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How temperature-dependent elasticity alters host rock/magmatic reservoir models: A case study on the effects of ice-cap unloading on shallow volcanic systems

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ABSTRACT

In geodynamic numerical models of volcanic systems, the volcanic basement hosting the magmatic reservoir is often assumed to exhibit constant elastic parameters with a sharp transition from the host rocks to the magmatic reservoir. We assess this assumption by deriving an empirical relation between elastic parameters and temperature for Icelandic basalts by conducting a set of triaxial compression experiments between 200 °C and 1000 °C. Results show a significant decrease of Young's modulus from ∼38 GPa to less than 4.7 GPa at around 1000 °C. Based on these laboratory data, we develop a 2D axisymmetric finite-element model including temperature-dependent elastic properties of the volcanic basement.

As a case study, we use the Snæfellsjökull volcanic system, Western Iceland to evaluate pressure differences in the volcanic edifice and basement due to glacial unloading of the volcano. First, we calculate the temperature field throughout the model and assign elastic properties accordingly. Then we assess unloading-driven pressure differences in the magma chamber at various depths in models with and without temperature-dependent elastic parameters. With constant elastic parameters and a sharp transition between basement and magma chamber we obtain results comparable to other studies. However, pressure changes due to surface unloading become smaller when using more realistic temperature-dependent elastic properties. We ascribe this subdued effect to a transition zone around the magma chamber, which is still solid rock but with relatively low Young's modulus due to high temperatures. We discuss our findings in the light of volcanic processes in proximity to the magma chamber, such as roof collapse, dyke injection, or deep hydrothermal circulation. Our results aim at quantifying the effects of glacial unloading on magma chamber dynamics and volcanic activity.

1. Introduction

Decompression of magmatic reservoirs can be caused by crystallization (Blundy et al., 2006), un-roofing (Manconi et al., 2009; Pinel and Albino, 2013), passive degassing (Girona et al., 2014), or unloading of confining tectonic stress (Walter and Amelung, 2007). Similarly, removal of overburden may promote volcanic eruptions by reducing the lithostatic load acting on a magmatic reservoir. This effect can for example be caused by deglaciation (e.g., Pagli and Sigmundsson, 2008) and flank collapse (e.g., Manconi et al., 2009). A more direct response to load removal may occur in active or dormant volcanoes. It was previously suggested that a surface unloading of 40 bar (due to flank collapse) results in a pressure decrease of 5 to 6 bar within a magma chamber storage zone at depths of 18–22 km (Manconi et al., 2009). While some recent studies have investigated the effects of ice-cap retreat on shallow magmatic bodies (e.g., Albino et al., 2010; Manconi et al., 2009), to the best of our knowledge the effects on the upper mantle are still not investigated. Schmidt et al. (2013) suggested that unloading (due to ice-cap retreat) may also affect the upper mantle by inducing lithospheric relaxation and enhancing decompression-induced melting over timescales of hundreds to thousands of years. However, major uncertainties are still to be quantified. These are for instance the geometry of the magmatic reservoir and the lack of temperature-dependent measurements of the elastic parameters used to model such systems. As a result,

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magmatic systems are often modelled with the major assumption that the crust is isotropic and homogeneous with constant elastic properties.

In studies of time-dependent deformation of volcanic systems, temperature is typically considered an important parameter by employing a visco-elastic approach (e.g., Del Negro et al., 2009; Gregg et al., 2012; Parks et al., 2015). The rheology of the crust is modelled as a generalised Maxwell body with parallel spring-dashpot systems, whereas temperature affects the viscous response of the material (dashpot), but not the elastic (spring) part. This practice might not reflect the real elastic properties of the crust accurately. In particular, it ignores the temperature-dependence of elastic parameters (e.g., Anderson et al., 2013), especially when partial melts are considered (e.g., Kohlstedt and Zimmerman, 1996). Several studies have shown that bulk-rock elastic parameters vary significantly with temperature, especially above 600 °C (e.g., basalt: Violay et al., 2012; andesite: Smith et al., 2009; microgabbro: Violay et al., 2015; limestone: Bakker et al., 2015). Hence, neglecting the temperature-dependence of elastic properties, especially in volcanic and hydrothermal environments, may result in misleading conclusions. Gregg et al. (2012) did apply a temperature-dependency to the elastic part of the system to investigate the effects of magma over-/under-pressure, by using lowered Young's modulus at $T > 650$ °C.

The goal of our study is to compare models of a volcanic system using both temperature-dependent and temperature-independent elastic properties and hence to quantify the effect of temperature-dependency of the elastic properties. The innovative aspect of the present study is that we feed our numerical model with measured temperature-dependent elastic properties. As an application, we model pressure changes due to removal of a surface load. To provide a realistic case-study we consider a deglaciation scenario: the Snæfellsjökull volcanic system, Iceland, whose ice cap is thinning at a rate of 1.25 m/yr on average (Jóhannesson et al., 2003).

The manuscript is structured as follows. First, we describe the Snæfellsjökull volcanic system and describe how we sampled lithologies representative of Iceland. Next, we describe our experiments to characterise the pressure- and temperature-dependent elastic properties of the crust. The elastic properties are based on triaxial deformation experiments on basaltic lavas and hyaloclastite (i.e., hydrated tuff-like breccia) samples tested under elevated confining pressure, P (a proxy to depth), and temperature, T (depth/proximity to magma chamber), conditions appropriate for a shallow magmatic system. We then introduce the thermo-mechanical numerical model where we use the acquired laboratory data. The model quantifies the variation of stresses and pressure at crustal depths induced by ice-cap removal (i.e., we consider the thickness of the ice cap covering the Snæfellsjökull volcanic system). We finally discuss our results and draw the main conclusions.

2. Methods

The Snæfellsjökull central volcano, like most of the Icelandic stratovolcanoes, consists of alternating layers of Tertiary basement and hyaloclastites (Alfredsson et al., 2013; Kokfelt et al., 2009). Unfortunately, the basement geology is mostly only constrained by surface observations (Tibaldi et al., 2013) and only recent studies began to investigate the volcanic system with geophysical methods (Obermann et al., 2016). Based on Tibaldi et al. (2013), we assume the Tertiary basalts to best represent the basement of the Snæfellsjökull volcanic complex and assume that hyaloclastite layers are only present in the shallow part (i.e., the volcanic edifice). The deep parts of the Snæfellsjökull volcanic system (Fig. 1) are not accessible and are therefore represented by Tertiary lavas that form the basement (Tibaldi et al., 2013). The Tertiary basement samples without significant surface alteration used in this study

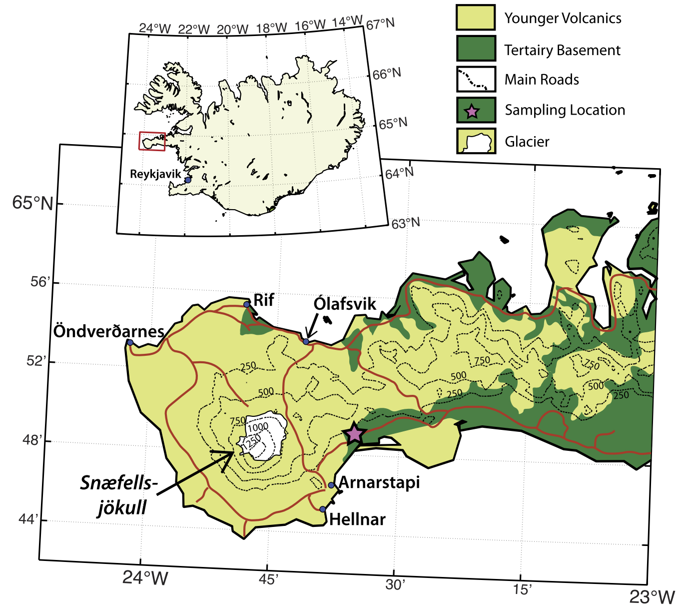

Fig. 1. Simplified geological map of the Snæfellsness peninsula (after Jóhannesson, 2009). For a coloured version of this figure we refer to the online version of this work.

were sampled from outcrops as close as possible to the volcanic edifice (Fig. 1). Samples comprise hydrothermally altered basalt with clinopyroxene (augite) and plagioclase phenocrysts in a fine-grained crystalline (glass-free) matrix with saponite and chlorite as alteration products. The material has a density of 2750 ± 50 kg m^{-3} and a connected porosity of 4.14 ± 0.02%, measured using a helium pycnometer (Micrometrics® Accupyc 1330). We measured the chemical composition using X-ray Fluorescence (XRF) techniques, which showed 4.344% loss on ignition (LOI) likely due to water released from hydrous minerals, which formed by hydrothermal alteration. For comparison, a basaltic lava flow from a recent eruption did not reveal measurable water content based on LOI (see supplementary material, Table S-2 for further details). Hyaloclastite samples used in this study consist of poorly consolidated hydrated basaltic glass spheroids with an average grain size of 0.5 mm. The samples had an initial density of 1510 ± 10 kg m^{-3} and a connected porosity of 40.01 ± 0.02%. No suitable outcrop of hyaloclastite was found in relative close proximity to the summit, nor is there comprehensive data available on the elastic properties of this rock. Therefore, samples were obtained from a roadside outcrop in the Hellisheiði volcanic field with similar chemical properties (oxides, see Table S-2). These samples are not compacted due to overburden, thus do not strictly represent deeper hyaloclastite layers (Jaya et al., 2010). To account for this caveat, we compacted the samples before experimental deformation by applying a hydrostatic confining pressure.

2.1. Rock deformation experiments

We drilled cylindrical samples (12 mm diameter, 30 mm long) from blocks of the Tertiary basalts (former lava flows) and hyaloclastite and cut them to plane-parallel end faces. Before experiments, we oven-dried the samples at 70 °C for a minimum of 24 h to ensure a dry starting material. Samples were jacketed and placed in a Paterson-type triaxial deformation apparatus. Samples were initially subjected to a hydrostatic stress (argon gas pressure) and subsequently heated to the desired temperature. Finally, axial deformation is imposed by driving up a piston, maintaining a constant strain rate, while the piston displacement and axial load is measured (see Bakker et al., 2015, for further details). Experi-