Lithospheric Dynamics - Can plate cooling and shrinkage explain everything?

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Plate tectonics provides an efficient means for the Earth to shed its excess radiogenic heat. Plates, created at the seafloor spreading ridges are driven across the slippery asthenosphere by a combination of gravitational sliding force and pull from the negatively-buoyant subducted slabs. Cooling and contraction of the plates with increasing seafloor age produces an array tectonic signals ranging from the well documented to the mysterious. Here we will review the effects of plate cooling beginning with the most obvious expressions and ending with predictions, uncertainties, and questions.

Obvious signatures of the cooling lithosphere

The most obvious signals of lithospheric cooling appear in measurements of heat flow, depth, geoid height, and surface wave velocity and they are best understood in terms of conductive cooling models. Heat flow is a measure of surface temperature gradient and is most sensitive to shallow thermal structure. Unfortunately, conductive heat flow versus age data do not confirm the cooling models because much of the heat is advected by hydrothermal circulation near the ridge axes (Hofmeister and Criss, 2005; Pollack et al., 1993). Seafloor depth reflects the integrated heat loss from cooling. The depth vs. age signal dominates the topography of the ocean basins and provides a firm foundation for plate tectonic theory (Parsons and Sclater, 1977). Geoid height mainly reflects the temperatures at the base of the lithosphere (Haxby and Turcotte, 1978). Unfortunately the lithospheric signal is masked by contributions from deeper in the mantle. Similarly velocities derived from surface waves reflect lithospheric cooling although there is uncertainty in mapping from velocity to temperature (Ritzwoller et al., 2004). Combined, these data sets provide a definitive picture of the bulk cooling and volumetric contraction of the lithosphere with age.

Problem 1. Use Fourier's law, energy conservation, and isostasy to derive the following expression relating the increase in seafloor depth with age $\partial d/\partial t$ to difference between the surface heat flow and the into the bottom of the lithosphere $(q_s - q_\infty)$

$$\frac{\partial d}{\partial t} = \frac{\alpha}{C_p(\rho_m - \rho_w)}(q_s - q_\infty)$$

where α is the volumetric coefficient of thermal expansion, C_p is the heat capacity and $(\rho_m - \rho_w)$ is the density difference between mantle and seawater (Doin and Fleitout, 1996; Parsons and McKenzie, 1978). We use topography and age grids to map this heat flow globally to reveal where the Earth's heat engine is most efficient.

Inferred signatures of the cooling lithosphere

The lithospheric cooling model makes a number of predictions that have been, or could be, tested experimentally including the relationship between swell-push force and geoid height and the thickening and strengthening of the plates with age.

Problem 2. Using isostasy and a long-wavelength approximation to the geoid, derive the model- independent relationship between swell-push force F_s and geoid height N

$$F_s = \frac{g^2}{2\pi G} N$$

where G is the gravitational constant and g is the acceleration of gravity (Parsons and Richter, 1980). How does geoid height, and thus swell-push force, increase with seafloor age?

Taken at face value, this equation suggests that measurements of geoid height could provide global, model-independent measurements of global lithospheric stress. However, this mapping is a miserable failure and we discuss the many assumptions needed to provide results consistent with the few existing stress data.

The thickening and strengthening of the plates with age is predicted by combining lithospheric cooling models with ductile flow laws and Byerlee's law. These models are confirmed by analyzing the gravity and topography at seamounts as well and bending of the plates at subduction (Watts, 2001).

Problem 3. (a) Using a triangular shape for the lithospheric yield strength envelope show that the saturation bending moment is related to the age of the lithosphere to the 3/2 power. (b) Show that the observed bending moment at a trench/outer rise can be simply measured using the expression

$$M(x_0) = g \int_0^\infty \rho w(x)(x - x_0) dx$$

where $\rho w(x)$ is the topographic load and $(x - x_0)$ is the moment arm (McNutt and Menard, 1982). How can these ideas be used to bound lithospheric strength at subduction zones?

Mysterious signals of lithospheric contraction

How far can this cooling/shrinking model be taken? Top-down cooling and contraction of the lithosphere will lead to a thermoelastic bending moment.

Problem 4. Calculate the thermal stress that develops in a plate that is cooled uniformly from the top down (free edges) and explain why the surface of the plate is in compression while the base is in extension (Parmentier and Haxby, 1986)? What is the magnitude of this stress? Horizontal temperature gradients in the cooling lithosphere will also produce thermoelastic stress but strain rates are low. Unanswered questions include: Are transform faults thermal contraction cracks (Turcotte, 1974)? Are gravity lineaments warps and cracks in cooling plate (Gans et al., 2003)?

How do we determine if a volcanic ridge is a crack in the shrinking plate or a hole from edifice above a hot plume?

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