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# Rheological responses to plate boundary deformation at the Eastern Volcanic Zone in Iceland

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ABSTRACT

Located on the mid-Atlantic ridge, Iceland allows for direct measurement of crustal deformation. Global Positioning System (GPS) data from the Eastern Volcanic Zone (EVZ), Iceland, and crustal deformation of the rift near its southern end at 64°N show a spreading rate of $13.8 \pm 1.8$ mm $yr^{-1}$. About 90% of the deformation occurs in an 80 to 90-km wide zone. To understand how the rheology of the lithosphere influences rifting, we applied a thermo-mechanical stretching model that includes thermal states in Iceland using temperature- and stress-dependent wet and dry olivine rheology. We attempt to reproduce the thermal structure of a rift by defining 700 °C from 5- to 15-km depth at the rift axis that leads to variation in rheological structure, and to estimate the layer (from surface to a depth of 700 °C) where the elastic deformation of the lithosphere is the greatest. At a fixed spreading rate, the deformation field is controlled by the sub-surface thermal state. The vertical subsidence rate at the ridge axis increases almost linearly as the half-velocity increases. The best fitted model suggests a thermal gradient of ~54 °C $km^{-1}$ at depth below where 700 °C occurs at the ridge axis. The models have little sensitivity to the wet or dry olivine rheology.
Estimated viscosity is ~$1 \times 10^{19}$ Pa s at 20-km depth at the ridge axis and ~$1 \times 10^{18}$ Pa s up to 100-km depth in the model. The spreading rate influences the tangential (non-linearity) shape of the deformation field, and a change in spreading rate affects the deformation field the most. After spreading velocity, the model's second most sensitive parameter is the location of the 700 °C at the rift axis. The thermomechanical model confirms that the rheological responses at the central part of the rift zone in the EVZ, Iceland caused of plate spreading is nonlinear, comparable with surface deformation observed by GPS measurement.

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## 1. Introduction

The 60,000 km of Mid-oceanic ridges (MOR) and their associated systems is where most of the earth's crust is created (Toomey, 2012; Wright et al., 2012). Most MOR systems (about 98%) are beneath the ocean (Toomey, 2012), but some rise above sea level and the largest system above sea level is in Iceland (Sigmundsson, 2006). This exposed MOR, a small segment of the Mid-Atlantic Ridge (MAR) system, is the boundary between the Eurasian and North American plates (Fig. 1). Rifting in Iceland is cyclical. The divergent spreading rate and spatial distribution along the spreading direction vary largely depending on rifting cycle, as the deformation is controlled by tectonic and magmatic activities (Sigmundsson, 2006; Wright et al., 2012). A complete rifting cycle has three phases: inter-rifting, co-rifting, and post-rifting (Sigmundsson, 2006). An inter-rifting phase is dominated by steady spreading that is in good agreement with a global plate motion 1A (NUVEL-1A) prediction (Pedersen et al., 2009; DeMets et al., 2010). During a co-rifting phase, dyke injections and eruptions intrude the upper crust, releasing stresses and extensional strains that are accumulated during the inter-rifting phase (e.g., Pedersen et al., 2009). In Iceland, two examples of the co-rifting phase are the Krafla event 1974–1989 (Buck et al., 2006; Einarsson, 2008) and the Barðarbunga event 2014 (Sigmundsson et al., 2015).

Since the Global Positioning System (GPS) network was established in the 1980s, researchers have used both space geodetic techniques and modeling to study surface deformations in Iceland during inter-rifting phases (e.g., LaFemina et al., 2005; Árnadóttir et al., 2006, 2008, 2009; Geirsson et al., 2006, 2012; Pedersen et al., 2009; Scheiber-Enslin et al., 2011; Islam and Sturkell, 2015). These deformation fields have been interpreted using homogeneous elastic dislocation models with an elastic rheology and using formulas from Okada (1985) to calculate corresponding surface displacement (e.g., LaFemina et al., 2005; Árnadóttir et al., 2006, 2009; Scheiber-Enslin et al., 2011; Geirsson et al., 2012). Many studies of

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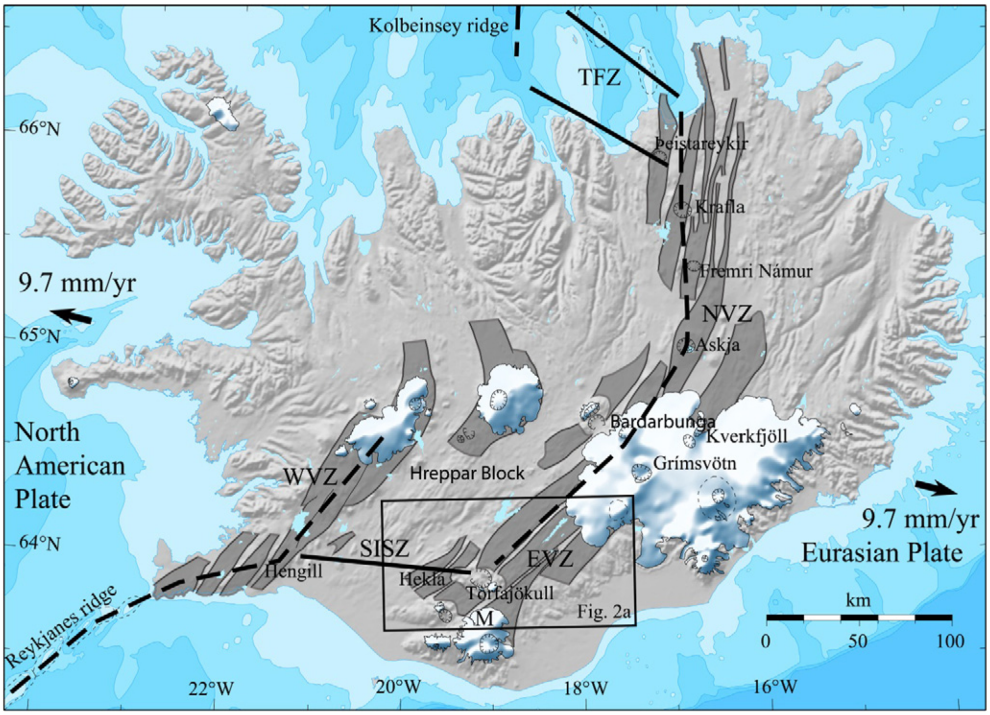


**Fig. 1.** Plate boundary in Iceland. Black dash lines show approximate central axis of plate boundaries. Black lines indicate two transform fault zones, i.e., the South Icelandic Seismic Zone (SISZ) in the south and the Tjörnes Fracture Zone (TEZ) in the north. The three individual plate boundary segments are indicated: Western Volcanic Zone (WVZ), Eastern Volcanic Zone (EVZ), and Northern Volcanic Zone (NVZ) (Einarsson and Sæmundsson, 1987). Dark ash colour indicates fissure swarms. White indicates major glaciers, including Mýrdalsjökull (M). The black rectangle shows the location of the studied profile and GPS sites in Fig. 2a.

Iceland's MAR system have used models based on purely elastic and/or uniform viscoelastic layer/s beneath an elastic layer to investigate different tectonic phenomena: inter-rifting effects (e.g., LaFemina et al., 2005; Árnadóttir et al., 2006, 2009; Pedersen et al., 2009; Scheiber-Enslin et al., 2011; Geirsson et al., 2012); rifting cycle effects (e.g., LaFemina et al., 2005); post-rifting relaxation (e.g., Foulger et al., 1992; Heki et al., 1993; Jónsson et al., 1997); volcanic activity (e.g., de Zeeuw-van Dalfsen et al., 2013); volcano-tectonic activity (e.g., de Zeeuw-van Dalfsen et al., 2012); and Glacial Isostatic Adjustment (GIA) (e.g., Sigmundsson and Einarsson, 1992; Pagli et al., 2007; Árnadóttir et al., 2009; Auriac et al., 2013). For example, Pedersen et al. (2009) have applied Finite Element Method (FEM) for stretching models using elastic-viscoelastic rheology to investigate an inter-rifting event in the Northern Volcanic Zone (NVZ), Iceland. Irrespective of horizontal deformation and stretching plate depth, their study found a drastic geometrical relationship between elastic and viscoelastic layers that corresponded to vertical surface deformation. Using a similar approach as Pedersen et al. (2009), de Zeeuw-van Dalfsen et al. (2012) were unable to reproduce the observed pattern of horizontal surface deformation in an investigation of the Askja volcano in the NVZ. These studies use models that apply either elastic or uniform Newtonian/Maxwell rheology and suggest a more realistic rheological model is needed to interpret surface deformation. In addition, the models in these studies omit the fact that thermal and rheological structures next to the ridge axis in Iceland are heterogeneous (Pedersen et al., 2009). Clearly, rheological modeling of surface deformation in Iceland needs more work. Moreover, because earth's rheology may be non-Newtonian/non-linear, studies should consider strain rate, a function of subsurface temperature and differential stress (Turcotte and Schubert, 2002). To address all these shortcomings, we compare the results of FEM models and geodetic GPS measurements to better understand the kinematics and the effects of lithospheric heterogeneous thermal structures in the Eastern Volcanic Zone (EVZ), Iceland.

### *1.1. Geological and tectonic settings*

Iceland has several volcanic systems that clearly mark the boundary between the North American and the Eurasian plates (Fig. 1). The MAR segments in Iceland have been divided into the NVZ, EVZ, and WVZ. Surface deformation of the ridge segments is characterized by divergent plate spreading and central volcanoes and their associated fissure swarms. According to the NUVEL–1A model, full plate spreading rate across Iceland is ~20 mm $yr^{-1}$, a value that is a function of latitude (DeMets et al., 2010).

The EVZ has been active for ~2–3 Myr during the last eastward jump of spreading (Sæmundsson, 1974), and is propagating at ~35–50 mm $yr^{-1}$ towards the southwest (Einarsson, 1991). The EVZ surface formations consists of Postglacial lava (<11 kyr), Upper Pleistocene (<0.8 Myr), and Plio-pleistocene (0.8–3.3 Myr) lava successions, and Holocene sediment (Jóhannesson and Sæmundsson, 1998). The Torfajökull volcanic system is located at the intersection of the EVZ and the South Iceland Seismic Zone (SISZ), a transform fault system (Fig. 1). The estimated spreading rate in the EVZ varies between 19.8 and 11 mm $yr^{-1}$ from the north (crossing central Vatnajökull) to the south (south of Torfajökull) depending on its interaction with the WVZ (LaFemina et al., 2005). The deformation zone includes several volcanic systems with their fissure swarms, Hekla, Torfajökull, Katla (including Eldgjá fissure), Grímsvötn (including Lakagígar fissure), and Bárðarbunga (including the Vatnaöldur, Veiðivötn and Tröllagígar eruptive fissures). The fissure swarms have a N45°E trend (Fig. 1). The most significant recent rifting episode occurred during the Laki eruption (1783–1784), that produced about 16 $km^3$ of erupted material and formed the Lakagígar eruptive fissure (Jónsson et al., 1997). The most recent rifting event occurred in the Bárðarbunga volcanic system in 2014–2015, involving a 45 km long dyke intrusion lasting two weeks, leading to an eruption from its distal end. The eruption lasted six months. The total dyke volume was about 0.5 $km^3$ and the erupted volume was about 1.5 $km^3$

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