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Sebastian Garcia

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RIDGE JUMP PROCESS IN ICELAND

Sebastian GARCIA
Freie Universität Berlin – Department of Geologie, sgarcia@zedat.fu-berlin.de

Abstract

Eastward ridge jumps bring the volcanic zones of Iceland back to the centre of the hotspot in response to the absolute westward drift of the Mid-Atlantic Ridge. Mantellic pulses triggers these ridge jumps. One of them is occurring in Southern Iceland, whereas the exact conditions of the last ridge jump in Northern Iceland remain controversial. The diachronous evolution of these two parts of Iceland may be related to the asymmetric plume-ridge interaction when comparing Northern and Southern Iceland.

Introduction

Iceland is an emerged ridge that results from the interaction between the Mid-Atlantic Ridge (MAR) and the Icelandic hotspot. The apex of hot mantle upwelling is localized beneath the Vatnajökull ice cap (Fig.1) [Tryggvason et al., 1983]. Presently, accretion in Iceland occurs with a spreading rate of ~18 km/Myr [DeMets et al., 1990; DeMets et al., 1994]. It is localised along a curved ridge zone centred above the hotspot which includes two branches, the North and East Volcanic Zones (NVZ and EVZ, respectively). The Tjörnes Fracture Zone and the South Iceland Seismic Zone are transform fault zones that accommodate the eastward shift of the NVZ and of the EVZ relative to the Kolbeinsey Ridge and to the Reykjanes Ridge, respectively (Fig.1). In Southern Iceland, a third volcanic zone, the West Volcanic Zone (WVZ), accommodates part of the plate divergence. It corresponds to the inland continuation of the Reykjanes Ridge (Fig.1).

The North American-Eurasian plate boundary, marked by the MAR, migrates westward relative to the Icelandic hotspot [Burke et al., 1973]. Assuming a symmetrical accretion, the rate of the westward ridge migration varies from 3.7 km/Myr [Müller et al., 1993] to 11.5 km/Myr [Gripp and Gordon, 2002] along the N106°E divergence trend [De Mets et al., 1990; DeMets et al., 1994]. Because the westward ridge migration furthers off the active ridges from the hotspot, eastward ridge jumps are expected to bring the volcanic zones of Iceland back to the centre of the hotspot. Although the precise mechanism of ridge jump is still strongly discussed [e.g., Jurine et al., 2005; Kendall et al., 2005; Mittelstaedt and Ito, 2005], all models agree on the creation of a zone of weakness in the plate overriding the hotspot that triggers and localises the ridge jump.

A ridge jump implies the extinction of the formerly active ridge and the initiation of a new one. It has been documented on mid-oceanic ridges [e.g., d'Acremont et al., 2010], but generally remains difficult to analyze because the evidences for plume-ridge interaction are underwater. Iceland, as an emerged part of the MAR, offers the opportunity to study precisely such ridge jumps. Ward [1971] and Saemundsson [1974] first interpreted, in an eastward ridge jump context, the WVZ and its hypothetical extinct northern continuation as a paleo-ridge, and the EVZ and NVZ as the new ridges (Fig.1). This implies that a ridge jump is presently occurring in Southern Iceland, with the development of the EVZ at the expense of the WVZ [e.g., Aronson and Saemundsson, 1975; Perlt et al., 2008]. On the other hand, the exact timing of the last ridge jump in Northern Iceland, as the locus of the extinct paleoridge, remains controversial [e.g., Garcia, 2003; Saemundsson, 1974].

Ridge jump in Northern Iceland

In Northern Iceland, limits of the lava flows of the NVZ are easily recognisable as they unconformably overlie lava flows of the paleo-ridge (Fig.1). Lava flows of the NVZ dip 4-5°to the west on the eastern side of the NVZ and a few degrees to the east on the western side of the NVZ and then define a synform-like structure [Walker, 1964; Young et al., 1985]. This dip toward the ridge axis is a typical feature of the Icelandic volcanic systems [e.g., Palmason, 1980]. The ages of the lava increase away from the central part of the NVZ and reach 6-6.5 Myr in the vicinity of the eastern and the western unconformities [Jancin et al., 1985; McDougall et al., 1976a; McDougall and Wensink, 1966; Musset et al., 1980], the latest unconformity being named the Flateyjarskagi one.

A proposed location of the paleo-ridge axis, the Hunafloi-Skagi paleo-ridge, is similarly based on the description of a synform-like structure (Fig.1) [Saemundsson, 1974]. This paleo-ridge would cease to accrete around 6-7 Ma [Everts et al., 1972]. All along its eastern flank, lava flows coming from the paleo-ridge are presumed to dip westward with increasing ages. It is the case along the eastern coast of Iceland where 12-14 Myr old lava flows [Bagdasaryan et al., 1976; McDougall et al., 1976b; Moorbath et al., 1968; Musset et al., 1980] dip 6-10°to the west. However, on the eastern side of the NVZ, paleo-

ridge lava flows define a down-bending zone with westward dips as great as 15-18° [Walker, 1964]. This westerly increase in dip of the old lava pile may be due to excess loading from the capping NVZ lava pile. Considering the same deflection process, paleo-ridge lava flows close to the western side of the NVZ steeply dip eastward (20-25°E). Thus, they define a broad antiform between the Hunafloi-Skagi paleo-ridge axis and the western limit of the NVZ. This antiform structure, the Eyjafjördur antiform (Fig.1), strikes approximately NE-SW through the Flateyjarskagi and Tröllaskagi Peninsulas [Saemundsson et al., 1980; Young et al., 1985]. On both sides of the unconformities, the paleo-ridge lava flows are 9-10 Myr old [Bagdasaryan et al., 1976; Jancin et al., 1985; McDougall et al., 1976b; Moorbath et al., 1968; Musset et al., 1980].

On the other hand, 7.5±0.5 Myr old dykes have been dated west of the Flateyjarskagi unconformity [Jancin et al., 1985]. As these dykes are attributed to the NVZ, their present sites imply retreat of the extent of the NVZ lava flows, probably due to glacial erosion. In addition, it implies that the exhumed, underlying paleo-ridge lava flows have been intruded at the earliest stage of the ridge jump by dykes injected by the NVZ. Garcia et al. [2003] also dated some dykes along a profile trending parallel to the plate divergence direction in Northern Iceland. They proposed a model for the ridge jump history in which the NVZ initiated at 8-8.5 Ma intruding 9-9.5 Myr old lava flows. They also localised the paleo-ridge approximately 60 km to the east of the Hunafloi-Skagi synform. This Skagafjordur paleo-ridge (Fig.1) has been active until 3 Ma [Garcia et al., 2003]. In their model, the Hunafloi-Skagi synform simply result from the down-bending of Tertiary lavas under the weight of excess Plio-Pleistocene lavas emitted from the central part of Iceland (i.e., from the equivalent to the present Langjökull and Hofsjökull volcanic systems). The process that leads to the down-bending of paleo-ridge lava flows under the weight of the NVZ lavas would explain this down-bending of the Tertiary lavas [Garcia et al., 2008]. This would also explain the partial disappearing of the synform-like structure supposed to localise the Skagafjordur paleo-ridge.

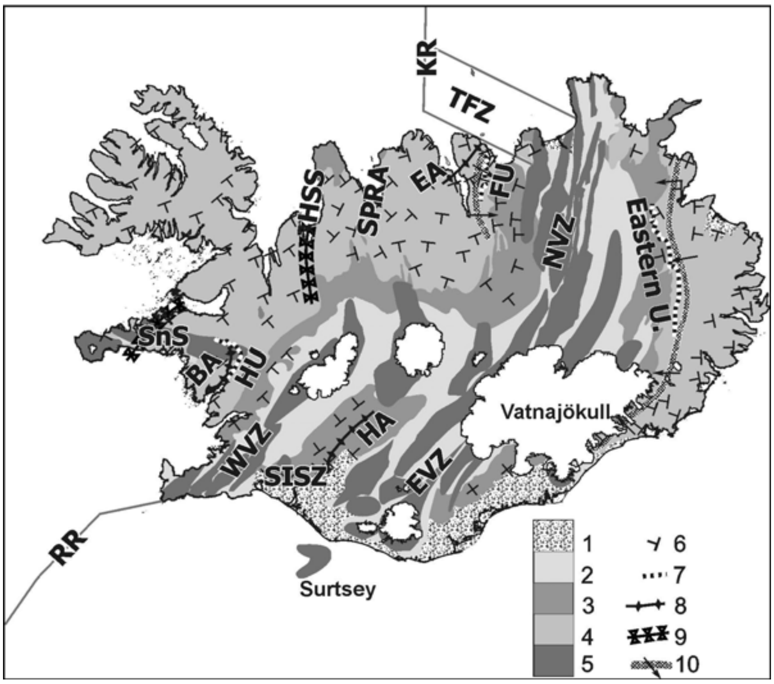

Figure 1: Structural map of Iceland: main active structures or resulting from rift jump process.
1: Holocene sediments; 2: Upper Pleistocene-Holocene lava flows (<0.8 Ma); 3: Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 4: Tertiary lava flows (>3.3 Ma); 5: Active volcanic system; 6: Dip of lava flows; 7: Angular unconformity; 8: Axis of antiform-like structure; 9: Axis of synform-likestructure; 10: Flexure zone with sense of lava flows dip. BA: Borganes Antiform; EA: Eyjafjördur Antiform; EVZ: Eastern Volcanic Zone; FU: Flateyjarskagi Unconformity; HA: Hreppar Antiform; HSS: Húnaflói-Skagi Synform; HU: Hredavatn Unconformity; KR: Kolbeinsey Ridge; NVZ: Northern Volcanic Zone; RR: Reykjanes Ridge; SISZ: South Iceland Seismic Zone; SnS: Snaefellsnes; SPRA: Skagafjördur Paleo-Rift Axis; TFZ: Tjörnes Fracture Zone; U: Unconformity; WVZ: Western Volcanic Zone. Modified from Johannesson and Saemundsson [1998] and Kristjansson et al. [1992]

Ridge jump in Southern Iceland

Two ridge jumps are usually considered in Southern Iceland. A major difference to Northern Iceland

is that the last ridge jump still occurs there. This explains the simultaneous existence of two active ridges in Southern Iceland (i.e., the WVZ and the EVZ). The EVZ, which initiated following the last ridge jump, is presently propagating southward. While developing, the new rift propagates through older, chemically and mineralogically stratified crust, giving rise to alkaline volcanism at the leading tip, followed by FeTi basalts and later by tholeiitic rocks [Steinthorsson et al., 1985]. This temporal spectrum of composition is presently observed in the spatial distribution from tholeiitic basalts to Fe-Ti basalts up to alkali basalts when going southward from the EVZ to the island of Surtsey (Fig.1) [Sigmarsson et al., 1992]. At the same time, recent GPS data show a northward decrease of the divergence rate localised along the WVZ, concomitant with a northward increase of the divergence rate localised along the EVZ [Perlt et al., 2008]. This result fits with the southward propagation of the EVZ and the progressive transfer of the accretion process along this last volcanic zone at the expense of the WVZ.

The initiation of the EVZ dates from 2-3 Ma [Aronson and Saemundsson, 1975]. However, no unconformity underlying the contact between the lava flows erupted by the EVZ and those coming from the WVZ have been recognised in the field. Solely the Hreppar antiform (Fig.1) allow to distinguish lava flows dipping in direction of the WVZ from lava flows dipping in direction of the EVZ [Aronson and Saemundsson, 1975]. Moreover, the WVZ is active since ~7 Ma [Bagdasaryan et al., 1976; McDougall et al., 1977; Moorbath et al., 1968; Smith, 1967]. To the west, lava flows from the WVZ are separated along the unconformity of Hredavatn from lava flows as old as 9.4±0.7 Ma [Aronson and Saemundsson, 1975; Moorbath et al., 1968]. These latest flows have been erupted along a paleo-ridge whose axis is localised along the NE-SW trending Snaefellsnes synform. This paleo-ridge has been active until 6-7 Ma [Moorbath et al., 1968]. As in Northern Iceland, lava flows erupted by the Snaefellsnes paleo-ridge and close to the western side of the WVZ have been tilted eastward and thus define a broad antiform structure, the Borganes antiform (Fig.1).

Triggering mechanisms of ridge jump in the Icelandic context: a discussion

Assuming hotspots overlie sources of anomalously hot asthenosphere, there are several mechanisms that can promote ridge jumps including lithospheric tension induced by buoyant and convecting asthenosphere [Mittelstaedt and Ito, 2005], mechanical and thermal thinning of the lithosphere due to hot flowing asthenosphere [Jurine et al., 2005], and thermal weakening of the lithosphere due to the penetration of magma [Kendall et al., 2005]. Mittelstaedt et al. [2008] investigated the effect of the latter, in the specific Icelandic context. They demonstrate that, beyond a certain value of hotspot flux, the ridge can migrate away from the hotspot -or escape from it -, only if the migration rate of the ridge is equal or higher to the half-spreading rate. The exact timing of the ridge jump is then controlled by these two rates. If the velocity of migration is inferior to the halfspreading rate, then the ridge remains constantly above the hotspot. On the other hand, the described timing of ridge jumps in Iceland implies that escape of the ridge alternates with ridge being locked above the hotspot (the present-day situation in Northern Iceland since at least 7 Myr). A very convincing explanation for the observed alternation between these end-member situations can be a temporal variation in the hotspot flux. Temporal variations of temperature of the plume would be the source for these variations in the magmatic flux [e.g., Jones et al., 2002]. The related, enhanced melting events propagate along the MAR and have been imaged through the V-shaped ridges observed along the Kolbeinsey and Reykjanes Ridges [e.g., Appelgate, 1997; Smallwood et al., 1995]

In the model proposed first by Saemundsson [1974], the NVZ initiates at 6-6.5 Ma, through the 2.5-4 Myr older eastern flank of a paleo-ridge; the latter, the Hunafloi-Skagi paleo-ridge, stopped its activity simultaneously with the NVZ initiation. In their model, Garcia et al. [2003] suggest that the NVZ initiates at 8-8.5 Ma, intruding the 0.5-1.5 Myr older eastern flank of the Skagafjordur paleo-ridge; the two ridges being active simultaneously for 5-5.5 Myr. In Southern Iceland, following the model proposed first by Aronson and Saemundsson [1975], the actual ridge jump occurs since 2-3 Myr; whereas the previous ridge jump started at 7 Ma by intruding the 1.5-3 Myr older eastern flank of the Snaefellsnes paleo-ridge that may have been active for a maximum of 1 Myr more. Modelling of Mittelstaedt et al. [2008] tells us that a ridge jump in Iceland needs from 1 to 4 Myr to be completely achieved and that the intruded seafloor can not be older than 1.5 Myr. These boundary conditions fit with the available data for the rift jump process in Southern Iceland, but do not permit us to discriminate between the two available models for Northern Iceland. The melting anomalies that are behind the observed V-shaped ridges started to propagate from the Icelandic hotspot around 2.5, 7 and 9 Myr ago [Jones et al., 2002]. The times of these mantellic pulses, supposed to be the triggering factor of the ridge jumps, are compatible with both models of ridge jump in Northern Iceland as with the two described ridge jumps in Southern Iceland.

When considering the timing of the different ridge jumps that occurred in Iceland, a clear diachronism appears between the respective evolutions of Northern and Southern Iceland. In addition,

northward and southward profiles, from the Icelandic hotspot to the Kolbeinsey and the Reykjanes Ridges respectively, show that the topography, the bathymetry, and the crustal thickness are asymmetric [Hooft et al., 2006]. This is also the case when comparing the halo of mixing with an enriched source [Blichert-Toft et al., 2005; Graham, 2002; Mertz et al., 1991; Poreda et al., 1986; Schilling, 1999]; this interaction being more extended along the Reykjanes Ridge than along the Kolbeinsey Ridge. All these data suggest an asymmetric plume-ridge interaction. One can then hypothesise that the diachronous evolution of Northern Iceland relative to Southern Iceland is somehow related to this asymmetric plume-ridge interaction.

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