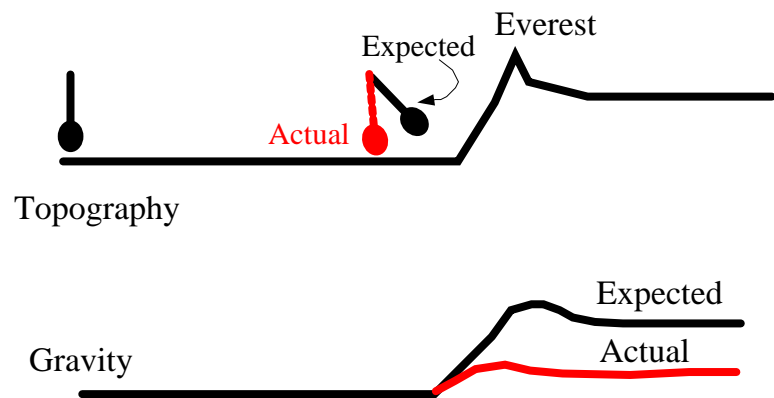


Gravity Fields – part II

(see Chapter 2 of Lowrie)

ISOSTASY

The concept of isostasy arose in the middle of the 19th Century as a result of gravity surveys carried out in mountainous areas. One of the most famous was carried out by Pratt in a pendulum survey carried out by trekking northward on the Indian plain toward Mt. Everest and the Tibetan Plateau. The deflection of the pendulum from the “vertical” was about 1/3 of that expected from calculations based on the assumption that the Himalayas and the Tibetan Plateau were a lump of mass sitting on the Earth. Something must be nearly canceling out the mass of the mountain.

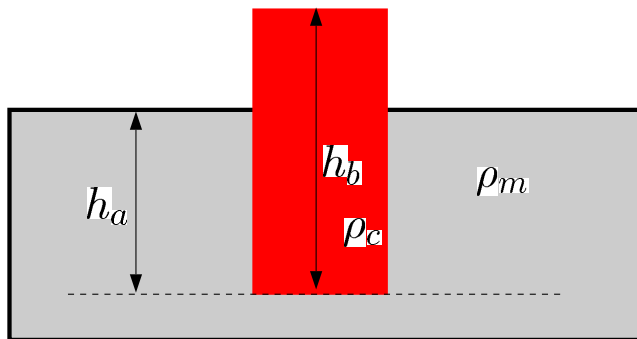


Archdeacon Pratt pendulum/plumb-bob survey (1855)

$$T = 2\pi \sqrt{\frac{L}{g}}$$

Figure 5

The interpretation that became popular (the hypothesis of *isostasy*) was that at some depth the weight of the rock (or the pressure exerted) was the same everywhere. The depth is called the *depth of compensation*. This idea follows directly from *Archimedes Principle*: a body immersed in a fluid is subject to an upward force equal in magnitude to the weight of the fluid it displaces.



$$W_a = W_b$$

$$m_a g_0 = m_b g_0$$

$$\rho_m h_a A = \rho_c h_b A$$

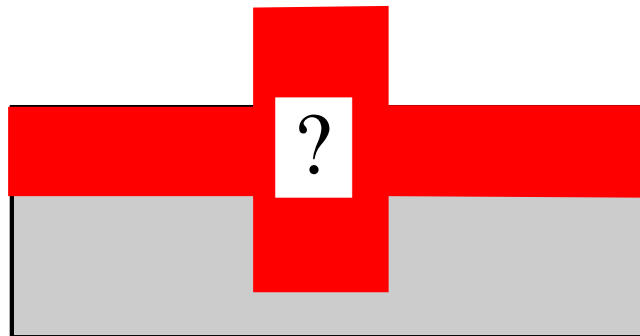


Figure 6

An assumption in the isostatic hypothesis is that the lithosphere can act as a series of uncoupled vertical columns that independently exert lithostatic (~ hydrostatic) pressure.

Although there was acceptance of the isostatic hypothesis, there was great controversy regarding just what the arrangement of rock must be to give rise to equal pressure at the depth of compensation. Two major competing hypotheses emerged: Airy in 1855 proposed that Archimedes principle be taken literally, that masses of rock would sink in a weak substratum (the asthenosphere?) until

Archimedes principle was satisfied. This led to the concept that mountains have “roots”.

Figure 6 is a cartoon of Airy isostasy. If we take the bottom of the mountain block as depth h_a , then a statement of equal pressure under the mountain versus in the surrounding “plains” is:

$$\rho_c g_0 h_m + \rho_c g_0 T_c + \rho_c g_0 h_r = \rho_c g_0 T_c + \rho_m g_0 h_r$$

where h_m , h_r , T_c , are the thicknesses of the mountain, the “root”, and the crust, respectively. Rearranging:

$$\rho_c h_m = (\rho_m - \rho_c) h_r$$

Since a typical crustal density is 2900 kg m^{-3} and a typical mantle density might be 3300 kg m^{-3} , the root will be considerably thicker than the mountain. Note also that the mountain is a *mass excess* proportional to $\rho_c h_m$ above the plains and that the root replaces dense mantle with less dense crust and is a *mass deficiency* proportional to $(\rho_c - \rho_m) h_r$ in the mantle. By the above equation, the two masses must be equal in magnitude and opposite in sign. **What does this about the gravity anomaly over the mountains? What does this say about the structure of the Tibetan Plateau (remember Mr. Pratt’s survey)?**

Pratt in 1859 proposed an alternative hypothesis that differences in elevation were simply explained by differences in density: higher elevations had less dense columns than lower elevations such that all columns had the same weight at the depth of compensation.

To repeat: **The classical concept of isostasy supposes that the weight of rock at some depth, called the depth of compensation, is everywhere equal.**

The two classical types of isostatic compensation are illustrated below (Figure 7). In Airy compensation, columns of different thickness, but the same density, “float” at different depths in the material beneath. Thus,

$$\rho_1 = \rho_2 = \rho_3 = \rho_{\text{crust}}$$

Isostasy requires that the pressure be the same everywhere at the depth of compensation, so if h_i is the thickness of block i and t_i = the distance from the bottom of block i to the depth of compensation, then:

$$\rho_1 g_0 h_1 + \rho_m g_0 t_1 = \rho_2 g_0 h_2 = \rho_3 g_0 h_3 + \rho_m g_0 t_3$$

This gives the same result as we just derived above. In Pratt compensation, the densities of the blocks are different, but the block bases are all at the depth of compensation:

$$\rho_2 > \rho_1 > \rho_3$$

and

$$\rho_1 g_0 h_1 = \rho_2 g_0 h_2 = \rho_3 g_0 h_3$$

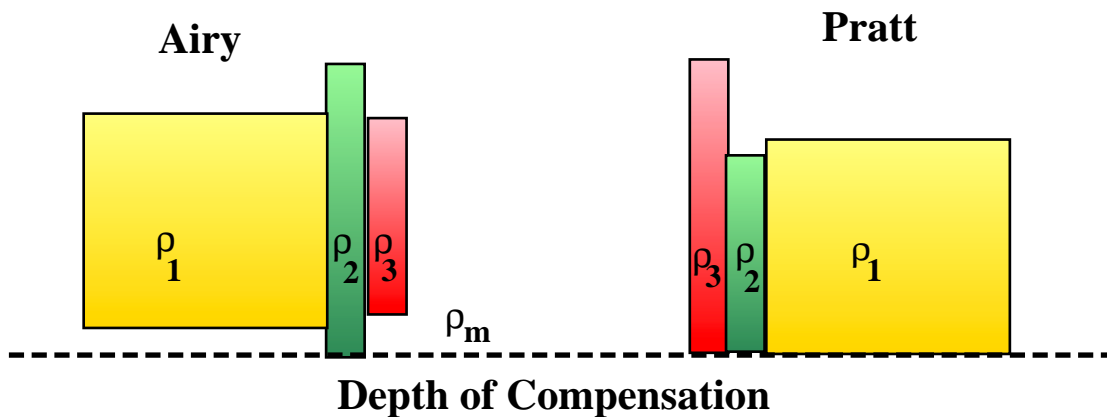


Figure 7

At first blush, isostasy seems rather implausible. The blocks can be arbitrarily narrow. They must be able to move independently of one another. This means they are free to slide up and down ($\sigma_{xz} = 0$) and stress cannot be transmitted across block interfaces ($\sigma_{xx} = 0$). **Can this happen?** Yes, if the lithosphere has little elastic strength, or the *flexural rigidity* is close to zero. When this is not the case, the term *flexural compensation* is used (an older, but useful, term is *regional compensation*). Most regional to small scale features on the continents and in the ocean basins are flexurally compensated to varying degrees, but are much closer to Airy compensation than Pratt compensation. The figure below illustrates the concept.

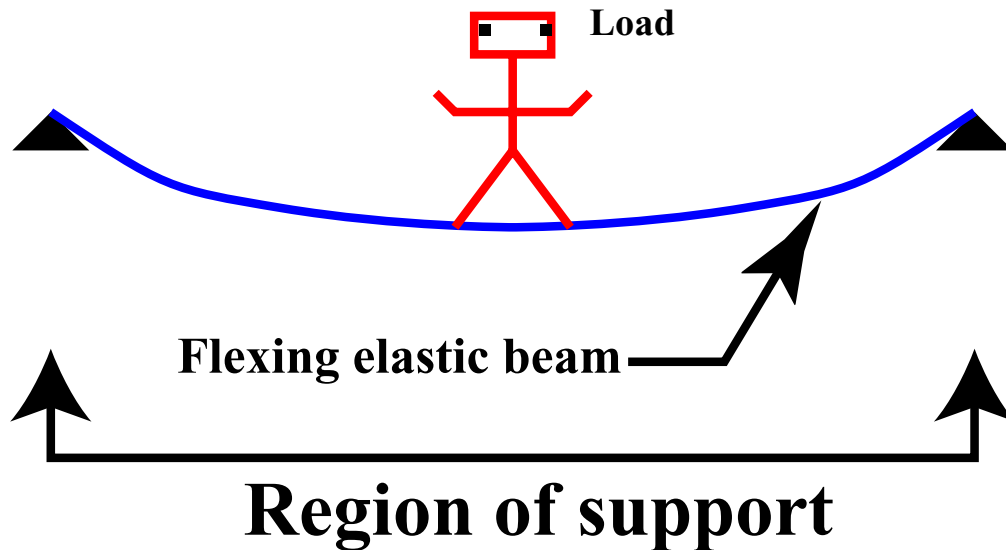


Figure 8

The other possibility is that the crust is sufficiently weak so that it acts like a viscous fluid over long periods of geological time. Figure 9 below shows that if the crust and mantle are treated as viscous fluids, and if a mountain is created in the crust, then Airy isostasy will develop (**relatively**) rapidly, but eventually all of the disturbances must disappear. The fluid flows to minimize stress (“**Nature abhors a stress**”), and the isostatic state is one of very low stress. Under the assumption of a fluid, all density interfaces would eventually flow to horizontal, but the situation doesn’t usually get that far **Why?**

Viscous Crust with Plateau

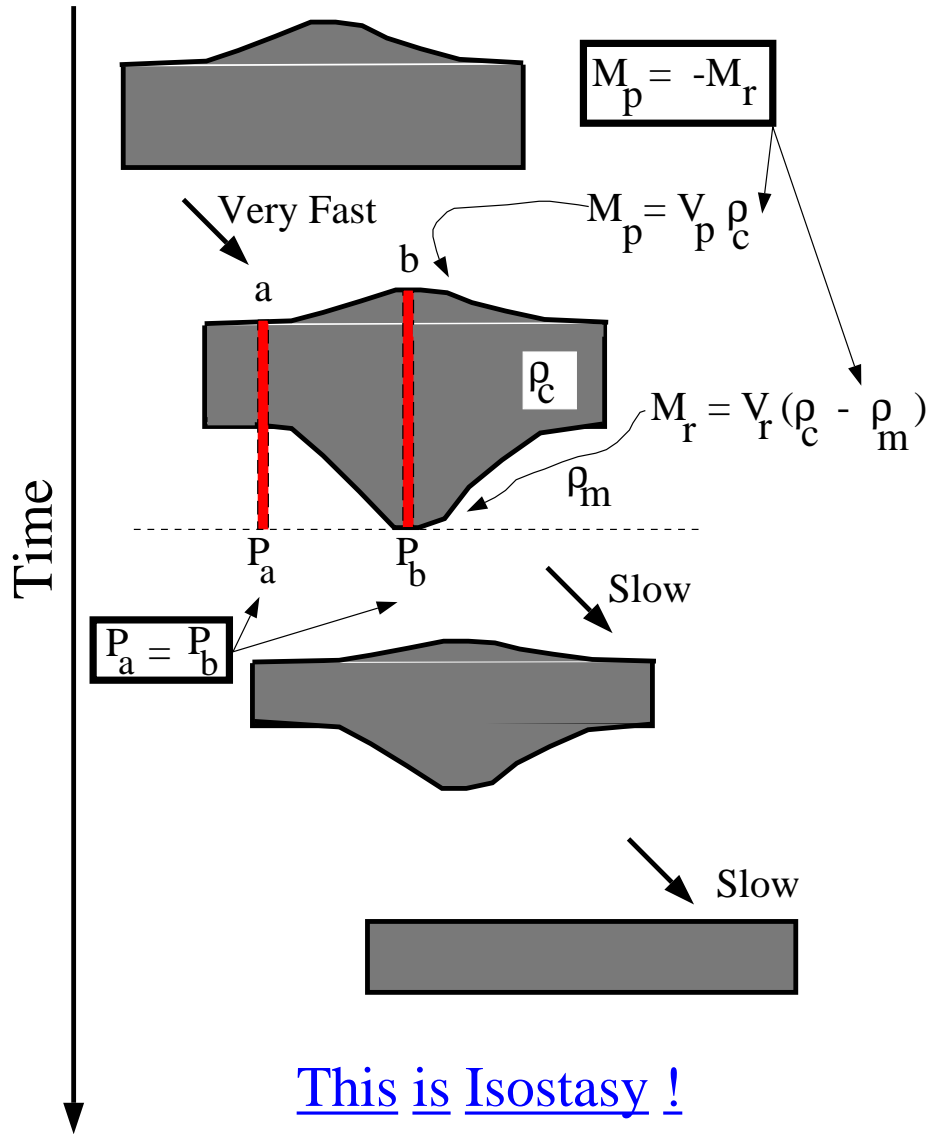


Figure 9

Bouguer Gravity

Bouguer gravity, as we discussed earlier, is the result of subtracting the gravity from topography only from the observed gravity. Over mountains, it should be negative if Airy isostasy is operating.

(See the U.S. Bouguer Anomaly Map)

Why is the observed gravity so small in the figure below?

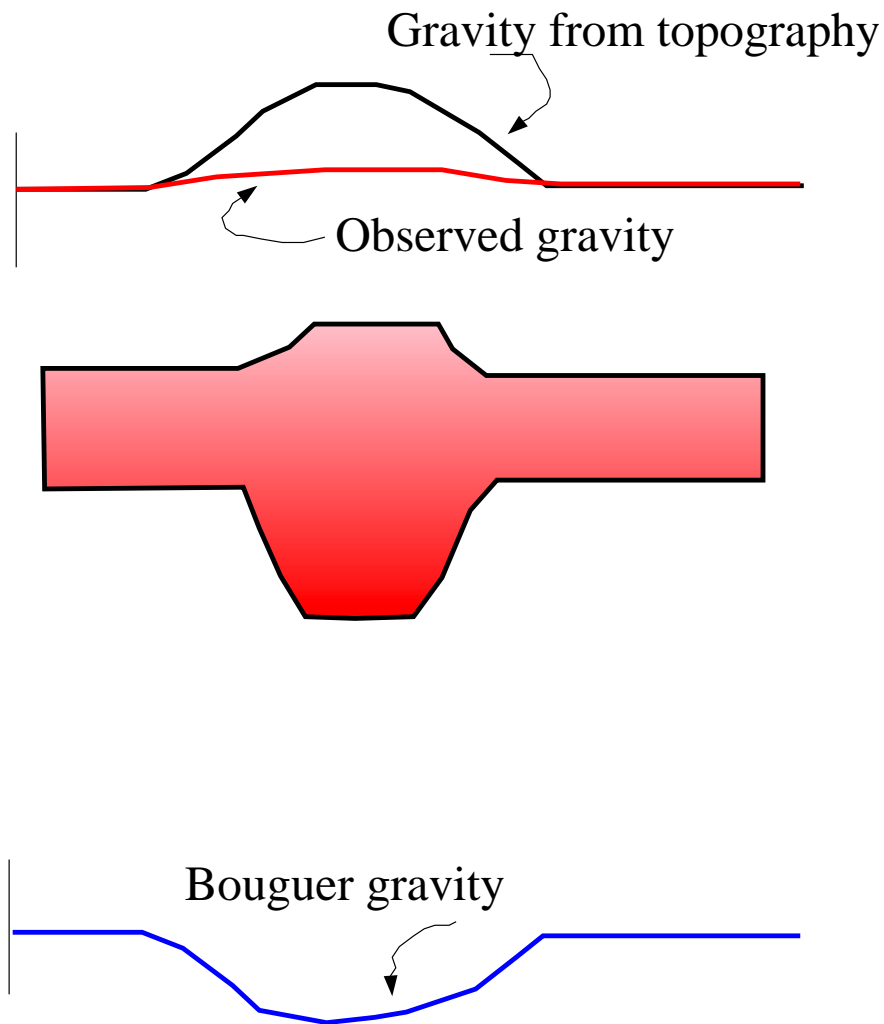


Figure 10

Thermal Isostasy

The most common type of compensation on Earth is “none of the above”. The depth to ocean floor is controlled by thermal compensation, which appears to have elements of both Pratt and Airy compensation.

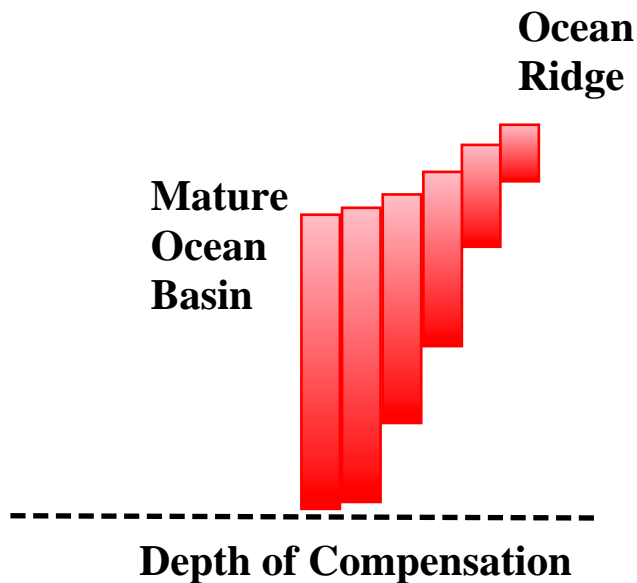


Figure 11

As young lithosphere moves away from the ocean ridges, it cools and thickens. As it cools, it also becomes denser and the depth of the seafloor increases, so this seems like Pratt compensation. But the base of the oceanic lithosphere is defined by an isotherm, as is the seafloor itself. As the lithosphere cools, it also thickens. If we assume that the temperature gradient is linear in the lithosphere (**What does that mean?**), then the average density is the same from column to column (Figure 11). But the density **beneath** the lithosphere (i.e., in the asthenosphere) is less than the lithosphere itself (There is a complication to this argument because of the presence of a crust). This means that as the columns become thicker, **they must sit lower to maintain the same pressure at the depth of compensation**. This is why the seafloor deepens away from midocean ridges. **It is isostasy!**

All of the above fall under the heading of “isostatic equilibrium”, which is a special case of mechanical equilibrium. We also consider dynamic equilibrium or dynamic compensation, in which flowing material is part of the equilibrium process.

Examples

Tibetan Plateau

Arc Environments

Collisional Environments

Thermal isostasy --- Basin and Range, plumes

Long and short wavelength Bouguer maps of U.S.

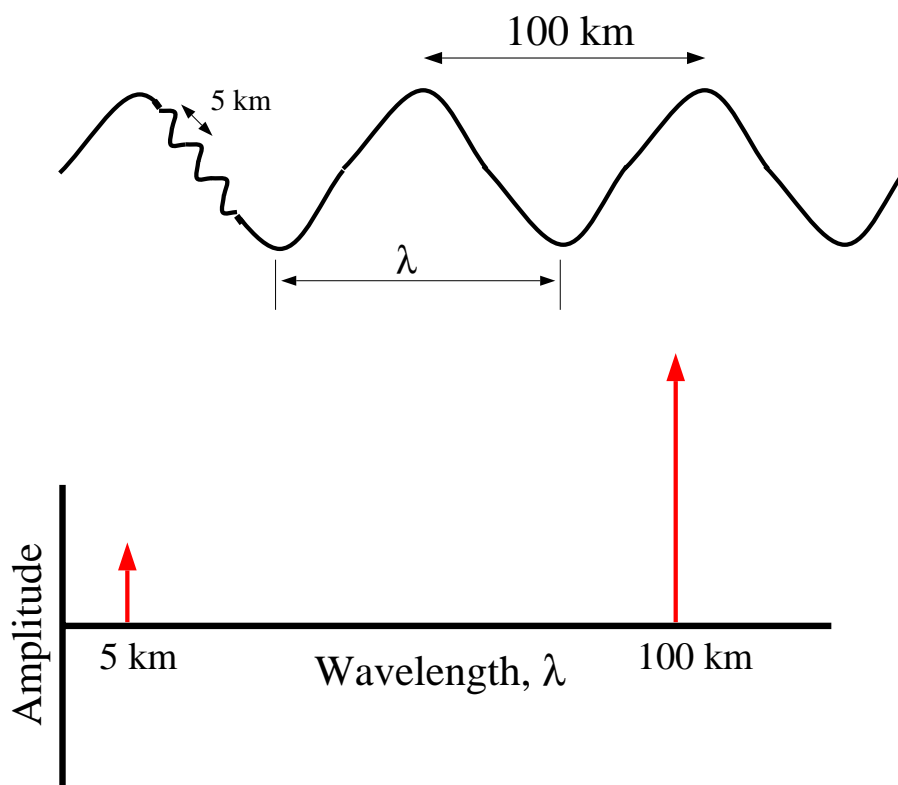


Figure 12