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North Atlantic geoid high, volcanism and glaciations

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[1] Shallow topography, geoid high and intense volcanism in the northern Mid Atlantic Ridge are interpreted as enhanced by the loading on the adjacent continents by ice caps during upper Cenozoic glaciations. The load of ice packs on the continental lithospheres of North America and northern Europe generated radial mantle flow at depth. In our model, these currents, flowing from west and east, faced each other below the northern Atlantic, joining together and upwelling. Numerical modeling of this process supports the development of dynamic topography leading to uplift of the sea-floor and inducing a regional geoid high. The mantle rising to shallower levels may have contributed to larger asthenospheric melting, and to ridge centered excess magmatism, as observed in the Northern Atlantic.
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1. Introduction

[2] The lithosphere generated by the Mid Atlantic Ridge (MAR) east of Greenland underlies the youngest (<60 Myr) and narrowest part of the Atlantic Ocean. This portion of the northern Atlantic shows three peculiar characters, 1) it is about 1–3 km shallower than the average mid-oceanic ridge (Figures 1a and 1b); 2) it displays diffuse positive gravity (>30 mGal) and geoid (>50 m) anomalies (Figures 1c, 1d, and 1f); 3) it is the seat of larger than average magmatic productivity, resulting in the thickest oceanic crust of the entire MAR, up to about 40 km below Iceland [*Kaban et al.*, 2002]. The thickness of the Cretaceous-Early Cenozoic (pre-glaciations) oceanic crust in the northern Atlantic is rather 4–6 km in average [e.g., *Shillington et al.*, 2006].

[3] A number of papers attributed these features to the Iceland mantle plume [*Vink*, 1984]. However, the deep hotspot hypothesis has been questioned on various grounds [e.g., *Foulger and Anderson*, 2005]: the persistence of magmatism on the westerly moving ridge and the presence of a double tail both west and east of Iceland; the absence of a relevant heat flow positive anomaly, and the possible presence of a hydrous mantle lowering the melting point [*Bonath*, 1990; *Asimow and Langmuir*, 2003]. There is also contrasting topologic and tomographic evidence on whether the source of the plume is in the deep or in the upper mantle [*Foulger et al.*, 2001; *Courtillot et al.*, 2003; *Ritsema and Allen*, 2003; *Montelli et al.*, 2004]. Moreover, the geochemical Icelandic signature is not restricted to Iceland, but continues both north and south along the Mid Atlantic Ridge [*Taylor et al.*, 1997]. In this article we test numerically a model in which the far field superficial loading of the mantle by the ice caps in North America and northern Europe can contribute to generate the anomalous features of the North Atlantic.

[4] *Jull and McKenzie* [1996] and *Maclennan et al.* [2002] have demonstrated that the removal of ice load over Iceland triggers volcanism. Here we show that an inverse correlation can occur for magma production, i.e., the ice loading on the adjacent continental areas may have contributed to the uplift of the north Atlantic mantle, to the geoid anomaly and, possibly, to the higher degree of melting due to faster adiabatic decompression induced by mantle upwelling.

2. Model Description and Results

[5] Assuming a viscous Earth (uniform viscous half-space) and a cylindrical ice-load, it can be shown by analytical solutions [e.g., *Cathles*, 1975] that the depth at which the vertical displacement induced by ice loading/unloading is 0.5, 0.2 or 0.1 times the surface value is equal to $1.4R_0$, $2.5R_0$ and $3.3R_0$ (where R_0 is the radius of the cylinder; i.e., 825 km, 1474 km and 1815 km for the Fennoscandian ice sheet, characterized by R_0 = 550 km) respectively. Numerical solutions have also shown that the ice cycles in the Canadian region induced vertical motions (either uplift or subsidence) up to more than 60° (more than 6600 km) from the ice center [e.g., *Cathles*, 1975].

[6] Here we test the combined effects the glacial cycles in North America and Europe on regional mantle flow. The aim of our finite element modeling, performed using COMSOL 3.5 software (http://www.comsol.com/), is to evaluate the velocity field induced within the upper mantle by glaciation cycles rather than to reproduce exactly the surface velocities. This limited objective allowed us to adopt some major simplifying assumptions, such as the 2D nature of the model, neglecting the load due to water redistribution during the ice formation and melting, and using a simplified ice model.

[7] The model adopts a 2D plane strain approximation and includes lithosphere, upper and lower mantle (Figure 2). All the layers are described by a compressible linear viscoelastic (Maxwell) rheology; the assumed elastic constants and viscosities are listed in Table 1. The elastic structure is consistent with the PREM model [*Dziewonski and Anderson*, 1981] and the viscosities are consistent with values normally used for glacial isostatic rebound modeling [e.g., *Mitrovica and Peltier*, 1993; *Kaufmann and Lambeck*, 2002]. Gravity acceleration and density vary with depth according to the PREM model. Gravity is applied as a body force and the ice load as a boundary condition. The ice thickness varies with time but it is kept laterally constant for each area. The model is run from 150 Kyr BP to the present.

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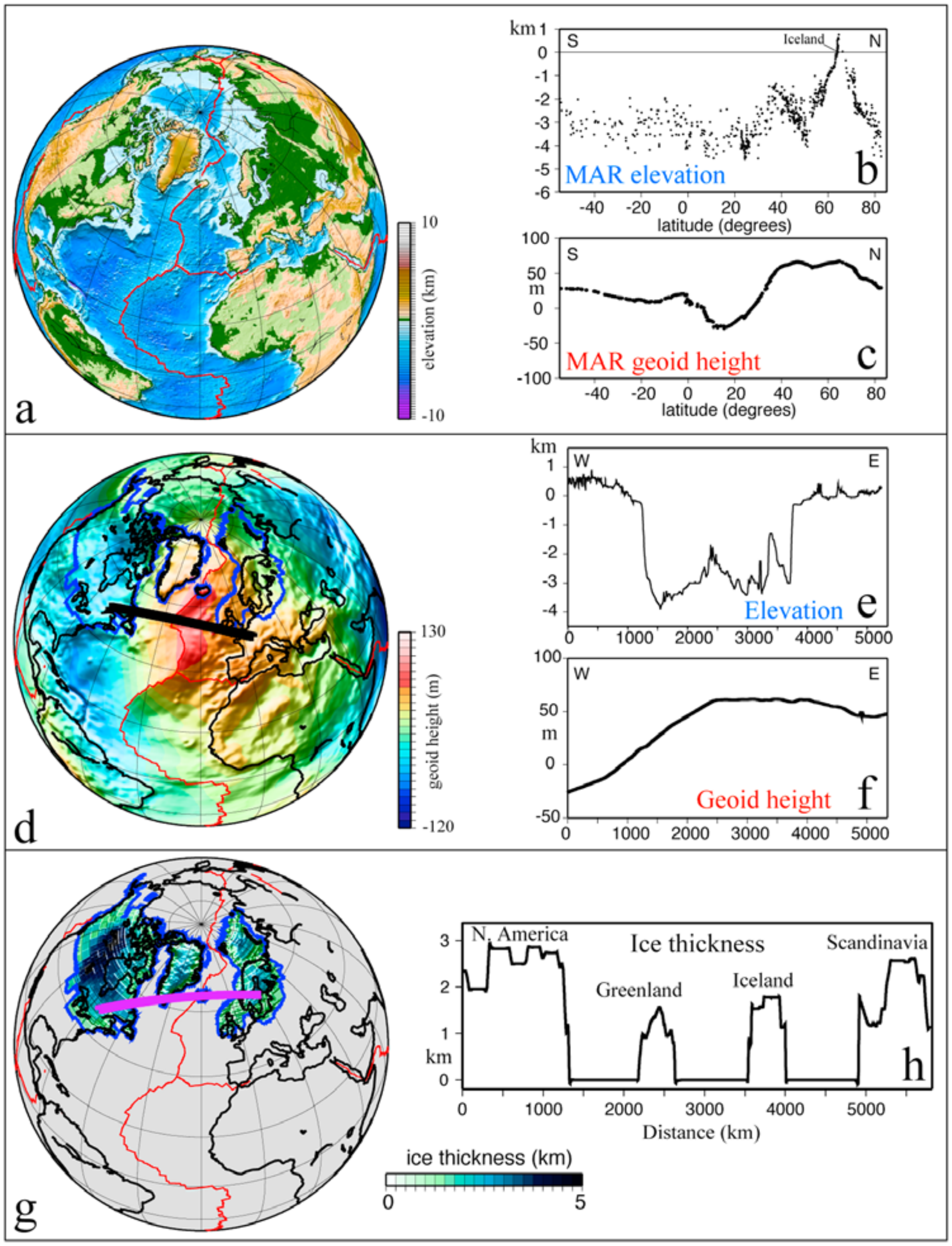

Figure 1. (a) Topography (data after ETOPO1, http://www.ngdc.noaa.gov/mgg/global/global.html); (b) elevation of the Mid Atlantic Ridge; the bathymetric distribution along the MAR shows a high in the northern Atlantic which is limited not only to the Iceland area but it extends ca 20° northward and 40° southward; (c) geoid anomaly along the Mid Atlantic Ridge (data after the EGM96 model, http://cddis.nasa.gov/926/egm96/egm96.html); (d) geoid height; notice how the northern Atlantic geoid high is located between the North American and Scandinavian ice bodies; (e) topography-bathymetry along the cross-section on the map to the left; (f) geoid height along the same section. The blue curves in panel Figure 1d show the borders of the ice bodies according to ICE-5G. The geoid is shallower along the eastern flank of MAR and the crest of the anomaly is offset to the east of the oceanic ridge. (g) Thickness in map and (h) cross-section in purple of the ice cap at the last glacial maximum (21 Kyr BP; data after the ICE-5G model [*Peltier*, 2004]). Mid-ocean ridges are shown as red lines. The purple great circle in Figure 1g shows the trace of the modeled profile of Figure 2.

The ice thickness is kept at zero between 150 Kyr and 120 Kyr BP and then it is linearly increased to reach the maximum thickness at 105 Kyr BP. It is then kept constant until 21 Kyr BP. Between 21 Kyr and 6 Kyr BP the ice thickness is linearly decreased to zero, with the exception of Greenland, where it is decreased to 750 m. The maximum thicknesses is assumed to vary regionally: 2500 m for North America, 1300 m for Greenland, 2000 m for Scandinavia and 2000 m for Iceland (when applied). Such values are consistent with the diagram of Figure 1h, showing maximum ice thicknesses along the trace of the modeled section at 21 Kyr BP according to the ICE-5G model [*Peltier*, 2004]. The bottom of the model is fixed normally to the boundary and free to slip tangentially. Symmetry conditions

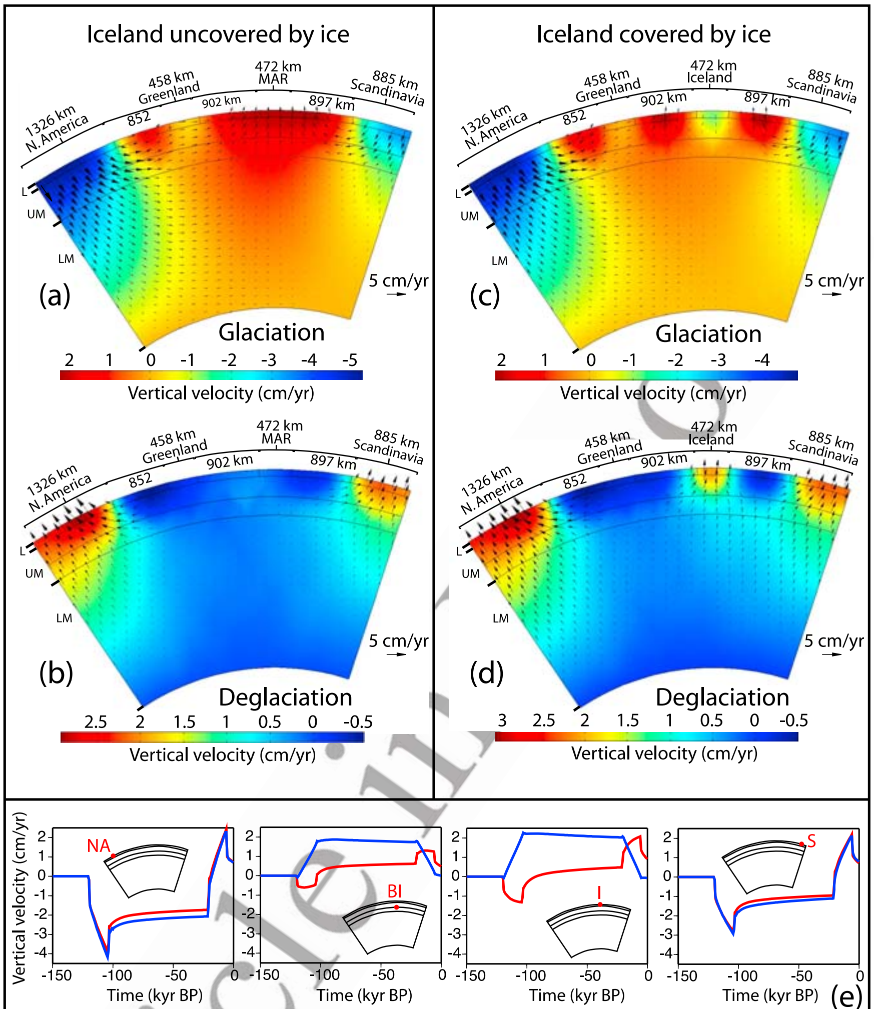

Figure 2. Vertical velocities and velocity fields predicted by the models (a and c) immediately after the formation of the ice caps (105 Kyr BP) and (b and d) soon after their melting (6 Kyr BP). Figures 2a and 2b are referred to a model characterized by the absence of ice during the glacial period in the Iceland region, while panels c and d to a model characterized by Iceland affected by ice. (e) Vertical rates through time at four different locations marked by the red dots (NA, North America; BI, beneath Iceland; I, Iceland; S, Scandinavia). Blue line is with Iceland unaffected by ice, whereas the red line represents the case of Iceland covered by ice.

are imposed on the left and right boundaries. This is reasonable since the tips of the modeled section are located approximately at the center of the American and Scandinavian ice masses. The model surface is left free in areas unaffected by ice formation. We use a set of ca. 3800 triangular elements. Modeling results are shown for the time steps of 105 Kyr and 6 Kyr BP, representative of the glaciation and deglaciation scenarios respectively. Although no constraints are available for past mantle velocity simulations, we are confident that the patterns and the order of magnitude of the calculated velocities are realistic. This confidence is justified by the positive match between simulated and observed present-day vertical velocities for well-constrained areas such as Scandinavia.

[8] Two scenarios are modeled. In the first Iceland is covered by ice during the glaciation, while in a second Iceland is assumed to be ice-free. The first model simulates the evolution in the transect of Figure 1, while the second simulates a section just north or south of Iceland. Figure 2 shows the vertical velocities and the velocity field predicted for the two scenarios. Both scenarios indicate a convergence of velocity vectors towards the Atlantic area during formation of the ice cap, with a prevalence of horizontal directions of motion. Below Iceland and the surrounding Atlantic the velocity vectors turn vertical with a general upwelling (rates of up to 2 cm/yr in the Iceland ice-free scenario). In the Iceland-covered scenario, the upwelling is limited to the Atlantic region with rates of less than 2 cm/yr. Below Iceland the lowermost upper mantle moves upward at slow rates (<0.5 cm), while the shallower upper mantle moves downward, due to the Icelandic ice load. During the same glaciation period, a negative (i.e., downward) velocity field with rates of $-2/-4$ cm/yr is predicted for North America and Scandinavia.

[9] The velocity field is reversed during deglaciation, with the mantle flowing downward and away from the central Atlantic region and upward below Scandinavia and North America. Figure 2e shows that the development of the velocity field associated to glaciation and its reversal during deglaciation is very fast, due to the elastic compo-

Table 1. Elastic and Viscous Parameters Used in the Calculations

Layer	Poisson's Ratio	Young Modulus (Pa)	Viscosity (Pa s)	Depth Interval (km)
Lithosphere	0.27	1.75e11	5e22	0–100
Upper Mantle	0.27	1.39e11	1e21	100–670
Lower Mantle	0.27	1.27e11	1e22	670–2890

nent of rheology. Present-day rates, although with lower magnitude, show for the two scenarios velocity patterns similar to those of Figures 2b and 2d. This is consistent with literature [e.g., *Vestøl*, 2006; *Milne et al.*, 2001]. Thus the dynamic topography attained during the glaciation period has not been completely recovered, due to the viscous component of the rheology of lithosphere and mantle. Although not shown, a sensitivity analysis showed that the described patterns of the velocity field are stable also when the rheological parameters and ice thickness are modified within reasonable bounds.

[10] Therefore the models show that the ice load induces a upward flow below the Mid Atlantic ridge generating a dynamic topography consistent with the geoid high measured in the region. The results of the model that assumes Iceland free of ice allowed us to predict, at 21 ka BP (i.e., just before the beginning of deglaciation), a geoid anomaly of ca. 70 m for the center of the Atlantic ocean (location I in Figure 2e). The geoid anomaly was calculated as $\Delta h = -\frac{2\pi G}{g}\int_0^D \Delta\rho(z) z dz$ [*Turcotte and Schubert,* 2002], where Δh is the geoid anomaly, g is the gravity acceleration, $\Delta\rho(z)$ is the anomalous density at depth z and D is the compensation depth (chosen as the bottom of our model) and G is the Newtonian constant (6.67×1011 m^3 kg^{-1} m^{-2}). Although this calculation is to be considered a rough estimate, since it includes only the upward motion of particles below the MAR and does not include crust formation, mantle partial melting and other thermal processes, it is compatible with the present day anomaly of the region (ca. 60 m; Figure 1), showing that present-day geoid anomaly and high topography of the region are remnants of the glaciation. These findings also explain the topographic low below Scandinavia and North America, consistent with the observed geoid low (the low geoid anomaly of North America has been already tentatively explained with the ice load by *Turcotte and Schubert* [2002]).

[11] Moreover, mantle upwelling may enhance mantle partial melting and explain, at least in part, the anomalously intense magmatic activity of the region. Assuming an average 7–10% melt of the asthenosphere [e.g., *Langmuir and Forsyth*, 2007] under the northern Mid Atlantic Ridge, the cumulative uplift of ca. 2 km of the mantle during the glaciations would increase the melting by a few percent (depending on water content, initial mantle composition and temperature, spreading rate, etc.), producing a larger volume of magma delivered to the surface.

3. Discussion and Conclusions

[12] Our modeling has shown, consistently with previous studies, that ice loading/unloading can have a regional impact on mantle flow velocities. The MAR swollen bathymetry (Figure 1) and the geoid regional positive anomaly of the northern Atlantic [*Lemoine et al.*, 1998; *Tapley et al.*, 2005] are located in an area intermediate between the ice caps in Northern America and Europe during the last glaciation. Moreover, the same area is occupied by the largest volcanic province of the northern Atlantic. If our model is correct, we speculate a glacio-eustatic Milankovitch periodicity in north Atlantic magma production.

[13] The oldest rocks in Iceland are about 15 Ma old [*Hardarson et al.*, 1997]. The same Authors noted chemical variations of basalts, generated by a variably depleted mantle. Iceland possibly emerged at that time or later, and it experienced ice loading as well. The time of the onset of glaciations in the northern hemisphere is still debated. It has been shown how the onset of glaciations in the northern hemisphere is older (Eocene-Oligocene) than previously estimated [*Eldrett et al.*, 2007]. Recent deep sea drilling provided evidence for a middle Eocene initiation of the icehouse of the Arctic area [*Moran et al.*, 2006]. High magma productivity has been documented in Iceland 13–11 Myr, and 8–7 Myr intervals together with periodicity in magma composition [e.g., *Kitagawa et al.*, 2008]. *Gee et al.* [1998] detected a close relationship between the geochemistry of lavas and glacioisostacy. They found that eruption of primitive lavas with depleted chemical and isotopic characteristics coincides with a period of glacioisostatic instability at the end of the last glaciation (13–9 Kyr).

[14] *Sigvaldason* [2002] described a Holocene rhyolitic eruption triggered by the melting of the ice cap in central-eastern Iceland, hinting at a relation between magmatic emplacement and vertical loading.

[15] Therefore, loading and unloading of the ice cap [*Watts*, 2001] appears to be a factor controlling locally or even regionally the production of mantle melts. Although we modeled a single ice cycle, the productivity of magma over geological periods is expected to be influenced by the superposition of several ice cycles on the process of oceanic spreading. The remote loading of ice can determine an upwelling of the mantle elsewhere, generating larger volumes of melt due to mantle adiabatic decompression below the ridge. Vice versa, the ice load in a volcanic area (e.g., along the MAR in Iceland) can locally buffer eruption, tuning the frequency of magmatic delivery, and generating a lower degree of melting and a longer residence time of melts in the mantle. These factors, together with the variable source depth of the melts, could cause significant variations of the lava's geochemistry. Therefore, in Iceland, the following two complementary processes could interfere, overlap, and buffer each other: deglaciation-induced magmatism (a in-situ mechanism associated with stress release related to ice unloading) and glaciation-induced magma production (a far-field effect, as shown by our model). In the remaining areas of the MAR, not directly covered by ice, a different time correlation between magma production and eruption is expected.

[16] Our model predicts a relatively low intensity of magmatism along the northern segment of the MAR during the present interglacial period. We note that the North Atlantic geoid height is presently decreasing, while it is increasing on the adjacent continental areas, as shown by the Grace project data [e.g., *Tapley et al.*, 2004]. The decrease of the geoid has been related to the melting of ice in Greenland [*Ramillien et al.*, 2006], but it could be related also to the decreasing upwelling beneath the north-

ern MAR due to the absence of ice caps on the continents. Conversely, the continental areas show an increase of the geoid because the mantle is rising, recovering the subsidence previously generated by the ice loading. However, when the mantle rises and melts beneath a ridge [*McKenzie*, 1984], it becomes lighter [*Oxburgh and Parmentier*, 1977]. Therefore the process is possibly not entirely reversible since the uplifted and depleted mantle cannot be re-pulled down at its original position, by the down-flow motion induced by deglaciation, because of the permanent increase in buoyancy characterizing the mantle after melting.

[17] During the time frame considered (e.g., say the last 20–30 Ma) we may expect about 180–250 oscillations associated to the eccentricity of the Earth's orbit, or more than twice oscillations in case of obliquity related cycles. The model presented rather shows the effects of only one single cycle of loading and unloading. Assuming an irreversible component on each cycle, the present geoid high would represent the sum of the all episodes, a sort of vibration generating hysteresis in the uplift of the mantle.

[18] In summary, we suggest that the ice caps on the continents of the northern hemisphere generated a flow in the underlying mantle that converges in the northern Atlantic from west and east, upwelling along the northern MAR. The eastward offset of the geoid high relative to the MAR could be due to a larger ice load on the northern American continent, although we cannot neglect a contribution from the relative eastward mantle flow implicit in the notion of the net rotation of the lithosphere [*Gripp and Gordon*, 2002], able to generate an asymmetry of ocean ridges worldwide [*Doglioni et al.*, 2003]. This model implies that the over production of magmatism in the northern Atlantic could be sourced by the shallower location of the asthenosphere, being the upraise of the asthenosphere pumped from the deep mantle flow.

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