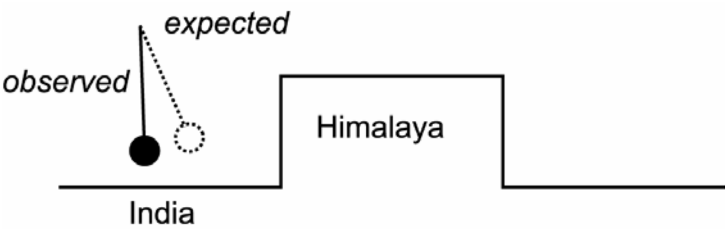
325 B8. Isostacy and the structure of the Earth

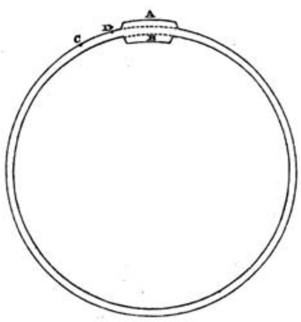
Himalayan peaks on the Tibet-Bhutan border

In the 19th century surveyors used pendulums and theodolites to survey the British empire. They also calculated the height of the Himalaya by triangulation. It was noticed that the Himalayan peaks did not deflect the pendulum as much as predicted from calculations of their size and density. The difference was 5.236 arc seconds which is a very small angle.



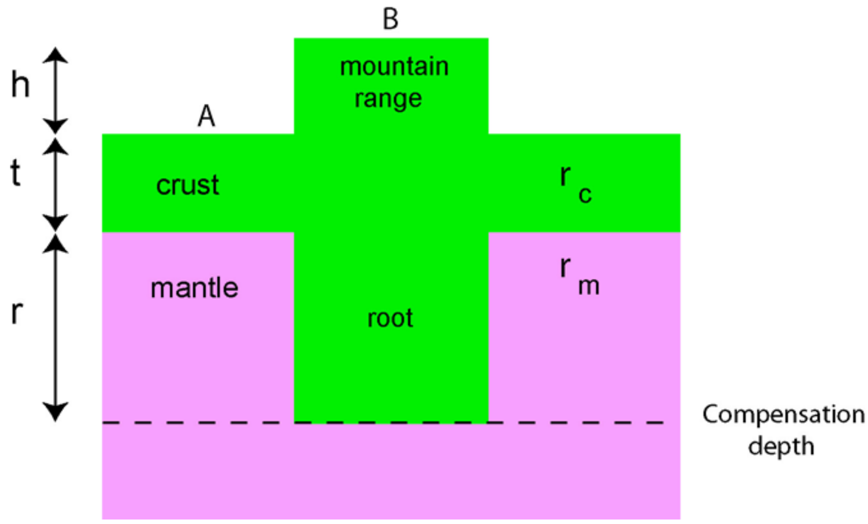
To account for this observation, George Airy suggested that mountain ranges have a low density region beneath them. In one explanation, this can be quantified as **Airy's hypothesis of isostacy**. The mountain range can be thought of as a block of lithosphere (crust) floating in the asthenosphere (lava). Mountains have roots, while ocean basins have anti-roots. In his 1855 paper, George Airy who was the Astronomer Royal wrote:

"*It appears to me that the state of the earth's crust lying upon the lava may be compared with perfect correctness to the state of a raft of timber floating upon water; in which, if we remark one log whose upper surface floats much higher than the upper surfaces of the others, we are certain that its lower surface lies deeper in the water than the lower surfaces of the others*"



III. *On the Computation of the Effect of the Attraction of Mountain-masses, as disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys. By* G. B. AIRY, *Esq., Astronomer Royal.*

Received January 25,—Read February 15, 1855.



If the system is stable (no external forces) it is said to be in **isostatic equilibrium**. At the **compensation depth**, the pressure due to material above is constant at all locations (below this depth the Earth behaves as a liquid). A plateau of height *h* is supported by a crustal root of depth *r*. The normal crustal thickness is *t*. In this region, the acceleration of gravity is *g*.

Pressure at a depth *h* in a medium of density ρ is given by $P = \rho g h$

Thus equating the **pressure** at the compensation depth at 'A' and 'B' we can write

$t\,\rho_c + r\,\rho_m = (h + t + r)\,\rho_c$

which simplifies to

$r\,\rho_m = h\,\rho_c + r\,\rho_c$

Note that we have assumed that g has the same value at each location. This may seem to contradict the last few weeks of classes, but is valid as a first order approximation.

Re-arranging this equation gives the thickness of the crustal root,

$r = h\,\rho_c / (\rho_m - \rho_c)$

Question

How deep a root is needed to support a 5 km plateau, such as the Tibetan Plateau?

Assume $\rho_c = 2800$ kg m^{-3} and $\rho_m = 3100$ kg m^{-3} ?

You should be able to show that this gives r = 47 km and the crustal thickness = h + t + r = 82 km.

Was George Airy correct about crustal thickness in Tibet? Modern seismic exploration has shown that the crustal thickness in Southern Tibet is in the range of 75-85 km.

Note : George Airy explained the small deflection of the pendulum as

"*It will be remarked that that the disturbance (gravity anomaly) depends on two actions; the positive attraction produced by the elevated table land; and the diminution of attraction, or negative attraction, produced by the substitution of a certain volume of light crust for heavy lava*"

Question : What Free Air and Bouguer anomalies would be measured across this plateau?

To consider this, compute the attraction of mass above the compensation depth at points 'A' and 'B'.

$g_A = 2\pi G\,(\rho_c t + \rho_m r)$ and $g_B = 2\pi G\,(h+t+r)\,\rho_c$

Consider the condition we previously derived for buoyancy? What does this tell us about g_A and g_B?

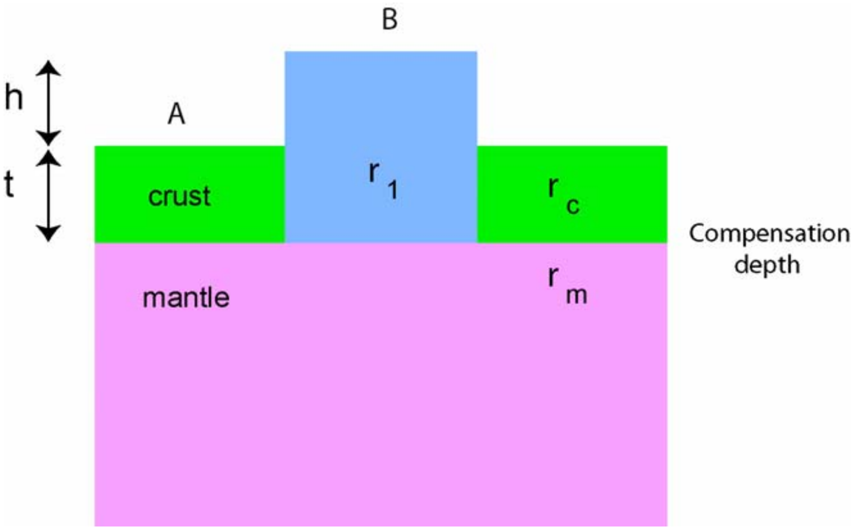
Are the values of g_A and g_B Bouguer or Free Air anomalies?

An alternative explanation was given by John Pratt who was Archdeacon of Calcutta (one of the people who actually made the measurements)**.**

II. *On the Attraction of the Himalaya Mountains, and of the elevated regions beyond them, upon the Plumb-line in India. By the Venerable* JOHN HENRY PRATT, *M.A., Archdeacon of Calcutta. Communicated by the Rev.* J. CHALLIS, *M.A., F.R.S. &c.*

Received October 23,—Read December 7, 1854.

Pratt's hypothesis of isostacy proposed that topography is produced by crustal blocks with **varying density**, that terminate at a uniform depth.



At the compensation depth, pressure is equal at all points (it behaves as a liquid)

$\rho_c\, t = (h + t)\, \rho_1$

Rearranging gives

$\rho_1 = \rho_c\, t / (h + t)$

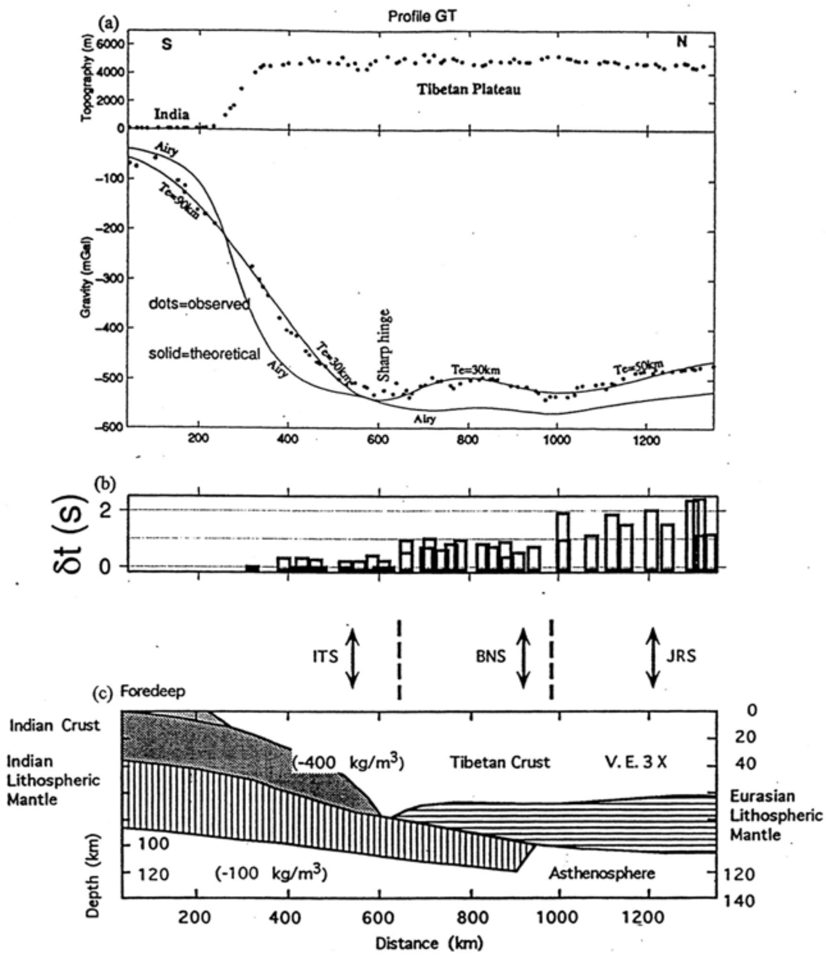
What change in density is needed to explain the 5 km mountain, when placed on a crust with regular thickness of 30 km?

You should be able to show that $\rho_1 = 2400$ kg m3. What could cause this type of density change?

Questions

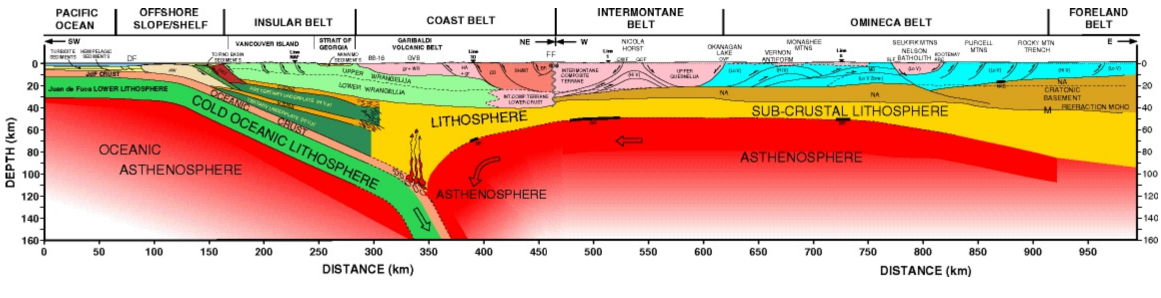
How could we determine which of these hypotheses is correct for mountain ranges?

Tibet and the Himalaya



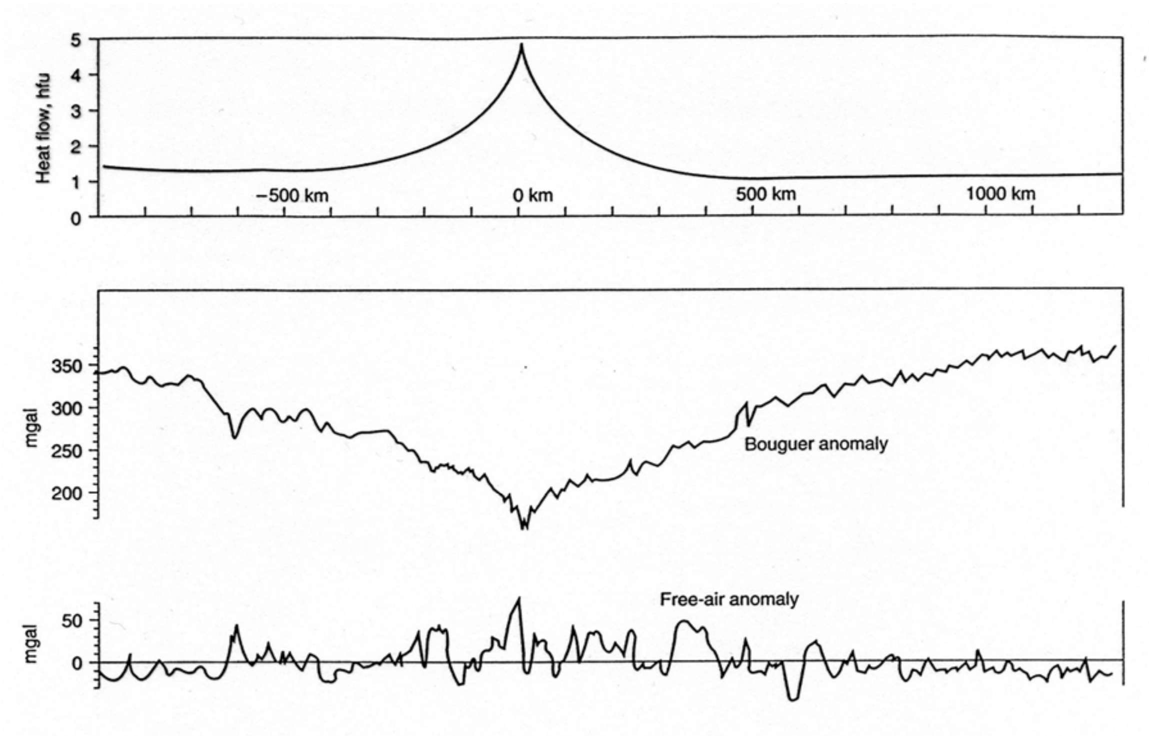
From Chen and Ozalaybey (1998)

Canadian Cordillera



From Clowes et al (1995).

Mid-ocean ridges? Are they in isostatic equilibrium?



From Fowler, The Solid Earth, Second Edition, 2005

References

Airy, G.B., On the computations of the effect of the attraction of the mountain masses as disturbing the apparent astronomical latitude of stations in geodetic surveys*, Phil. Trans. R. Soc. London,* **145**, 101-104, 1855.

Chen, W. P. and S. Ozalaybey, Correlation between seismic anisotropy and Bouguer gravity anomalies in Tibet and its implications for lithospheric structure, *GJI*, **135**, 93-101, 1998.

Clowes, C. Zelt, J. Amor and R. M. Ellis, Lithospheric structure in the Southern Canadian Cordillera from a network of seismic refraction lines, *CJES*, **32**, 1485-1513, 1995.

Pratt, J.H., On the attraction of the Himalaya Mountains, and of the elevated regions beyond them, upon the plumb line in India, *, Phil. Trans. R. Soc. London,* **145**, 53-100, 1855.

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