12.710, Spring 2014, Problem Set 5, Isostacy

Isostacy is the concept that adjacent "columns" of mass, extending from some reference level at the Earth's surface to some *depth of compensation*, should be equal. Isostacy follows from a balance of buoyancy forces under the assumption that Earth's mantle behaves like a fluid over geologic time scales. A number of inferences about the density structure of the earth and the temperature structure of the mantle are based on isostatic calculations.

The mass of any given column over the depth interval z_1 to z_2 for a depth-dependent density is

$$mass = \int_{z_1}^{z_2} g \rho(z) dz ,$$

and for a layered Earth with discrete densities the mass is

mass =
$$\sum_{i=1}^{nlayers} g \rho_i h_i$$
, where the h_i are layer thicknesses.

For the cartoon mountain in the middle of a continent shown here:



isostatic balance is described by the equation:

$$h_0 \rho_{air} + h_2 \rho_1 + (z_c - h_2 - h_0) \rho_2 = h_1 \rho_1 + (z_c - h_1) \rho_2$$

If the height of the mountain, h_0 , is known, and the crustal and mantle densities can be reasonably guessed at, and some depth of compensation, z_c , is assumed, then the thickness of the mountain, h_1 , including its "root", can be determined. The compensation depth is the depth below which no lateral variations in density exist. Usually this is in the asthenosphere.

Problem 1: Rift Basins

When continental lithosphere is extended, or stretched, it thins, and the surface expression of this is usually the formation of a basin, referred to as a rift basin. Surprisingly, the simple relationship between extension, isostacy, and basin formation was only appreciated in the 1970's, after plate tectonics began to be accepted; this despite the fact the all of the world's petroleum resources are derived from sedimentary rocks deposited in basins formed through extension.

Consider the problem of continental rifting and rift basin formation. Suppose that 150km-thick continental lithosphere, consisting of 40-km-thick crust and 110-km-thick lithospheric mantle, has been extended by 50% so that the crust and lithospheric mantle are both now 0.5 times their original thicknesses. In addition, suppose that the elevation of the surface was initially at sea level.

Assume that the density of the air is 0, the density of the crust is 2.7 gm/cm^3 , the density of the lithospheric mantle is 3.3 gm/cm^3 , the density of the asthenospheric mantle beneath the lithosphere is 3.2 gm/cm^3 , and that the rift basin is not filled with either water or sediments.

- a) Determine the depth of the basin relative to sea level.
- b) Now assume that the basin is filled by sediments with a density of 2.5 gm/cm³. How deep does the basin become with this additional load?
- c) Now suppose that the lithospheric mantle beneath the sediment-filled basin cools and thus thickens so that the base of the lithosphere attains it's original depth of 150 km, with the entire column still in isostatic equilibrium. How thick does the basin become?



This is basically the situation in Missouri, where the New Madrid fault zone causes lots of earthquakes. The New Madrid fault zone is a so-called failed rift, a region of continental lithosphere that thinned through extension but then stopped extending before completely rifting and establishing a new ocean basin. Subsequent cooling of the thinned lithosphere has resulted in ongoing basin subsidence and associated seismicity.

Problem 2: How deep is the ocean?

In order to have both oceans and land, you need a bunch of water and something like a bi-modal distribution of topography. Oceanic and continental crusts are different in terms of both thickness and bulk composition. Mean topography on land is near sealevel, so let's assume sealevel for the elevation of continental crust. How do we explain an average ocean depth of something like 5 km?

- a) Let's assume ocean depth relative to the continents is due solely to differences in the crust. Assume the thickness of continental crust is 35 km (a good average for near coasts) and the thickness of oceanic crust is 6 km (a good average), and that the density of continental crust is 2700 kg/m³, the density of oceanic crust is 2850 kg/m³, the density of seawater is 1000 kg/m³, and the density of the mantle is 3200 kg/m³. How deep is the ocean?
- **b**) For (a), you should get a depth that is too deep. So we have to consider the mantle. For the oceanic lithospheric mantle, assume the density of oceanic mantle is:

$$\rho = \rho_{0^{\circ}C} (1 - \alpha \Delta T),$$

where $\rho_{0^{\circ}C} = 3300 \text{ kg/m}^3$, the density at 0°C, and $\alpha = 3x10^{-5} \text{ °C}^{-1}$ is the coefficient of thermal expansion of. Assume a steady-state, plate-model geotherm for a mantle temperature of 1350°C at the base of the lithosphere, with the base of the lithosphere at 125 km depth. For the isostacy calculation, you can use an average lithospheric-mantle density based on an average lithospheric temperature. If we believe all of these assumptions about the oceanic lithosphere, then we can use the observation of oceanic depth to estimate the density of the continental lithospheric mantle. Do that assuming that the continental lithosphere is the same thickness as oceanic lithosphere and that the temperature everywhere below the lithosphere is 1350°C. Why might these densities be different?

c) Various observations suggest that the continental lithosphere is thicker than oceanic lithosphere. What would the density of continental lithosphere be if it were 200 km thick (a number lots of people like) and we stuck with the rest of our assumptions?

Problem 3: Thermal subsidence

Consider the problem of oceanic-lithosphere subsidence. Suppose we observe that the depth below sea level of the spreading ridge axis is 2.5 km, and the depth of the sea floor away from the ridge axis above 50-million year-old lithosphere is 4.0 km. We want to estimate the thickness of the 50 m.y. old lithosphere.

Assume that the density of the crust is 2800 kg/m³, the density of seawater is 1000 kg/m³, the density of the "asthenospheric" mantle is $\rho_{1300^{\circ}C} = 3100$ kg/m³, and the average temperature of the lithosphere is 600°C (i.e. assume a constant temperature for the lithospheric mantle of 600°C); there is no lithospheric mantle at the spreading center; and the value of α is a = 3x10⁻⁵ °C⁻¹.

- a) Determine the thickness of the 50-m.y.-old lithosphere.
- b) What would the depth to the seafloor be if a 1-km-thick sequence of sediments with a density of 2500 kg/m³ were placed on top of this 50-m.y.-old lithosphere?
- c) Write down an equation that gives the "unloaded" seafloor depth, i.e. the depth of the seafloor after removing a sedimentary load assuming instantaneous isostatic rebound.