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Thierry VILLEMIN
EDYTEM, Université de Savoie, 73376 Le Bourget du Lac, Thierry.Villemin@univ-savoie.fr

Abstract

The reological properties of the crust and the upper mantle beneath Iceland make the earth surface sensitive to recent ice mass changing. On a short time scale, strong correlation exists between seasonal variations in continuous GPS time series and snow covering. The overall retreat of Icelandic glaciers is causing uplift of over 2 cm/yr around Vatnajökull, the largest Icelandic ice cap. Recent modelling also suggests that the same phenomena is causing increased mantle melting and magma generation under Vatnajökull

RIFT AND ICE CAP CONJUNCTION

In Iceland, the plate boundary crosses Iceland from S to N and links with the Mid-Atlantic ridge through two south and north transform zones, the South Iceland Seismic Zone and the Tjörnes Transform Zone respectively (SISZ and TFZ). The rift zone outcrops along volcanic zones, most active of them being the Eastern Volcanic Zone and the Northern Volcanic Zone (EVZ and NVZ). Both of them are shifted eastward with regard to the axis of the oceanic ridge (RR and KR). This particular situation is known as resulting of the global movement of the lithospheric plate system relative to the Icelandic mantle plume.

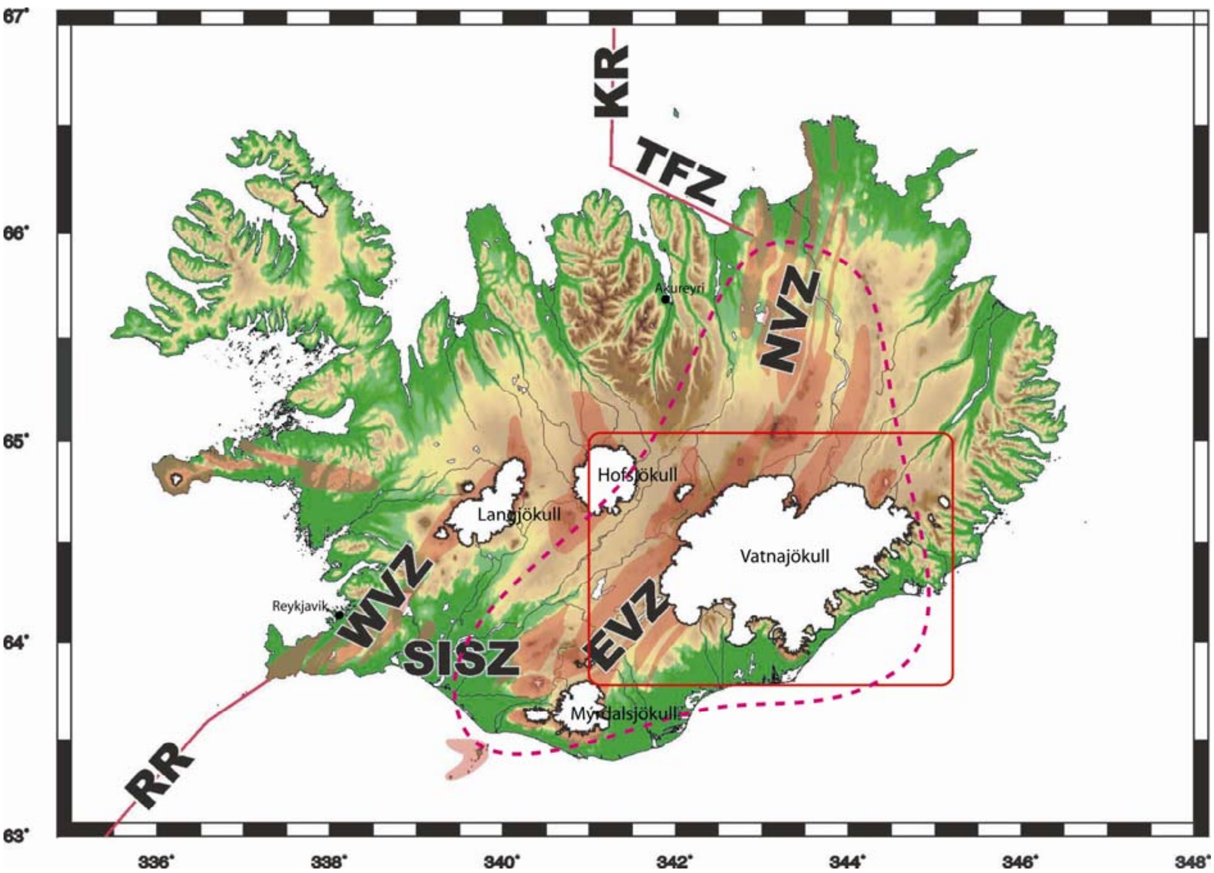

Figure 1 : Iceland general overview : plate boundary and ice caps. EVZ : eastern Volcanic Zone ; KR : Kolbeinsey Ridge; NVZ :Northern Volcanic Zone ; RR : Reykjanes Ridge; SISZ :South Iceland Seismic Zone; TFZ : Tjörnes Fracture Zone; WVZ : Western Volcanic Zone. Purple dotted line figures the hotspot trace whose apex is located below Vatnajökull.

The junction between the EVZ and NVZ is covered by the western half of **Vatnajökull**. Vatnajökull is the largest ice cap in Iceland (Björnsson, 1988), covering an area of about 8100 km2 with a mean radius of 50.7 km and a maximum thickness of about 900 m (e.g. Björnsson et al., 2002). The ice volume loss at Vatnajökull since 1890 is estimated to be about 400 km3 and ongoing glacio-isostatic deformations around Vatnajökull has been reported by several geodetic studies. The average altitude of the glacier is around 1500 m. The ice cap is maintained by strong annual precipitation, exceeding locally 4 m. The feedback between mass balance and altitude settles the ice cap to steady state for the recent past (last millennium). Nevertheless, this steady state is bounded by a critical elevation line as shown by (Aðalgeirsdóttir et al., 2005).

There are three other ice caps of smaller volume and surface west and southwest of Vatnajökull:

- **Langsjökull** (the "long glacier") covers the northern end of the Western volcanic zone (WVZ). The glacier is following more or less the direction of the active volcanic zone. Under Langjökull there are two volcanic systems with caldeiras well discerned from air. Langjökull is the second-largest of the glaciers of Iceland (1021 km^2), after Vatnajökull. Its highest peak reaches 1360 metres.
- **Hofsjökull** is the third largest glacier in Iceland. It situates at the west of the Highlands of Iceland between, outside the active rift zone. It covers an area of 925 km^2, reaching 1,765 m at its summit. The subglacial volcano is a shield type with caldera.
- **Mýrdalsjökull** is situated south of Iceland, at the southern end of the EVZ and is connected to the smaller glacier Eyjafjallajökull. The top of Mýrdalsjökull reaches 1493 m in height and the ice extends on an area of 595 km^2. The icecap covers the active volcano Katla. The eruption cycle range 40 – 80 years. Eldgjá, a fissure swarm of about 30 km length, erupting in 936, is part of the same volcanic system.

All ice caps in Iceland have negative mass balances and are retreating since the end of the Little Ice Age (16th to mid 19th century). This tendency is likely accelerated nowadays due to global climatic change.

EARTH RESPONSE TO ICE MASS CHANGING

The response of the Earth to stress loading imposed on the surface of the Earth, or within the Earth, depends on the rheology of the Earth. This rheology can be constrained by measuring geodetically the response to various loading of different spatial extent and different time scales. On a short time scale, the Earth behaves elastically whereas on a long time scale the Earth behaves as a viscoelastic body, with an elastic outermost layer. The rheological structure of crust and mantle under Iceland has been constrained by modelling of various geodetic results, e.g. evaluated by modeling spreading across the plate boundary in Iceland, and studies of co-seismic and post-seismic deformation. Studies of the response of the Earth to changing ice mass on the surface of Iceland have addressed the following topics:

- "Icelandic rhythmics" - the annual Earth response to change in ice mass at Icelandic glaciers. Strong correlation has been found between seasonal variations in continuous GPS time series (peak-to-peak amplitude of more than 10 millimeters) and predicted response to annual snow load in Iceland [Graphenthin et al., 2006]. The load has been modeled using Green's functions for an elastic halfspace and a simple sinusoidal load history on Iceland's four largest ice caps, constraining the elastic Young's modulus of the Earth response.
- The overall retreat of Icelandic glaciers that is causing uplift of over 2 cm/yr. Glaciers in Iceland began retreating around 1890, and since then the Vatnajökull ice cap has lost over 400 km3 of ice. The associated unloading of the crust induces a glacio-isostatic response. From 1996 to 2004 a GPS network was measured around the southern edge of Vatnajökull. These measurements, together with more extended time series at several other GPS sites, indicate vertical velocities around the ice cap ranging from 9 to 25 mm/yr, and horizontal velocities in the range 3 to 4 mm/yr. The vertical velocities have been modeled using the Finite Element Method (FEM) in order to constrain the viscosity structure beneath Vatnajökull [Pagli et al., 2007]. An axisymmetric Earth model with an elastic plate over a uniform viscoelastic halfspace was used in modeling. The observations are consistent with predictions based on an Earth model made up of an elastic plate with a thickness of 10-20 km and an underlying viscosity in the range $4{-}10\times10^{18}$ Pa s. Knowledge of the Earth structure allows us to predict uplift around Vatnajökull in the next decades. According to the estimates of the rheological parameters, and assuming that ice

thinning will continue at a similar rate during this century (about 4 km^3/year), a minimum uplift of 2.5 meters between 2000 to 2100 is expected near the current ice cap edge. If the thinning rates were to double in response to global warming (about 8 km^3/year), then the minimum uplift between 2000 to 2100 near the current ice cap edge is expected to be 3.7 meters.

- Sudden redistribution of ice mass due to glacial surges. Mass redistribution on the surface of the Earth may induce deformation and flexure at the site of loading. However, this general uplift may be interrupted by sudden subsidence next to ice caps. Instability in ice flow at outlet glaciers can cause sudden glacial surges, when large volumes of ice flow from accumulation areas on the ice caps towards their edges. InSAR observations have revealed subsidence associated with such glacial surges [Sigmundsson et al., 2006].
- Influence on volcanic systems. Recent modelling suggests that the ice reduction is causing increased mantle melting and magma generation under the largest ice cap in Iceland. Global warming causes retreat of ice caps and ice sheets. Can melting glaciers trigger a higher frequency of magmatic events? Since 1890 the largest ice cap of Iceland, Vatnajökull, has been continuously retreating losing about 10% of its mass during last century. Present-day uplift around the ice cap is as high as 25 mm/yr. Interactions between ongoing glacio-isostasy and current changes to mantle melting and in crustal stresses at volcanoes underneath Vatnajökull have been evaluated. The modeling indicates that a substantial volume of new magma, 0.014 km^3/yr, is produced under Vatnajökull in response to current ice thinning.
- Ice retreat also induces significant stress changes in the elastic crust that may contribute to high seismicity, unusual focal mechanisms, and unusual magma movements in NW-Vatnajökull.

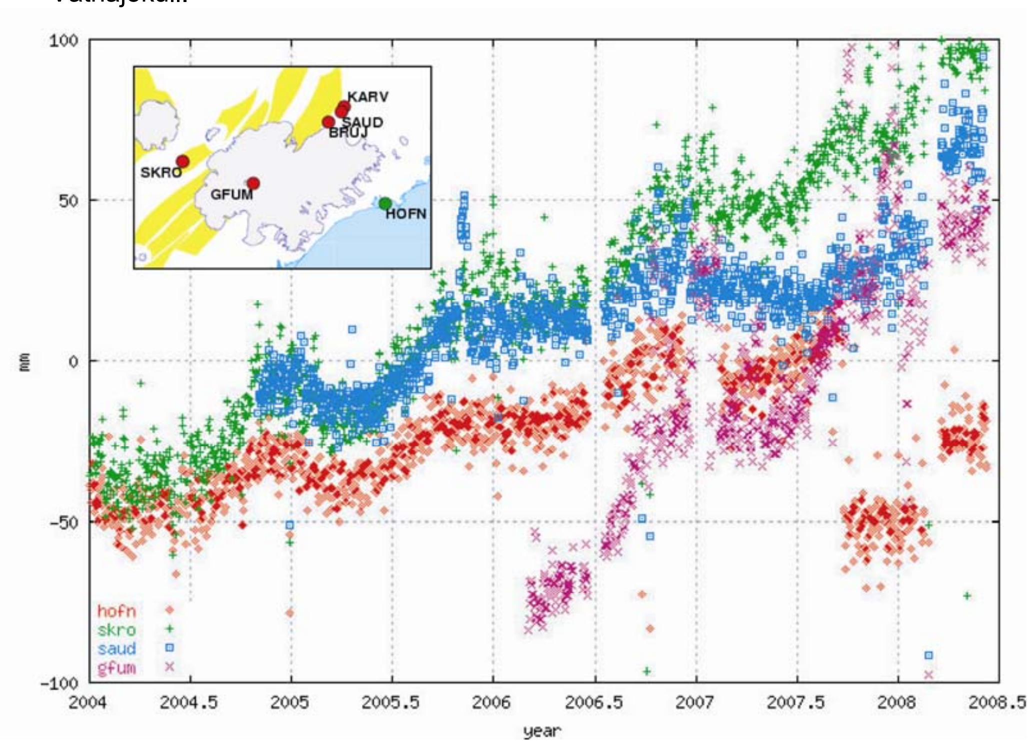

Figure 2 : Crustal uplift measured by the continuous GPS network ISGPS around Vatnajökull.
This diagram shows the evolution of the vertical component at four places, relative to REYK, a station set up in Reykjavik, SW Iceland. Stations show velocities of 27 mm/yr (SKRO), 18 mm/yr (SAUD), 17 mm/yr (HOFN) et 60 mm/yr (GFUM) in the ITRF2005 reference frame.

Deglaciation in Iceland at the end of the Weichselian glaciation, about 10000 14C years BP, was associated with rapid glacial rebound, apparently reaching completion in only about 1000 years in coastal areas. This exceptionally fast postglacial rebound suggests a viscosity under Iceland on the order of 10^{19} Pa s or less (e.g. Sigmundsson, 1991). Such a low viscosity results in the rapid response of the Earth to contemporary changes in ice volume. Major ice retreat is currently ongoing at ice caps in Iceland in response to a warmer climate.

Previous studies of the rheological structure under Vatnjökull are based on geodetic measurements around the glacier edge (e.g. Thoma and Wolf, 2001; Sjöberg et al., 2004; Pagli et al., 2007). From 1996 to 2004, a GPS network was measured around the southern edge of Vatnajökull (Pagli et al., 2007). These measurements, together with more extended time series at several other GPS sites, indicate vertical velocities around the ice cap ranging from 9 to 25 mm/yr, and horizontal velocities in the range 3 to 4 mm/yr. Recently, a nationwide network of GPS stations, the Isnet network, was used to investigate glacial isostatic adjustment in all of Iceland (Árnadóttir et al., 2009). The IsNET data confirms high uplift rates all around Vatnajökull and the need to consider all the larger glaciers and ice caps when analyzing the rebound signal.

Lake leveling measurements at Lake Langisjór at the SW edge of Vatnajökull were performed in 1959, 1991 and in 2002. The measurements show a relative uplift rate of about 4 mm/yr between benchmarks spaced 15 km perpendicular to the ice edge (Sigmundsson and Einarsson, 1992).

The GPS station at Jökulheimar on the western edge of Vatnajökull has the highest uplift rate observed outside an active volcano. The uplift at JOKU relative to the REYK station is 28 5 mm/yr, and is interpreted to be mostly caused by glacio-isostatic adjustment around Vantajökull.

The velocities derived from GPS measurements have been modeled using the Finite Element Method (FEM) in order to constrain the viscosity structure beneath Vatnajökull (Pagli et al., 2007; Arnadottir et al., 2009). Pagli et al., 2007 used an axisymmetric Earth model with an elastic plate over a uniform viscoelastic halfspace was used. The observations are consistent with predictions based on an Earth model made up of an elastic plate with a thickness of 10-20 km and an underlying viscosity in the range $4\text{-}10\times10^{18}$ Pa.s (Pagli et al., 2007). Knowledge of the Earth structure allowed them to predict uplift around Vatnajökull in the next decades. According to their estimates of the rheological parameters, and assuming that ice thinning will continue at a similar rate during this century (about 4 km3/year), a minimum uplift of 2.5 meters between 2000 to 2100 is expected near the current ice cap edge. If the thinning rates were to double in response to global warming (about 8 km3/year), then the occurring minimum uplift 2000 - 2100 near the current ice cap edge is expected to be 3.7 meters.

Árnadóttir et al. (2009) have modeled GPS nation-wide measurements of crustal uplift 1993-2004 with glacial isostatic adjustments due to thinning of the five largest ice caps in Iceland, using a 3D model. An Earth model with a 10 km thick elastic upper crust, underlain by a 20 km thick viscoelastic lower crust with viscosity of 10^{20} Pa.s, over a mantle with viscosity of 10^{19} Pa.s, can explain the measurements well. The authors also stresses that in order to model the crustal uplift at Vatnajökull, it is necessary to include the ice thinning at the smaller glaciers of Langjökull, Hofsjökull, Mýrdalsjökull and Eyjafjallajökull. The uplift signals taking place at the various glaciers interact with each other and with the uplift around Vatnajökull, i.e. causing a broad uplift signal in western Vatnajökull.

Since 1890 the mass balance of Vatnajökull has been negative and the entire ice cap lost about 11% of its total volume. The net loss has been equal to 1 m/yr on the average over the entire area, but in the marginal regions of the southern outlets (Breiðamerkurjökull and Skeiðarárjökull terminating below 100 m elevation) the loss equal to 8 m/yr and to 3 m/yr in the western and northern edge. The retreat of the outlet glaciers has been extensive over the last century, and areas at the southern edge of the ice cap that were covered with 200 m thick ice at the beginning of the 20th century are now ice free.

The retreat will lead to changes in the drainage pattern of the glacier. This will lead to continuous challenges for structures such as roads, bridges, power dams and power lines around Vatnajökull. One striking example of rapid change in drainage patterns is at Jökulsárlón in southern Vatnajökull. Prior to 1992, Jökulsárlón and Stemárlón were two separate lagoons at the margin of the same outlet glacier (Breiðamerkurjökull), with separate drainage systems. As Breiðamerkurjökull retreated the barrier between the two lagoons disappeared and one larger lagoon was formed. The river that used to drain Stemárlón dried up and now all the water drains from the river flowing from Jökulsárlón. Such increased water discharge can lead to accelerate erosion, and this may be a future threat to the bridge and the road.

In 1996 a GPS campaign of 15 stations was performed around the Öraefajökull volcano at the southern edge of the Vatnajökull ice cap. In 2002, four GPS points were re-measured. In 2003, all the stations from the 1996 campaign were re-measured. In 2004, three GPS points were re-measured. The results from these GPS campaigns are presented by Pagli et al. (2007), showing vertical velocities around the ice cap ranging from 9 to 20 mm/yr –campaign measurements show vertical velocities max 20 mm/yr, higher rates are obtained at STEM-HAMA-JOKU, maybe add that-, and horizontal velocities in the range 2 to 4 mm/yr.

On a still larger scale, it is known that ice unloading can influence eruptive activity. During the deglaciation of Iceland, at the Pleistocene-Holocene boundary, eruption rate is inferred to have been about 30-100 times its steady state. Increased decompressional mantle melting due to ice removal has been suggested as the main cause of the increase in melt production during deglaciation.

A similar situation, on a smaller scale, exists in Iceland today. According to Pagli and Sigmundsson (2008) a substantial volume of new magma, 0.014 km3/yr, is produced under Vatnajökull in response to current ice thinning. They also suggest that ice retreat induces significant stress changes in the elastic crust that may contribute to high seismicity, unusual focal mechanisms, and unusual magma movements in NW-Vatnajökull.

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