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- Rheological modeling of upper mantle under Iceland
- Low upper mantle viscosity and lithospheric thickness
- Modeling shows large lateral variations in viscosity and lithospheric thickness
- Indications for a dry upper mantle under Iceland
- Increase in lithospheric thickness away from the mid-oceanic ridge axis

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Upper mantle viscosity and lithospheric thickness under Iceland

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Abstract

Deglaciation during the Holocene on Iceland caused uplift due to glacial isostatic adjustment. Relatively low estimates for the upper mantle viscosity and lithospheric thickness result in rapid uplift responses to the deglaciation cycles on Iceland. The relatively high temperatures of the upper mantle under the newly formed mid-ocean ridge under Iceland are responsible for the low upper mantle viscosity values. In this study, estimates for lithospheric thickness and upper mantle viscosity under Iceland from glacial isostatic adjustment studies are complemented by a microphysical modelling approach using the theoretical temperature distribution under mid-ocean ridges combined with olivine diffusion and dislocation creep flow laws. The lithospheric thickness (27-40 km) and upper mantle viscosity (2×10^{18} – 10^{19} Pas) outcomes for the upper mantle recent glaciation under the Vatnajökull glacier are consistent with previous reports of viscosity and lithospheric thickness from glacial isostatic adjustment studies. A combination of a 40 km thick elastic lithosphere and an average upper mantle viscosity of 5×10^{18} Pas would suggest that the upper mantle under Iceland is most likely dry. The earlier and larger Weichselian glaciation event (~10000 BP) on Iceland is predicted to have had a slightly larger upper mantle viscosity $\sim 10^{19}$ Pas and a lithospheric

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thickness of ~100 km. Large lateral variations in upper mantle viscosity and especially lithospheric thickness are expected for Iceland perpendicular to the ridge axis.

Keywords

Rheology, deformation mechanism, creep, water content, melt content, mid-ocean ridge, plume

Introduction

The Vatnajökull glacier, located in the south-east of Iceland is the largest ice cap of Iceland having a mean radius of 50.7 km covering an area of ~8100 km² (Björnsson, 1998). Its estimated mass loss since 1890 is 435 km³ (Árnadóttir et al., 2009), much more than the earlier estimate by Sigmundsson and Einarsson (1992) where the mass loss between 1890 and 1978 is estimated at only 182 km³. The Vatnajökull glacier is situated directly on top of the spreading axis in the eastern volcanic zone (EVZ) of the Icelandic mid-ocean ridge and near the inferred centre of the Icelandic hotspot (e.g. Wolfe et al., 1997). Due to the vicinity of the glacier to the active tectonic area, the response of the solid earth to melting of the ice cap is strongly controlled by the properties of the newly formed upper mantle underneath the mid-ocean ridge. The relatively high temperatures in the mantle during rifting result in relatively low upper mantle viscosities and fast relaxation times in comparison with tectonically stable areas such as Fennoscandia. Upper mantle viscosity estimates from glacial isostatic adjustment (GIA) studies for Iceland range between 5×10^{17} Pas and 5×10^{19} Pas (e.g. Sigmundsson, 1991; Sigmundsson and Einarsson, 1992; Thoma and Wolf, 2001; Sjöberg et al., 2004; Fleming et al., 2007; Pagli et al., 2007; Biessy et al., 2008; Árnadóttir et al., 2009; Le Breton et al., 2010) compared to 10^{20} - 10^{21} Pas in Fennoscandia (e.g. Lambeck et al., 1998; Milne et al., 2001). Elastic thickness estimates in those studies including estimates from

seismological studies (e.g. Kaban et al., 2002; Kumar et al., 2005) range between a very thin lithospheric thickness of 10 km up to 80 km. Recent glacial isostatic adjustment studies by Pagli et al. (2007) and Árnadóttir et al. (2009) provides estimates for both the lithospheric thickness and the upper mantle viscosity. It resulted in a lithospheric thickness of 10-20 km and a viscosity of $4\text{-}10 \times 10^{18}$ Pas for Pagli et al. (2007) and a lithospheric thickness of 40 km and a viscosity of 10^{19} Pas for Árnadóttir et al. (2009).

In this study, we present a microphysical approach to determine the lithospheric thickness (elastic layer) and upper mantle viscosity under the Icelandic mid-ocean ridge and specifically under the Vatnajökull glacier. Information on the rheological behaviour of the main upper mantle mineral olivine is combined with information on the temperature distribution under mid-ocean ridges, information on the microstructural state of the upper mantle under mid-ocean ridges (grain size, water content) and stress levels within the upper mantle due to glaciation events to determine the viscosity of the upper mantle. This approach provides detailed estimates on the lateral and radial variations in upper mantle viscosity and lithospheric thickness that can be tested in geodynamical models and compared with glacial isostatic adjustment studies that so far neglected lateral variability in viscosity and lithospheric thickness. In this study, we have based estimates of viscosity and elastic thickness for Iceland on data from the temperature distribution of the mantle under oceanic lithosphere calculated from a half-space cooling model for oceanic lithosphere (Turcotte and Schubert, 2002) and the olivine flow laws from Hirth and Kohlstedt (2003) for linear diffusion creep and non-linear dislocation creep in a wet and dry upper mantle. The half-space cooling model simulates a normal mid-ocean ridge setting and a simplified approximation of plume activity under Iceland. Temperatures of the plume at the center of the ridge axis are 100 °C and 200 °C higher than temperatures at the ridge in a mid-ocean ridge setting, based on estimates of excess temperatures of 75-200 °C due to plume activity under Iceland (e.g. Ito

et al., 1996; 1999; Ruedas et al., 2004; Schmeling and Marquart, 2008). The static temperature distribution in the upper mantle, based on the half-space cooling model, used here (Fig. 1) is less complicated than dynamic models for plume activity and mantle melt generation (e.g. Ito et al., 1996; 1999; Ruedas et al., 2004; Marquart, 2001; Schmeling and Marquart, 2008). However, those models only contain a relatively simple dependency of viscosity on pressure and temperature, whereas the viscosity dependence of this study includes also the influence of water, melt fraction and grain size. By using the flow laws of Hirth and Kohlstedt (2003) for olivine rheology, solid-state viscosity variations (both radially and laterally) under an active mid-ocean ridge are calculated. The study shows that large variations in elastic thickness and viscosity are expected under the mid-ocean ridge setting of Iceland due to cooling-related temperature variations.

Temperature dataset and olivine viscosity modeling

Geotherms for the oceanic lithosphere under Iceland are constructed using a time-dependent half-space cooling model (Turcotte and Schubert, 2002):

$$T(z) = T_s + (T_m - T_s) \operatorname{erf} \left(\frac{z}{2\sqrt{\kappa\tau_c}} \right) \quad (1)$$

where T_s is the surface temperature, T_m the mantle temperature at a depth of 410 km (in this study we used $T_m = 1400, 1500$ or 1600 °C), τ_c the age of the oceanic lithosphere and κ the thermal diffusivity (taken as $1 \text{ mm}^2\text{s}^{-1}$; Turcotte and Schubert, 2002). Estimates of upper mantle temperatures from Goes et al. (2000) using P- and S-wave tomography data for Iceland (Fig. 1A) give temperatures in accordance with a time-dependent cooling model of the oceanic lithosphere. The oldest volcanic rocks outcropping on Iceland have an age of approximately 16 Ma (Foulger, 2006). The steady-state spreading rate of Iceland in plate motion models is 19-20 mm/year (e.g. Árnadóttir et al., 2009). Average growth rate of each plate on both sides of the spreading ridge is thus around $1 \text{ cm/year} = 10 \text{ km/Ma}$. Based on the

age constraint and the spreading rate, geotherms for the oceanic lithosphere between 0 and 20 Ma (Fig. 1A) and a two-dimensional cross-section of the temperature distribution under the Icelandic mid-ocean ridge (Fig. 1B) are constructed. The cross-section encompasses the first 200 km on either side of the ridge axis corresponding to the first 20 Ma of oceanic lithosphere generation. Mantle temperatures at the base of the modelled range are set at 1400, 1500 and 1600 °C to reflect the temperature distribution in a normal mid-ocean ridge setting ($T_m = 1400$ °C; Turcotte and Schubert, 2002) and settings where a plume with excess temperatures for Iceland of 100-200 °C (e.g. Ito et al., 1996; 1999; MacLennan et al., 2001; Ruedas et al., 2004; Putirka, 2005; Schmeling and Marquart, 2008) is imposed on a mid-ocean ridge setting ($T_m = 1500$ and 1600 °C). The olivine-wadsleyite transition at ~410 km is taken as the lower boundary of the vertical temperature distribution in the upper mantle (Fig. 1B). The dry solidus of for an anhydrous mantle and the solidus at 100 ppm H₂O for a wet upper mantle of Hirschmann et al. (2009) are taken as melting curves. When the temperatures along the geotherms of Fig. 1A exceed the solidus temperature a partially molten upper mantle is assumed to be present (Fig. 1C).

Olivine viscosity modelling

Diffusion and dislocation flow laws for olivine from Hirth and Kohlstedt (2003) are used to calculate the upper mantle viscosity distribution for a dry/wet and melt-free upper mantle and a dry/wet and melt-bearing upper mantle. The diffusion and dislocation creep flow laws describe the dependence of the strain rate ($\dot{\epsilon}$) on temperature (T), grain size (d), deviatoric stress (σ), pressure (P), water content (fH_2O) and melt content (ϕ):

$$\dot{\epsilon} = A \sigma^n d^{-p} fH_2O^r \exp(\alpha \phi) \exp\left(-\frac{E + PV}{RT}\right) \quad (2)$$

where A and α are constants, n , p and r are the stress, grain size and water fugacity exponents, E the activation energy and V the activation volume. For the modeling of dry/wet, melt-

bearing upper mantle a melt fraction (ϕ) of $\phi = 0.04$ is used. A melt content of 4% is just above the upper limit for estimates for melt that can remain in a peridotite (up to 2-3%; Faul (1997), 1-3%; Ruedas et al. (2004)). We have used a higher value of 4% to illustrate that the presence of melt has only a relatively small reducing effect on the overall viscosity within the upper mantle under Iceland. A study of the Oman ophiolite (Dijkstra et al., 2002) shows that olivine grain sizes in mantle rocks of mid-ocean ridges have grain sizes between 0.8 and 3.3 mm. An average grain size of 2 mm is used in the modelling as a representative grain size for the upper mantle in mid-ocean ridge settings. Stress profiles within the upper mantle due to glacial loading have been calculated for Iceland using a three-dimensional finite element model for glacial isostatic adjustment based on the commercial program Abaqus. We use the geometry of Schotman et al. (2009) who studied Scandinavia, and scaled down the spatial dimensions by a factor of 10 because the Icelandic glaciations cover a much smaller area. The model has a total of 97x97 elements in the horizontal direction and 7 element layers in the vertical direction. Elements in the inner surface area of 292 x 292 km are 8 x 8 km wide. Density and Young's modulus parameters are obtained by volume averaging from PREM. The rheology is a combination of dislocation and diffusion creep (Van der Wal et al., 2010) with parameters taken from Hirth and Kohlstedt (2003) and a temperature-depth profile for a cooling oceanic lithosphere of 4 million years old (Turcotte and Schubert, 2002). The top 15 kilometer is taken to be fully elastic, which is reasonably close to the 10 km elastic thickness of Sigmundsson (1991). Note however, that the real elastic thickness in the model for glacial loading depends on the effective viscosity which is a function of stress.

The model is loaded separately by two glaciations. (i) the Weichselian (or Younger Dryas) glaciation is modelled following Sigmundsson (1991), approximating the ice cap by four discontinuities in height. The surface extent of the ice cap is 160 km and the maximum height is 1800 m. We have included a 100000 year growth phase of the ice cap ; unloading

takes place at different time steps between 10000 and 9500 years before present according to Sigmundsson (1991). (ii) A model for the recent growing and melting of the Vatnajökull ice cap is taken from Fleming et al. (2007). A perfectly plastic ice cap (discretised on our 8 x 8 km elements) grows from a radius of 45 km and central thickness of 800 m at 900 AD to a radius of 52 km and a central thickness of 915 m at 1890 AD. After that melting takes place in two different rates to end up with a radius of 51 km and 904 m in 2001 AD. The GIA model provides the von Mises equivalent stress as output:

$$q = \sqrt{\frac{3}{2} \sigma_{ij} \sigma_{ij}} \quad (3)$$

where σ_{ij} is an element of the stress tensor. Von Mises equivalent stresses are calculated at the center of the layers (3.75, 11.25, 20, 37.5, 70, 120, 185) and averaged (Fig. 2) over a horizontal area of 200 km radius and also averaged over time (from 20 ka BP up to 9 ka B.P. for the Weichselian ice cap; from 10 ka B.P. up to 2001 for the recent melting of the Vatnajökull ice cap). The stresses are interpolated for every kilometre in the upper mantle to produce Fig. 2. Using a faster melt rate between 1890 and 2003 (Árnadóttir et al. , 2009) than reported by Fleming et al. (2007) resulted in average stress values that differed by less than 7% in areas where the stress is high enough to influence the effective viscosity. The resulting difference in stress using both melt rate estimates is too small to significantly influence the outcomes of this microphy modelling study. The Von Mises stress is a measure of deviatoric stress and can be used directly in flow laws derived from uni-axial experiments (Ranalli, 1995). We assume that the equivalent stress can be used as the stress parameter in Eq. (2). The von Mises stresses is the equivalent stress multiplied by $\sqrt{3}$. The maximum equivalent stress value of 1 MPa at shallow depths for the Weichselian glaciation (Fig. 2) can be compared to estimates of an average stress in the lithosphere and upper mantle due to a simple model of glacial unloading in Scandinavia which are in the range of ~0.5 to at maximum 30

MPa (Barnhoorn et al., in press). The smaller ice cap of Iceland in comparison to Scandinavia causes the average stresses due to glacial loading to be lower for this study. A stress of 1 MPa is also the lower stress estimate for convective processes in the upper mantle (Ranalli, 1995). Pressure (P) is calculated as $P = 0.033 \text{ GPa/km}$.

A composite flow law (e.g. Ranalli, 1995) in which both competing mechanisms dislocation creep and diffusion creep contribute to the deformation is used to calculate the total viscosity where:

$$\dot{\epsilon}_{total} = \dot{\epsilon}_{diff} + \dot{\epsilon}_{disl} \quad (4)$$

and

$$\eta_{disl} = \sigma / 2\dot{\epsilon}_{disl} ; \quad \eta_{diff} = \sigma / 2\dot{\epsilon}_{diff} ; \quad \eta_{total} = \sigma / 2\dot{\epsilon}_{total} \quad (5)$$

Two melt contents have been modelled (0% and 4%) for a dry ($C_{OH} = 0 \text{ H}/10^6 \text{ Si}$) and wet upper mantle ($C_{OH} = 100 \text{ H}/10^6 \text{ Si}$). The lateral extent of the melting zone in the 4% melt scenario is controlled by the crossing of the geotherm with the solidus of the upper mantle of Hirschmann et al (2009). Melt-controlled rheology is in this scenario concentrated under the present-day ridge axis and extends $\sim 120 \text{ km}$ for $T_m = 1400 \text{ }^\circ\text{C}$ away from the ridge axis.

Outside of this melting zone, the upper mantle deforms by a melt-free rheology ($\varphi = 0$). The lithospheric thickness is defined as the layer in which the viscosity is high enough so that no measurable influence on the relaxation process is exerted. Analyses of the viscosity cut-off value for Scandinavia (Barnhoorn et al., in press) shows that viscous deformation starts to affect predicted sea-level changes by around one meter for an average viscosity in the lithosphere below 10^{25} Pas . Since relaxation times for the Icelandic ice caps are much smaller than the relaxation times for Scandinavia (hundreds of years compared to tens of thousands of years), we have selected a viscosity cut-off value of 10^{23} Pas to represent the maximum viscosity value at which viscous deformation contributes to glacial isostatic adjustment due to recent melting on Iceland. We have determined the lithospheric thickness for any distance

away from the ridge axis in two ways: 1) as the depth at which the average viscosity from the top surface of the Earth to that depth is less than 10^{23} Pas, 2) as the depth at which the viscosity falls below 10^{20} Pas. We have chosen a maximum viscosity value of 10^{20} Pas since Árnadóttir et al. (2009) state that in their GIA model the lithosphere behaves essentially elastic above 10^{20} Pas. The lithospheric thickness varies in both cases perpendicular to the ridge axis. Below the lithosphere, the upper mantle is deforming viscously and the average viscosity values reported here are the averages of the viscosity values below that lithospheric thickness. The radius of ~50 km for the Vatnajökull glacier present nowadays (Sigmundsson, 1991) indicates that roughly the first vertical 100 km of the upper mantle is affected by recent glaciation, whereas the radius of ~160 km present during the Weichselian glaciation (Sigmundsson, 1991) indicates that in that period the first ~300 km of the upper mantle is affected by the Weichselian glaciations. In addition, our stress distribution profiles calculated for both glaciation events show that at depths of 100 km for the recent glaciation event and at 300 km for the Weichselian glaciation event the upper mantle is still subjected to some loading induced stresses. At larger depths for both events the stresses decrease towards zero. We therefore have calculated average viscosities from depths below the lithospheric thickness to a depth of 100 km for recent glacial isostatic adjustments on Iceland and from depths below the lithospheric thickness to a depth of 300 km for the glacial isostatic adjustment during the Weichselian period. Maximum depths of the upper mantle affected by the glaciation events are approximations. Establishing the exact depth-sensitivity requires more detailed computations using for example Frechet kernels (Mitrovica and Peltier 1991). Horizontally averaged viscosity profiles and vertically averaged viscosity trends have been produced for both glaciation events. Single values representing the average viscosities and lithospheric thicknesses under both icecaps have been determined for comparison with glacial isostatic

adjustment studies on Iceland. Those studies usually assume that the upper mantle under Iceland only has one viscosity and lithospheric thickness without any lateral variations.

Results

The rheological modelling for the Iceland mid-ocean ridge shows that diffusion creep dominates the deformation in the upper mantle (Fig. 3). Only at shallow depths under the mid-ocean ridge a small region can occur where dislocation creep dominates the deformation. This is only the case for the Weichselian glaciation event. All deformation during the recent glaciation event is controlled by diffusion creep according to our model. As a result of the dominance of diffusion creep under Iceland most of the upper mantle experiences stress-independent viscosities and therefore the Weichselian and recent glaciation events produced almost identical viscosity fields within the upper mantle (Fig. 4). Significant variations in upper mantle viscosity occur during both glaciation events both with depth and with increasing distance from the ridge axis (Fig. 4). The radial variations in viscosity are characterised by a decrease in viscosity up to depths of ~70 km caused by the rapid increase in temperature with depth and the presence of a partially molten region to depths of ~70 km (Fig.2b). Below that the radially averaged viscosity (Fig. 5) increases from depths >70 km to 410 km caused by the increased importance of the pressure dependence of the rheology (Fig. 4 and 5), while temperatures are relatively constant at those depths (Fig. 1).

The microphysical modelling shows a strong, but narrow low-viscosity layer for the Weichselian glaciation at depths of ~30-70 km (Fig. 6) due to the influence of the melt content on viscosity and the increase in temperature close to reaching the adiabatic temperature gradient. The decrease in viscosity in this layer due to the presence of the melt is ~1-2 orders of magnitude in comparison with the viscosities in a melt-free upper mantle. The low viscosity zone for the recent glaciation starts even shallower (~15 km) due to closer

proximity of the Vatnajökull glacier to the mid-ocean ridge axis where higher temperatures prevail (Fig. 6). A wet upper mantle ($C_{OH} = 100 \text{ H}/10^6 \text{ Si}$) results in a reduction of the viscosity of around 1 order of magnitude in comparison with a dry upper mantle (Fig. 5B and 5D). The melting temperatures for a wet upper mantle solidus are lower than those for a dry upper mantle (Fig. 1) causing the partially-molten region, and hence melt-induced lowering of the viscosity, to extend to larger distances away from the mid-ocean ridge axis within a wet upper mantle (Fig. 1 and Fig. 5). Plume activity within the upper mantle under Iceland may have resulted in lower upper mantle viscosities than in a normal mid-ocean ridge scenario. Higher temperatures in the range of ΔT of 100-200 °C have been postulated for Iceland (e.g. Ito et al., 1996; 1999; MacLennan et al., 2001; Ruedas et al., 2004; Putirka, 2005; Schmeling and Marquart, 2008). We have simulated the effect of additional plume activity on Iceland by increasing the mantle temperatures at the bottom of time-dependent half-space cooling model (Turcotte and Schubert, 2002) with 100 and 200 °C to $T_m = 1500 \text{ °C}$ or 1600 °C (Fig. 7). The higher temperatures with the mantle due to the plume lower the viscosities by ~ 0.6 orders of magnitude per 100 °C excess temperatures (Fig. 6 and 8).

The vertical temperature gradients and resulting viscosity gradients underneath a mid-ocean ridge result in a large increase in lithospheric thickness (Fig. 5A and 5C) with an increasing distance from the ridge axis irrespective of the method used to determine the lithospheric thickness (the depth at which the average viscosity between the top and bottom of the elastic layer falls below 10^{23} Pas or the depth at which the viscosity is smaller than 10^{20} Pas). The temperature gradients due to cooling of the lithosphere away from the ridge axis cause a rapid increase in viscosity in cooled upper mantle material thereby increasing the lithospheric thickness. Melt content in the partially molten region only slightly lowers the lithospheric thickness (at maximum a couple of kilometres, Fig. 5A and 5C). The stress-

independent viscosities for Iceland due to the dominance of diffusion creep results in similar lithospheric thicknesses for the Weichselian and recent glaciation events (Fig. 5A and 5C), Fig. 5 shows that defining the lithosphere as the depth at which the average viscosity is lower than 10^{23} Pas produces thicknesses significantly larger than defining the lithosphere as the depth at which the viscosity is lower than 10^{20} Pas (~130-150 km at a distance of 200 km (20 Ma upper mantle from the mid-ocean ridge axis, Fig. 5) versus ~50 km). Close to the ridge axis the viscosity gradient is so high that both methods result in more similar lithospheric thicknesses (differences smaller than 50 km). Excess temperatures due to plume activity lower the viscosity estimates for the upper mantle under Iceland and thus also lower the lithospheric thickness. Lithospheric thicknesses 200 km away from the mid-ocean ridge axis are reduced by ~20 km per 100 °C excess temperatures using the lithospheric thickness definition of average viscosity below 10^{23} Pas and only a reduction of a few kilometres per 100 °C excess temperatures (Fig. 8) using the lithospheric thickness definition of a viscosity below 10^{20} Pas.

Vertically averaged upper mantle viscosity estimates below the elastic lithosphere in sections from the ridge axis to a distance of 200 km from the ridge axis are fairly constant (Fig. 5B and 5D) for both the Weichselian and recent glaciation events with the lowest average viscosities at the ridge axis. However, averaged viscosities for the recent glaciation event are considerably lower than the averaged viscosities for the Weichselian glaciation event (Fig. 5B and 5D). This is primarily caused by the fact that the upper mantle viscosities for the Weichselian glaciation are averaged from the bottom of the elastic layer to a depth of 300 km (maximum depth affected by the Weichselian glaciation), whereas for the recent glaciation event the viscosities are averaged between the bottom of the elastic layer to a depth of 100 km. Thus, Weichselian viscosity averages are dominated by the larger viscosity values of the deeper parts of the upper mantle with only a relatively minor influence of the shallow

low-viscosity zone, whereas recent viscosity averages are primarily dominated by the viscosities of the shallow low-viscosity zone (Fig. 6). For a dry upper mantle, average upper mantle viscosities are predicted to be between $\sim 6 \times 10^{18}$ Pas and 1×10^{19} Pas for the Weichselian glaciation event and $\sim 1 \times 10^{18}$ Pas and 8×10^{18} Pas for the recent glaciation event (Fig. 5). In the case of a wet upper mantle, average upper mantle viscosities range are predicted to be between 3×10^{18} Pas and 7×10^{18} Pas during the Weichselian glaciation event and 7×10^{17} Pas and 7×10^{18} Pas for the recent glaciation event (Fig. 5).

To compare the results of this microphysical modelling with estimates of constant viscosity and constant lithospheric thickness from glacial isostatic adjustment studies for Iceland we have produced a single upper mantle viscosity value and lithospheric thickness value for each of the two glaciation events (averaging out all lateral variations in viscosity and thickness). We have used the range in lateral extent for the Weichselian glaciation event underneath all of the land mass of Iceland (Sigmundsson, 1991) and the lateral extent of the Vatnajökull glacier for the recent glaciation event to determine the average viscosities and lithospheric thicknesses. Maximum viscosity values in a dry upper mantle under the recent Vatnajökull glacier are around 5×10^{18} Pas and would have been around 10^{19} Pas during the Weichselian glaciation. Plume activity and/or a wet upper mantle scenario reduce average viscosities to be around 10^{18} Pas or lower (Fig. 9). The average lithospheric thicknesses for both glaciations differ depending on which method is used to define the lithospheric thickness. For the Weichselian glaciation, the average lithospheric thickness in a dry upper mantle are either 100 km or ~ 30 km depending on the definition used and ~ 40 km or ~ 10 km for the recent glaciation event (Fig. 9). Additional plume activity or a wet upper mantle scenario reduce the lithospheric thickness estimates considerably.

Discussion

322 The microphysical modelling in this study predicts the lithospheric thickness and upper
 323 mantle viscosities under Iceland using a theoretical temperature distribution under mid-ocean
 324 ridges combined with the rheological behaviour of olivine. It results in estimates that are in
 325 line with estimates from glacial isostatic adjustment studies and seismological studies. All
 326 studies show smaller elastic thicknesses (<100 km) and relatively low viscosity values ($< 10^{20}$
 327 Pas) in comparison with studies of continental areas such as Fennoscandia. This is due to the
 328 relatively high temperature conditions under the newly formed oceanic lithosphere of Iceland.
 329 There is a significant spread in upper mantle viscosity estimates for Iceland between 10^{17} Pas
 330 and 10^{20} Pas and in elastic lithospheric thickness estimates between 10 and 80 km amongst
 331 the different studies (Fig. 10) over the past two decades (Sigmundsson, 1991; Sigmundsson
 332 and Einarsson, 1992; Thoma and Wolf, 2001; Kaban et al., 2002; Sjöberg et al., 2004; Kumar
 333 et al., 2005; Pagli et al., 2007; Biessy et al., 2008; Árnadóttir et al., 2009; Le Breton et al.,
 334 2010). The most recent glacial isostatic adjustment studies that provide estimates of both
 335 upper mantle viscosity and lithospheric thickness for Iceland (Pagli et al., 2007; Árnadóttir et
 336 al., 2009) are compared with estimates from our study. The best correspondence for the recent
 337 glaciation event of both the elastic thickness and average upper mantle viscosity estimates of
 338 this study is with the study of Árnadóttir et al. (2009). An average viscosity in the range of
 339 6×10^{18} Pas to $\sim 2 \times 10^{19}$ Pas and an elastic thickness of 40 km (Árnadóttir et al., 2009) is only
 340 approached by the results of this study for a dry upper mantle scenario without any additional
 341 plume activity (average viscosity $\sim 5 \times 10^{18}$ Pas, Fig. 9). All other scenarios produce too low
 342 average viscosity values for the recent glaciation event (Fig. 9). Using the depth at which the
 343 viscosity falls below 10^{20} Pas as the definition for the lithospheric thickness produces a
 344 thickness of ~ 10 km (Fig. 9), which is considerably below the thickness preferred by
 345 Árnadóttir et al. (2009). This suggests that using the definition of the depth at which the
 346 average viscosity is lower than 10^{23} Pas results in more realistic estimates of lithospheric

347 thicknesses in this microphysical study. Using the preferred dry upper mantle scenario with a
 348 lithospheric thickness definition of an average viscosity smaller than 10^{23} Pas results in an
 349 average viscosity of 10^{19} Pas and an lithospheric thickness of ~ 100 km for the Weichselian
 350 glaciation event (Fig. 9). Our viscosity estimates are in line with estimates of glacial isostatic
 351 adjustment studies for the Weichselian deglaciation (Sigmundsson 1991, Biessy et al 2008;
 352 Le Breton et al. 2010), although here significantly larger lithospheric thickness values (~ 100
 353 km) are predicted for the Weichselian glaciation event than the ~ 15 km lithospheric thickness
 354 predicted by Sigmundsson (1991). A correspondence of the upper mantle viscosities estimates
 355 of this study can also be achieved with the study for the recent glaciation event of Pagli et al.
 356 (2007). A mean upper mantle viscosity of $\sim 10^{18}$ Pas of Pagli et al. (2007) would imply that
 357 the upper mantle under Iceland is most likely wet (Fig. 9), as a dry upper mantle produces a
 358 higher average viscosity of $\sim 5 \times 10^{18}$ Pas. However, the lithospheric thickness estimates of 10-
 359 20 km of Pagli et al. (2007) do not correspond to our estimates of elastic thickness in a wet
 360 upper mantle of ~ 30 km. Upper mantle viscosity values in the range of 10^{18} Pas can also be
 361 achieved by the presence of a plume under Iceland affecting the viscosities of the mantle. This
 362 possibility can not be excluded in the comparison with Pagli et al. (2007), but a plume can not
 363 explain the viscosity estimates of Árnadóttir et al. (2009). Upper mantle viscosity estimates in
 364 the range of 10^{17} Pas (e.g. Sjöberg et al., 2004) or as high as 10^{20} Pas are not preferred by
 365 Árnadóttir et al (2009) since they do not fit with recent GPS uplift data for Iceland. Using our
 366 modeling approach, very low viscosities values around 10^{17} Pas can only be produced with
 367 either a very wet upper mantle ($C_{OH} \geq 1000$ H/ 10^6 Si) or with very high deep mantle
 368 temperatures due to additional plume activity under Iceland ($T_m > 1600$ °C). Upper mantle
 369 viscosity estimates around 10^{20} Pas or even higher can on the other hand only be achieved by
 370 having very large olivine grain sizes around 5-10 mm in a dry upper mantle, which is much
 371 larger than the average grain size present at mid-ocean ridges (e.g. Dijkstra et al., 2002). Since

those very low or very high viscosity estimates do not fit with the most recent uplift rate scenarios (Árnadóttir et al., 2009), a wet and/or hot upper mantle scenario or a very large grain size in combination with a dry upper mantle scenario are not likely to be present in the upper mantle under Iceland.

By comparing the glacial isostatic adjustments studies of Pagli et al. (2007) and Árnadóttir et al. (2009) with this study using a different approach, similar and relatively low average upper mantle viscosity estimates for the mid-ocean ridge under Iceland can be obtained. However, this study shows that lateral variations in upper mantle viscosity and lithospheric thickness are likely to occur under an active tectonic setting such as the Icelandic mid-ocean ridge. A large heterogeneity in temperature distribution within the upper mantle causes large lateral and radial variability in viscosity. So far, glacial isostatic adjustment studies have neglected any lateral variability in their geophysical models of the upper mantle (e.g. Sigmundsson, 1991; Sigmundsson and Einarsson, 1992; Sjöberg et al., 2004; Fleming et al., 2007; Árnadóttir et al. 2009). This study shows that glacial isostatic adjustment studies of Iceland, particularly concerning the Weichselian glaciation event, should in the future incorporate such lateral and radial variability in viscosity and lithospheric thickness.

The modelling of a mid-ocean ridge setting assumes a relatively thin crust of <10 km under Iceland. Different observations of the thickness of the crust under Iceland are reported with thickness varying between a thin crust scenario of 10-15 km and a thick crust scenario of 20-40 km (summarised by Björnsson, 2008). If, in the thick crust scenario, the temperature distribution of the thickened crust is the same as the temperature distribution would be in a time-dependent cooling lithosphere, then the mechanically defined elastic lithosphere values reported here would still be valid estimates. If, on the other hand, the thickened crust under Iceland is also significantly cooler, then the lithospheric thicknesses of 25-40 km obtained in

this study will be too small. The thin crust scenario, also favoured by Björnsson (2008) for Iceland, is in line with the mid-ocean ridge model used in this study.

In conclusion, based on the closest match of upper mantle viscosity and lithospheric thickness between Árnadóttir et al. (2009) and this study, upper mantle viscosity estimates around 5×10^{18} Pas of this study for the recent glaciation event are preferred, implying that a dry upper mantle is most likely present under Iceland. A dry upper mantle scenario is in contrast with the conclusion drawn from a similar rheological modelling study for Scandinavia and where a wet upper mantle was concluded to be most likely present (Barnhoorn et al., in press; Schotman et al., 2009). The different outcomes may point to lateral variations in water content within the upper mantle e.g. between continental lithosphere and oceanic lithosphere.

Conclusions

Microphysical modelling using the temperature distribution under mid-ocean ridges combined with olivine diffusion and dislocation creep flow laws with an olivine grain size of 2 mm and stress distributions for the upper mantle produced lithospheric thickness and upper mantle viscosity estimates for the upper mantle under Iceland during the Weichselian glaciation event and the recent glaciation event which nowadays forms the Vatnajökull glacier. Using the most recent estimates of Árnadóttir et al. (2009) as best estimates for upper mantle viscosity and lithospheric thickness, the results of this study that best match the estimates of Árnadóttir et al. (2009) (viscosity $\sim 5 \times 10^{18}$ Pas and thickness of ~ 40 km) suggest that the upper mantle under Iceland is most likely dry. Also, the presence of a plume under Iceland can not explain the recent viscosity values reported for Iceland. Glaciation during the Weichselian glaciation event should have produced viscosity values $\sim 10^{19}$ Pas and a lithospheric thickness of ~ 100 km for Iceland based on this microphysical modelling study. The Weichselian viscosity

estimate is in line with GIA studies (Sigmundsson 1991, Biessy et al 2008; Le Breton et al. 2010). However, this study predicts a significantly larger Weichselian lithospheric thickness due to the lateral variability of the lithospheric thickness in the modelling. Because the deviatoric stress level is mostly below 1 MPa, dislocation creep only dominates in a small area underneath the ridge axis. However, viscosity between the two Weichselian and recent glaciations still differs because of the depth-sensitivity which depends on the size of the ice caps. Large lateral variations in upper mantle viscosity and lithospheric thickness are present perpendicular to the ridge axis with a lithospheric thickness in excess of 100 km at 200 km from the ridge axes.

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Figure captions

Figure 1: A) Geotherms (black lines) for oceanic lithospheres with an age between 0 and 20 Ma (Turcotte and Schubert, 2002) using a mantle temperature of 1400 °C. Dry solidus (red solid line) and wet solidus at 100 ppm H₂O (red dotted line) taken from Hirschmann et al., 2009) and mean temperatures (blue symbols) for Iceland from the temperature dataset of Goes et al. (2000; personal communications) are plotted as well. B) Two-dimensional temperature distribution in the upper mantle under mid-ocean ridges between 0 and 200 km (equivalent to 0 and 20 Ma using a spreading rate of 1 cm/year) constructed using the geotherms of Fig. 1A. Temperature distribution represents a simplified two-dimensional cross-section of the upper mantle under Iceland. The lateral extent of the Vatnajökull glacier during the recent glaciation event and during the Weichselian glaciation event are indicated on the cross-section. C) Partially molten area (red area) in which the temperatures are above the dry solidus (dark red) and wet solidus (light red) temperatures for the mantle.

Figure 2: Averaged von Mises equivalent stress for the upper mantle under Iceland at seven different depths for the Weichselian glaciation (filled squares) and recent glaciation (open squares) determined using a three-dimensional finite element model for glacial isostatic adjustment for Iceland. Stresses between 0 and 410 km have been interpolated from the von Mises stress determined in the modelling at the seven different depths.

Figure 3: Dominant deformation mechanism map for the Weichselian glaciation event in a dry and upper mantle without excess temperatures due to plume activity. Red colours indicate dominance of diffusion creep; blue colour dominance of dislocation creep and brown colours indicate very high viscosities $> 10^{30}$ Pas). Lower stress values during the recent glaciation event caused the absence of any dislocation creep dominance underneath the ridge axis.

Figure 4: Viscosity distribution under Iceland for a dry and wet ($C_{OH} = 100 \text{ H}/10^6 \text{ Si}$) upper mantle without excess temperatures due to additional plume activity at melt contents of 0 and, 4% during the Weichselian glaciation event.

Figure 5: Elastic thickness (A and C) and mean upper mantle viscosity (B and D) for Iceland for a dry and wet ($C_{OH} = 100 \text{ H}/10^6 \text{ Si}$) upper mantle at melt contents of 0 and 4% during the Weichselian (solid lines) and recent glaciation events (broken lines). Elastic thickness at every distance from the ridge axis is determined either as the depth at which the average of the logarithm of the viscosity from the surface to that depth becomes smaller than 10^{23} Pas (black lines) or as the depth at which the logarithm of the viscosity becomes smaller than 10^{20} Pas (grey lines). Mean upper mantle viscosity at every distance from the ridge axis is the average of the logarithm of the viscosities from the depth of the elastic thickness at that

distance to a depth of 300 km for the Weichselian glaciation event and 100 km for the recent glaciation event.

Figure 6: Horizontally averaged upper mantle viscosity profiles of the upper mantle for the Weichselian glaciation event and the recent glaciation event for melt contents of 0 and 4 % in a dry upper mantle for a normal mid-ocean ridge scenario (A) and for excess temperatures of 100 °C and 200 °C (mantle temperature of 1500 °C (B) and 1600 °C (C)) due to additional plume activity (averaged for each depth accros the section of the upper mantle under the Weichselian and recent glaciation). The profiles show averages for each depth of all the viscosities present underneath the Weichselian and recent glaciated areas. D) Comparison of viscosity profiles for the different temperature regimes in the absence of melt.

Figure 7: Viscosity distribution under Iceland for a dry, melt-free upper mantle at excess temperatures of 100 °C and 200 °C (mantle temperatures of 1500 °C and 1600 °C) due to additional plume activity.

Figure 8: Elastic thickness (A and C) and mean upper mantle viscosity (B and D) for Iceland for a dry upper mantle during the Weichselian (A and B) and recent glaciation events (C and D) for a normal mid-ocean ridge scenario and excess temperatures of 100 °C and 200 °C (mantle temperatures of 1500 °C and 1600 °C) due to additional plume activity.

Figure 9: Mean lithospheric thickness (mean of all thicknesses under the glaciated areas) and mean upper mantle viscosity (mean of all viscosities under the glaciated areas during the Weichselian and recent glaciation events of Fig. 5 and 7) for various mantle temperatures at the base of the modelled upper mantle in a dry and wet ($C_{OH} = 100 \text{ H}/10^6 \text{ Si}$) upper mantle.

593

594 Figure 10: Compilation of lithospheric thickness and upper mantle viscosity estimates for

595 Iceland from glacial isostatic adjustment studies, seismology and the rheological modelling of

596 this study.

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