

THE DEEP ROOTS OF THE ROCKY MOUNTAINS: GEOPHYSICAL STUDIES OF WESTERN CANADA

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INTRODUCTION

The Rocky Mountains in western Canada have some of the most spectacular scenery in the world, with rugged terrain and snow-covered peaks. The Rockies are part of the North American Cordillera, a ~4000 km mountain belt that runs along the western side of North America (Figure 1). This mountain belt formed over the last 200 million years, as rocks were added to the western side of North America during the convergence of tectonic plates. ¹ As a result, the North America plate has grown westward. Western Canada can be divided into two main geological regions: (1) the craton, which corresponds to the ancient core of North America that has persisted for more than 1 billion years, and (2) the Cordillera mountain belt consisting of younger accreted rocks. The geological boundary between the two regions is marked by the Rocky Mountain Trench and its northern extension, the Tintina Fault. These appear as a linear zone of low elevation along the eastern part of the mountains.

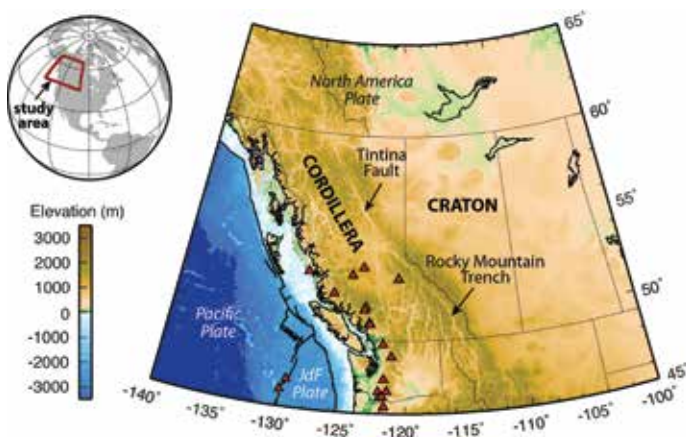


Figure 1: Surface topography in western Canada. Red triangles indicate active volcanoes and thick black lines mark tectonic plate boundaries, with plate names in italics. JdF = Juan de Fuca.

As shown in Figure 1, the Cordillera and craton regions have very different topographic expressions. The Cordillera is characterized by high elevations and rugged topography. In contrast, the craton region

is relatively flat and low-lying. The average Cordillera elevation is about 1100 m and the average craton elevation is about 350 m. Some mountainous terrain extends up to 100 km east of the Rocky Mountain Trench, corresponding to rocks that were emplaced on top of the craton during plate convergence and accretion.

This paper explores why the Cordillera sits 750 m higher than the craton. To do so, geophysical data is used to study the deep structure of the Earth. I first encountered this topic when I was an undergraduate student in geophysics. I had initially chosen to study geophysics because I was interested in earthquakes. Between my 3rd and 4th year of undergraduate studies, I was fortunate to obtain a summer job with the Geological Survey of Canada in Sidney, BC. There, I worked with researchers studying Earth's structure and deformation on a range of timescales, from earthquakes to long-term geological motions. This broadened my perspective, and I realized that there are many aspects of the dynamics of the Earth's interior that are poorly understood and that some relatively simple observations (such as topography) provide significant information about the complex structure and processes occurring below the Earth's surface.

One of my supervisors at the Geological Survey of Canada was Dr. Roy Hyndman (who would become my Ph.D. advisor when I started graduate studies the following year). At the time, he was analyzing the relationship between surface topography and subsurface structure in western Canada. He demonstrated that the cause of the high elevations in western Canada is not straightforward.² This intrigued me, and during my Ph.D., and in some of my recent research, I have explored this topic in more detail. This has involved the combination of various geophysical observations, theoretical calculations and computer models in order to understand the structure of the upper ~300 km of the Earth and its relationship to surface topography. In this paper, I summarize some of this work and discuss some

of my research experiences in geophysics.

ISOSTASY AND SURFACE ELEVATION

Variations in surface topography in many parts of the world can be explained using the idea of isostasy. The upper part of the Earth is divided into two main layers: the low-density, silica-rich crust and the high-density, silica-poor mantle. According to the theory of Airy isostasy, the low-density crust “floats” on the more fluid mantle, similar to an iceberg floating on water. Just as the height of the iceberg depends on its thickness, isostasy states that variations in crustal thickness cause changes in surface elevation. Thus, regions of high elevation (e.g., mountains) should correspond to areas of thick crust and regions of low elevation should have thinner crust.

As shown in Box 1, the relationship between surface elevation (e) and crustal thickness (h'_c) is given by:

$$e = \frac{(\rho_m - \rho_c)}{\rho_m} (h'_c - h_c)$$
 where ρ_c is the density of the crust, ρ_m is the density of the mantle, and h_c is the thickness of reference crust. The reference crust is chosen to be the crustal thickness that results in elevations at sea level; for the Earth h_c is about 35 km. To apply this equation, we use typical densities of $\rho_c = 2850 \text{ kg/m}^3$ and $\rho_m = 3300 \text{ kg/m}^3$.

Equation 1 predicts that if the crust is thicker than 35 km, the elevation will be positive (above sea level); conversely thinner crust should lie below sea level. For example, if the crust doubles

in thickness ($h'_c = 70 \text{ km}$), the expected elevation is 4.77 km. This is comparable to the observed elevation of the Tibetan plateau (about 5 km above sea level), where the crustal thickness is 70-75 km. In contrast, the average crustal thickness below the oceans is 7 km. Equation 1 gives an elevation of -3.82 km, which is similar to the average seafloor depth, if the effect of water weight is not included.

CRUSTAL THICKNESS AND SURFACE ELEVATION IN WESTERN CANADA

Does isostasy explain the contrast between the high-elevation Cordillera and low-elevation craton in western Canada? To answer this, we must measure the thickness of the crust. However, it is difficult to study crustal thickness directly. To date, the deepest borehole has reached a depth of only 12 km (less than 0.2% of the Earth's radius). Therefore, Earth scientists rely on indirect geophysical measurements. In geophysics, we use signals that are recorded at the Earth's surface to understand the properties of the material below the surface. Seismic waves are one of the most widely used tools, as these waves travel through the Earth's interior and carry information about all the material they have encountered. An important parameter is the velocity of the seismic waves. By measuring the travel time of seismic waves from distant earthquakes to seismic stations, it is possible to determine spatial variations in seismic wave velocity

(i.e., the speed at which seismic waves travel in each part of the Earth's interior). Seismic waves travel more slowly through crustal rocks than mantle rocks, and therefore the interface between the two layers can be mapped by detecting the velocity change.

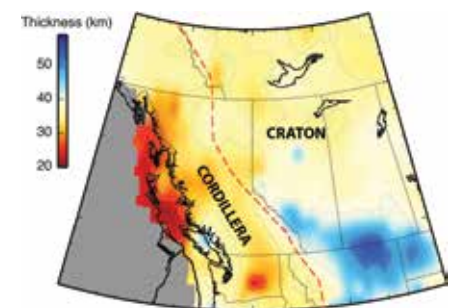


Figure 2: Thickness of the crust in western Canada from observations of seismic waves³. The dashed red line marks the location of the Rocky Mountain Trench / Tintina Fault.

Figure 2 shows the crustal thickness for western Canada based on an analysis of seismic waves.³ The crustal thickness varies between about 25 km and 50 km below the continental region. Interestingly, the Cordillera does not correspond to the areas of thickest crust, as would be expected for a mountain belt. The average crustal thickness for the Cordillera is 33.6 km, which is 3 km thinner than the craton crust (average 37.6 km). For comparison, Equation 1 predicts that the Cordillera crustal thickness should be 43.1 km in order to explain the observed average elevation of 1100 m.

Another way to look at this is to use the observed crustal

thicknesses (Figure 2) to calculate the expected surface elevation, assuming Airy isostasy. The result is shown in Figure 3. For much of western Canada, the craton region has a predicted elevation similar to the observed elevation. The discrepancies in the northern and southern parts of the craton can be resolved by considering variations in crustal density. On the other hand, the thin Cordillera crust is predicted to result in elevations that are on average 200 m below sea level for much of British Columbia and not a high-elevation mountainous region!

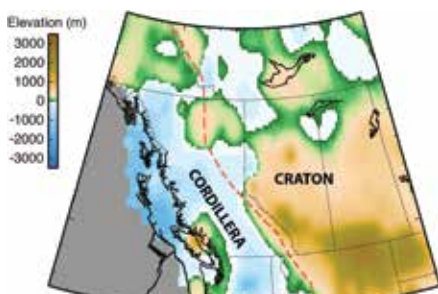


Figure 3: Predicted surface elevation in western Canada, based on the observed crustal thickness. The dashed red line marks the location of the Rocky Mountain Trench / Tintina Fault.

From these calculations, we find that the observed Cordillera elevation is about 1300 m higher than predicted for its crustal thickness. It should be noted that these calculations assume a constant composition (and therefore density) for the crustal layer. In a more detailed study that included data for all of North America, we found that when compositional variations are included, the Cordillera elevation is 1600 m higher than expected. ⁴

MANTLE STRUCTURE IN WESTERN CANADA

Based on the above results, we cannot explain the Cordillera elevation by thick crust. Therefore, we must look deeper in the Earth. Geophysical observations can be used to study the mantle, the layer of rock below the crust. Detailed observations of seismic wave travel times can be used to map small variations in velocity within the mantle and learn about the properties of this layer.

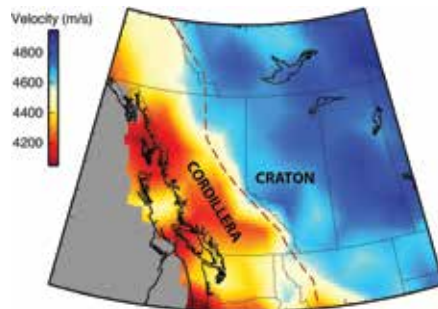


Figure 4: Seismic shear wave velocity at 90 km depth below western Canada. The dashed red line marks the location of the Rocky Mountain Trench / Tintina Fault.

Figure 4 shows a map of the seismic shear wave velocity at a depth of 90 km below western Canada.⁵ In western Canada, shear wave velocities vary between 4100 m/s and 4900 m/s. There is a clear difference in velocity below the Cordillera and craton regions. The craton has a relatively high velocity (average 4739 m/s), compared to an average velocity of 4344 m/s for the Cordillera. The boundary between high and low velocity corresponds closely with the Rocky Mountain Trench / Tintina Fault.

MANTLE TEMPERATURE AND SURFACE ELEVATION

Within the Earth's mantle, the main control on the seismic wave velocity is the temperature of rocks; factors such as compositional variations are secondary. It is possible to use theoretical studies to calculate how seismic wave velocity varies with temperature e.g.,^{6,7}. Figure 5 shows the relationship between shear wave velocity and temperature for a typical mantle composition at 90 km depth. With increasing temperature, the wave velocity decreases as the rocks become less able to transmit the seismic disturbance.

The theoretical relationship in Figure 5 can be used to convert the observed seismic velocities in western Canada (Figure 4) into a map of mantle temperature. This is shown in Figure 6. The low velocities below the Cordillera mountain belt indicate high mantle temperatures, with an average of 1258°C. In contrast,

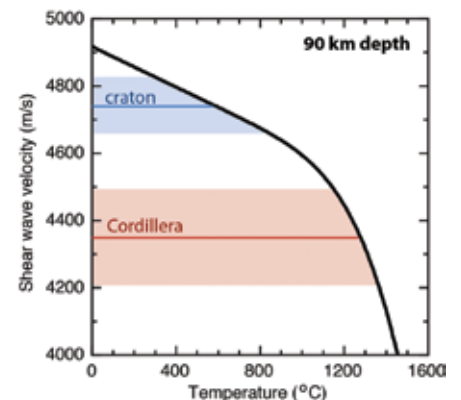


Figure 5: Variation in shear wave velocity with temperature at 90 km depth (black line). The average velocity (and standard deviation) for the craton and Cordillera are shown in blue and red, respectively.

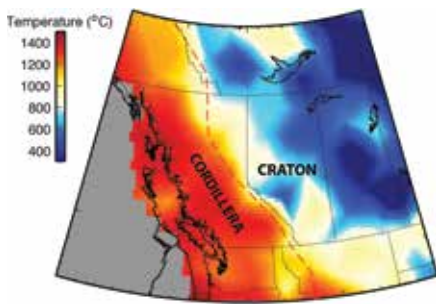


Figure 6: Calculated temperature at 90 km depth below western Canada. The dashed red line marks the location of the Rocky Mountain Trench / Tintina Fault.

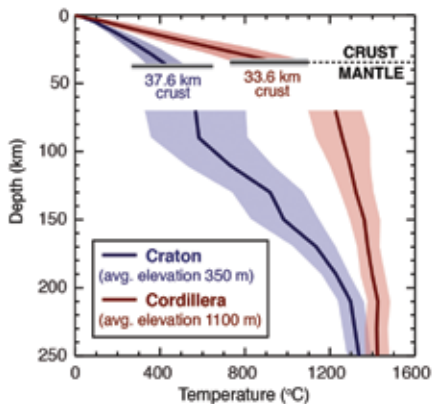


Figure 7: Variation in average temperature with depth for the Cordillera (red line) and craton (blue line). The shaded region shows the standard deviation. Mantle temperatures were calculated based on observed seismic velocities; crustal temperature are from an analysis of surface heat flow⁸.

lower temperatures are predicted for the craton region, where the average temperature is 583°C.

I have done a similar calculation to convert seismic velocities into temperatures at depths from 70 km to 250 km for western Canada. At all depths, the seismic wave velocities in the Cordillera mantle are less than those in the craton

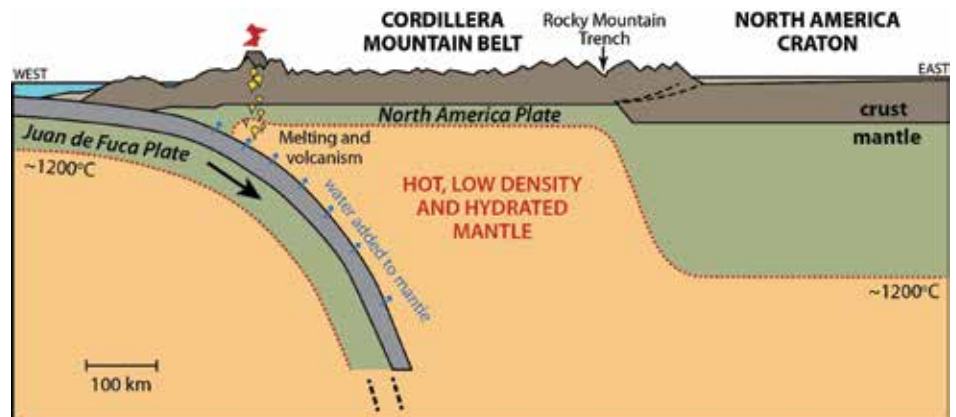


Figure 8: Schematic cross-section through southwestern Canada. Hydration of the mantle below the Cordillera may enable convection that carries heat into this region and provides the buoyancy to support the high elevations below the mountain belt.

mantle, and the Cordillera mantle is predicted to be hotter. Figure 7 shows the average temperature as a function of depth for both regions. These new temperature calculations are in good agreement with my previous work⁸, and they confirm that the Cordillera and craton regions have distinct temperature structures. The temperature difference is largest at shallow mantle depths and decreases with depth. There is little difference between the two areas below about 220 km depth.

The temperature difference has important implications for surface topography. As rocks are heated, their density decreases through thermal expansion. For a temperature change of ΔT , the rock density is: $\rho = \rho_0 (1 - \alpha \Delta T)$ where ρ_0 is the reference mantle density (3300 kg/m³) and α is the thermal expansion coefficient ($3 \times 10^{-5} \text{ K}^{-1}$ for mantle rocks). From Figure 6, the Cordillera mantle is an average of 300°C hotter than the craton mantle to a depth of 220 km. This suggests that the

density of the Cordillera mantle is 3270 kg/m³ (30 kg/m³ less dense than craton mantle).

In the previous isostasy calculations¹, it was assumed that the density of the crust and mantle are the same for all regions. However, the seismic observations show that the Cordillera mantle is less dense than craton mantle because it is hotter. The equations in Box 1 can be modified to include this density difference. With this, we find that the predicted elevation of the Cordillera is about 1500 m above sea level,⁴ which is similar to the observed elevation.

GEODYNAMICS OF WESTERN CANADA

The geophysical observations presented above show that the Cordillera mountain belt in western North America is unusual. Whereas many mountain belts, such as the Tibetan Plateau, have high elevation because of a thick, low-density crust, the Cordillera crust is anomalously

Box 1: Airy Isostasy

The diagram on the right shows how the isostasy equation is derived. First, consider the reference column of material that is made of a crustal layer (thickness h_c and density ρ_c) and mantle layer (thickness h_m and density ρ_m). The weight of this column is given by the pressure at point P1:

$P1 = \rho_c g h_c + \rho_m g h_m$ where g is the gravitational acceleration (9.81 m/s^2). Point P1 is placed at the compensation depth, which is the depth at which the mantle becomes hot and weak enough to flow very slowly (a few cm/yr) over millions of years.

Now consider a region with a thicker crust (thickness h'_c). If the excess crustal thickness is simply added to the top of the reference crust, the pressure at the compensation depth increases. Airy isostasy says that the deep mantle rocks will slowly flow outward due to the high pressure, and flow will stop once the pressure at the base of this column is equal to that in the reference column. This condition is called isostatic equilibrium. As a result, the thick crust sinks and displaces some of the underlying mantle. At the time of isostatic equilibrium, the thick crust will sit at an elevation (e) higher than the reference column, and it will have a root (r) that extends to larger depths into the mantle. The new mantle layer thickness is h'_m and the pressure at the compensation depth for this column is:

$$P2 = \rho_c g h'_c + \rho_m g h'_m$$

At this point, the two columns are in isostatic equilibrium ($P1 = P2$) and therefore:

$$\rho_c g h_c + \rho_m g h_m = \rho_c g h'_c + \rho_m g h'_m$$

From the figure, we see that:

$$h'_c = e + h_c + r \quad \text{and} \quad h'_m = h_m - r = h_m - (h'_c - e - h_c) = h_m - h'_c + e + h_c$$

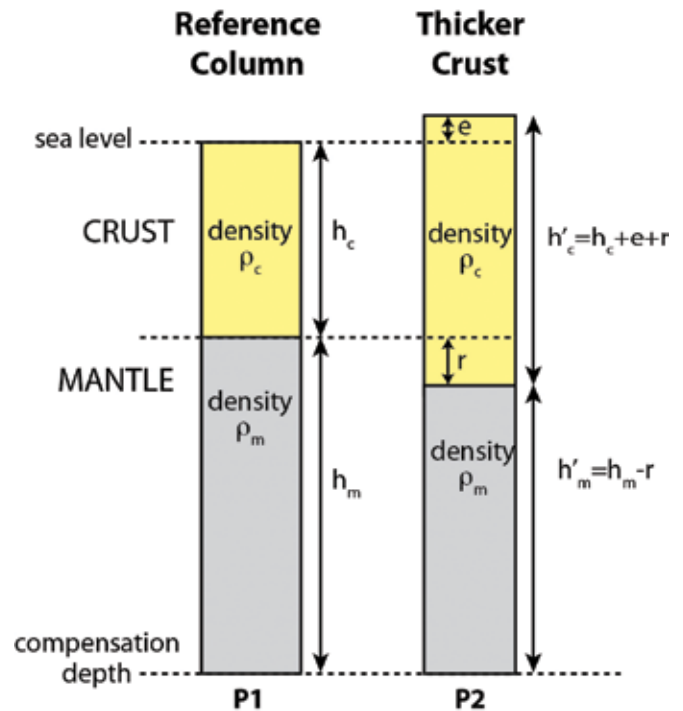
These equalities can be substituted into the previous equation, allowing it to be rearranged into an equation that gives the predicted elevation (e) as a function of crustal thickness (h'_c):

$$\rho_c g h_c + \rho_m g h_m = \rho_c g h'_c + \rho_m g h_m - \rho_m g h'_c + \rho_m g e + \rho_m g h_c$$

$$\rho_c h_c = \rho_c h'_c - \rho_m h'_c + \rho_m e + \rho_m h_c$$

$$\rho_m (h'_c - h_c) = \rho_c (h'_c - h_c) + \rho_m e$$

$$e = \frac{(\rho_m - \rho_c)}{\rho_m} (h'_c - h_c)$$



thin. Instead, the high elevations in this mountain belt appear to be supported by the hot, low-density mantle. Figure 8 shows a schematic cross-section through southwestern Canada, emphasizing the decrease in surface elevation, increase in crustal thickness and increase

in mantle temperature from the Cordillera to the craton.

Why is the Cordillera mantle so hot? During my Ph.D. research, we proposed that this may be related to the plate tectonic setting of this region.⁸ For the last 200 million years, the western side of North America has been

an area where oceanic plates (such as the modern Juan de Fuca plate in Figure 1) converge and descend below the continent, a process called subduction. During descent, water within the plate is released and hydrates the overlying material, resulting in a low viscosity for the Cordillera

mantle. We speculate that the low viscosities enable this mantle to undergo convection and that this efficiently carries heat from deep Earth to the shallow mantle. Computer models show that our proposed idea may work⁹; however, many details are still not understood.

CONCLUSIONS

In geophysics, we aim to gain a quantitative understanding of the structure and dynamics of the Earth's interior. In this paper, I have shown how geophysical observations allow us to study the deep structure of the craton and Cordillera regions in western Canada. At the surface, the craton is clearly distinct from the Cordillera. The craton is composed of relatively old rocks and has an elevation <500 m above sea level. In contrast, the Cordillera contains younger rocks and sits >1 km above sea level. To understand the origin of the elevation difference, geophysical methods can be used to examine the structure of the subsurface. This paper has highlighted two important observations that come from the analysis of seismic waves: (1) the Cordillera crust is 3 km thinner than the craton crust, and (2) the Cordillera mantle is 300°C hotter than the craton mantle to a depth of 220 km. The observations show that the high elevations in the Cordillera region are not due to the presence of an anomalously thick, low-density crust. Rather, it appears that the high mantle temperatures result in low densities that buoyantly support the mountain belt.

MY EXPERIENCES IN GEOPHYSICS

In this article, I have highlighted how geophysical observations can be used to study the internal structure of the Earth. This is one aspect of my research. The other aspect is trying to understand the dynamics of the Earth's interior. Geophysical observations provide a "snapshot" of the current structure, and so I use computer models and theoretical calculations to understand the dynamical processes that occur within the Earth and assess their effects on surface geology.

The goal of my research is to put the observations and models together into a coherent understanding of the factors that control the evolution of the Earth. What I like most about my work is that I use a wide range of tools to solve "big picture" problems, such as the development of mountain belts. This is also challenging because I must understand the methods used to collect each data set and the details of the model calculations. Much of my work is carried out in collaboration with geophysicists and geologists who have collected the data that I am using. Through the collaborations, I am always learning new things. Each person brings a different perspective to the collaboration, which can lead to new ideas and research directions.

I am currently an associate professor in geophysics at the University of Alberta. To reach this point, I had a relatively straightforward path, as I started my undergraduate degree knowing that I wanted to study

geophysics. I completed a B.Sc. in geophysics at the University of Western Ontario and a Ph.D. in geophysics at the University of Victoria. I then spent 2.5 years as a post-doctoral researcher at Dalhousie University. In contrast, many people who become geophysicists do not discover their interest in the field until later in their undergraduate studies, perhaps after taking an Earth sciences course as an elective. Geophysics is offered as a B.Sc. degree at several universities in Canada. Alternatively, it is possible to complete a B.Sc. degree in physics or Earth sciences (geology), and then specialize in geophysics through a graduate degree (M.Sc. or Ph.D.). For people interested in pursuing geophysics, it is necessary to have a strong background in the physical sciences (e.g., physics, math, chemistry). As well, it is important to develop skills in computer programming, scientific writing and public speaking; these are essential for almost any career in the sciences.

There are different career options in geophysics. The majority of geophysicists work in the petroleum or mining industries, where they conduct field trips to collect data or work on computers to analyze and interpret the data. Geophysicists can also work in other industries (e.g., environmental monitoring, geotechnical consulting, natural hazard assessment) or as researchers at a university or government lab.

My job at the University of Alberta involves a combination

of research and teaching. In addition to my own research projects, I teach undergraduate courses in geophysics, and I work with undergraduate and graduate students on research projects. A significant part of my current work is to continue the research in this paper. My students and I are now analyzing different types of geophysical data, such as measurements of the electrical structure, in order to better constrain the mantle structure in western Canada. We are also working on computer models to understand the links between mantle convection, thermal structure and surface elevation. In addition, we are looking at the consequences of the temperature contrast between the Cordillera and craton. For example, temperature controls the strength of rocks, and therefore the hot Cordillera is relatively weak and prone to earthquakes and geological deformation. In contrast, the craton is cold and strong and will be earthquake-free, except at zones of weakness.

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