The consequences of Canadian Cordillera thermal regime in recent tectonics and elevation: a review[1,2]

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Abstract: The crust and upper mantle thermal regime of the Canadian Cordillera and its tectonic consequences were an important part of the Cordillera Lithoprobe program and related studies. This article provides a review, first of the thermal constraints, and then of consequences in high surface elevation and current tectonics. Cordillera and adjacent craton temperatures are well constrained by geothermal heat flow, mantle tomography velocities, upper mantle xenoliths, and the effective elastic thickness, Te. Cordillera temperatures are very high and laterally uniform, explained by small scale convection beneath a thin lithosphere, 800–900 °C at the Moho, contrasted to 400–500 °C for the craton. The high temperatures provide an explanation for why the Cordillera has high elevation in spite of a generally thin crust, ~33 km, in contrast to low elevation and thicker crust, 40–45 km, for the craton. The Cordillera is supported ~1600 m by lithosphere thermal expansion. In the Cordillera only the upper crust has significant strength; Te ~ 15 km, in contrast to over 60 km for the craton. The Cordillera is tectonically active because the lithosphere is sufficiently weak to be deformed by plate boundary and gravitational forces; the craton is too strong. The Canadian Cordillera results have led to new understandings of processes in backarcs globally. High backarc temperatures and weak lithospheres explain the tectonic activity over long geological times of mobile belts that make up about 20% of continents. They also have led to a new understanding of collision orogenic heat in terms of incorporation of already hot backarcs.

Résumé : Le régime thermique de la croûte et du manteau supérieur de la Cordillère canadienne et les conséquences tectoniques ont représenté une partie importante du programme Lithoprobe de la Cordillère et des études connexes. Le présent article analyse tout d'abord les contraintes thermiques puis les conséquences à de hautes élévations et sur la tectonique en cours. Les températures de la Cordillère et des cratons adjacents sont bien contenues par le flux géothermique, les vitesses déterminées par tomographie du manteau, les xénolites dans le manteau supérieur et l'épaisseur élastique effective, Te. Les températures dans la Cordillère sont très élevées et latéralement uniformes, ce qui s'explique par de la convection à petite échelle sous une lithosphère mince, 800–900 °C au Moho, par rapport à 400–500 °C pour le craton. Les températures élevées expliquent la raison pour laquelle la Cordillère a une altitude élevée malgré une croûte généralement mince, ~33 km, par rapport à une élévation moindre et une croûte plus épaisse, 40–45 km, pour le craton. Environ 1600 mètres de la Cordillère sont supportés par une expansion thermique de la lithosphère. Dans la Cordillère, seulement la croûte supérieure possède une résistance importante, Te ~15 km, par rapport à plus de 60 km pour le craton. La Cordillère est tectoniquement active parce que la lithosphère est assez faible pour être déformée par les forces gravitationnelles et aux limites de la plaque; le craton est trop fort. Les résultats obtenus de la Cordillère canadienne ont mené à une nouvelle compréhension des processus globaux des arrières-arcs. Des températures élevées dans les arrières-arcs et des lithosphères faibles expliquent l'activité tectonique, sur de longues périodes géologiques, des ceintures mobiles qui composent environ 20 % des continents. Elles ont aussi mené à une meilleure connaissance de la chaleur de collision orogénique en terme d'incorporation d'arrières-arcs déjà chauds.

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Introduction

Among the many Lithoprobe geophysical data sets from the southern and northern Canadian Cordillera were two related surprises that are interpreted in terms of hot thin lithosphere. The first is the high and laterally nearly constant crust and upper mantle temperatures across the whole Cordillera, not just near the Cascadia volcanic arc, from high heat flow, low upper mantle seismic velocities, and other thermal indicators. The high temperatures are ascribed to thin lithosphere and shallow convection in the upper mantle (Fig. 1). The second, related surprise is the remarkably uniformly thin crust, Moho at an average of ~33 km, in spite of the high elevation. The adjacent craton and stable plat-

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Fig. 1. A schematic cross-section of the southern Canadian Cordillera illustrating the uniform high temperatures and thin weak lithosphere in contrast to the low temperatures and thick strong lithosphere of the adjacent craton. The high temperatures are inferred to result in a weak detachment zone in the lower Cordillera crust that allows translation of the upper crust toward the foreland thrust zone driven by terrane collisions.

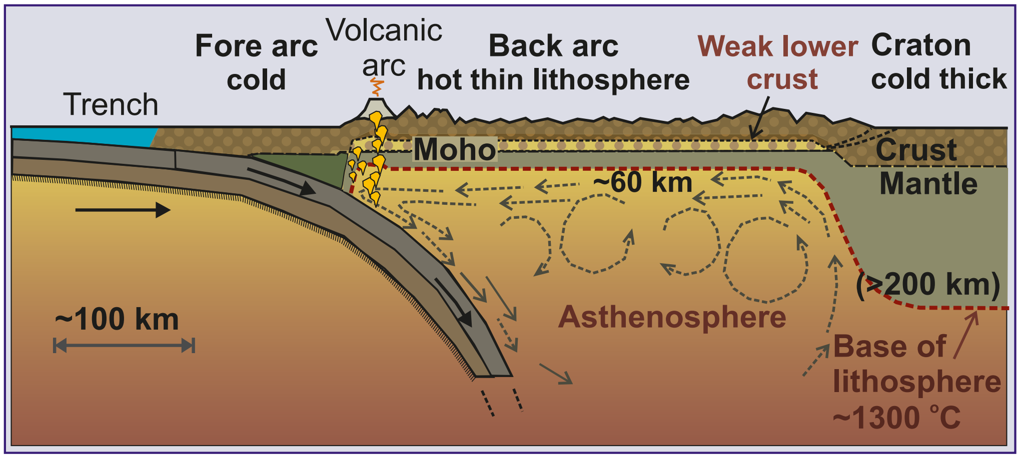
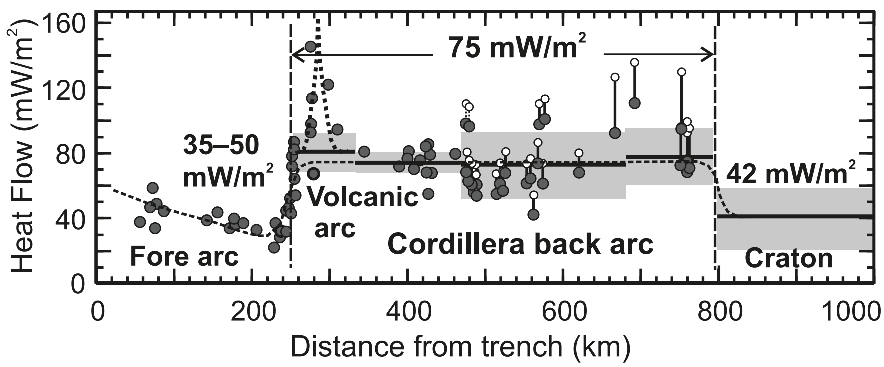


Fig. 2. Heat flow data across the southern Canadian Cordillera. The open symbols are uncorrected, the filled symbols are corrected to that expected for an upper crustal heat generation of 1.3 μWm (see Lewis et al. 1992).



form has thicker crust, Moho depth of 40–45 km, and lower elevation. This contrast is the opposite of that predicted by simple Airy isostasy. The contrast can be explained by the high Cordillera temperatures and elevation supported by lithosphere thermal expansion. In this review, we first summarize the constraints on deep crust and upper mantle temperatures in the Cordillera and adjacent North American Craton, and then discuss the main consequences in terms of mountain belt elevation and ongoing mobile belt tectonics. Finally, we summarize the case that past orogenic heat evident in the geological record may commonly be explained by the incorporation of already hot backarcs into continental collision orogenies.

Constraints to deep crust and upper mantle temperatures

Heat flow and upper crust heat generation

Extensive high quality borehole heat flow data are available across both the southern and northern Canadian Cordillera Lithoprobe transects. For the southern transect there are also measurements from marine probes in coastal inlets, petroleum exploration wells on the shelf, and marine probes in the adjacent deep sea. In both regions, there are also extensive measurements of upper crust radioactive heat generation in plutonic rocks, as required for accurate deep temperature extrapolation and modelling.

For the southern Canadian Cordillera, the heat flow is high in the volcanic-arc region and for 500 km east into the backarc, approximately to the Rocky Mountain Trench (Davis and Lewis 1984; Lewis et al. 1988; Hyndman and Lewis 1999). Blackwell et al. (1990) reported similarly high heat flows across the backarc in adjacent northwestern USA. The entire Cordilleran mountain belt in this region appears to be uniformly hot as concluded by Blackwell (1978). The heat flow is very low, 30–50 mWm^{-2}, in the Cascadia forearc, as expected from the heat absorbed by the cold underthrusting oceanic plate (e.g., Lewis et al. 1988; Hyndman 1995; Hyndman and Wang 1995). In the backarc, heat flow increases eastward from ~70 mWm^{-2} near the arc to >100 mW m^{-2} toward the Rocky Mountain Trench (Fig. 2). Numerous measurements of near-surface radiogenic heat production show that the eastward increase in surface heat flow is correlated with an eastward increase in heat production, from ~1 μW m^{-3} in the west to 3.6 μWm^{-3} in the east, such that the deep thermal structure is concluded to be nearly uniform across the backarc. The reduced heat flow is ~60 mWm^{-2} (Lewis et al. 1992; Hyndman and Lewis

Fig. 3. Temperature–depths for the southern Canadian Cordillera and adjacent craton from heat flow-heat generation to 40 km, and from *S*-wave velocity (*V*s) tomography and xenoliths deeper (modified from Hyndman et al. 2009, see it for details). Pn velocities, seismic velocities from the uppermost mantle.

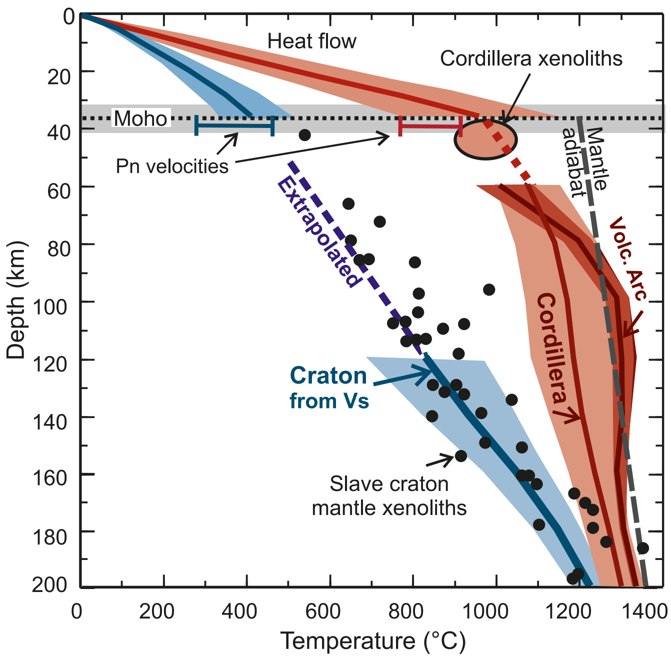
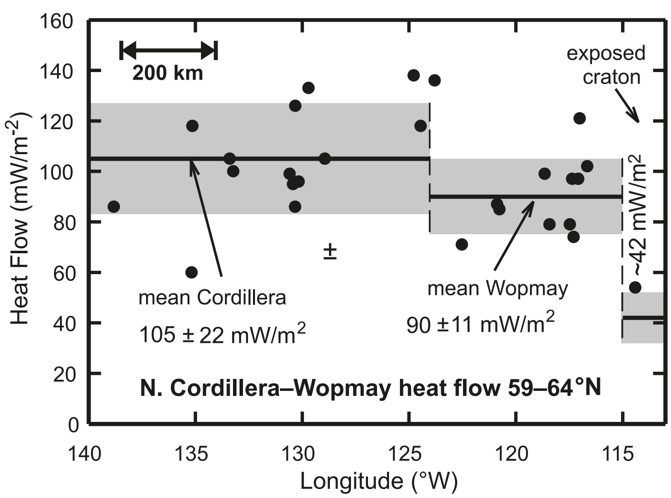


Fig. 4. Heat flow measurements across the northern Canadian Cordillera showing the high values and large scatter inferred to result from the large variations in upper crustal heat generation (modified from Lewis et al. 2003).



1999). For a common upper crustal heat production of 1.3 μWm^{-3} in the upper 10 km of the crust, the Cascadia backarc heat flow corrected to this reference is quite uniform, ~75 mW m^{-2} (Fig. 2). Geotherms calculated for the corridor indicate very high temperatures in the lower crust and upper mantle (e.g., Hyndman and Lewis 1999; Lowe and Ranalli 1993; Lewis et al. 1992; Currie and Hyndman 2006; Fig. 3). The temperatures at the Cordillera Moho are 800–900 °C, and for the adjacent craton 400–500 °C. This well constrained contrast between the two regions is also evident in the other temperature constraints discussed later in the text. Thermal measurements in the Western Canada Sedimentary Basin that overlies the western craton have disturbances due to hydrothermal water flow, but the deep heat flow is concluded to be generally low, similar to that further to the east in the exposed craton (e.g., Osadetz et al. 1992; Grasby et al. 2009 and references therein).

For the northern Canadian Cordillera Lithoprobe corridor, from the coast to the craton, extensive borehole heat flow measurements and radioactive heat generation measurements are also available (Lewis et al. 2003; Lewis and Wang 1998; Majorowicz 1996; Jessop et al. 1984; Sass et al. 1985; Beach et al. 1987; Majorowicz et al. 1999; Majorowicz et al. 2005). There are no measurements in the Yakutat collison zone near the coast or near the northernmost Queen Charlotte – Fairweather fault. In the area of the Queen Charlotte Basin, the heat flow is high as expected for a mid-Tertiary extensional basin (Lewis et al. 1991, 1994). Across the Queen Charlotte Islands margin, the heat flow decreases from the deep sea landward to low values near the coast, interpreted to be due to the effect of oblique underthrusting (Hyndman et al. 1982). The regional northern Cordillera heat flow is unusually high, average 105 mW m^{-2} (Fig. 4), higher than the southern profile (e.g., Hyndman et al. 2005*a*). The very high heat flow is concluded to be due to unusually high crustal heat generation, average 4.6 μWm^{-3}. The estimated average geotherm for the northern Cordillera is very similar to that for the south, although the former may be slightly hotter because of the high heat generation in the upper crust. The adjacent stable platform in this region is the Paleoproterozoic Wopmay orogen, which has unusually high heat flow for its age, average ~90 mW m^{-2}. The heat generation for this region has considerable uncertainty but is concluded to be exceptionally high, about 4.8 μWm^{-3} (Lewis et al. 2003). Lewis et al. (2003) inferred that the deep temperatures are cooler than for the Cordillera although higher than for the craton further to the east due to the high upper crust heat generation (also Flück et al. 2003; Flück 2003; Fig. 5).

Temperatures from upper mantle seismic velocities

Upper mantle seismic velocities, especially from shear wave tomography, appear to be the best thermal constraint that can be mapped over large areas (e.g., Goes and van der Lee 2002). Some additional information is provided by Pn velocities, i.e., the compressional wave velocities from just below the Moho as noted later in the text. Temperature is the dominant control of upper mantle seismic velocity, in contrast to the crust where composition is usually the main control. Second-order effects in the mantle are from variation in composition, anisotropy, water content, and partial melt. In the upper mantle, the main composition effect appears to be the small difference between tectonically active areas and stable cratons, and a first-order correction can be defined by the compositions of upper mantle xenoliths. For the Lithoprobe areas, van der Lee and Frederiksen (2005) have provided a detailed *S*-wave velocity (*V*s) tomography study. The *V*s data for the region was converted to temperatures and temperature–depth profiles using laboratory-based mineral elastic properties as a function of temperature, pressure, and composition by Hyndman et al. (2009).

The resulting velocity–temperature relationship was then

Fig. 5. Geotherms and estimated uncertainties for northern Canadian Cordillera from heat flow and heat generation data (modified from Lewis et al. 2003).

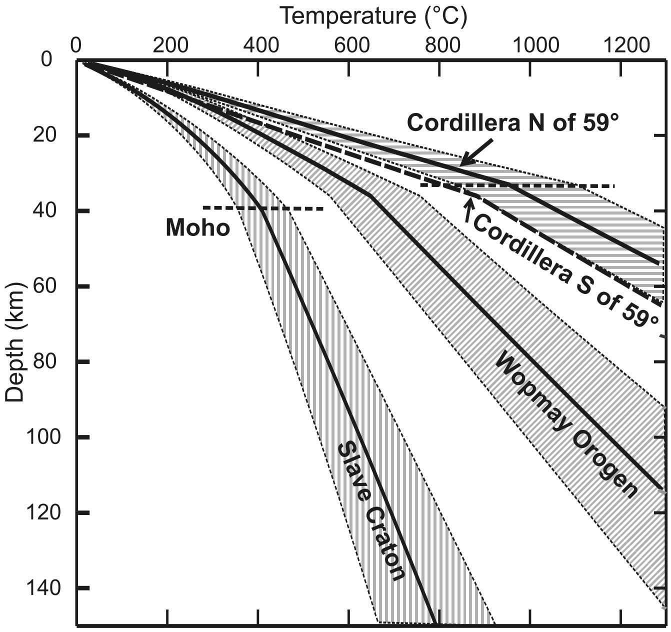
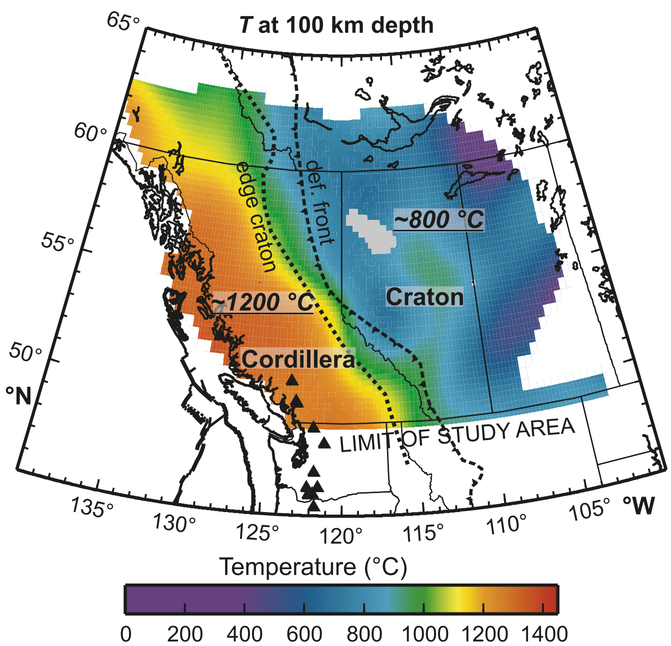


Fig. 6. Map of temperature at a depth of 100 km from *V*s tomography showing the high Cordillera temperatures compared with those of the adjacent craton (adapted from Hyndman et al. 2009).



used to calculate the three-dimensional (3-D) upper mantle temperature distribution from 100 to 200 km depth. The estimated uncertainty ranges from 50–100 °C at 100 km based on the uncertainty of *V*s plus the uncertainty of the *V*s versus temperature (*T*) relation. Figure 6 shows a map of the temperatures at a depth of 100 km, and Fig. 3 shows average temperature–depth estimates in the upper mantle. The latter are in good agreement with those from modelling the surface heat flow and heat generation data and mantle xenoliths. As inferred from the heat flow data, the Cordillera temperatures are remarkably high and uniform, and contrasted to the adjacent craton; i.e., temperatures at the Moho of 800–900 °C for the Cordillera and 400–500 °C for the craton. The boundary between the hot backarc and cold cratonic mantle regions is approximately at the Rocky Mountain Trench in the southern corridor (Hyndman and Lewis 1999). The Cordillera temperatures approach the mantle adiabat (near first melting) at a depth of about 60 km, which is taken as the base of the lithosphere. There appears to be nearly adiabatic temperatures at greater depths. For the craton, the adiabat is reached at depths >200 km. In the area of the Cascadia volcanic arc, the calculated temperatures are slightly higher between 100–150 km depth than for the main part of the Cordillera (Fig. 3). However, the especially high temperatures may be biased because of the velocity reduction effect of partial melt and hydrous fluids.

Temperatures from mantle xenoliths and other constraints

There is very extensive high-quality xenolith temperature–depth data for the adjacent craton (e.g., MacKenzie and Canil 1999; also see Kopylova and Caro 2004, and references therein). The Slave craton may have slightly lower temperatures, 400–500 °C at the Moho, compared to other Canadian Shield regions and most other cratons globally, but the differences are small compared with the contrast with the Cordillera. For the Cordillera, the xenolith mineralogy is such that the insitu pressure cannot be determined accurately and must be estimated indirectly. However, the in situ temperatures in the Cordillera uppermost mantle from xenoliths are concluded to be very high, in the range 1000–1200 °C (e.g., Ross 1983; Harder and Russell 2005, and references therein; Fig. 3).

A number of other constraints to deep temperatures in the Cordillera have been summarized by Currie and Hyndman (2006, and references therein). They include the uppermost mantle Pn velocity, which is strongly temperature dependent (e.g., Black and Braile 1982; Hyndman and Lewis 1999). Pn velocity is everywhere low in the Cordillera, 7.8–7.9 km s^{-1}, compared with the common ~8.2 km s^{-1} in the adjacent craton, consistent with high temperatures in the Cordillera. The seismograph stations are too widely spaced for earthquake depths to be determined routinely, but where determined, the maximum depths are 10–15 km, implying very high temperature gradients. There also are the thermal constraints discussed later in the text of high elevation and thin crust, which appears to require very high temperatures and a thin lithosphere, and the thin effective elastic thickness in the Cordillera reflecting high temperatures.

Figure 3 shows average temperature–depths for the whole Canadian Cordillera and for the adjacent craton from a variety of constraints (adapted from Currie and Hyndman (2006); and Hyndman et al. (2009)). The uncertainty bounds include a combination of real spatial variability and uncertainty of the estimates. There is a surprisingly small temperature variability within the Cordillera and within the adjacent craton. For the Cordillera, the temperatures at the Moho (~35 km) average about 900 ± 100 °C and the base of the lithosphere, defined by the temperature approach to the adiabat (near first melting), is at about 60 km. At greater

Fig. 7. Effective elastic thickness for the Canadian Cordillera and adjacent USA illustrating the thin upper crust elastic layer of the Cordillera associated with the high temperatures, compared with the adjacent craton (data from Flück et al. 2003).

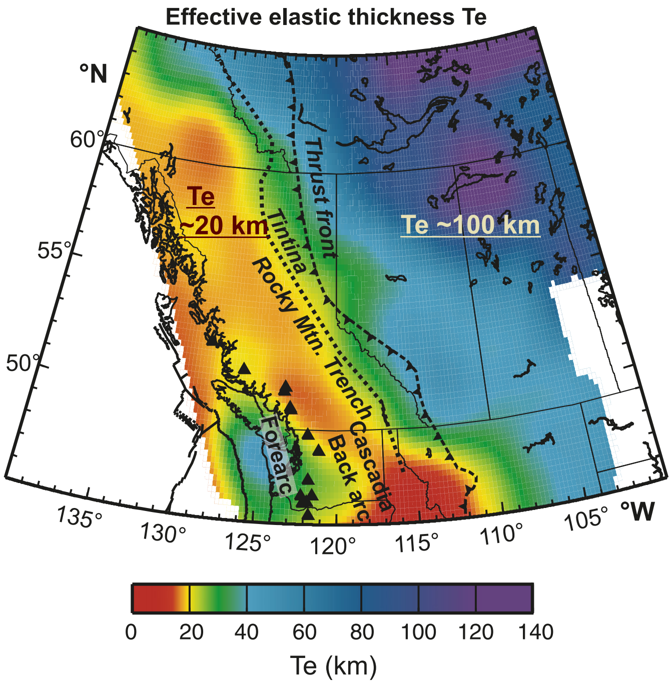
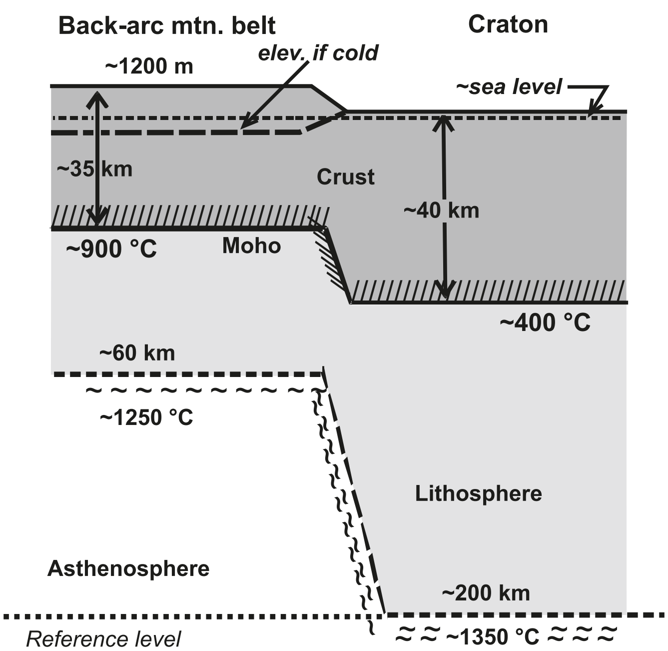


Fig. 8. Illustrated isostatic balance between the average high elevation thin crust Cordillera and the low elevation thick crust craton because of the contrast in thermal regime. If the Cordillera was cold like the craton, the surface ("elev. if cold") would be below sea level.



depths, the temperatures based on shear wave tomography *Vs* increase only very slowly, approximately as expected for the adiabat (constant potential temperature). For the adjacent craton, the temperatures at the Moho (~40 km) average 400–500 °C, and the base of the lithosphere is at a depth >200 km.

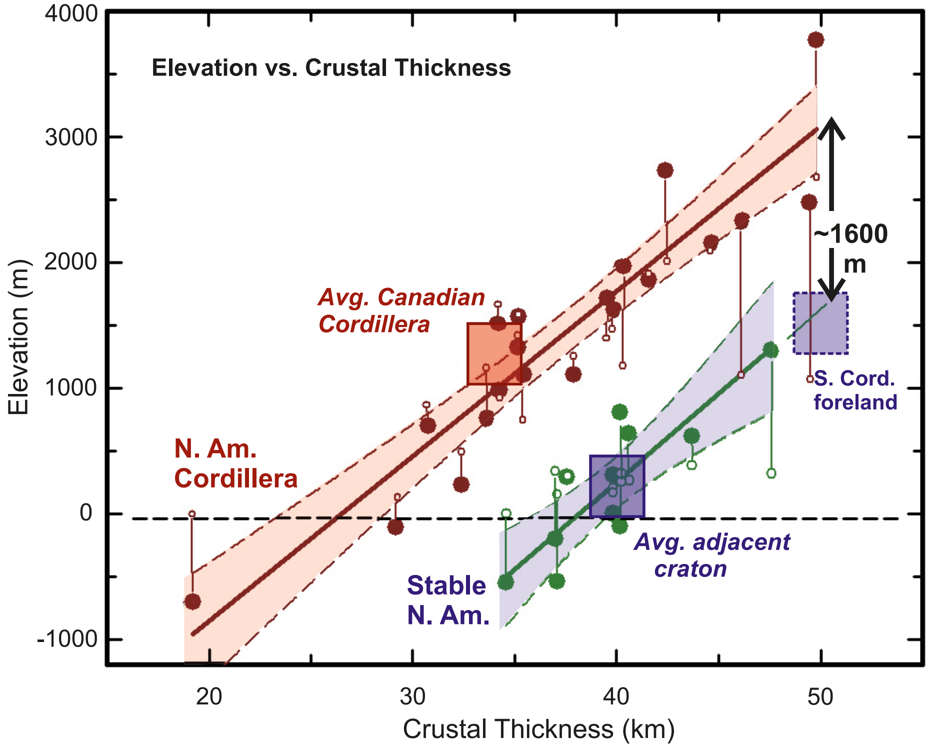
Temperature and effective elastic thickness, Te

The effective elastic thickness of the continental lithosphere, Te, (e.g., Watts and Burov 2003, and references therein) provides an important tool for regional mapping of the thickness and strength of the lithosphere and its susceptibility to tectonic deformation. It is strongly temperature dependent. Te is determined from the horizontal wavelengths over which topography and gravity (a measure of internal mass distribution and lithosphere flexure) are well correlated. For areas with a single elastic layer, Te approximates the depth to the brittle–ductile transition and the downward transition from narrow fault zones to broad shear zones (e.g., Sibson 1977). For very hot backarc lithosphere, only the upper crust (to approximately 450 °C), has significant strength (discussed later in the text). For cool stable areas, all of the crust and the uppermost mantle (to ~800 °C) have significant strength. For intermediate thermal regimes, there may be a weak zone in the lower crust underlain by a stronger uppermost mantle, and Te is the thickness of the equivalent single layer with the same flexure as the two layers combined.

In this study, the Te is reported for the Canadian Cordillera and adjacent craton as has been computed by Flück et al. (2003) (also Flück 2003) and to the south in western USA by Lowry and Smith (1995) using almost identical methods. Other Te studies in the region using a variety of methods have been carried out by Wang and Mareschal (1999), Audet et al. (2007), and Poudjom Djomani et al. (2005). Thin lithosphere in the Cordillera and a transition to thicker values in the craton was found by Audet et al. (2007), similar to that of Flück et al. (2003). However, the Audet et al., (2007) and especially Poudjom Djomani et al. (2005) generally found thinner values of Te for the craton. The origin of the differences is not yet clear, but Poudjom Djomani et al. (2005) used small window sizes of 300 km × 300 km for the craton that Flück et al. (2003) argued biases Te to values that are too small. Flück et al. (2003) concluded that 800 km × 800 km windows are needed to resolve the thick Te of the craton; their thick Te values are in good agreement with those expected for the cold craton thermal regime (e.g., Hyndman et al. 2009). The horizontal resolution of Te is several 100 km for the Cordillera and over 1000 km for the craton (Flück 2003).

Figure 7 shows the clear contrast between quite uniform Te of about 20 km in the Cordillera and about 100 km in the adjacent craton from Flück et al. (2003). As expected, the low temperature Cascadia forearc has thick Te, and the currently extending Basin and Range in USA has unusually thin Te (Lowry and Smith 1995; northern part of Basin and Range shown in Fig. 7). Te is not well resolved for the volcanic arc but appears similar to the rest of the Cordillera, although the inferred deep temperatures under the arc from seismic tomography are slightly higher than for the rest of the Cordillera (Hyndman et al. 2009). The boundary between the thin Te (hot) and thick Te (cold) regions is approximately at the Rocky Mountain Trench in the southern

Fig. 9. Relation between elevation and crustal thickness for the North American (N. Am.) Cordillera and stable eastern North America (data from Hasterok and Chapman 2007). The small open symbols are uncorrected and the solid symbols corrected for crustal density variations. The boxes are averages for Canadian Cordillera and adjacent craton. The Cordillera is ∼1600 m higher than stable areas, as predicted by the difference in average temperature to ∼200 km depth. See text for details. S. Cord, southern Cordillera.



corridor, in agreement with that from the upper mantle seismic tomography velocities. The boundary for the northern Corridor is less well defined but again the two parameters agree well. The temperature–depths implied by the Te values are in very good agreement with the temperatures from *V*s tomography and other deep temperature indicators for both the Cordillera and the craton (Hyndman et al. 2009).

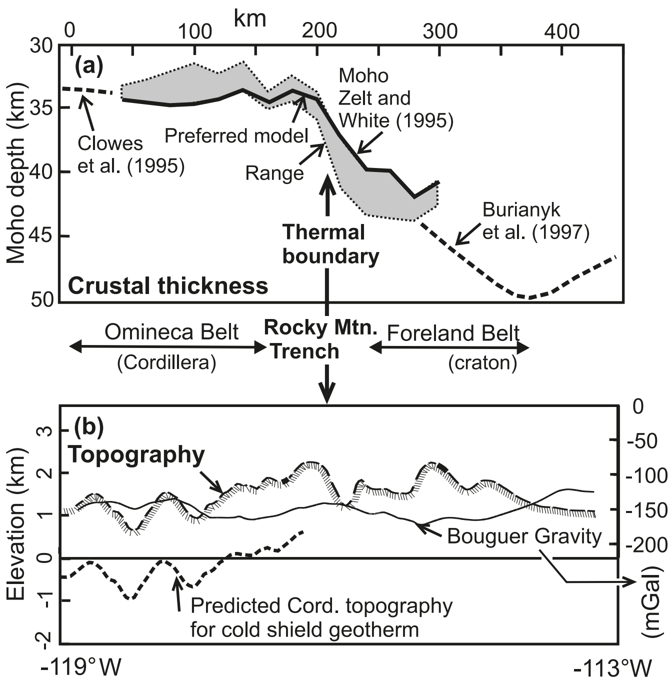
Topographic elevation and crustal thickness

There is remarkably uniform thin crust, 33 ± 2 km, for most of the 1400 km long Canadian Cordillera, in spite of the high elevation, except for a small width of the eastern foreland that may be underlain by cratonic lithosphere (data summarized by Clowes et al. 1995, 2005). In contrast, the adjacent craton has thicker crust (average ∼40 km) and much lower elevation. This is the opposite to that expected from simple Airy isostasy. The explanation of the high elevation of the Cordillera in spite of the thin crust appears to be thermal expansion density reduction associated with the high temperatures. A number of authors have concluded that the surface elevation is strongly affected by lithosphere temperature (e.g., Lachenbruch and Morgan 1990). Hasterok and Chapman (2007) presented an especially important study relating elevation to the thermal regime estimated from heat flow data.

The temperature difference between Cordillera and North American Craton in the uppermost mantle is up to 500 °C (Figs. 3, 8). For determination of the thermal effect on elevation, the average temperature difference between backarcs and stable areas is about 250 °C from the surface to ∼200 km depth where the two geotherms converge. Applying this temperature difference to 200 km and the coefficient of thermal expansion, gives a thermal isostasy contribution of about 1600 m (Hyndman et al. 2010), very close to that observed. For the whole of North America, Hyndman et al. (2010) found that the elevation is quite uniformly 1600 m higher than the adjacent craton for the same crustal thickness (corrected for crustal density differences from Hasterok and Chapman 2007; Fig. 9), in excellent agreement with that predicted using the contrast in thermal regimes.

Figure 9 shows the average crustal thickness and elevation for the Canadian Cordillera and adjacent craton, compared with a relation for all North America using the data of Hasterok and Chapman (2007). Both the elevations and crustal thicknesses are averaged over horizontal distances approximately corresponding to the lithosphere flexural wavelengths, which are related to the effective elastic thickness Te. The Cordillera points are for the main backarc part of the Cordillera, excluding the forearc and foreland belt. The stable North America points are from the remainder of North America to the east. The elevations are corrected by small amounts to those expected for a reference crustal average density (shown in Fig. 9). The average density was estimated using average crustal seismic velocity and velocity–density relations, following Hasterok and Chapman (2007). The regional average elevation and crustal thickness are also illustrated for the southern foreland belt, where the

Fig. 10. (*a*) Crustal thickness transition from $\sim$33 to $\sim$50 km beneath southern Canadian Cordillera fold and thrust belt (after Hyndman and Lewis, 1999). (*b*) There is little change in elevation or in Bouguer gravity across the boundary; the crustal thickness change is balanced by the thermal contrast. The predicted elevation for Cordillera if it had the cool stable area thermal regime is below sea level.



crust is especially thick and elevation is high; east of the Rocky Mountain Trench; and for the Canadian Cordillera.

The Cordillera–craton contrast in crustal thickness is quite abrupt, over a horizontal distance of $\sim$150 km, with little change in elevation, as shown for the southern Cordillera in Fig. 10. At this boundary, the crust thickens by more than 10 km eastward with little change in surface elevation or in Bouguer gravity. Isostatic balance is maintained by the thinner Cordillera crust being balanced by the Cordillera thermal expansion density reduction. Lowe and Ranalli (1993) modelled this abrupt thermal contrast. Hyndman et al. (2005*b*, 2010) generalized that because most backarcs and recent backarcs globally have approximately the same high temperatures (Currie et al. 2004), they likely, therefore, have similar thermally supported elevations. The northern Cordillera was in a backarc position about 40 million years ago, prior to being cut off by the Queen Charlotte transform fault, but the thermal time constant for cooling a backarc appears to be $\sim$500 million years so it remains hot. The Canadian Cordillera elevation, therefore, is interpreted to be an example of global current and recent backarc mountain belts, most of which have elevation support of about 1600 m from thermal expansion. A few very high areas, such as Tibet and central Andes, have large additional elevation supported by very thick crusts. A comprehensive global thermal, elevation, and crustal thickness study to test the conclusions for the North American Cordillera is an important future effort.

Origin of high temperatures and thin lithosphere in the Cordillera

As summarized earlier, a range of thermal constraints indicate that the Canadian Cordillera has surprisingly high and uniform temperatures in the crust and upper mantle. The lithosphere is only about 60 km thick. Hyndman et al. (2005*b*) and Currie and Hyndman (2006) argued that such high and uniform temperatures are a characteristic of most current and recent backarcs globally. Following Hasebe et al. (1970), Blackwell (1978), Honda and Saito (2003) and others, the high temperatures are ascribed to rapid upward convective heat transport beneath thin lithospheres. Most models of backarc convection limit the thermal effects to near the arc and have circulation driven by the traction and thermal effects of the downgoing oceanic plate. However, it has proven difficult to produce uniform high heat flow across the backarc with such models, and regional small-scale and vigorous convection seems to be required (e.g., Nyblade and Pollack 1993; Currie et al. 2004) (Fig. 11). As noted by Currie et al. (2004) no model of simple traction-driven flow has been found that is able to simultaneously produce high temperatures beneath the volcanic arc and throughout the backarc. The most likely way to produce hot and isothermal conditions in the backarc is through vigorous small-scale-free convection in a shallow low-viscosity asthenosphere. It is suggested that in addition to high temperatures, the mantle viscosity is lowered by the incorporation of water expelled from the underlying dehydrating subductiong oceanic plate (e.g., Honda and Saito 2003; Dixon et al. 2004). Only a small amount of water is required for a significant reduction in effective viscosity.

The thickness and strength of the Cordillera and adjacent craton lithosphere

One of the most important consequences of variations in lithosphere temperature and thickness is the variation in the strength of the lithosphere and its susceptibility to tectonic deformation. Lateral variations in lithosphere strength are expected to be the primary control on the nature of tectonic processes. Lithosphere strength increases with depth in the shallow brittle frictional regime because of the increasing load on fault surfaces. At greater depths where there is ductile deformation, temperature and composition, especially crust versus mantle, are the most important controls (e.g., Ranalli 1995), and strength decreases rapidly with depth. Simple strength versus depth profiles for the average Cordillera (“wet rheology” assumed) and the adjacent craton (“dry rheology” assumed) are shown in Fig. 12 (Hyndman et al. 2009). In these two models, the rapid decrease in strength with depth may be taken loosely as the “brittle–ductile transition.” There is a striking difference between the thin weak lithosphere in the Cordillera and the much thicker stronger lithosphere of the craton. In the Cordillera, only the upper $\sim$15 km has significant strength and is involved in transferring tectonic forces. There is very little strength in the lower crust or in the mantle. With the inferred very weak lower crust, the upper crust may move over the lower crust and upper mantle. Also, the lower crust may be sufficiently weak for lateral flow under tectonic or gravitational forces.

Fig. 11. Schematic cross-section of the northern Cascadia subduction zone and southern Canadian Cordillera illustrating the inferred effect of subducted water generating reduced mantle viscosity and shallow, small-scale asthenosphere convection. Lith., Lithosphere.

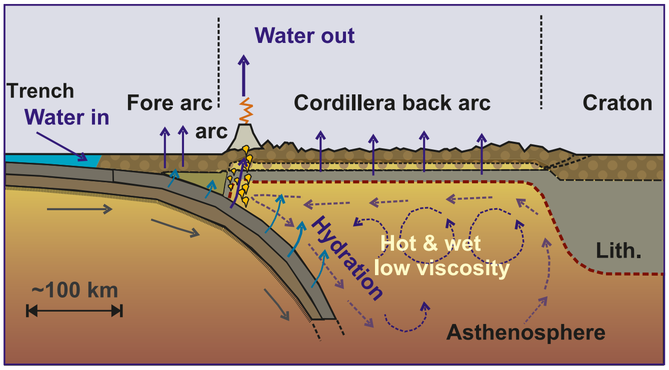


Fig. 12. Lithosphere strength versus depth for the Canadian Cordillera (right) and adjacent craton (left). The upper section exhibits frictional, and the lower exhibits ductile, temperature-dependent deformation. The fine details shown depend on the composition versus depth assumed and the strain rates. The total strength of the craton lithosphere is an order of magnitude greater than the Cordillera (see Hyndman et al. 2009 for model details). Te, effective elastic thickness; elast., elastic.

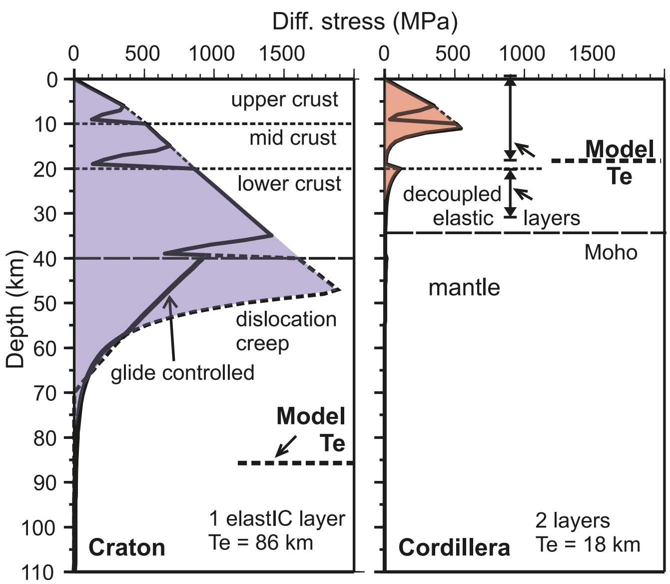
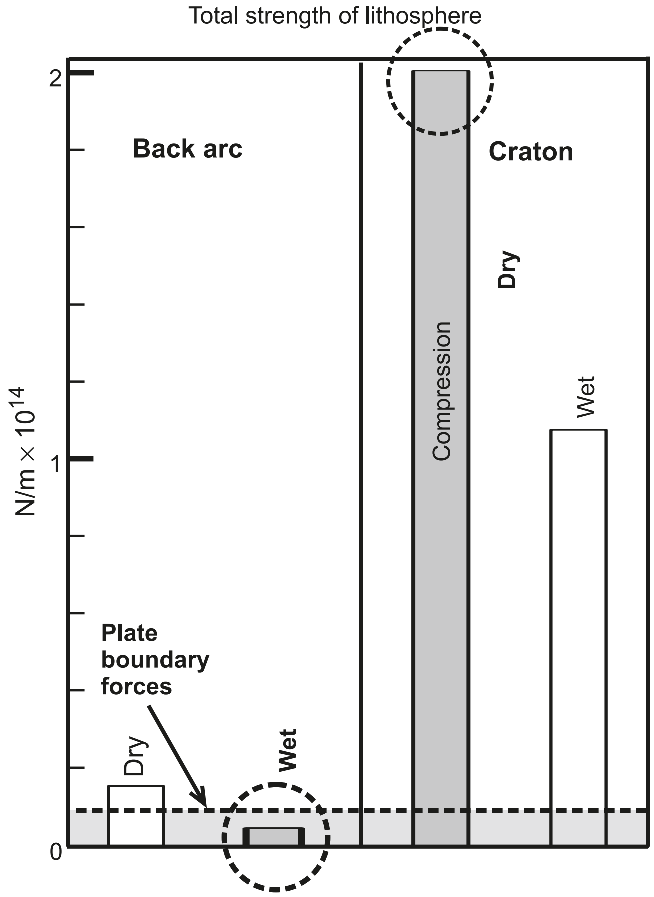


Fig. 13. Total strength of the lithosphere for the Cordillera backarc and adjacent craton. The horizontal broken line shows an estimate of common plate tectonic and gravitational potential forces. Backarcs like the Cordillera are readily deformed by available forces, whereas cold stable areas are much too strong.

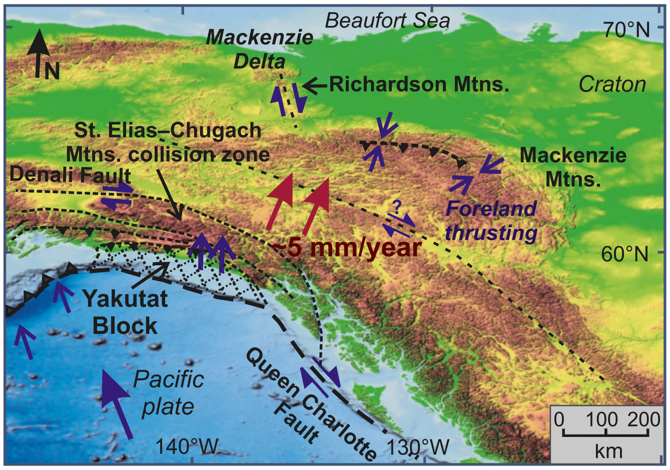


The total strength of the lithosphere may be estimated by integrating the strength over depth (Fig. 13). The combined crust and mantle strength for the Cordillera is more than a factor of 10 weaker than that of the craton. An estimate of the common magnitude of plate tectonic forces and the gravitational potential of mountain belts is shown for comparison. The Cordillera and most continental backarcs are sufficiently weak to be deformed by tectonic forces, which explains their role as long-lived mobile belts (e.g., Hyndman et al. 2005*a*). Cratons are much too strong to be deformed, explaining why they remain stable over long geological periods.

The Yakutat collision and strain transfer across the Cordillera

The Yakutat block is a small terrane that has migrated northwestward along the North America western margin until it collided obliquely with the continent in the corner of the Gulf of Alaska (e.g., Plafker et al. 1994). The collision and uplift of the St. Elias Mountains probably started in the mid-Miocene, with a recent phase starting at about 5 Ma. The block acts as an indenter, resulting in crustal thickening, rapid uplift, and intense seismicity in the adjacent St. Elias and Chugach mountains. A small but significant component of motion (up to 5 mm/year) is concluded to be transferred northeasterly inland across the Cordillera to the northeast (Mazzotti and Hyndman 2002; Leonard et al. 2007, 2008; Hyndman et al. 2005*b*; Fig. 14). This motion is argued to be responsible for the current strong seismicity and thrust faulting in the foreland Mackenzie Mountains and right-lateral strike-slip in the Richardson Mountains. This large-scale motion is explained by a quasi-rigid displacement, probably of the upper crust over a lower crust detachment (Fig. 15) allowed by the very high temperatures of the northern Cordillera. In the eastern Cordillera foreland belt, the upper crust overthrusts the strong adjacent craton.

Fig. 14. Current tectonic elements of northern Cordillera illustrating the Yakutat terrane collision in the corner of the Gulf of Alaska that is inferred to drive the whole northern Cordillera to overthrust the craton in the Mackenzie Mountains. This process may be a model for earlier terrane collision-driven thrusting in the Rocky Mountain front of the southern Canadian Cordillera (see Leonard et al. 2007, 2008, for details).



Mazzotti and Hyndman (2002) used a 2-D thermomechanical model to reproduce the observed deformation pattern across the northern Canadian Cordillera, with the Yakutat block as an indenter (Fig. 16). The crust and mantle rheologies are based on the estimated thermal regime. To reproduce the deformation in the Mackenzie Mountains the model requires a weak foreland belt that is ascribed to the weak sedimentary thrust sheets and high pore pressure above a deep detachment. The preferred model parameters produce a decoupling zone in the lower crust. After about 2 million years of convergence, the model reproduces the observed topography reasonably well. The model with cooler temperatures in the lower crust, <700–800 °C, do not produce significant decoupling in the lower crust. Kinematic models with no weak lower crust either do not allow deformation to extend into the continent or produce continuous deformation across the whole Cordillera rather than focusing it in the eastern foreland belt. The Yakuktat collision, which results in deformation transmitted across a backarc with a lower crust weak zone or detachment, may be widely applicable to continental collision with backarc deformation elsewhere. A similar lower crust detachment and overthrusting of the backarc upper crust over the craton crust may describe the processes involved in the earlier formation of the Rocky Mountain fold and thrust belt in the southern Canadian Cordillera.

Continental collision and orogenic heat

The finding that the Canadian Cordillera current and recent backarc is uniformly hot prompted an examination of global backarcs, and the recognition that almost all backarcs are similarly hot, even if they have had no recent crustal extension (Hyndman et al. 2005*b*; Currie and Hyndman 2006). Since most ocean closing and continental collision orogeny involves a backarc on at least one side (Fig. 15), hot backarcs provide a resolution to the long-standing problem of the

Fig. 15. Schematic model for the Yakutat terrane collision illustrating the northern Cordillera translation of the upper crust over a deep detachment and overthrusting of the adjacent craton in the Mackenzie Mountains. Asth., asthenosphere; Lith., lithosphere.

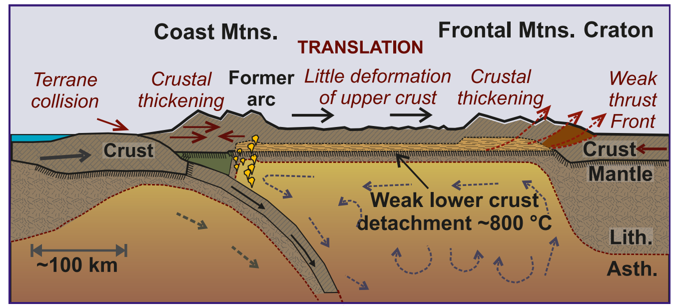
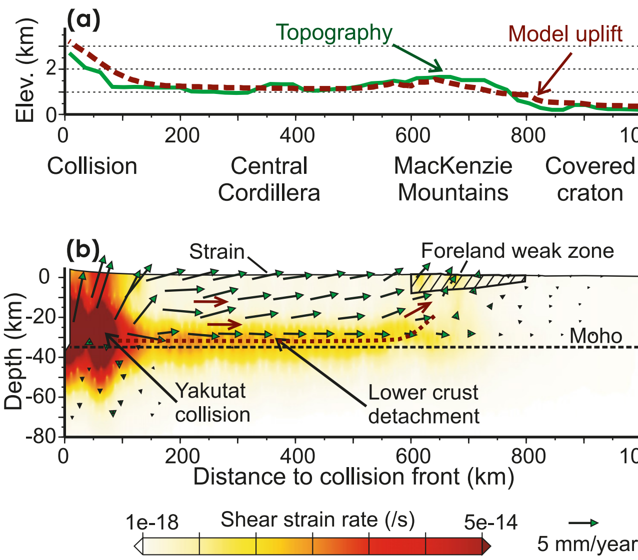


Fig. 16. Numerical model for the collision of the Yakutat terrane driving the upper crust of the northern Cordillera to the east and overthrusting the stable craton in the Mackenzie Mountains. (*a*) observed and model topography. (*b*) cross-section showing model upper crustal motion over deep detachment toward weak foreland basin (see Mazzotti and Hyndman 2002, for details).



heat of orogeny (e.g., Collins 2002). High temperatures are a defining feature of orogenic belts, in wide-spread plutonism, high grade metamorphism, and ductile deformation at mid-crustal depths, usually ascribed to some heat generation process involved in the deformation. However, most of the processes involved should absorb heat. It is proposed that orogenic heat predates the collision crustal shortening; it comes from the pre-existing hot backarc. Also, only backarcs are sufficiently weak to be readily deformed in continental collision, as discussed earlier in the text. Cool stable lithosphere is usually too strong to be readily deformed. The Yakutat block collision in the Gulf of Alaska discussed earlier provides a small-scale example of collision and orogeny backarcs globally.

Conclusions

The temperatures in the deep crust and upper mantle of the Cordillera and adjacent craton are now well constrained by numerous data. The surprisingly high and laterally uniform temperatures in the Cordillera, 800–900 °C at the Moho, are contrasted to cool 400–500 °C at the adjacent craton Moho. The uniform high temperatures in the Cordillera and similar other backarcs are explained by small-scale convection beneath a thin, ~60 km, lithosphere facilitated by viscosity reduction by incorporation of water driven upwards off the current Juan de Fuca plate and the Cenozoic subducted oceanic plates to the north.

The high topographic elevation in spite of a crust that is much thinner than the adjacent low elevation craton, is explained by thermal expansion in the hot thin Cordillera lithosphere. The high temperatures in the Cordillera also have the consequence that only the upper ~15 km of the crust has significant strength (i.e., thin effective elastic thickness, Te), in contrast to over 60 km for the craton (thick Te). The Cordillera is tectonically active because the lithosphere is weak enough to be deformed by plate boundary and gravitational potential forces; the craton is much too strong and remains stable for geologically long periods of time. The inferred weak lower crust and upper mantle of the Cordillera has allowed current Yakutat terrane collision in the Gulf of Alaska to drive the upper crust across the whole Cordillera to active thrusting over the craton in the Mackenzie Mountains. This conclusion of lower crust detachment and upper crust translation in backarcs needs to be examined more fully globally.

The Canadian Cordillera results and interpretations have led to several new fundamental understandings of processes in current and recent backarcs globally. First, an initial study has shown that most current and recent backarcs are uniformly hot, similar to the Canadian Cordillera. Second, about 1600 m contribution to surface elevation is suggested for most backarc mountain belts because of high temperatures, without thick crust. This thermal contribution to elevation in backarcs also needs to be demonstrated globally. Third, consistently high backarc temperatures and weak lithospheres explain tectonic activity over long geological times in the mobile belts that make up about 20% of continents. Fourth, there commonly may be a weak zone in the lower crust that allows the quasi-rigid upper crust to be translated separately for considerable distances and to override the lithosphere of adjacent stable areas in fold and thrust belts. The importance of backarc mid-crust detachment in tectonic deformation needs to be examined globally. Finally, The Cordillera results have led to a new understanding of orogenic heat in terms of incorporation of already hot backarcs into continental collision orogenies, rather than heat generated by orogenic processes. Again this explanation needs to be tested in ancient orogenic belts globally.

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