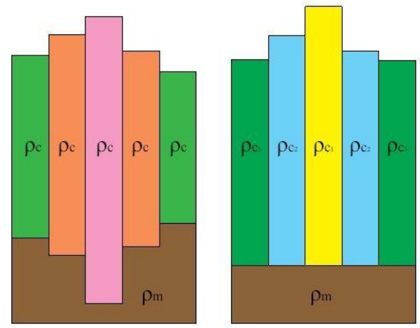
Lab 4: Planetary Interiors

Activity 1: Isostasy

Isostasy is the process which maintains gravitational equilibrium between a planets rigid shell (the lithosphere, on Earth consisting of the crust and upper mantle) and the "softer" underlying asthenosphere (on Earth the lower mantle). It is essentially a geologic application of Archimedes principle (when he supposedly shouted "Eureka!" in his bathtub).



There are two end-member cases of isostasy (see figure to right): the **Airy Model** (left), where topographic heights are compensated by changes in crustal thickness (they have "roots" like an iceberg), and the **Pratt Model** (right), where all blocks float at the same depth (they lack roots), but have different densities. These are **end member models**, so in the real world we will have situations that are some blend of the two. Typically mountain ranges tend to follow the Airy Model, while mid ocean ridges follow the Pratt Model.

Assume that a mountain range is in isostatic equilibrium according to the Airy model. The initial height is 5 km. The crust and the mantle Airy Pratt densities are $\rho_c = 2.8$ g/cm^3 and $\rho_m = 3.3$ g/cm^3, respectively.

1. Sketch this situation (as a cross-section). Label the mountain height above sea level (h) and mountain root depth (d).

2. What is the depth of the mountain root (d)?

3. Suppose a layer of thickness 2 km is removed from the mountains during a period of erosion. How high are the mountains after the new isostatic equilibrium is achieved? What if 8 was eroded away?

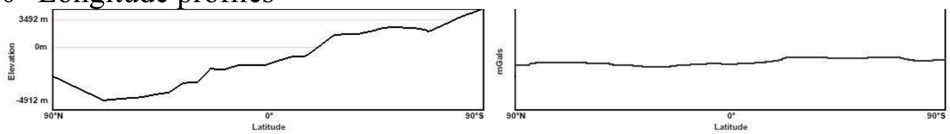
4. In order to bring the area down to sea level, how much material would have to be removed?

Activity 2: Geodesy

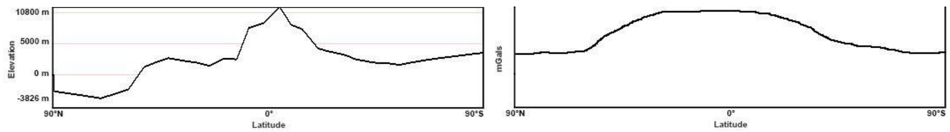
If something is isostatically compensated, there are no lateral variations in pressure beneath a certain depth, which means that the total mass above this depth does not vary either. This means that we should expect to see very small gravity anomalies over isostatically compensated surfaces. In fact, we can use the size of a gravity anomaly to tell us about whether or not a load is isostatically compensated.

Here we are going to use some topographic and gravimetric data from the Mars Global Surveyor (MGS) spacecraft to examine the crustal thicknesses on Mars. The surface of Mars is dominated by several features, one being the "hemispheric dichotomy" and the other being the Tharsis volcanic province. We are going to look at two N-S global profiles, one at ~140° East (Tharsis) and the other at 0° longitude. These are very simplified versions, so I'd suggest not using them for actual spacecraft navigation.

0° Longitude profiles



140° Longitude profiles



1. Lets use the profile highlighting the hemispheric dichotomy (0°) to estimate Mars' crustal thickness. Assume Pratt isostasy, and densities of 2700 kg m^{-3} (granite) and 2900 kg m^{-3} (basalt). How thick is the crust?

2. The actual crustal thickness on Mars varies between 32 km in the north to 58 km in the south, with an average of 45 km. Compare this with your estimates.

3. Now look at the gravity measurements. mGal is a measurement of gravitational acceleration. Is the dichotomy isostatically compensated? What about Tharsis? What does this tell you about the rigidity of the crust underneath each feature (i.e. is it completely rigid or have no strength at all?)?

4. Using crater counts we can determine that the dichotomy occurred well before the formation of Tharsis. What does this tell us about how Mars' crust has changed over time?

Activity 3: Flexure

So far we have looked at two end-member cases: a completely rigid lithosphere, and when it has no strength at all (isostasy). In the real world we have to deal with something in the middle, meaning a lithosphere that only partially supports the load on top of it. The lithosphere behaves elastically (i.e. it bends) when a load (i.e. volcano or mountain range) is applied. A load will be supported by both elastic stresses (the lithosphere's rigidity) and buoyancy forces (asthenosphere).

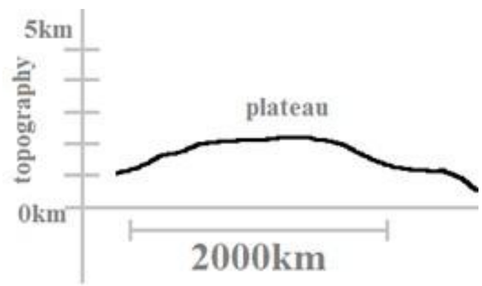
Suppose we are flying over a planetary surface collecting topographic and gravimetric data. We would like to be able to learn something about the thickness of the rigid lithospheric layer (this doesn't always have to be rocky, it could be ice in the case of the outer planet satellites). A value that we can identify is the flexural parameter, which is the **natural wavelength** of an elastic plate. If we were to apply a concentrated load to the center of the plate, the natural wavelength would be the distance outward from that point that we would see deformation. We can relate the flexural parameter to the thickness of the lithosphere with the equation

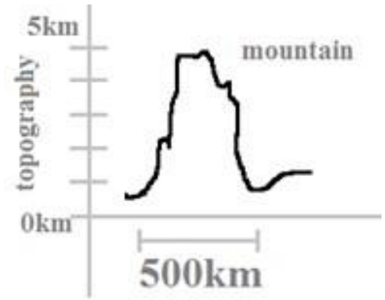
$$\alpha = \left[\frac{ET_e^3}{3g(\rho_m - \rho_c)(1 - v^2)}\right]^{\frac{1}{4}}$$

where E is Young's modulus (a measure of rigidity…higher is more rigid), T_e^3 is the elastic thickness (lithosphere thickness), g is gravity, ρ_m and ρ_c are the densities of the mantle and crust, and v= Poisson's ratio (a measure of "stretchability"…if you apply a stress in one axial dimension this measures the deformation in the perpendicular direction).

1. What happens to the flexural rigidity if you increase the elastic thickness, gravity, or the change in densities? Does this make physical sense?

2. Here are topographic profiles of two geologic features on two completely different planets.

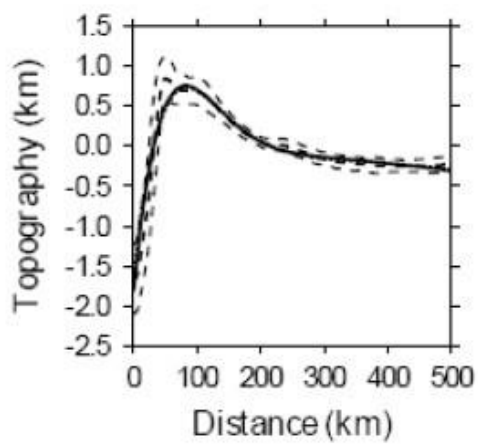




   a. What is the flexural parameter (half distance of deformation) for both features?
   b. Calculate the elastic thickness for each feature. Assume that $g = 9$ m s^{-2} (Earth- or Venus-sized planet), $\nu = 0.3$, the density contrast is 500 kg m^{-3} and $E = 100$ GPa (typical for rock)

   c. Are your elastic thicknesses reasonable? Why or why not? There isn't necessarily a correct answer here, just be sure to justify what you say.

3. **The figure to the right** shows a topographic profile across part of a *corona* (a circular feature with a trench surrounding it) on Venus. We are going to interpret the trench and rise as a flexural feature due to loading. Note the horizontal and vertical scales are much different.



   a. Mark on the figure the approximate distance over which flexure is deforming the lithosphere. What is the flexural parameter?

   b. Assuming that this distance is the flexural parameter, use the expression above to determine the *elastic thickness* of the lithosphere on Venus. You may assume that $g = 9$ m s^{-2}, $\nu = 0.3$, the density contrast is 500 kg m^{-3} and E = 100 GPa.

   c. How does the elastic thickness on Venus compare with that of continents on Earth? Why might this be a surprising result, given what we know about the two planets?

   d. The base of the elastic layer is determined by a temperature of about 1000 K (this is the temperature at which the rock becomes pliable) and the surface temperature of Venus is 700 K. What is the thermal gradient (the change of temperature over the change in depth) on Venus?

   e. Thermal gradients on Earth are about 25 K/km. What does this result imply about the relative rates at which the Earth and Venus are cooling down?

   f. How might you explain this difference in cooling rates?