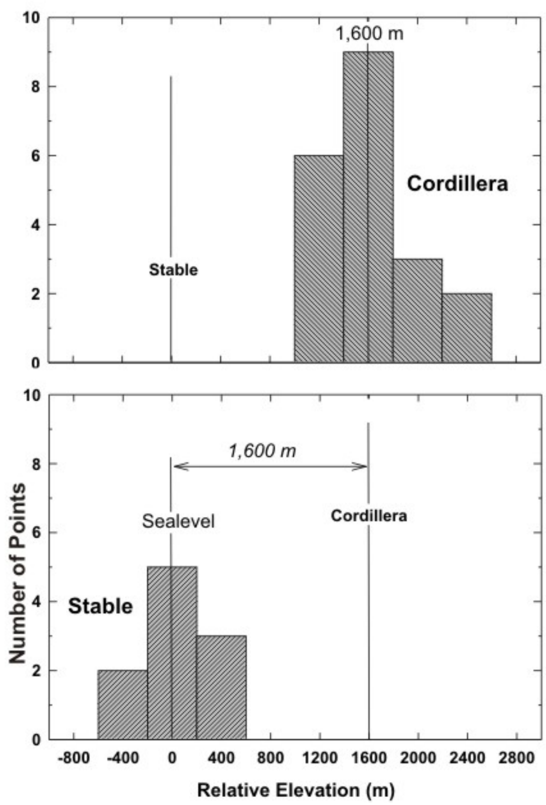

Figure A2. Histograms of elevations in Cordillera backarc compared to the craton and other stable areas of North America. Elevation corrections for average crustal density Elevation corrections for crustal thickness and density variations

Corrections to elevation from crustal density

Figure A3 shows the corrections to give equivalent elevations for variations in average crustal density estimated from average seismic velocity. This correction reduces the scatter significantly and removed the bias resulting from the systematic variations in crustal density illustrated in **Figure A4**.

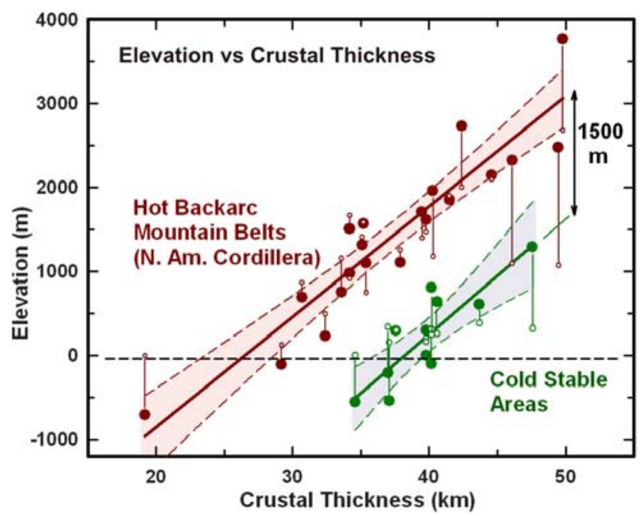

Figure A3. Elevation versus crustal thickness data for North America, showing the elevation corrections for average crustal density based on average crustal seismic velocity. Solid points are corrected, open points are uncorrected (data from Hasterok and Chapman, 2007).

Average crustal density versus crustal thickness

Figure A4 illustrates the average crustal density estimated from average seismic velocity showing the trend of higher average density for thicker crust as noted by Hasterok and Chapman (2007). The result is that thick crust areas are at slightly lower elevation compared to thin crust areas than expected for simple isostasy. This trend is as yet unexplained.

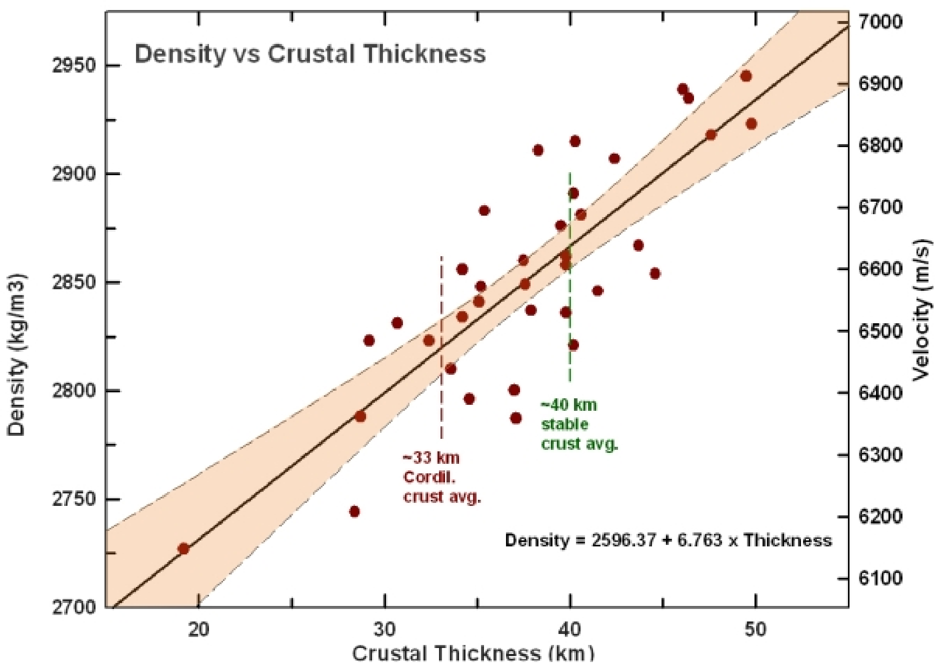

Figure A4. Average crustal density versus crustal thickness, based on density from average seismic velocity. Although there is considerable scatter, average crustal density appears to increase with crustal thickness (data from Hasterok and

Sensitivity of thermal elevation to backarc lithosphere thickness

Figure A5 shows the sensitivity of backarc thermal elevation to lithosphere thermal regime as illustrated by lithosphere thickness. A simple linear thermal gradient approximation and no lateral variations in radioactive heat generation are assumed. For lithosphere less than about 80 km thick, there is low sensitivity of elevation to lithosphere thickness, less than about 15% smaller predicted thermal elevation for 80 km vs 60 km, because in backarcs the deeper part of the thermal regime has everywhere inferred approximately the same convective adiabat to the reference depth of about 200 km. The thermal elevation anomaly relative to the craton reference decreases more rapidly for lithosphere thicknesses greater than about 100 km, reaching zero at the reference depth of about 200 km for craton lithosphere.

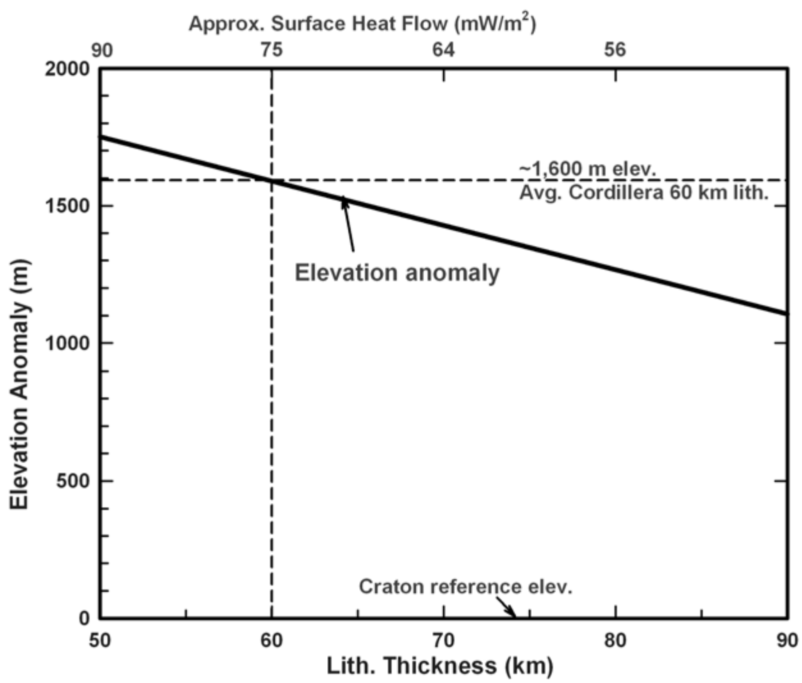

Figure A5. Simple model elevation as a function of lithosphere thickness and approximate heat flow (see text for explanation).

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