Geodynamics
G456-556

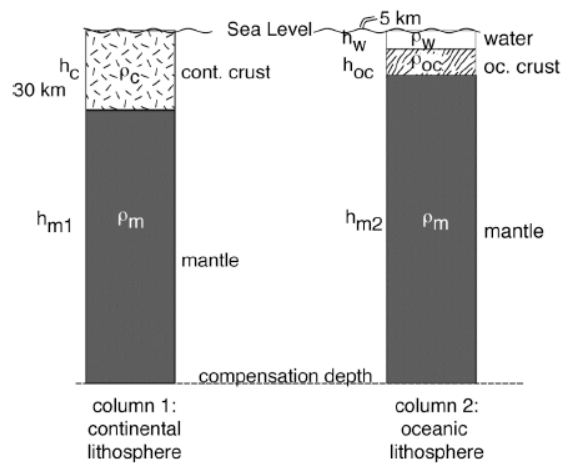Lab #4: Airy Isostasy

Introduction

The study of plate tectonics usually emphasizes horizontal motions of plates, but vertical dynamics are intimately related to mantle motion, and we're beginning to re-recognize their importance. Vertical motions have some very important consequences -subduction, mountains building, basins development, weather pattern alteration, erosion rate acceleration, and exposure of deep rocks, to name a few. In this problem set, you will explore the vertical dynamics of the lithosphere through the concept of isostasy.

Some background on isostasy

Isostasy is an equilibrium condition characterized by equal pressure within some fluid. In the case of plate tectonics, the fluid happens to be the mantle. (Beware! Do not confuse the word *fluid* here to mean that the mantle is a liquid – solid rock can be a fluid provided that it can flow in response to stresses. It's just that this flow occurs over geologic time scales.) For the pressure in the mantle to be equal at a given depth, there must be an *equal amount of overlying mass* everywhere above that depth.

Imagine that we take a particular depth within the mantle to call our *compensation depth*. We then define a series of vertical columns rising from that depth to the surface (of land or sea). If the mass of each of these columns is the same, then we have a state of isostatic equilibrium; any deviation from this will provoke an isostatic adjustment in the form of a vertical motion whose speed is determined by the viscosity of the mantle and the magnitude of the pressure difference within the mantle.

For example, if one column is deficient in mass, then the mantle in that region is at lower than normal pressure, and this initiates flow in the mantle to fill in this low pressure area. More mantle material is thus added to the column, causing upward motion of the surface. If a column has too much mass, the mantle below is at a higher than normal pressure, so mantle material moves away from that region, causing the surface to drop in elevation. This concept of isostasy can be applied to a number of questions. For instance, we can figure out the thickness of oceanic crust as shown in the example below, by equating two lithospheric columns in isostatic equilibrium.

Example: Calculating the thickness of the oceanic crust

Sea Level — 5 km

h_w ρ_w water
h_{oc} ρ_{oc} oc. crust

h_c ρ_c cont. crust
30 km

h_{m1} ρ_m mantle

h_{m2} ρ_m mantle

compensation depth

column 1:
continental
lithosphere

column 2:
oceanic
lithosphere

Figure 1: two columns in isostatic equilibrium

If we say that these two columns of rock in Figure 1 are in isostatic equilibrium, then they are neither rising nor subsiding, and the masses of these two columns must be equal. To determine the thickness of oceanic crust in this example, we therefore need to create an equation relating the masses of these two columns:

$$(\text{mass}_{\text{column1}} = \text{mass}_{\text{column2}})$$

$$\Sigma(\rho_i h_i)_{\text{column1}} = \Sigma(\rho_i h_i)_{\text{column2}}$$

and solve for the unknown we desire (i.e., h_{oc})

For the two columns in figure 1, we get

(1) $h_c\rho_c + h_{m1}\rho_{m1} = h_w\rho_w + h_{oc}\rho_{oc} + h_{m2}\rho_{m2}$

Now, in this case, we also know that the total height of each column above the compensation depth is the same, which give us

(2) $h_c + h_{m1} = h_w + h_{oc} + h_{m2}$

solving equation (2) for h_{m2} and plugging into equation (1) we get

$h_c\rho_c + h_{m1}\rho_m = h_w\rho_w + h_{oc}\rho_{oc} + (h_c + h_{m1} - h_w - h_{oc})\rho_m$

Simplifying and rearranging, we get an expression for the thickness of the oceanic crust

$h_{oc} = [h_c(\rho_c - \rho_m) h_{m1} + h_w(\rho_m - \rho_w)] / (\rho_{oc} - \rho_m)$

Plugging in realistic values for the different parameters:

$h_c = 30$ km; $h_w = 5$ km; $\rho_c = 2.83 g/cm^3$; $\rho_m = 3.3$ g/mc^3; $\rho_w = 1.0$ g/cm^3
we find that $h_{oc} = 7.4$ km.

In this example, we didn't insert values until the equation was solved symbolically. Although you could plug in values sooner in the solution process, symbolically solving the system of equations allowed us to cancel terms and end up with a fairly simple expression for thicknesses and densities and easily recalculate crustal thicknesses.

These kinds of problems always boil down to the same thing: you draw two lithospheric columns and assume they are in isostatic equilibrium, which means that their masses are the same. If there is just one unknown in this equation, then you're all set.

If there are two unknowns, you need another equation. Sometimes, you can also assume that the heights of the columns are the same, and this gives you two equations. Combining your two equations allows you to solve the problem.

On the continents, we have slightly different columns than in the oceans, shown in Fig. 2. On continents, continental lithosphere with the surface at sea level has a thickness of T_A. while mountain ranges with an elevation h have "roots" of thickness r.
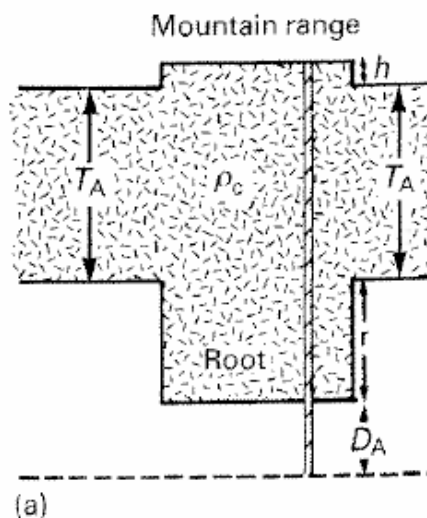

Figure 2: Continental Columns in isostatic equilibrium

Supplies:

- global data files of topography (map2.topo) and crustal thickness (map2.thick).

- matlab function, readTopo.m, to load in the topography data file and plot a map. The script provides you with a cross hair which you move around to extract the lat, long, and elevation at a selected location. To run this function, type in

>   Elev=readTopo()

-matlab function, getCrustThick.m, to load in the crustal thickness data file and retrieve the crustal thickness at the locations you selected for readTopo. To run this function, type in

>   getCrustThick (lat, long) %where you type in the lat and long of the point of interest

Assignment:

Determine the expected crustal thickness of the 5 following regions, and determine if they are in Airy isostatic equilibrium

- Basin and Range
- Tibetan Plateau
- Norway
- The Andes
- Southern Africa

If a region is not in equilibrium, discuss what could account for the imbalance.

Procedure:

1) Following a similar method as the one used for oceanic lithosphere, determine the equation that solves for the thickness of the mountain root in terms of the mountain height and the density of crust and mantle.

2) From this equation, determine another equation that solves for the crustal thickness in terms of the mountain height, and "typical" values for crustal thickness, T_A; and density of the crust, $\rho_{c;}$ and mantle, ρ_m. (Gee, isn't this cool- you can now quickly guess the crustal thickness of any location on the earth!)

3) Okay, now you have an equation that gives you the "expected" crustal thickness. Using the code provided (readtopo.m), select points within the 5 regions of interest and note the lat, long, and elevation.

4) Write your own script to calculate the expected crustal thicknesses at these locations. Use the values of T_A=30 km ρ_m=3.3 g/cm^3 and ρ_c=2.8 g/cm^3 (watch your units!). This is a good opportunity to use "for" loops.

5) Using the code provided (readCrustThick.m) retrieve the crustal thicknesses and compare to your expected crustal thicknesses.

To hand in:

1- Your M-Flies
2- A table of the five locations giving lat, long, elevation, calculated crustal thickness, actual crustal thickness
3- For each of the locations where the calculated and actual crustal thicknesses are different, discuss plausible geodynamic reasons why.