The New World Order

Post-glacial rebound

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Post-glacial rebound (sometimes called continental rebound, glacial isostatic adjustment) is the rise of land masses that were depressed by the huge weight of ice sheets during the last glacial period, through a process known as isostasy. It affects northern Europe (especially Scotland, Fennoscandia and northern Denmark), Siberia, Canada, the Great Lakes of Canada and the United States, the coastal region of the US state of Maine, parts of Patagonia, and Antarctica.

Contents

Overview

During the last glacial period, much of northern Europe, Asia, North America, Greenland and Antarctica were covered by ice sheets. The ice was as thick as three kilometres during the last glacial maximum about 20,000 years ago. The enormous weight of this ice caused the surface of the Earth's crust to deform and warp downward, forcing the viscoelastic mantle material to flow away from the loaded region. At the end of each glacial period when the glaciers retreated, the removal of the weight from the depressed land led to slow (and still ongoing) uplift or rebound of the land and the return flow of mantle material back under the deglaciated area. Due to the extreme viscosity of the mantle, it will take many thousands of years for the land to reach an equilibrium level.

Studies have shown that the uplift has taken place in two distinct stages. The initial uplift following deglaciation was near-instantaneous due to the elastic response of the crust as the ice load was removed. After this elastic phase, uplift proceeded by slow viscous flow so the rate of uplift decreased exponentially after that. Today, typical uplift rates are of the order of 1 cm/year or less. In northern Europe, this is clearly shown by the GPS data obtained by the BIFROST GPS network. Studies suggest that rebound will continue for about at least another 10,000 years. The total uplift from the end of deglaciation depends on the local ice load and could be several hundred metres near the centre of rebound.

Recently, the term post-glacial rebound is gradually being replaced by the term glacial isostatic adjustment. This is in recognition that the response of the Earth to glacial loading and unloading is not limited to the upward rebound movement, but also involves downward land movement, horizontal crustal motion, changes in global sea levels, the Earth's gravity field, induced earthquakes and changes in the rotational motion.

Effects

Post-glacial rebound (or glacial isostatic adjustment) produces measurable effects on vertical crustal motion, global sea levels, horizontal crustal motion, gravity field, Earth's rotational motion and state of stress and earthquakes. Studies of glacial rebound give us information about the flow law of mantle rocks and also past ice sheet history. The former is important to the study of mantle convection, plate tectonics and the thermal evolution of the Earth. The latter is important to glaciology, paleoclimate and changes in global sea level. Understanding postglacial rebound is also important to our ability to monitor recent global change.

Vertical crustal motion

Erratic boulders, U-shaped valleys, drumlins, eskers, kettle lakes, bedrock striations are among the common signatures of the Ice Age. In addition, post-glacial rebound has caused numerous significant changes to coastlines and landscapes over the last several thousand years, and the effects continue to be significant.

In Sweden, Lake Mälaren was formerly an arm of the Baltic Sea, but uplift eventually cut it off and led to its becoming a freshwater lake in about the 12th century, at the time when Stockholm was founded at its outlet. Marine seashells found in Lake Ontario sediments imply a similar event in prehistoric times. Other pronounced effects can be seen on the island of Öland, Sweden, which has little topographic relief due to the presence of the very level Stora Alvaret. The rising land has caused the Iron Age settlement area to recede from the Baltic Sea, making the present day villages on the west coast set back unexpectedly far from the shore. These effects are quite dramatic at the village of Alby, for example, where the Iron Age inhabitants were known to subsist on substantial coastal fishing.

As a result of post-glacial rebound, the Gulf of Bothnia is predicted to eventually close up at Kvarken. The Kvarken is a UNESCO World Natural Heritage Site, selected as a "type area" illustrating the effects of post-glacial rebound and the holocene glacial retreat.

In several other Nordic ports, like Tornio and Pori (formerly at Ulvila), the harbour has had to be relocated several times. Place names in the coastal regions also illustrate the rising land: there are inland places named 'island', 'skerry', 'rock', 'point' and 'sound'. For example, Oulunsalo "island of Oulujoki" is a peninsula, with inland names such as Koivukari "Birch Rock", Santaniemi "Sandy Cape", and Salmioja "the ditch of the Sound".

In Great Britain, glaciation affected Scotland but not southern England, and the post-glacial rebound of northern Great Britain (up to 10 cm

per century) is causing a corresponding downward movement of the southern half of the island (up to 5 cm per century). This will eventually lead to an increased risk of floods in southern England and south-western Ireland.

Since the glacial isostatic adjustment process causes the land to move relative to the sea, ancient shorelines are found to lie above present day sea level in areas that were once glaciated. On the other hand, places in the peripheral bulge area which was uplifted during glaciation now begins to subside. Therefore ancient beaches are found below present day sea level in the bulge area. The "relative sea level data", which consists of height and age measurements of the ancient beaches around the world, tells us that glacial isostatic adjustment proceeded at a higher rate near the end of deglaciation than today.

The present-day uplift motion in northern Europe is also monitored by a GPS network called BIFROST. Results of GPS data shows a peak rate of about 11 mm/year in the north part of the Gulf of Bothnia, but this uplift rate decreases away and becomes negative outside the former ice margin.

In the near field outside the former ice margin, the land sinks relative to the sea. This is the case along the east coast of the United States, where ancient beaches are found submerged below present day sea level and Florida is expected to be submerged in the future. GPS data in North America also confirms that land uplift becomes subsidence outside the former ice margin.

Global sea levels

To form the ice sheets of the last Ice Age, water from the oceans evaporated, condensed as snow and was deposited as ice in high latitudes. Thus global sea level fell during glaciation.

The ice sheets at the last glacial maximum were so massive that global sea level fell by about 120 metres. Thus continental shelves were exposed and many islands became connected with the continents through dry land. This was the case between the British Isles and Europe, or between Taiwan, the Indonesian islands and Asia. A sub-continent also existed between Siberia and Alaska that allowed the migration of people and animals during the last glacial maximum.

The fall in sea level also affects the circulation of ocean currents and thus has important impact on climate during the Ice Age.

During deglaciation, the melted ice water returns to the oceans, thus sea level in the ocean increases again. However, geological records of sea

level changes show that the redistribution of the melted ice water is not the same everywhere in the oceans. In other words, depending upon the location, the rise in sea level at a certain site may be more than that at another site. This is due to the gravitational attraction between the mass of the melted water and the other masses, such as remaining ice sheets, glaciers, water masses and mantle rocks and the changes in centrifugal potential due to Earth's variable rotation.

Horizontal crustal motion

Accompanying vertical motion is the horizontal motion of the crust. The BIFROST GPS network shows that the motion diverges from the centre of rebound. However, the largest horizontal velocity is found near the former ice margin.

The situation in North America is less certain; this is due to the sparse distribution of GPS stations in northern Canada, which is rather inaccessible.

Tilt

The combination of horizontal and vertical motion changes the tilt of the surface. That is, locations farther north rise faster, an effect that becomes apparent in lakes. The bottoms of the lakes gradually tilt away from the direction of the former ice maximum, such that lake shores on the side of the maximum (typically north) recede and the opposite (southern) shores sink. This causes the formation of new rapids and rivers. The effects are similar to that concerning seashores, but occur above sea level.

Gravity field

Ice, water and mantle rocks have mass, and as they move around, they exert a gravitational pull on other masses towards them. Thus, the gravity field, which is sensitive to all mass on the surface and within the Earth, is affected by the redistribution of ice/melted water on the surface of the Earth and the flow of mantle rocks within.

Today, more than 6000 years after the last deglaciation terminated, the flow of mantle material back to the glaciated area causes the overall shape of the Earth to become less oblate. This change in the topography of Earth's surface affects the long-wavelength components of the gravity field.

The changing gravity field can be detected by repeated land measurements with absolute gravimeters and recently by the GRACE satellite mission. The change in long-wavelength components of Earth's gravity field also perturbs the orbital motion of satellites and has been detected by LAGEOS satellite motion.

Vertical datum

The vertical datum is a theoretical reference surface for altitude measurement and plays vital roles in many human activities, including land surveying and construction of buildings and bridges. Since postglacial rebound continuously deforms the crustal surface and the gravitational field, the vertical datum needs to be redefined repeatedly through time.

Earth's rotation

Examination of ancient Chinese and Babylonian eclipse records reveals that the Earth's rotation rate is not constant. For example, if the rotation rate were constant, then the shadow path of an ancient Babylonian eclipse would lie somewhere across western Europe and the ancient eclipse could not have been observed at the recorded time in Babylon. It is well known that tidal interaction between Earth and the Moon (tidal friction or tidal dissipation) causes the Earth's rotation to slow. But taking into account the tidal interaction alone over-corrects the eclipse path which would lie east of Babylon. To have the shadow path pass through Babylon at the recorded time, we need to take into account the effect of glacial isostatic adjustment on Earth's rotational motion.

To understand how glacial isostatic adjustment affects Earth's rotation rate, we note that the movement of mass on and beneath the Earth's surface affects the moment of inertia of the Earth; by the conservation of angular momentum, the rotational motion must also change. This is illustrated by a rotating ice skater: as she extends her arms above her head, her moment of inertia decreases, and she spins faster. On the other hand, as she extends her arms horizontally, her moment of inertia increases and her spin slows.

During glaciation, water is taken from the oceans, whose average position is nearer the equator, and deposited as ice over the higher latitudes closer to the poles, which is closer to the rotational axis. This causes the moment of inertia of the Earth–ice–water system to decrease and just like the rotating figure skater bringing her arms closer to her body, the earth should spin faster. During deglaciation, the melted ice water returns to the oceans – farther from the rotational axis – causing the Earth's spin to slow down. The mantle rocks flow in a direction opposite to that of the water, but the rate is much slower. After the end of deglaciation, the dominant mass movement is from the return flow

of the mantle rocks back to the glaciated areas at high latitude, making the shape of the Earth less oblate. This process would, in isolation, lead to an increase in the rotation speed of the Earth and therefore to a decrease of the length of day. Lambeck estimated that the isolated effect of post-glacial rebound on the length of the day would be a decrease of about 0.7 milliseconds per century. This process of nontidal acceleration of the rotation of the earth is corroborated by observations of the satellite LAGEOS and is generally attributed to glacial isostatic adjustment.

In addition to the changes in the Earth's rotation rate, the changes in the moment of inertia due to glacial isostatic adjustment also cause the rotational axis to move from the current position near the North Pole[clarification needed] towards the center of the ice masses at glacial maximum (polar wander); thus it is moving[clarification needed] towards eastern Canada at a rate of about 1 degree per million years.

This drift of the Earth's rotational axis in turn affects the centrifugal potential on the surface of the earth, and thus also affects sea levels.

State of stress and intraplate earthquakes

According to the theory of plate tectonics, plate-plate interaction results in earthquakes near plate boundaries. However, large earthquakes are found in intraplate environment like eastern Canada (up to M7) and northern Europe (up to M5) which are far away from present-day plate boundaries. An important intraplate earthquake was the magnitude 8 New Madrid earthquake that occurred in mid-continental USA in the year 1811.

Glacial loads have provided more than 30 MPa of vertical stress in northern Canada and more than 20 MPa in northern Europe during glacial maximum. This vertical stress is supported by the mantle and the flexure of the lithosphere. Since the mantle and the lithosphere continuously respond to the changing ice and water loads, the state of stress at any location continuously changes in time. The changes in the orientation of the state of stress is recorded in the postglacial faults in southeastern Canada. When the postglacial faults formed at the end of deglaciation 9000 years ago, the horizontal principal stress orientation was almost perpendicular to the former ice margin, but today the orientation is in the northeast-southwest, along the direction of seafloor spreading at the Mid-Atlantic Ridge. This shows that the stress due to postglacial rebound had played an important role at deglacial time, but has gradually relaxed so that tectonic stress has become more dominant today.

According to the Mohr–Coulomb theory of rock failure, large glacial loads generally suppress earthquakes, but rapid deglaciation promotes earthquakes. According to Wu & Hasagawa, the rebound stress that is available to trigger earthquakes today is of the order of 1 MPa. This

stress level is not large enough to rupture intact rocks but is large enough to reactivate pre-existing faults that are close to failure. Thus, both postglacial rebound and past tectonics play important roles in today's intraplate earthquakes in eastern Canada and southeast USA. Generally postglacial rebound stress could have triggered the intraplate earthquakes in eastern Canada and may have played some role in triggering earthquakes in eastern USA including the New Madrid earthquakes of 1811. The situation in northern Europe today is complicated by the current tectonic activities nearby and by coastal loading and weakening.

Recent global warming

Recent global warming has caused mountain glaciers and the ice sheets in Greenland and Antarctica to melt and global sea level to rise. Therefore, monitoring sea level rise and the mass balance of ice sheets and glaciers allows us to understand more about global warming.

Recent rise in sea levels has been monitored by tide gauges and Satellite Altimetry (e.g. TOPEX/Poseidon). In addition to the addition of melted ice water from glaciers and ice sheets, recent sea level changes are also affected by the thermal expansion of sea water due to global warming, sea level change due to deglaciation of the last Ice Age (postglacial sea level change), deformation of the land and ocean floor and other factors. Thus, to understand global warming from sea level change, one must be able to separate all these factors, especially postglacial rebound, since it is one of the leading factors.

Mass changes of ice sheets can be monitored by measuring changes in the ice surface height, the deformation of the ground below and the changes in the gravity field over the ice sheet. Thus ICESat, GPS and GRACE satellite mission are useful for such purpose. However, glacial isostatic adjustment of the ice sheets affect ground deformation and the gravity field today. Thus understanding glacial isostatic adjustment is important in monitoring recent global warming.

One of the possible impacts of global warming-triggered rebound may be more volcanic activity in previously ice-capped areas such as Iceland.

Applications

The speed and amount of postglacial rebound is determined by two factors: the viscosity or rheology (i.e., the flow) of the mantle, and the ice loading and unloading histories on the surface of Earth.

The viscosity of the mantle is important in understanding mantle convection, plate tectonics, dynamical processes in Earth, the thermal state and thermal evolution of Earth. However viscosity is difficult to observe because creep experiments of mantle rocks take thousands of years to observe and the ambient temperature and pressure conditions are not easy to attain for a long enough time. Thus, the observations of postglacial rebound provide a natural experiment to measure mantle rheology. Modelling of glacial isostatic adjustment addresses the question of how viscosity changes in the radial and lateral directions and whether the flow law is linear or nonlinear.

Ice thickness histories are useful in the study of paleoclimatology, glaciology and paleo-oceanography. Ice thickness histories are traditionally deduced from the three types of information: First, the sea level data at stable sites far away from the centers of deglaciation give an eastimate of how much water entered the oceans or equivalently how much ice was locked up at glacial maximum. Secondly, the location and dates of terminal moraines tell us the areal extent and retreat of past ice sheets. Physics of glaciers gives us the theoretical profile of ice sheets at equilibrium, it also says that the thickness and horizontal extent of equilibrium ice sheets are closely related to the basal condition of the ice sheets. Thus the volume of ice locked up is proportional to their instantaneous area. Finally, the heights of ancient beaches in the sea level data and observed land uplift rates (e.g. from GPS or VLBI) can be used to constrain local ice thickness. A popular ice model deduced this way is the ICE5G model. Because the response of the Earth to changes in ice height is slow, it cannot record rapid fluctuation or surges of ice sheets, thus the ice sheet profiles deduced this way only gives the "average height" over a thousand years or so.

Glacial isostatic adjustment also plays an important role in understanding recent global warming and climate change.

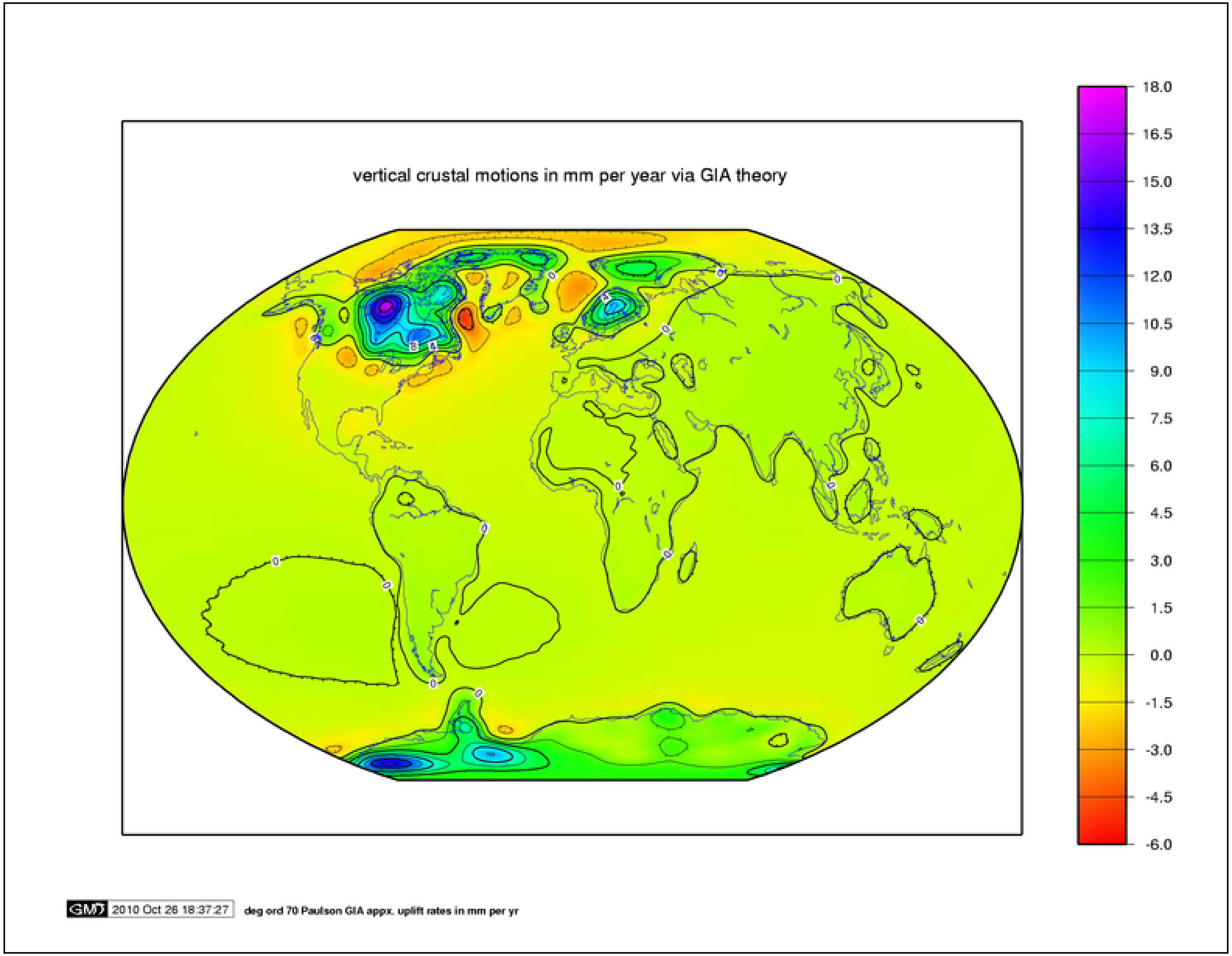
Discovery

Before the 18th century, it was thought in Sweden that sea levels were falling. On the initiative of Anders Celsius a number of marks were made in rock on different locations along the Swedish coast. In 1765 it was possible to conclude that it was not a lowering of sea levels but an uneven rise of land. In 1865 Thomas Jamieson came up with a theory that the rise of land was connected with the ice age that had been first discovered in 1837. The theory was accepted after investigations by Gerard De Geer of old shorelines in Scandinavia published in 1890.

Legal status

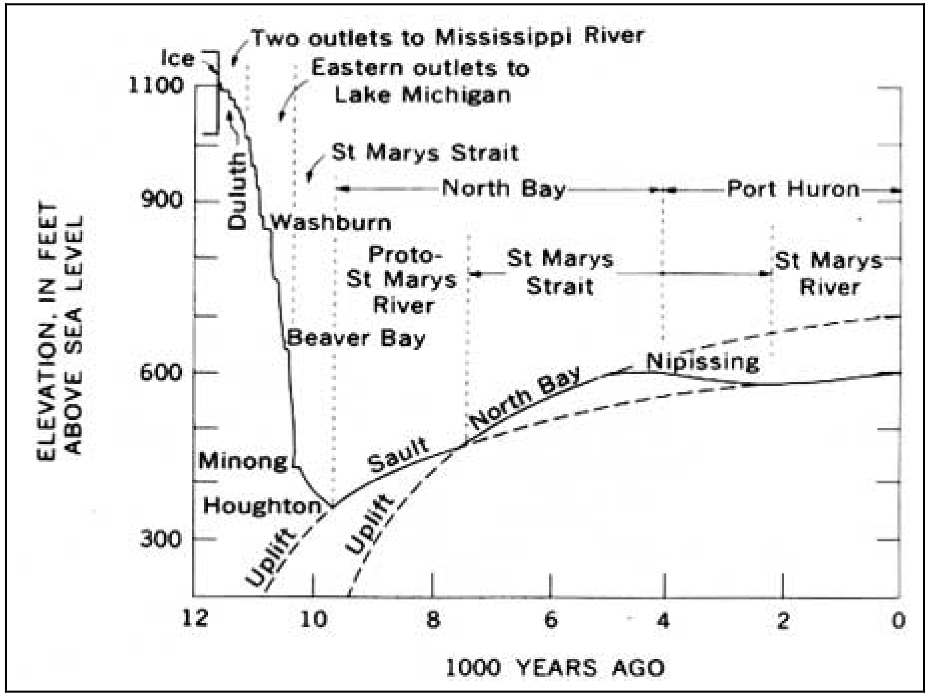
In areas where the rising of land is seen, it is necessary to define the exact limits of property. In Finland, the "new land" is legally the property of the owner of the water area, not any land owners on the shore. Therefore, if the owner of the land wishes to build a pier over the "new land", he needs the permission of the owner of the (former) water area. The landowner of the shore may redeem the new land at market

price. Usually the owner of the water area is the partition unit of the landowners of the shores, a collective holding corporation.

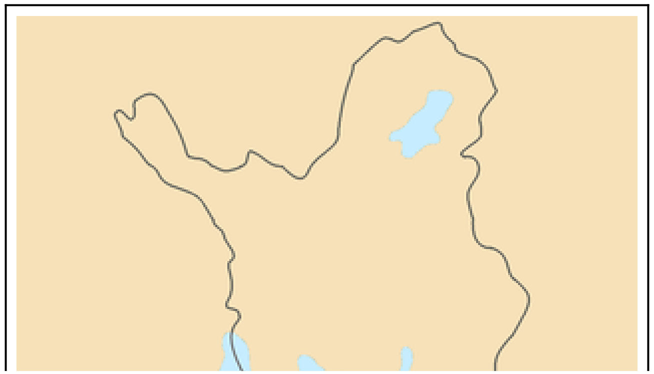


A model of present-day mass change due to post-glacial rebound and the reloading of the ocean basins with seawater. Blue and purple areas

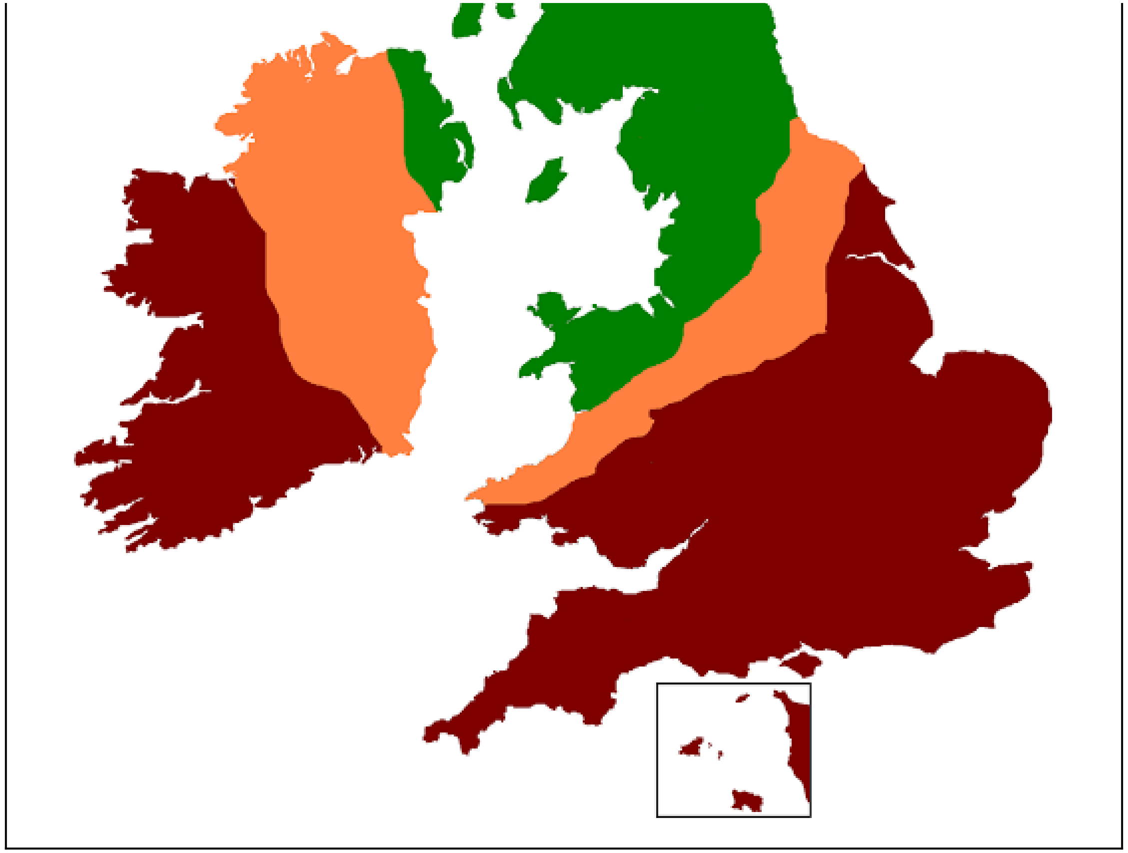
indicate rising due to the removal of the ice sheets. Yellow and red areas indicate falling as mantle material moved away from these areas in order to supply the rising areas, and because of the collapse of the forebulges around the ice sheets.



Changes in the elevation of Lake Superior due to glaciation and post-glacial rebound



Much of modern Finland is former seabed or archipelago: illustrated are sea levels immediately after the last ice age.



Map of Post Glacial Rebound effects upon the land-level of the British Isles.

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"God so loved the world that He gave His only Son, so that whoever believes in Him should not perish, but have everlasting life." John 3:16. "For whosoever shall call upon the name of the Lord shall be saved." Romans 10:13

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