Oblique Rifting on Reykjanes Peninsula, SW Iceland

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Abstract

Reykjanes Peninsula offers the only on-shore outcrop of an currently active, oblique spreading zone of the Mid-Atlantic Ridge and thus, it is an excellent natural laboratory to investigate the structural geometries and the evolution of oblique rift zones. The Reykjanes Peninsula is characterised by distinct regions of (1) seismic activity along the current spreading axis and (2) discrete en-échelon fracture zones being volcanically very active. Whereas periods of high seismicity and dormant volcanism are alternating with periods of strong volcanism and low seismicity. In fact, understanding of the interaction of volcanism and seismicity is very important for hazard assessment of earthquakes and volcanic eruptions for this area. Moreover, studies may be helpful for drawing analogies to other oblique rift zones.

Key words: Oblique Rifting, Iceland, Reykjanes Peninsula, monocline, fault evolution

1. Introduction

Iceland’s tectonics are significantly influenced by the Icelandic hot spot leading to a complex tectonic framework (e.g. Einarsson, 1991; Hreinsdóttir and Einarsson, 2001; Sigmundsson, 2006). At present, the mantle plume lies under the ice cap of Vatnajökull (Wolfe et al., 1997) forcing the plate boundary to split up into transform and rift zones where some of them are oblique (Hreinsdóttir and Einarsson, 2001).

6-7 Ma ago the Reykjanes Peninsula became active as an oblique rift due to a ridge jump (Sæmundsson, 1979). It exhibits highly oblique rifting differing from all other volcanic zones which are orthogonal rift zones (Sigmundsson, 2006). Here, the displacement direction of normal faults is approximately 30° oblique to ridge trend striking 076° (e.g. Hreinsdóttir and Einarsson, 2001; Clifton and Schlische, 2003).

The Peninsula is marked by four distinct fissure swarms whereas fissures within the zone of active volcanism strike approximately 30° to 40° to the plate boundary and non-eruptive fissures and normal faults at the margin seem to be bended into the general strike of the deformation zone (Clifton and Schlische, 2003). Typical features of the fractured surface are nearly vertical normal faults either with monoclines on their hanging wall sides or relay ramps connecting en-échelon fractures (Grant and Kattenhorn, 2004). Faults are discussed to be less steep at the subsurface, nucleating at depth and propagating upwards (Grant and Kattenhorn, 2004). Crustal deformation appears to be localised at the four fissure systems. However, seismicity is only measured along the current spreading axis (Hreinsdóttir and Einarsson, 2001). GPS measurements suggest left-lateral transform motion of the seismic zone and subsidence towards the seismic zone (Hreinsdóttir and Einarsson, 2001).

This work focuses on some new studies about fault evolution and spatial distribution of fractures on the Reykjanes Peninsula to better understand the processes of oblique rifting.
2. Tectonical Overview

Iceland is located on the North Atlantic plate boundary dividing the North American Plate and the Eurasian Plate. It is the largest portion of a mid-ocean system extending above sea level coming along with strong volcanism (Sigmundsson, 2006). The geodynamic of Iceland is consequently controlled by the E-W divergent Mid-Atlantic Ridge spreading system.

Fig. 1. Map of general geometry of rift segments in Iceland (modified after Clifton and Schlische (2003)). Iceland is dominated by two main rift branches: (1) the NVZ and EVZ and (2) the WVZ. To - Torfajökull, He - Hengill, ⋆ - present position of hot spot center. Arrows indicate spreading direction. Box marks the Reykjanes Peninsula (RP), more details see Figure 2.

Lithology is mainly built up by basalts (92%), 4% basaltic andesites, 1% andesites and 3% dacite-rhyolites (Sigmundsson, 2006). The main neovolcanic zones are (see Figure 1a):
- Northern volcanic Zone (NVZ), approx. 6–7 Ma
- Western volcanic Zone (WVZ), approx. 6–7 Ma
- Eastern volcanic Zone (EVZ), approx. 2–3 Ma, with
  - South Iceland Flank Zone (SIFZ) and
  - Eastern volcanic Rift Zone (EVRZ)
- Reykjanes Peninsula oblique rift zone (RP), approx. 6–7 Ma

The Tjörnes Fracture Zone (TFZ) connects the NVZ with the off-shore Kolbeinsey Ridge by partly strike-slip and extensional faulting (e.g. Young et al., 1985; Gudmundsson, 1993; Fjader et al., 1994). The EVZ is generally marked by high volcanic and seismic activity. The Torfajökull Central Volcano divides EVZ into two regions due to structural and petrological changes: the EVRZ in the North and the SIFZ in the South (Sigmundsson, 2006). In the South Iceland Seismic Zone (SISZ) rift structures disappear. A zone of left-lateral faulting and rotation connects Hengill with Torfajökull Central Volcano (Sigmundsson et al., 1995).

On the Reykjanes Peninsula, in SW-Iceland, the Reykjanes Ridge comes on-shore and becomes progressively more bended (Figure 2) (Khodayar and Einarsson, 2002; Clifton and Schlische, 2003). The displacement direction of normal faults is approximately 30° oblique to ridge trend. Four spatial distinct fissure swarms are arranged along the rift axis: Reykjanes, Krisuvik, Brennisteinsfjöll and Hengill Fissure Swarm. They consists of (1) eruptive fissure within the zone of active volcanism and (2) non-eruptive fissures or normal faults at the margin (Clifton and Schlische, 2003).

3. Geological features

Typically, monoclinal folds on the downthrown blocks are observed. These are single-limbed folds flanking the fracture traces and have curved hinge zones (Figure 3).

In general, normal faults show a common geometry controlled by tectonic loads, e.g. sediments: As the hanging wall block slips on the fault, load on the foot wall block is reduced and the upthrown part reacts elastically so that a convex-like flexure forms (Figure 4a). Mostly, the hanging wall block is then characterised by a rollover fold tilting down into the fault or by an antithetic fault set (Twiss and Moores, 1992).
Fig. 3. Fracture zone in Vogar fissure swarm (see also Figure 1b): monoclinal fold is breached by a fault.

In contrast to that, e.g. on Reykjanes Peninsula, there are normal fault geometries which show monoclines accommodating throw between the footwall and the hanging wall blocks through a simple flexure which are about 10 to 20 m wide (Grant and Kattenhorn, 2004). Monoclines are then cut by faults along their upper hinge line (Grant and Kattenhorn, 2004) (Figure 4b or 3 respectively).

Fig. 4. Two major fault geometries observed at the surface: a) convex-like, flexural folding of top of footwall block and rollover fold on downthrown block as a result of elastic relaxation due to isostatic release and geometric problems (gap between footwall and hanging wall block), b) monoclinal fold due to bending induced by magma emplacement, fold is breached through by a fault along its upper hinge line.

Major fissure swarms, each with their own magma supply (Clifton and Schlische, 2003), are Reykjanes, Krísuvik, Brennisteinsfjöll and Hengill, comprising clusters of shear fractures (normal faults), extension fractures (gapping fractures with no shear displacement) and hybrid fractures (shear and extension component) (Clifton and Schlische, 2003).

Figure 5 shows an aerial photograph of the fissure swarm at Vogar. Among others, the fissure *Echelon Gjá* has been analysed by Grant and Kattenhorn (2004). Studied faults and joints are left-stepping and en-échelon. Where throw is accommodated, segments are separated by relay ramps (Figure 6). To link the single segments, structures have to cut through the ramps (Crider, 2001). Here, typically one finds *breached relay ramps* (Crider, 2001). However, monoclines are absent along en-échelon fracture zones. Other fracture zones in Vogar Fissure Swarm, fractures come along with monoclines and consist of overlapping, parallel segments (Grant and Kattenhorn, 2004).

Fig. 5. Vogar Fissure Swarm (modified after (Grant and Kattenhorn, 2004)): Upper picture shows an aerial photograph of the Vogar Fissure Swarm and a map of location, white box is investigation area of fissure *Echelon Gjá*; Lower picture illustrates detailed faults and fractures of Vogar fissure swarm, box shows details of *Echelon Gjá*.

4. Crustal Deformation

4.1. *Strike of faults*

Each volcanic system on Reykjanes Peninsula is related to a high-temperature geothermal area (Hreinsdóttir and Einarsson, 2001). The volcanic...
activity has been suggested to be episodic whereas a cycle lasts circa 1000 years (Sigurgeirsson, 1992). The last period of volcanism was in 1240 A.D. (Jóhannesson and Einarsson, 1998). Volcanically quiet periods seem to be seismically very active (Hreinsdóttir and Einarsson, 2001). The earthquake distribution suggests that the seismicity follows a narrow band, trending 76° along the peninsula, rather than the fissure swarms (Hreinsdóttir and Einarsson, 2001). This zone marks the current plate boundary (Klein et al., 1977). GPS measurements from 1993 to 1998 (Hreinsdóttir and Einarsson, 2001) indicate that parallel to the zone left-lateral shear strain is accumulated (Figure 7). Referring to the fissure swarms the predominant trend (NE) is perpendicular to the direction of maximum horizontal stress $E_{h_{\text{max}}}$ (Clifton and Schlische, 2003) which is

$$E_{h_{\text{max}}} = 90^\circ - \frac{1}{2} \tan^{-1}(\cot \alpha)$$

where $\alpha$ is the acute angle describing obliquity. For Reykjanes Peninsula $\alpha$ is 028°, or $E_{h_{\text{max}}}$ is 060° clockwise from the rift trend. The Reykjanes Fissure Swarm shows an average trend of $E_{h_{\text{max}}}$ of 055° in good agreement with the model after Clifton and Schlische (2003) (see Equation 1) and NE-trending normal faults open perpendicular to $E_{h_{\text{max}}}$.

4.2. Evolution of faults

Western most faults show a significant component of dip-slip (Clifton and Schlische, 2003) confirming that the vertical faults on Reykjanes Peninsula have both opening and vertical displacements. Grant and Kattenhorn (2004) focus on the evolution of vertical faults in regions of orthogonal and oblique spreading and use field studies and numerical modelling. On the Reykjanes Peninsula they mapped en-échelon fracture segments oriented oblique to the general trend of the fracture zone. They also take monoclinal folds along the faults into account and propose that faults propagate from below since it is unlikely that the monoclines form after the vertical faults have already cut the surface. It is stated that the monoclines accomodate throw between the footwall and the hanging wall block through bending of the Earth’s surface. Monoclines are then typically
breaching along their upper hinge line. So, furthermore there is no reason why monoclines should develop when faults would start as tension fractures at the surface and propagate downward as suggested by Gudmundsson (1992).

Numerical modelling by Grant and Kattenhorn (2004) comprises 3D, linear-elastic fracture mechanics to examine faults with (Figure 8b) or without vertical tension fracture (Figure 8a) and of varying dip (60° and 75°), depth (0 to 750 m) and heights to the upper fault tip (Figure 8) to determine displacement and near-fault stress. Results suggest that the monoclinal folds develop giving that initial faults do not start to slip at the surface rather than subsurface (Figure 9). Faults with the upper tip at 750 m depth produce wide, low monoclines independent of fracture height. Faults with their upper tips at 250 and 500 m (Figure 9e–h) form narrow monoclines.

Analysis of the stress field of the given geometry (see Figure 10) indicates that region of high tensile stresses occurs above the upper tips of the faults. The surface stress field seems unaffected where fault tip is at 500 m. Tips in depth of 250 m cause an area of increased tension at the surface. The strongest field of tension is produced by tips at 250 m with a 200 m high vertical fracture attached.

5. Summary

It is likely that faults or fractures wandering from below to the surface are strongly influencing the crust above. So, bending of the Earth’s surface can be triggered by faulting from underneath until stress field exceeds cohesiveness and the monocline is breaching. According to field observation of Grant and Kattenhorn (2004), faults either come along with monoclinal bending of the Earth’s surface or relay ramps linking fault segments. The latter case is probably induced by oblique slip motion prior to the development of a vertical fracture along the dipping faults tip line (Grant and Kattenhorn, 2004). Grant and Kattenhorn (2004) provide three models how fault evolution in SW-Iceland could be explained (see Figure 11):

- Orthogonal Rifting: Dip-slip faulting where less steep faults propagate upward while a vertical tension fracture forms along the upper tip line and produces a monocline at the surface which is breached by the fracture reaching the surface.
- Oblique-slip faulting where right-lateral oblique motion causes left-stepping en-échelon fractures breaching the monocline and are then linking together.
- Oblique-slip faulting with no monocline: Pre-existing joints in the basalt link en-échelon fractures and the hanging wall block can slip apart without forming a monocline, e.g., the fracture Echelon Gjá of the Vógur Fissure Swarm belonging to the Reykjanes Fissure Swarm.

Hreinsdóttir and Einarsson (2001) find that overall tectonical trends follow NUVEL-1A plate motion model from De Mets et al. (1994) (see Figure 12). Combining the direction of rifting of fissure swarms and the direction of left-lateral transform motion results in the NUVEL-1A plate motion direction or spreading direction.

6. Outlook

Characteristical for the Reykjanes Peninsula, periods of high seismicity and dormant volcanism are alternating with periods of strong volcanism and low seismicity. Understanding the interplay of volcanism and seismicity is very important for hazard assessment of earthquakes and volcanic eruptions for this area. It may estimate the magnitudes of earthquakes and the duration of eruptions.

Moreover, investigations of fracture growth and spatial distribution of faults in oblique rift zones helps to derive fundamental knowledge which could be applied to other oblique spreading zones like the Gulf of Aden or the Afar Depression.

References

Clifton, A. E., Schlische, R. W., 2003. Fracture populations on the Reykjanes Peninsula, Iceland: Comparison with experimental clay models of


