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Iceland structure and volcanism: An alternative vision based on the model of volcanic systems

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ABSTRACT

Iceland's crustal structure and volcanic history is critical in our understanding of the accretion and emergence of the island. The current tectonic model is based on a thick-crust model, which is challenged by a largely overlooked thin-crust model. These two models are based on different datasets and present several opposite features regarding the location of thinner and thicker crust. In this paper, in order to compare both models, we confront each of them with a new analysis of the spatial repartition of central and shield volcanoes across Iceland, and with an application of the hydrostatic model of volcanic systems from Cañón-Tapia (2009). As a result of this analysis the thin-crust model appears to be the best fitted to the Icelandic features. Using the hydrostatic model of volcanic systems from Cañón-Tapia (2009) we are able to present an alternative model explaining the complex volcanic history in Iceland as well as the crustal accretion mechanism. Instead of a complex plate boundary with several ridge-jumps and microplates, we consider Iceland as a diffuse plate boundary where volcanism occurs in clusters whose location and evolution are directly related to the crustal thickness.

1. Introduction

Considered as an emerged part of the North-Atlantic Ridge (Bodvarsson and Walker, 1963), Iceland's geochemical and geological characteristics make it one of the most studied islands around the world. Iceland's complex geochemistry, coupled with geological and seismic evidence, has been interpreted as the result of a ridge-centered hot-spot (e.g. Bjarnason and Schmeling, 2009; Bjarnason et al., 2002; Morgan, 1971; Ruedas et al., 2007; Sæmundsson, 1978; Schilling, 1973; Vinnik et al., 2005). The existence of a deep mantle plume, however, has been questioned (Foulger, 2002; O'Hara, 1975), leading to alternative interpretations based on the combination of an heterogeneous mantle and regular plate tectonic processes (e.g. Foulger, 2006; Foulger and Anderson, 2005; Foulger et al., 2005a, 2005b; Lundin and Doré, 2005). At present, most of the debate around the origin of Iceland is centered on different interpretations of geochemical and seismic information, whereas other geophysical and geological data usually receive less attention.

To understand the origin of Iceland, a critical source of information concerns its crustal structure. As discussed by Foulger et al. (2005b), a hot and thin crust would imply that the volume of any melting anomaly is small or even insignificant whereas a thick and cold crustal model would require a large melting anomaly. For this reason, numerous studies have been conducted to determine Icelandic crustal structure using different techniques over the years (Allen et al., 2002; Angenheister et al., 1979; Bjarnason et al., 1993; Darbyshire et al., 1998, 2000a, 2000b; Du and Foulger, 1999, 2001; Flóvenz and Gunnarsson, 1991; Foulger, 2002; Foulger et al., 2003; Kaban et al., 2002; Kumar et al, 2007; Menke et al., 1996, 1998; Staples et al., 1997). As a result, it has been established that the crust under Iceland has oceanic affinity. Nevertheless, its structure has proven to be extremely difficult to delineate, especially regarding the Moho, and still remains a subject of debate. In fact, the results from seismic data do not show a clear discontinuity marking a significant velocity increase between the mantle and the crust under Iceland (as stated on the original definition provided by Mohorovicic in 1910), but the structure that has been interpreted as the Moho is in fact an enigmatic, discontinuous seismic reflector, separating two complex layers, both of which contain small Low Velocity Zones that are not easy to explain (e.g. Björnsson et al., 2005; Foulger et al., 2003).

Regardless of its detailed structure, Iceland's crust must be intimately linked with volcanism. Icelandic volcanic systems are commonly described as constituted of one central volcano, or stratovolcano, and an associated fissure swarm, often highly elongated, along which several monogenetic edifices are built (Jakobsson et al., 1978). The elongation of the volcanic systems, and therefore the orientation of the fissure swarms, has often been taken into consideration in the definition of the tectonic structure of Iceland (e.g. Jakobsson et al., 1978; Sigmundsson, 2006). Until now, the orientation of the volcanic systems has been assumed to unequivocally mark the orientation of the underlying rifting. However, the distribution of the volcanic edifices themselves, and particularly the central volcanoes, has been mostly overlooked. In this paper, we use an entirely different approach that is based on a

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study of the distribution of central volcanoes in Iceland, and explore its relationship with crustal structure. Volcanic distribution is combined with GPS observations and other sources of information that allow us to obtain unbiased insights concerning the location of the plate boundaries in the region. This information is then compared with competing models of crustal structure within the framework of an alternative global model of volcanic systems (Cañón-Tapia, 2009; Cañón-Tapia and Walker, 2004).

2. Crustal structure

A thin-crust model was developed and widely accepted during the 1980's and early 1990's (Angenheister et al., 1979; Beblo and Björnsson, 1980; Flóvenz and Gunnarsson, 1991; Flóvenz and Sæmundsson, 1993; Gebrande et al., 1980; Mayer et al., 1985; Pálmason, 1986; Sæmundsson, 1978). It relied on measurements of electrical resistivity in the crust and mantle, correlated with various seismic data, heat-flow measurements, petrological information, crustal elasticity and theoretical modeling. This model was challenged by reinterpretations of seismic profiles and new seismic data, leading to the creation of a thick crust model (e.g. Allen et al., 2002; Bjarnason et al., 1993; Foulger et al., 2003; Menke et al., 1996) which quickly became very popular and was accepted by most geoscientists. The thick crust model was eventually supported with data obtained from new seismic networks, new techniques and combination between seismic studies and data obtained by a few other geophysical methods (gravimetry for example, Darbyshire et al., 2000b; Kaban et al, 2002). Despite its popularity, however, the debate concerning Iceland's crust remains open especially because of the discordance between the thick-crust model and a variety of data obtained by other methods, as will be shown next. One of the most recent and thorough discussions of both models was provided by Björnsson et al. (2005). Those authors reevaluated old and new MT data and reappraised many published results of seismic and heat flow analyses, comparing those sources of information with petrogenetic studies and with viscosity and rigidity studies of the crust. Based on such a thorough analysis, they interpreted the presence of a continuous low-velocity and high conductivity layer under Iceland at a depth of 10–25 km as an area containing 5–10% melt with a temperature ~1100 °C. Such an interpretation is in complete agreement with the isotherms predicted by the kinematic accretion and thermal model from Pálmason (1986) and other petrogenetic analyses, as for example the work of Schiellrup (1995) who estimated that primitive-tholeiitic magma erupted from Blafjall shield volcano in the NVZ came from a magma reservoir at a depth of ~13 km, corresponding to the depth of the high-conductivity layer in the area.

Other aspects having contributed to the reappraisal of the thin-crust model are precisely related to the inferred existence of the good conductor layer. The high-conductivity layer seems to be separating a complex lower crust created mostly by intrusions, underplating and anatexis from a high-density abnormal updoming asthenosphere (layer 4) containing pockets of melt at various depths. The melt pockets give rise to discontinuous seismic reflectors interpreted as the Moho in the thick-crust model. Based on viscosity studies, Björnsson et al. (2005) interpreted the layer located immediately beneath the high-conductivity layer as an updoming of ultramafic asthenosphere containing 1–5% melt according to laboratory measurements (e.g. Björnsson, 1985; Schmeling, 1985).

Interestingly enough, the thick-crust model also suggests the presence of low velocity zones (LVZ) in the upper and lower crust (e.g. Allen et al., 2002; Foulger et al., 2003). The difference with the thin-crust mode, however, is that these LVZ do not appear continuous across Iceland but are only located under some active areas, being mostly located under the neovolcanic zones, at depths similar to those of the good conductor described in the thin-crust model. In the context of the thick-crust model Allen et al. (2002) interpreted the discontinuous LVZ as "thermal halo" around the plumbing system of active volcanoes, linking the magma source in the uppermost mantle to the volcanoes on the surface. Although this interpretation is very reasonable, the discontinuity of the halo is not supported by the MT data obtained by Björnsson et al (2005), and in particular with their long period data (100 s – 24 h, and permanent MT stations that were measuring for several years), that confirms the existence of a crustal high-conductivity layer at depths of 10-25 km and probably of a second one at depths of 100 km.

In summary, although the thick-crust model has become increasingly popular especially among workers examining various sources of evidence gathered through seismic methods, the thin-crust model seems to have the ability to explain a wider range of observations. For this reason, it is entirely justified to search alternative approaches that can be used as a guide to discriminate between the two competing models of crustal structure.

2.1. Thick-crust model

The thick-crust model relies on the assumption that the discontinuity separating a thick cold crust from the mantle is represented by a seismic reflector located between 20 and 40 km depth. Within this constraint, the topography of the Moho and the exact location of the thickest and thinnest crust under Iceland still remain under discussion and vary slightly from one study to another (c.f., Fig. 1A–E). Interpretations depend on the assumptions made and the inversion techniques chosen by each working group (e.g. Björnsson et al., 2005; Darbyshire et al., 2000b; Foulger et al., 2003; Kaban et al., 2002; Kumar et al., 2007). Nevertheless, despite several local differences (see Fig. 1), all the thick-crust models present the same general pattern, with the thickest crust located in three places: around the junction of the Central Iceland Volcanic Zone (CIVZ), most of the Northern Volcanic Zone (NVZ) and the Eastern Volcanic Zone (EVZ). In contrast, the relatively thinnest zones of the crust are located under the Reykjanes Peninsula, the South Iceland Seismic Zone (SISZ), and the north end of the NVZ.

In general terms, the models from Darbyshire et al. (2000b), Kaban et al. (2002) and Allen et al. (2002) (Fig. 1B, D and E, respectively), are very similar among them. Similarities between the first two are not unexpected, because those models were obtained with similar databases and methodologies. The third of those models, however, was obtained with a completely different seismic methodology. The main feature of those models (i.e., thicker crust towards the center of Iceland) is also captured by the model of Foulger et al. (2003) (Fig. 1C), and the lack of agreement in the NVZ and SW Iceland could be related to lack of station coverage. In any case, all four of these crustal models can be considered to have the same fundamental features, and therefore we can focus attention in just one of them as representative of the set. In particular, we selected the model from Allen et al. (2002), although the results presented below equally apply to all other three models in this set. The only other model of thick crust shown in Fig. 1 is that of Kumar et al. (2007) (Fig. 1A). Although this model also captures the most basic essence of the other thick-crust models, it has some interesting features not displayed elsewhere, and therefore this model deserves independent attention.

2.2. Thin-crust model

Thin-crust models assume the existence of a thin hot crust (20-25 km) whose maximum thickness can be defined by a low-resistivity layer observed under almost all of Iceland (Björnsson et al., 2005). In contrast with the thick-crust models, the crust as defined by the thin-crust model appears thinner under the active zones (<15 km under NVZ and WVZ), and thicker under the oldest parts of Iceland (25 km under the NW Peninsula and Snaeffelsnes, 20 km under the northern part of EVZ, Fig. 1F).

In detail, the thinnest crust is found along two narrow bands that do not intersect. The southwest band extends from the Reykjanes