## B6 Isostacy

B6.1 Airy and Pratt hypotheses

Himalayan peaks on the Tibet-Bhutan border

- In the 19th century surveyors used plumblines and theodolites to map India. A plumb line was used when measuring the elevation angle of a particular star, as described in B1 when Jean Picard measured the radius of the Earth.

- North-South distances in India were measured with two methods (a) changes in elevation of stars and (b) direct measurements on the ground using triangulation.

- When a plumbline was used, corrections were made for the anticipated attraction of the Himalaya

- The results of (a) and (b) gave answers that differed by an angle of 5" (0.0014°). This discrepancy was shown to be because the Himalayan peaks did not deflect the plumbline as much as predicted (deflection was 1/3 of the expected value).
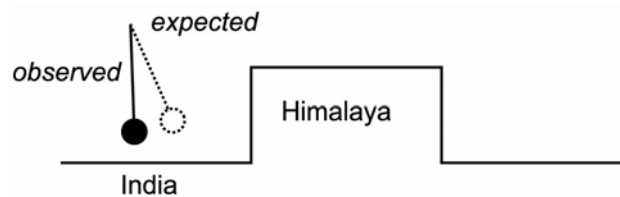

B6.1.1 Pratt's Hypothesis

An explanation of this phenomenon was given by John Pratt who was Archdeacon of Calcutta. **Pratt's hypothesis** of isostacy proposed that topography is produced by crustal blocks with **varying density**, that terminate at a uniform depth.

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.
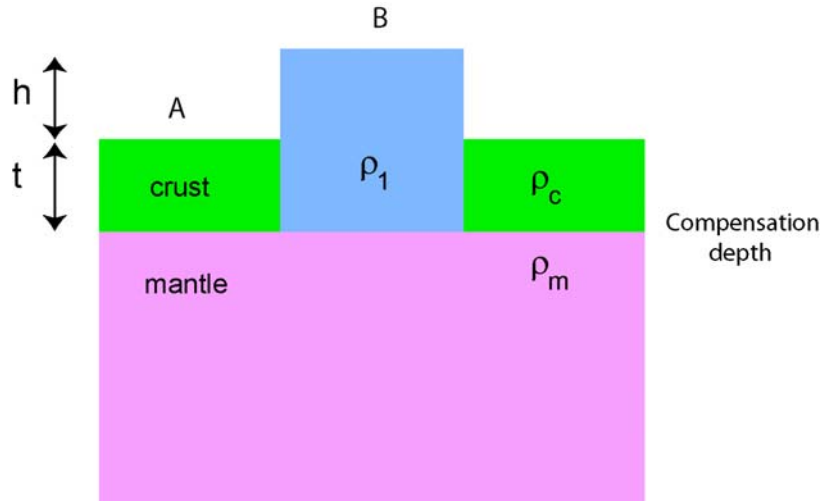
At the compensation depth, pressure is equal at all points (it behaves as a liquid). Thus at the compensation depth, the pressure below the mountain (B) must equal the pressure below the Indian plains (A).

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

Rearranging gives

$$\rho_1 = \frac{\rho_c t}{(h+t)} \qquad \text{which simplifies to} \qquad \rho_1 = \rho_c\, t\, /\, (h + t)$$

What crustal density (ρ_1) is needed to explain the 5 km high Tibetan Plateau? Assume $\rho_c = 2800$ kg m^{-3} and $\rho_m = 3100$ kg m^{-3} and t = 30 km.

ANSWER : $\rho_1 = 2400$ kg m^{-3}. What could cause this type of density change?

B6.1.2 Airy's hypothesis

George Airy accounted for these observations with a different idea. In **Airy's hypothesis** of isotacy, 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*"
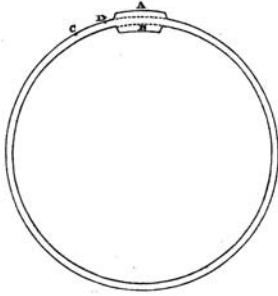
III. *On the Computation of the Effect of the Attraction of Mountain-masses, as disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys.* By G. B. Airy, Esq., Astronomer Royal.

Received January 25,—Read February 15, 1855.
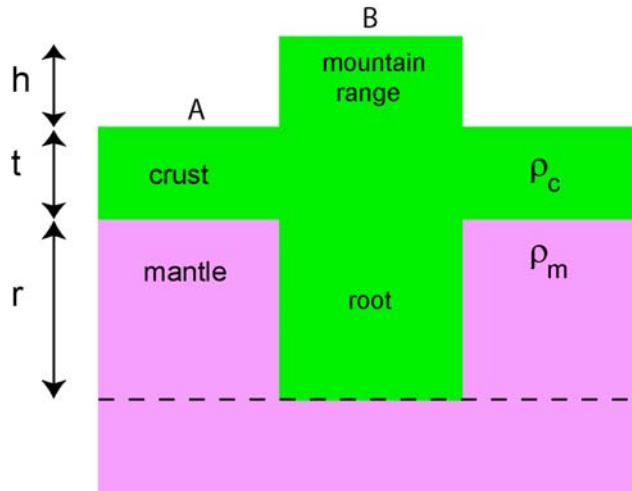
If the system is stable (no external forces) it is said to be in **isostatic equilibrium**. At the **compensation depth**, the pressure due to material above is constant at all locations (below this depth the Earth behaves as a liquid).

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

$$t\,\rho_c + r\,\rho_m = (h + t + r)\,\rho_c \qquad \text{which simplifies to} \qquad r\,\rho_m = h\,\rho_c + r\,\rho_c$$

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 the 5 km high Tibetan plateau?

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

Answer 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*"

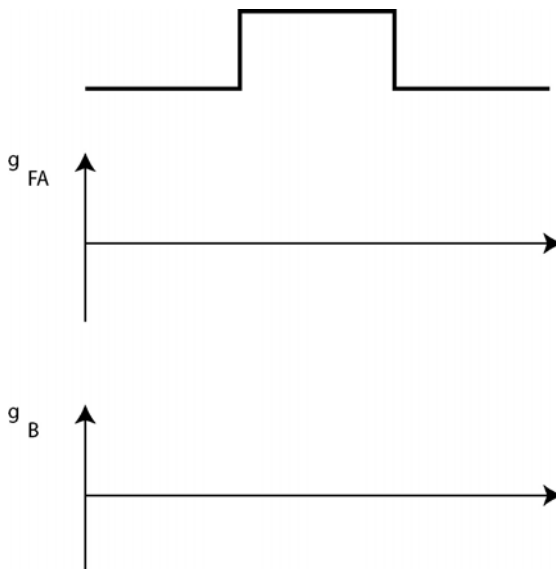**Question** : What Free Air and Bouguer anomalies would be measured?

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?

B6.2 Under compensation and over compensation

Are topographic features on the Earth's surface in isostatic equilibrium? This can be investigated by calculating the **isostatic gravity anomaly** as follows:

(1) Topography is used to predict the expected depth of the crustal root needed to support the topography in isostatic equilibrium.

(2) Using this depth, the predicted Bouguer anomaly Δg_R is computed.

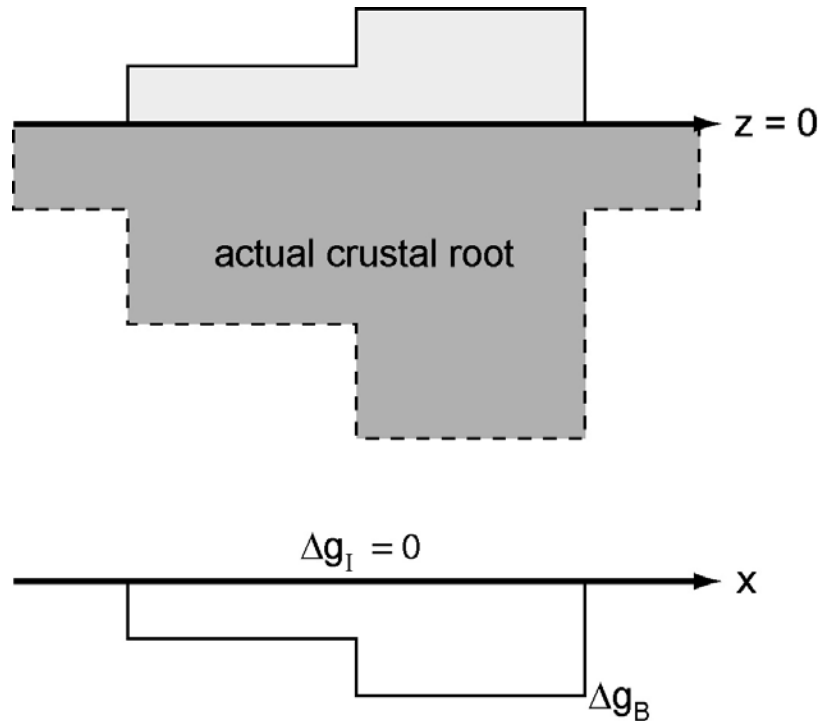(3)The **Isostatic Gravity Anomaly** is defined as

$$\Delta g_I = \Delta g_B - \Delta g_R \ ,$$

where Δg_B is the measured Bouguer anomaly and Δg_R is the predicted Bouguer anomaly of the root.
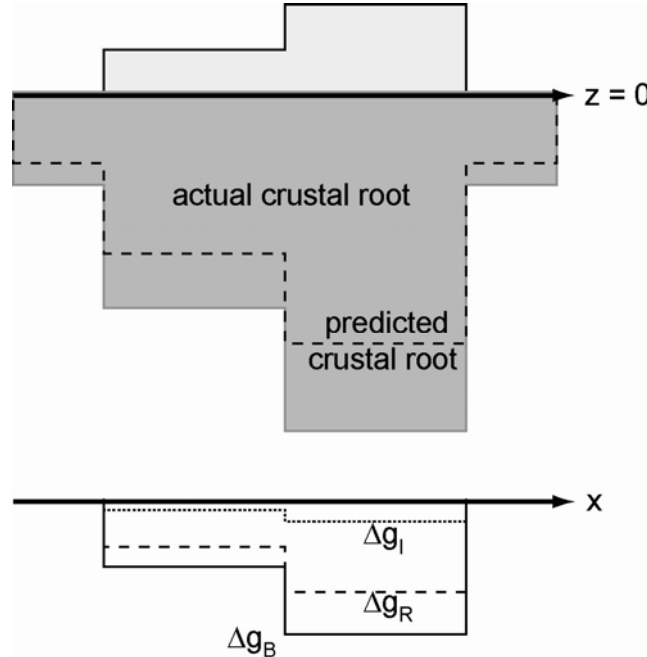
Three situations can arise:

(a) **Complete Compensation**: Topography and roots in equilibrium.

$\Delta g_B = \Delta g_R$ and $\Delta g_I = 0$

(b) **Over-compensation**: If surface material is removed (e.g. by erosion) then this results in a crustal root that is too large. To restore equilibrium, upward motion will occur.
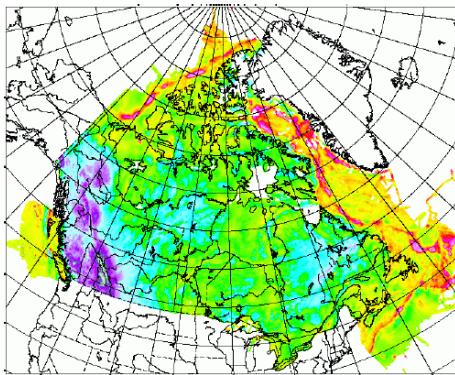
$\Delta g_B < \Delta g_R$ and $\Delta g_I < 0$ (negative)

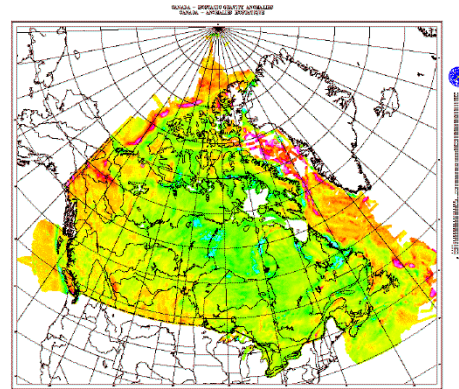(c) **Under-Compensation**: In this case, the root will be too small to support the feature the feature. Tectonic forces may give additional support (e.g. plate flexure, dynamic topography) or else subsidence will occur.

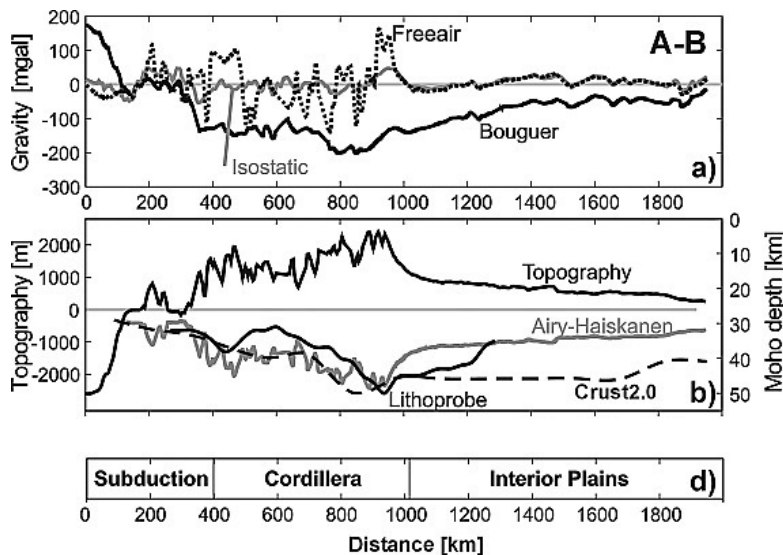$\Delta g_B > \Delta g_R$ and $\Delta g_I > 0$ (positive)
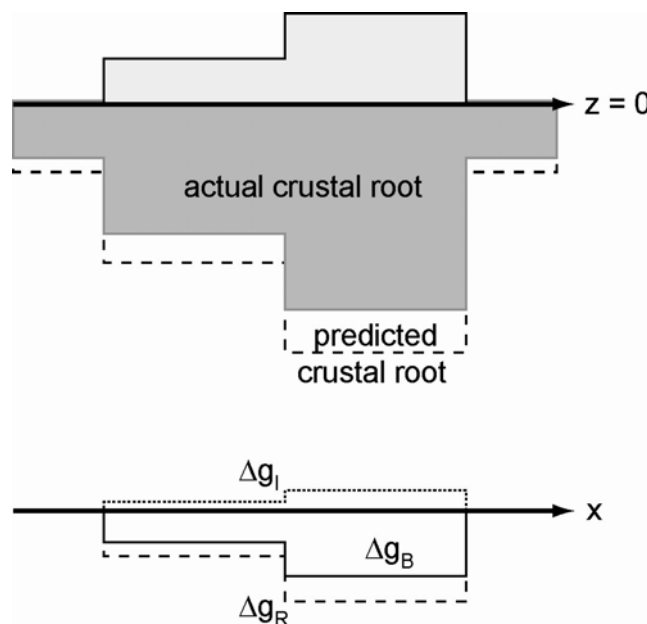
Bouguer gravity anomaly   Isostatic gravity anomaly

Details at : http://gdcinfo.agg.nrcan.gc.ca/products/grids_e.html

B6.3 Gravity anomalies and isostatic equilibrium of plate boundaries

B6.3.1 Are mountain belts in isostatic equilibrium?

Canadian Cordillera

- Figure above is taken from Fluch et al., (2003) and shows gravity anomalies across the Southern Canadian Cordillera on profile AB.
- Note the negative Bouguer anomaly.
- The isostatic gravity anomaly is quite close to zero, indicating that the Canadian Cordillera is close to isostatic equilibrium.
- This may be the result of a combination of Pratt and Airy hypotheses.
- The crust is thick under the Continental Ranges (Airy) but thinner and with a hot upper mantle under the Omineca belt (Pratt).
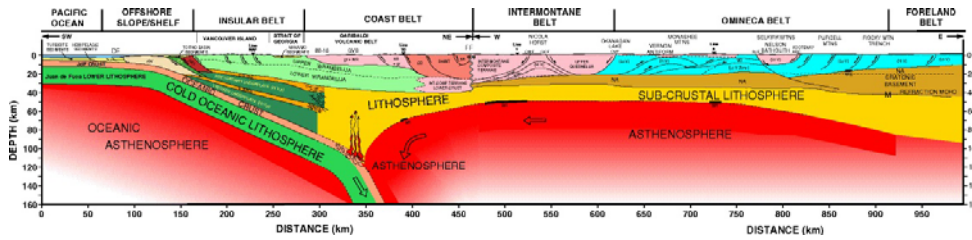
Clowes et al., CJES, (1995).

Tibet and the Himalaya

- Fowler Figure 10.19 on page 540 shows the Bouguer anomaly measured across the Himalaya from Cattin et al., (2001). It also shows the predicted Bouguer anomaly assuming complete isostatic compensation.
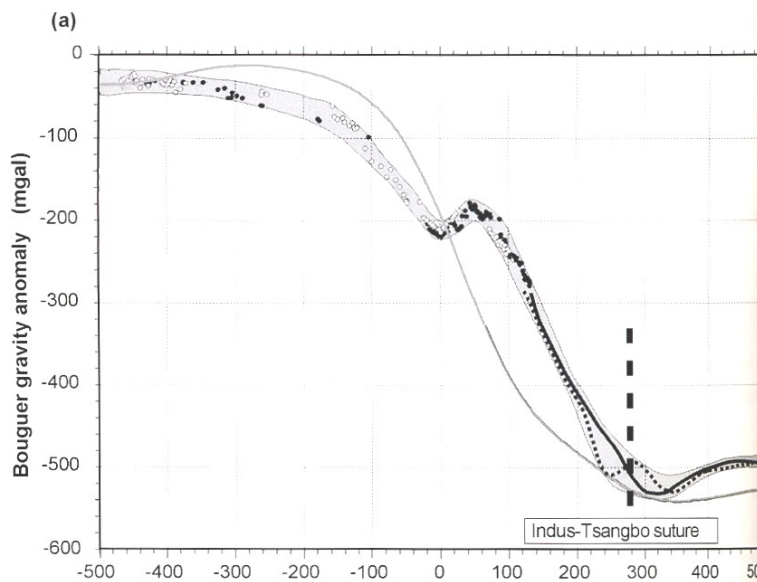

- In Ganges Basin $\Delta g_B < \Delta g_R$ which represents **over-compensation**. This occurs because the Indian Plate is deflected (pulled) downwards by loading in Tibet. This makes the crustal root thicker than needed to support the observed topography.

- The Himalaya and southern part of the Tibetan Plateau is **under-compensated** with $\Delta g_B > \Delta g_R$ which can be thought of not having enough crustal root to support the observed topography. Thus the Himalaya are partially supported by flexure of the Indian Plate.

- To the North of the Indus-Tsangbo suture, **complete compensation** occurs and the observed topography can be supported by buoyancy forces. George Airy was correct!

B6.3.2. Mid-ocean ridges

Figure 9.11 from Fowler (2005) shows gravity anomalies across the mid-Atlantic Ridge at 45° N. Mid-ocean ridges are large submarine mountain ranges located where plates move apart to create ocean basins.
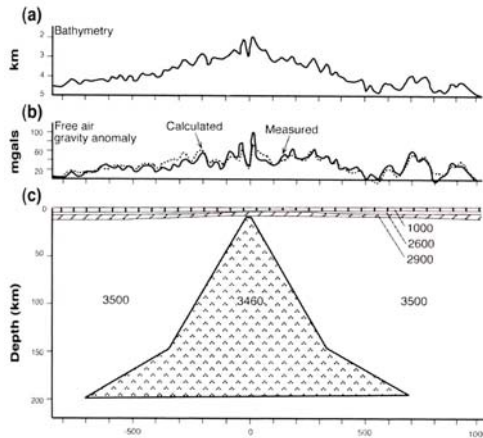
- Free air anomaly small, but not exactly zero. This shows that the ridge is not quite in isostatic equilibrium. Topography of ridge supported by low density upper mantle (hot and partially molten).

- Figure 9.11 shows a range of models that all fit the observed data, giving an illustration of non-uniqueness.

B6.3.3 Subduction zones

- Figure 9.59 from Fowler (2005) shows the Free Air gravity anomaly across the Chile Trench and Andes at 23° S, taken from Grow and Bowin, (1975).
- Like many subduction zones, this model shows a characteristic pair of low-high gravity anomalies.
- Note that the gravity modelling includes the phase transition of basalt to eclogite in the subducting slab. This corresponds to an increase in density of 400 kg m^{-3} within the slab.
- Negative gravity anomaly due to deep trench that is filled with low density water and sediments.
- Positive gravity anomaly on ocean side of the volcanic arc.
- Flexure in the subducted plate can cause **under compensation** on the overriding plate. This is because flexural forces give partial support to the topography. In this situation, Buoyancy forces do not completely support the observed topography.

<u>B6.4 Isostatic rebound</u>

- We can determine if topographic features are in isostatic equilibrium by studying gravity anomalies.
- An additional perspective on isostacy can be obtained by looking at **time variations** that result from rapid changes in the size of **ice sheets** or **large lakes**.
- These natural experiments allow the **viscosity** of the mantle to be determined.
- The basic concept shown in Figure 5.18 of Fowler (2005).

Canadian Shield

- Strong evidence for **post-glacial isostatic rebound** comes from the **raised beaches** on the coast of Hudson's Bay.
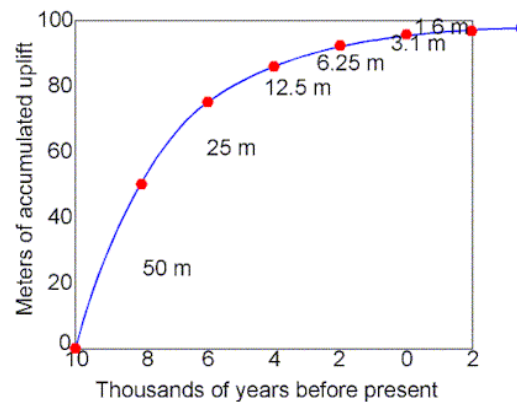

http://www.earth.ox.ac.uk/~tony/watts/LANDSCAPE/LANDSCAPE.HTM
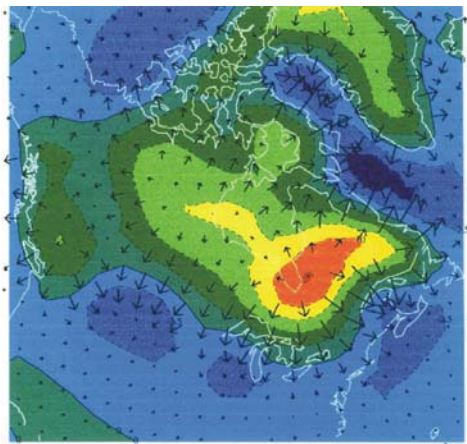
1 mm/a   http://gsc.nrcan.gc.ca/geodyn/gchange_e.php

- Surveying has revealed a pattern of uplift beneath the former location of the Laurentide Ice Sheet with a maximum rate of around 1 cm per year.
- This is surrounded by a ring of subsidence that is caused by flexure of the lithosphere. Note that horizontal motions also occur.

Isostatic Rebound in North America since 6000 y. B.P. (Contours in meters)
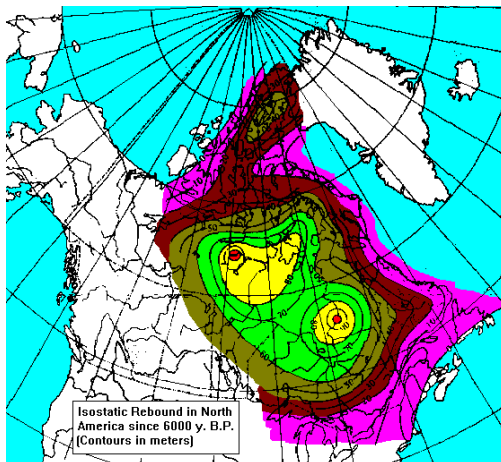
www.uwgb.edu/dutchs/STRUCTGE/EarthMvts.HTM   http://www.homepage.montana.edu/~geol445/hyperglac/isostasy1/

10

- Total uplift since the ice sheet melted is in excess of 100 m in the centre of Hudson's Bay.
- Modern uplift rates are much slower than immediately after the ice sheets melted.
- These values have been confirmed by gravity measurements made by the GRACE satellite (Tamisiea et al., 2007). Gravity changes have a peak change of 1 µGal per year from 2002-2007.
- Geoid motion was also determined by GRACE and is ~1 mm per year.
- Mantle convection can change gravity over timescales 10 times longer than the timescales for isostatic rebound. The shorter time scale of post-glacial rebound allows the phenomena of mantle convection and rebound to be separated.

Fennoscandia

- Very similar observations of isostatic rebound can be seen in Fennoscandia
- Maximum uplifts of 1 cm per year are observed in GPS data.
- Islands are emerging from the Baltic Sea and the border between Sweden and Finland have been revised on several occasions.
- Kvarken Archipelago in Finland has unique geography

- Note that horizontal motions also occur, and also the yearly variation that is due to climatic effects on the ground and atmosphere.
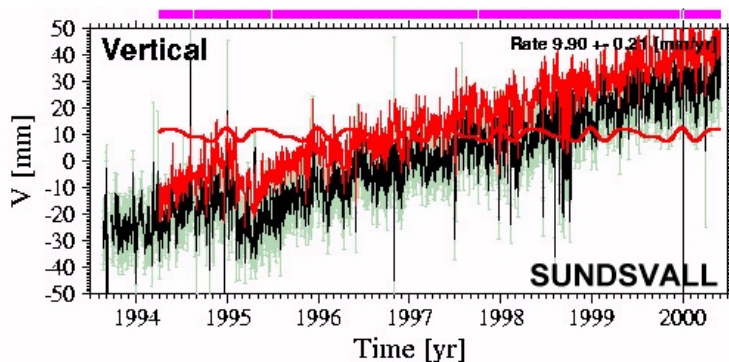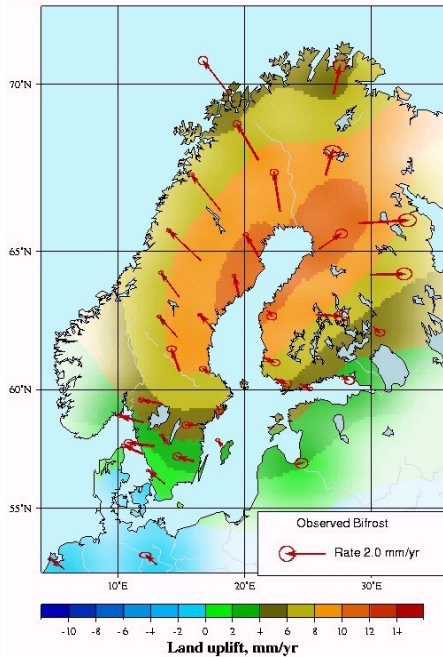
Figure 5.20 in Fowler (2005) shows that an asthenosphere viscosity of 10^{21} Pa s is consistent with the uplift history in the Baltic.

For reference, the following values are for the viscosity of some other liquids:

	Viscosity (Pa s)
Water	10^{-2}
Honey	2-10
Peanut butter	250
Pitch	10^{8}

B6.5 References

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MJU 2008