Earth's upper mantle viscosity may be lower than assumed

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The deformation of the lithosphere and asthenosphere is assumed by uniformitarian scientists to be very slow. The key measure of the resistance of the deformation of the solid earth is viscosity. When a load, like ice, is added to the surface of the earth, the surface is pushed down. When the load is taken off, the surface rebounds upward. Eastern Canada and Scandinavia are currently rising because of the melting of the Laurentide and Scandinavian ice sheets. Based on the assumed deep-time history of the Ice Age, uniformitarian geologists calculate a fairly high upper mantle viscosity of around 3–10 x 10^{20} Pa·s. However, calculations at many locations have shown a much lower viscosity for the asthenosphere, including pluvial lakes Bonneville and Lahontan, southeast Alaska, Iceland, and post-seismic earthquake motions in various areas. Regardless of the many complications and assumptions that go into viscosity estimates, it is safe to say that the viscosity and rheology of the upper mantle vary considerably. In biblical earth history, with a short timescale and a different Ice Age history, the upper mantle viscosities would be lower by at least a factor of five. This would imply deformation is faster and operates over shorter-length scales than commonly believed. This would be true in both a catastrophic plate tectonics and an impact Flood model.

Several creation scientists are attempting to produce a comprehensive global Flood model, but all models need work.[1] Such a Flood model is important because it would tie a lot of observations and deductions of the earth together that should be superior to uniformitarian models. We could also solve many other earth-science challenges by placing the challenges within the real framework for numerous earth processes—the Genesis Flood. One of those main processes involves deformation and tectonics. How fast does the earth deform by horizontal and/or vertical forces on the lithosphere? This question is of great practical importance as many people live in areas with seismic risk.

Secular scientists believe in very slow lithospheric deformation, partly based on their assumptions of deep time. On the other hand, any Flood model must postulate rapid deformation during the Flood—within a year or so.

What is viscosity?

Viscosity is "The property of a substance to offer internal resistance to flow."[2] The higher the viscosity, the more resistant to flow. Dynamic viscosity is in units of force x time divided by area or in SI units newtons x sec per m^2 or pascal seconds (Pa·s). Viscosity of natural materials, particularly solids, can be so large that only the order of magnitude is considered. The viscosity of water is about 10^{-3} Pa·s, while solid rock is on the order of 10^{20} Pa·s. A change from 10^{19} to 10^{20} Pa·s is an increase of 10 times the resistance to flow.

The viscosities in this paper will be applied to solid rock in the field of rheology, "the study of the deformation or flow of matter."[3] The viscosity is an important variable determining the flow or strain by an applied force. Strain is essentially the fractional change in thickness resulting from an applied force per unit area, or stress.

Earth's interior

The earth's interior is made up of layers of differing composition: crust, mantle, and core. The upper mantle and crust are fixed to each other and behave similarly mechanically, and together are called the lithosphere. Beneath the lithosphere is the asthenosphere, a low seismic velocity zone of unknown thickness. Lower seismic velocities likely correspond to higher temperature, and therefore lower viscosity layers. The origin and nature of the asthenosphere is very complex and debated.[4,5] It could be a layer of partial melt, increased water content, a compositional change, a temperature change, or a combination. Most believe it is a layer of partial melt.[6] But this is a simplification, since the asthenosphere is often missing beneath continents.[7] But a low velocity zone or zones, not necessarily the asthenosphere, have been detected below continents. The lithosphere/asthenosphere boundary can be sharp or diffuse. The depth of a low velocity layer can be variable, with poor lateral continuity.[8] The seismic velocity is greater in the lithosphere than in the asthenosphere, and thus the asthenosphere will more easily flow when a load is added to the surface of the earth, such as an ice sheet.

Another observation supporting the distinction between lithosphere and asthenosphere has been that earthquakes

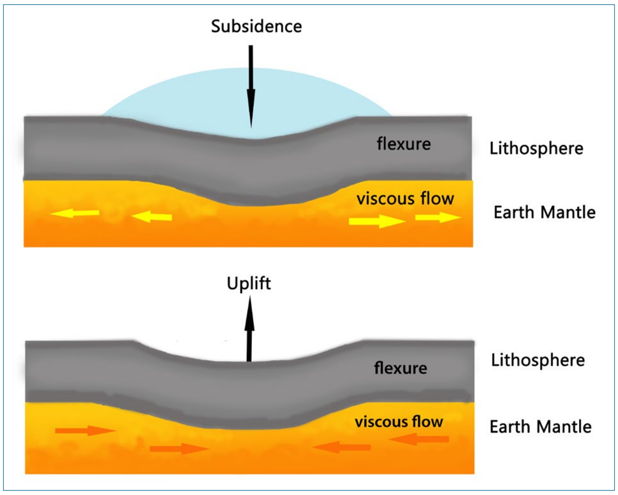

Figure 1. Glacial isostasy (drawn by Mrs Melanie Richard). In the top diagram, the ice pushes the lithosphere down, but after the ice melts, the lithosphere slowly rebounds upward.

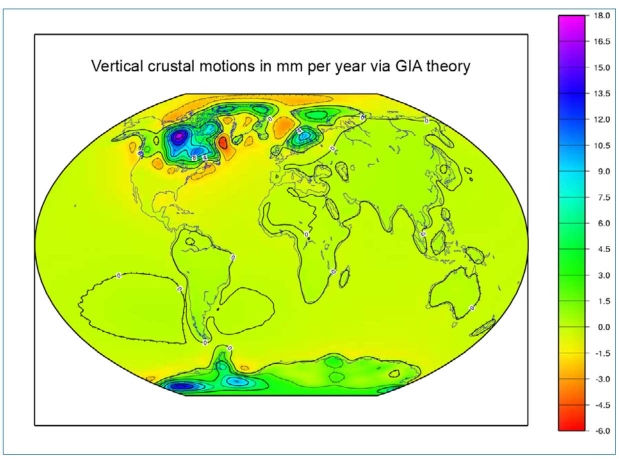

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Figure 2. Rate of lithospheric uplift due to post-glacial rebound. Note two centres of uplift for the melted Laurentide Ice Sheet corresponding to two ice domes.

caused by brittle failure of the rocks can occur both in the upper crust and the upper mantle.[9] However, with improved technology and higher resolution seismic networks, it is being recognized that the entire crust can be seismogenic (prone to earthquakes),[10] and the upper mantle may not significantly contribute to the strength of the lithosphere. This new understanding may undermine many of the rheological estimates done in the past.[11]

When modelling the earth's interior for glacial isostatic adjustment (GIA) studies, researchers commonly use PREM (Preliminary Reference Earth Model) derived from seismic data.[12] PREM is a 1 D average for the whole earth with depth of such variables as density and elastic structure.[13] Of course, it does not catch the horizontal variability of the upper mantle, and so may be a poor earth model to apply in some areas.

The assumed viscosity of the upper mantle based on Ice Age history

Isostatic depression and rebound is believed to be proportional to the density difference of the ice and the crust/upper mantle. Uniformitarian scientists commonly assume that the ice is about ⅓ the density of the crust and upper mantle.[14] So, for every 3 m of ice, the crust and upper mantle would have been pushed down about 1 m. During the build-up of ice, the rock of the crust and upper mantle is depressed and flows to the edges of the ice build-up, where rock accumulates and pushes the land up as the 'forebulge'. When ice melts, the depressed area slowly rebounds (figure 1) while the forebulge sinks, depending upon the rheology in the particular area.

Uniformitarian scientists assume that the thickness in the centre of the two ice sheets was about 3,000–4,000 m. So, the isostatic depression would be around 1,000–1,300 m in the centre of the ice sheet. Scandinavia and eastern Canada are observed to be isostatically rebounding (figure 2). Figure 3 shows a blow-up glacial isostatic rebound for Scandinavia. The shoreline of the northern Gulf of Bothnia of the Baltic Sea has been measured to be rising at about 1 cm/yr (figure 4), while the forebulge over the southwest United Kingdom is sinking (figure 5). The Hudson Bay area is also rising about 1 cm/yr,[15] leaving a series of shoreline terraces (figure 6). The highest estimated marine elevation in Scandinavia is 250 m.[16] Much of southern Finland was underwater right after the ice melted (figure 7). It is unknown how much rebound is left. Some have thought that some of this remaining uplift could be due to tectonic forces[17,18] or due to mantle convection.[19] However, this is unlikely, and likely difficult to know, since the areas of glacial isostatic and the proposed tectonic uplift are in the same locations.

Based on the isostatic rebound around the centre of the former Scandinavian and Laurentide Ice Sheets, uniformitarian scientists have calculated Earth's rheology:

> "Much of what is known about the rheology of Earth's deep interior has been inferred from modeling vertical motions caused by waxing and waning of ice sheets and recorded by marine shorelines."[20]

Early workers assumed a high viscosity of the upper mantle, which depended upon the uplift history and the estimated amount of isostatic rebound remaining. In 1941, Gutenberg estimated a viscosity of 3 x 10^{20} Pa·s, assuming the remaining uplift was only 20 m, while Vening Meinesz, in 1937, estimated a viscosity of 3 x 10^{21} Pa·s, assuming the remaining uplift is 180 m.[21]

Dividing the upper mantle up into the lithosphere and asthenosphere in later models resulted in a lithosphere viscosity of 0.7–1.0 x 10^{21} Pa·s and an asthenosphere viscosity of 7.0 x 10^{19} Pa·s, using an asthenosphere thickness less than 150 km and a very thick Scandinavian Ice Sheet.[22] The assumed thickness of the past ice sheet determines how much rebound should occur in the models, which vary.[23] However, there is a question of whether the asthenosphere even exists under Scandinavia. Because of the rheological assumptions, various models obtain different results.[24] Assuming no asthenosphere, the upper mantle viscosity beneath Scandinavia is 3–10 x 10^{20} Pa·s.[23]

The earth's mantle viscosity based on GIA modelling has been debated for many decades and especially depends upon model parameters and ice sheet history.[25] Lau *et al.* state: "Inferences of mantle viscosity using glacial isostatic adjustment (GIA) data are hampered by data sensitivity to the space-time geometry of ice cover."[26] With no asthenosphere below Scandinavia, the mantle viscosity is believed to slowly increase downward from an upper mantle value of about 3 x 10^{20} Pa·s.

Researchers are realizing that the upper mantle structure and viscosity vary considerably in the horizontal direction across the earth, and that GIA research over Scandinavia or Hudson Bay cannot determine the viscosity over the remainder of the earth.[27] Lithospheric thickness varies considerably, ranging from zero over mid-ocean ridges to about 280 km over Australia, North America, and northern European cratonic settings. The viscosity can vary by six orders of magnitude. Recent determinations in other areas of the world reinforce this (see below). This shows that a detailed, accurate ice model is crucial for GIA modelling and interpretation: "Thus, a well calibrated, detailed ice model is indispensable in GIA modelling."[28] The viscosities should be recalculated for Scandinavia and Hudson Bay region using biblical time and Ice Sheet variables.

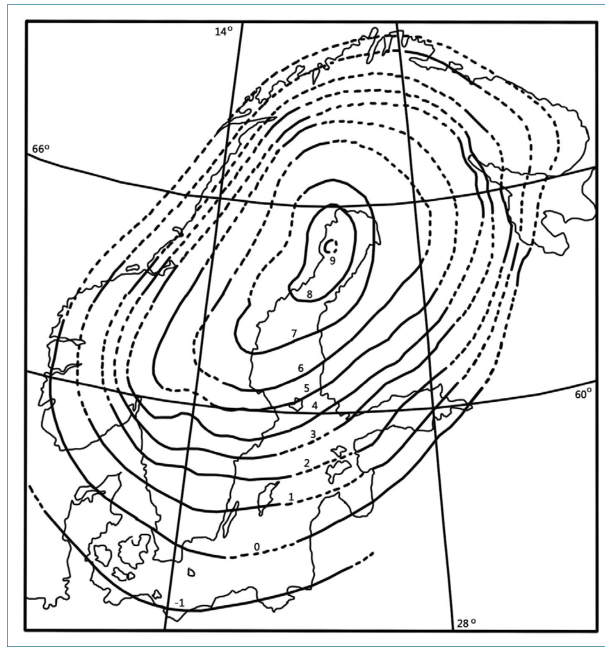

Figure 3. Map of post-glacial uplift in Scandinavia (1892–1991) in mm/year[57]

Figure 4. Sea level fall in the northern Gulf of Bothnia along the northeast Swedish coast, showing the location of sea level in 1846 and the amount of fall since then

The viscosity calculated from Lakes Bonneville and Lahontan shorelines

Earth scientists usually assume the Earth's upper mantle viscosity is similar to what they found with GIA studies of the melted ice sheets. The calculations made for Scandinavia and eastern Canada should apply only to those areas. But there are numerous indications that the earth's viscosity is much lower at many other locations.

Lake Bonneville was an Ice Age pluvial lake, one of dozens, that filled the Great Basin of the southwest United States in the vicinity of Great Salt Lake, Utah. It was about 350 m deep and about twelve times the size of Great Salt Lake.[29] The depth compares to the present average depth for Great Salt Lake of 3.7 m. Lake Bonneville had a volume of 10,300 km^3, near that of Lake Michigan. Shorelines are obvious and abundant (figure 8). Lake Bonneville fell about 100 m due to the Bonneville flood.[30] Then the rest of the lake evaporated, leaving behind salt and other minerals, creating the Bonneville Salt Flats of northwestern Utah (figure 9). The flats are used as a speedway for testing cars and attempting to set speed records.

The ancient shorelines of Lake Bonneville were among the first features in the late 1800s that indicated the earth responds to surface loads. Geologists G.K. Gilbert noticed the shorelines were bowed upward where the water was deepest. A recent analysis of Lake Bonneville uplift indicated the shorelines were bowed up more than 70 m in the centre. Using an updated uniformitarian lake chronology resulted in a best fit model with a thin elastic part of the upper lithosphere of 15–25 km and an asthenosphere viscosity about 10^{19} Pa·s.[31] An earlier estimate by Bills *et al.* had found a viscosity of about 4 x 10^{17} Pa·s from 40 km to 150 km depth.[32] These upper mantle viscosity estimates are more than 2 orders of magnitude less than the earlier assumed global average upper mantle viscosity estimated from the GIA for the past ice sheets.

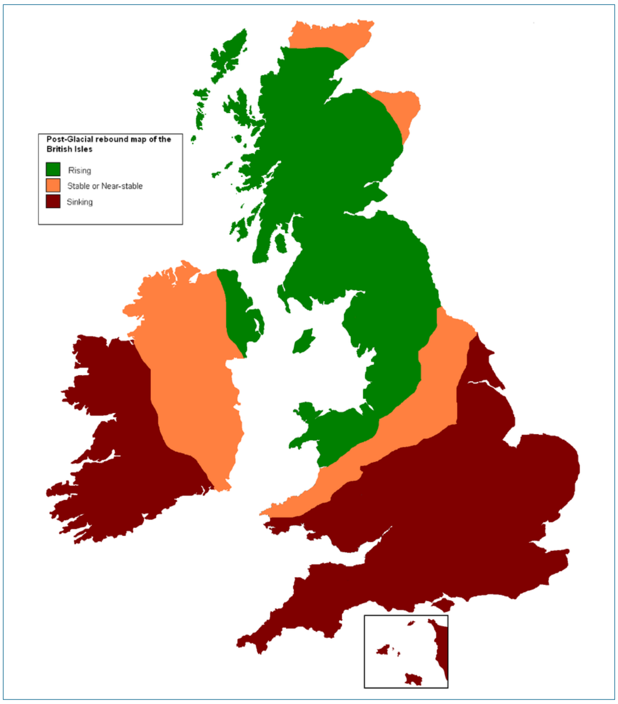

Figure 5. A map of post-glacial rebound on the British Isles, showing where land is still rising and where land is sinking due to the collapse of the forebulge

Figure 6. Layered beach ridges caused by isostatic rebound on Bathurst Inlet, Nunavut are an example of post-glacial rebound after melting of the Laurentide Ice Sheet after the last Ice Age.

One problem with this calculation from the point of view of biblical history is that deep time is built in, for instance by assuming Lake Bonneville existed 30–10 ka years ago. This age will influence the calculations, and the viscosity in biblical earth history would be lower in this area.

Lake Lahontan, western Nevada and a small part of California, USA, was another Ice Age lake in the Great Basin. Its shorelines were bowed up about 22 m.[33] Preliminary models indicate that the upper mantle viscosity beneath the former lake was about 10^{18} Pa·s and that rebound only lasted 300 years. Just like with calculations of Lake Bonneville isostasy, deep time is built in. So, within biblical earth history, the viscosity should be lower. A more recent calculation of Lake Lahontan uplift, but including earthquakes in western Nevada and adjacent California, USA, gave an asthenosphere viscosity of 5 x 10^{18} Pa·s.[34] However, the two-sigma uncertainty ranged from 5 x 10^{17} Pa·s to 5 x 10^{19} Pa·s because of uncertainties about Lake Lahontan.

Modern-day ice melting calculations

There are measures of upper mantle viscosity that contain few, if any, assumptions. These indicate an even lower asthenosphere viscosity, for at least those locations.

Practically all glaciers in the world have receded, and are currently receding, because of global warming, which has been only about 1°C, much of which can be attributed to natural processes.[35] Therefore, some glaciated areas have lost much ice over the last few hundred years, since the end of the Little Ice Age. For instance, Glacier Bay, Alaska, had an ice stream that had flowed all the way to the entrance of the bay by 1794, as observed by Joseph Whidbey on the ship *Discovery* during the Vancouver expedition. In 1879, naturalist John Muir observed that the glacier had retreated 77 km up to the end of the bay, losing an estimated 3,030 km^3 of ice, enough to raise sea level 8 mm. This retreat actually occurred before the end of the Little Ice Age in 1880 and before humans were adding significant CO_2 to the atmosphere.

Recent GPS measurements of Southeast Alaska, including the high St Elias Mountains, have shown that Southeast Alaska is uplifting at about 3 cm/yr.[36] It is believed that the onset of deglaciation of the St Elias Range began in 1880. Remarkably, GPS has also discovered seasonal and year-to-year variations of uplift rate based on annual temperatures and snowfall differences. The viscosity based on 55 km thick lithosphere and a 230 km asthenosphere resulted in a viscosity of 3 x 10^{19} Pa·s. Earlier estimates found a viscosity an order of magnitude less with a thinner asthenosphere of 110 km. There is a trade-off between the assumed thickness of the asthenosphere and the viscosity. The thinner the asthenosphere, the lower the viscosity and vice versa.

The viscosity below Iceland

All glaciers on Iceland advanced during the Little Ice Age (LIA). Glaciers were further advanced during the LIA than during the Great Ice Age caused by the Flood,[37] probably due to Iceland being surrounded by warm water for most of the time of the Great Ice Age, retarding glaciation. The largest glacier on Iceland, Vatnajökull, has been melting since the end of the LIA in about 1890 and the area has been rebounding upward. From this uplift, the asthenosphere viscosity has been variably estimated at 5 x 10^{17} Pa·s,[38] 1–2 x 10^{18} Pa·s,[39] 5 x 10^{18} Pa·s,[40] 4–10 x 10^{18} Pa·s,[41] and 1 x 10^{18} Pa·s – 5 x 10^{19} Pa·s.[42] Other researchers have estimated an asthenospheric viscosity as low as 7 x 10^{16} Pa·s.[39] These estimates are quite variable and probably depend upon the particular upper mantle model, the exact melting and uplift history of Iceland, and the mathematical solution to the equations. These low viscosities are much less than would be assumed from Scandinavia: "The sub-lithospheric [asthenosphere] viscosity has a maximum value of ~1 x 10^{19} Pa·s, about 100 times less than the commonly accepted value for the upper mantle."[43] The low viscosity is likely attributed to a fair percentage of upper mantle melt.

Earthquake viscosity measurements

When an earthquake strikes, the rapid co-seismic movement of the rupture relaxes during post-seismic relaxation, depending upon the viscosity of the upper mantle. The movements can be observed by GPS and other geodetic mechanisms in real time, so no assumptions of deep time enter in. The viscosities of the asthenosphere are sometimes measured to be very low. For instance, based on earthquakes in the northwest Pacific, the asthenosphere viscosity was estimated at 5 x 10^{17} Pa·s.[44] GPS discovered that after the 2002 M7.9 Denali, Alaska, earthquake, the viscosity was as low as 10^{17} Pa·s for two weeks.[45] A viscosity of 8 x 10^{18} Pa·s for a depth of 220–660 km was calculated for the great 2004 Sumatra–Andaman earthquake with a transient viscosity of 1–4 x 10^{17} Pa·s.[46,47] The great 2011 Tohoku-oki earthquake off Japan is believed to have shown a transient viscosity of around 2.5–5.0 x 10^{17} Pa·s with a steady state viscosity of 1.8 x 10^{18} Pa·s to 1.0 x 10^{19} Pa·s.[48] Based on earthquakes in the Mojave Desert of California, relaxation viscosities were 10^{17} Pa·s but may be as low as 10^{16} Pa·s.[49]

Some researchers suggest that the low transient viscosity may have been stress induced. Viscosities related to earthquake motion are much lower than those deduced from GIA studies:

> "Transient rheologies have also been suggested by other geodetic studies of postseismic deformation at times scales of a few days to decades … . For instance, *Pollitz et al.* [1998] inferred a steady state viscosity of 5 x 10^{17} Pa·s for the oceanic asthenosphere. This is in agreement with the value of the transient asthenospheric viscosity in the present model, and indicates again the existence of a LVZ [Low Velocity Zone] in the shallow mantle. Other studies in tectonically active continental regions … yield similar estimates of the steady state viscosity in the upper mantle, and they are generally much lower than those derived from postglacial rebound studies."[50]

The much lower viscosity deduced for earthquakes, melting of glaciers in mountains, and the other areas that were estimated are believed to be locations where the viscosity is low, possibly due to water and/or melt. It is difficult to know how representative these viscosities are for the asthenosphere in more stable areas, such as the US Midwest. But part of the reason these viscosity estimates are much lower than those derived from GIA of the past ice sheets could be that deep time is assumed in the latter.

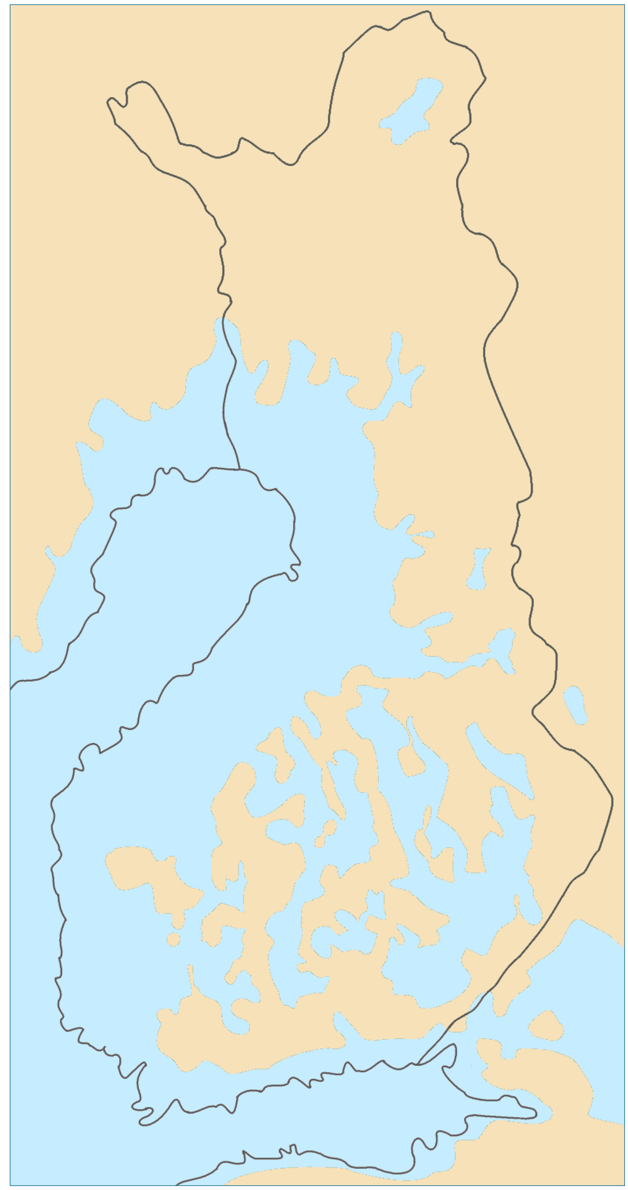

Figure 7. The coastline of Finland after the last ice age, about 11,000 years ago, before glacial rebound

Creation science applications

From the point of view of biblical earth history, the ice sheets were about 40% as thick as those postulated by uniformitarian scientists.[51,52] Moreover, deep time is built in, with the ice sheets melting from 21 ka to 7 ka,[12] while in the biblical model they melt at about 4,000–3,800 years ago. So, the viscosity determined by GIA models would very likely be much less in biblical earth history than calculated

Figure 8. Lake Bonneville shoreline at base of mountains north of Salt Lake City, Utah

Figure 9. Bonneville Salt Flat, northwest Utah

by uniformitarian models. Equations calculated with biblical Ice Age variables show the viscosity below the former ice sheets is lower, with a decrease that is proportional to the time since glaciation. Following the derivational approach of Turcotte and Schubert,[53] a simple two-dimensional half-space model of isostatic rebound, not taking into account flexural rigidity, can be derived, which yields a relation where initial displacements of the crust decays exponentially according to a characteristic relaxation time:

$$\tau_r = \frac{4\pi v}{g\lambda},$$

where ν is the kinematic viscosity of the mantle, and λ is the wavelength of the displacement feature. As can be seen, the mantle viscosity is linearly related to the relaxation time of the system. Simple as it is, for the size of Fennoscandia and the secular uplift time of 21 ka, this model yields results in close agreement with Simons and Hager.[54] Given the approximate available relaxation time in the biblical timeline of the Ice Age, this same model gives a mantle viscosity which is lower by a factor of five for Fennoscandia, since the available relaxation time in the biblical model is lower than that in the secular model by the same factor.

The newly emerging research regarding the relative strengths of lower crust and upper mantle would also imply that isostatic rebound happens at faster timescales[55] and is more localized to individual tectonic blocks than has previously been assumed.[56]

Regardless, it is likely that the viscosity and the rheology of the Earth's mantle are much lower in many other regions than just where the past ice sheets melted. Moreover, they vary horizontally and vertically. Could there be a cause of such variability resulting from Flood events? Could the upper mantle have been created with variable viscosity and rheology? Lower viscosities would result in faster folding and deformation of rocks, whether the Flood was caused by catastrophic plate tectonics, impacts, or both.

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