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Rheological Response to Tectonic and Volcanic Deformation in Iceland

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Abstract

Iceland is one of the few places in the world where a Mid-Oceanic Ridge (MOR) is exposed on land, and this gives good opportunity to study geodynamic processes. Spreading of Mid-Atlantic Ocean Ridge (MAR) segments in Iceland began ~60 million years ago. The MAR segments in Iceland have a divergent spreading rate between the Eurasian and North American plates of ~19 mm yr^{-1} and are divided into the Western (WVZ), Eastern (EVZ), and Northern Volcanic Zones (NVZ). These zones include 35 active volcanic systems and most of them are located on the plate boundaries. Often a volcanic system consists of a central volcano and an associated fissure swarm. Geothermal activities and Glacial Isostatic Adjustment (GIA) in Iceland occur in addition to the tectono-volcanic activities, adding to the complexity of the geodynamic investigation.

Crustal deformations due to tectonic and volcanic activities in Iceland have been studied with geodetic observations since 1938. This study uses geodetic Global Positioning System (GPS) data (1994–2015) collected in the WVZ, EVZ, and NVZ. These measurements suggest that the spreading velocities along profiles parallel to spreading directions are 6.7 ± 0.5 mm yr^{-1} (crossing Thingvellir graben) in the WVZ, 14.0 ± 2 mm yr^{-1} (between south of Vatnajökull glacier and Torfajökull volcanic system) in the EVZ, and 18.4 ± 1.5 mm yr^{-1} (crossing Fremri Námur volcanic system) in the NVZ. The widths of the deformation zones along those profiles are ~50 km in the WVZ, ~100 km in the EVZ, and ~56 km in the NVZ, where ~85–90% of the deformations are accumulated. At the center of Thingvellir rift graben in the WVZ, continuous subsidence of ~4 mm yr^{-1} is observed, whereas uplift is dominant in the NVZ and the EVZ. After GIA corrections, the western and eastern parts of the EVZ are dominated by uplifting and subsidence, respectively. In the NVZ, subsidence caused by plate stretching is mostly compensated by magmatic activities in the form of dyke intrusion. However, the center of the rift and the maximum subsidence geographically coincides in the WVZ and the NVZ, whereas in the EVZ, the maximum subsidence is offset ~8 km to the east of the spreading center. In the NVZ, the Askja volcano has a stretched magma chamber at a shallow depth (~3.5 km). GPS observations made between 2008 and 2013 at the Askja volcanic system suggests that absolute subsidence in the center of this volcanic system is 11.9 ± 0.1 mm yr^{-1} in International Terrestrial Reference Frame 2008. After GIA correction, this subsidence rate is ~30 mm yr^{-1} and the subsidence is caused by activities in the magma chamber. However, subsidence in Askja is decaying exponentially with time. On the other hand, in the isolated volcanic system of Surtsey, which is free of tectonic and GIA activities, GPS and leveling observations between 1992 and 2013 suggest that average subsidence rate is decaying: ~10 mm yr^{-1} between 1992 and 2000, ~8 mm yr^{-1} between 2000 and 2002, and ~3 mm yr^{-1} between 2002 and 2013. This subsidence is caused by the compaction of the volcanogenic material and lithostatic loading of the erupted material. However, today there is very little vertical deformation. This study uses temperature dependent rheological Finite Element (FE) modeling to analyze the crustal deformations of plate spreading and volcano-tectonic activities. Thermal properties in the models are taken from earlier thermal studies in Iceland. The models also account for dislocation, diffusion, and composite (the combined effect of dislocation and diffusion) in both wet and dry conditions. The 700°C isotherm is applied for long term brittle-ductile transition.

Rheological responses differ in horizontal and vertical directions. The thermal state has the greatest influence in deformation process with steady state velocity. Wet and dry rheological models give more or less similar results; however, dry rheological models provide slightly better results. In the rift zone of divergent rift environment in Iceland, the dominant deformation is governed by dislocation creep. The depth of the 700°C isotherm at the rift axis is 8, 13, and 6 km in the WVZ, EVZ, and NVZ, respectively. Different depths of the isotherm are governed by the configuration of volcanic systems and existence of geothermal activities

The rift zones in the WVZ and NVZ are fairly similar. In the WVZ, an overlap of two volcanic systems exists, but in the EVZ most recent activities have taken place away from the maximum subsidence of plate boundary. In the NVZ, all the spreading affects only one volcanic system (with little overlap of the neighboring systems). While in the EVZ, the geometry of the volcanic systems is very different, and five volcanic systems are arranged parallel to each other and no central volcano exists within any of these volcanic systems.

To explain the observed style of surface deformation in the EVZ, a maximum magmatic influx of ~11 mm yr^{-1} at 100-km depth is required to shift ~10–20 km west from the center of the horizontal deformations. On the other hand, the best fit model results in ~4 mm yr^{-1} and ~15 mm yr^{-1} subsidence, rates that are higher than observations due to magmatic and magmatic-tectonic activities at Askja, respectively. However, a uniform viscosity of 3×10^{18} Pa s for the asthenosphere and a 50-km thick lithospheric model results in 27.5 cm subsidence as the result of the load of eruptive materials in Surtsey.

Key words: Iceland, Tectono-volcanic deformation, Lithostatic loading, Geodynamic finite element model, Temperature- and stress-dependent rheology, Wet and dry rheology; Dislocation and diffusion creep