Tectonophysics 674 (2016) 101–113

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

The stress pattern of Iceland

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ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form 29 January 2016
Accepted 2 February 2016
Available online 12 February 2016

Keywords:
Iceland
Stress field
Stress pattern
Borehole image logs

ABSTRACT

Iceland is located on the Mid-Atlantic Ridge which is the plate boundary between the Eurasian and the North American plates. It is one of the few places on earth where an active spreading centre is located onshore but the stress pattern has not been extensively investigated so far. In this paper we present a comprehensive compilation of the orientation of maximum horizontal stress (S_{Hmax}). In particular we interpret borehole breakouts and drilling induced fractures from borehole image logs in 57 geothermal wells onshore Iceland. The borehole results are combined with other stress indicators including earthquake focal mechanism solutions, geological information and overcoring measurements resulting in a dataset with 495 data records for the S_{Hmax} orientation. The reliability of each indicator is assessed according to the quality criteria of the World Stress Map project.

The majority of S_{Hmax} orientation data records in Iceland is derived from earthquake focal mechanism solutions (35%) and geological fault slip inversions (26%). 20% of the data are borehole related stress indicators. In addition minor shares of S_{Hmax} orientations are compiled, amongst others, from focal mechanism inversions and the alignment of fissure eruptions. The results show that the S_{Hmax} orientations derived from different depths and stress indicators are consistent with each other.

The resulting pattern of the present-day stress in Iceland has four distinct subsets of S_{Hmax} orientations. The S_{Hmax} orientation is parallel to the rift axes in the vicinity of the active spreading regions. It changes from NE–SW in the South to approximately N–S in central Iceland and NNW–SSE in the North. In the Westfjords which is located far away from the ridge the regional S_{Hmax} rotates and is parallel to the plate motion.

1. Introduction

The regional stress pattern along divergent plate boundaries has not been studied extensively yet due to the inaccessibility of submerged Mid Oceanic Ridges. Few and scattered earthquake focal mechanism solutions are the only sources of stress orientation in these areas in the World Stress Map (WSM) database (Heidbach et al., 2008; Heidbach et al., 2010). These indicators generally show a ridge parallel maximum horizontal stress (S_{Hmax}) orientation (Zoback et al., 1989; Zoback, 1992). In intraplate regions the orientation of S_{Hmax} is often parallel to the absolute plate motion in a first order approximation and therefore generally normal to the ridges and subduction zones (e.g. Richardson, 1992; Müller et al., 1992; Grünthal and Stromeyer, 1992; Zoback, 1992; Zoback et al., 1989). A systematic rotation of S_{Hmax} from ridge parallel to ridge normal has been observed close to ridges in the Indian Ocean (Wiens and Stein, 1984) and at Mid Oceanic Ridges in general (Sykes, 1967; Sykes and Sbar, 1974).

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Iceland is one of the few places on the Earth with an onshore divergent plate boundary (e.g. Ward, 1971; Sæmundsson, 1979; Einarsson, 1991; Einarsson, 2008; Bird, 2003). It is in a unique geological and tectonic setting, where an oceanic ridge (the Mid-Atlantic Ridge) traverses a (purported) mantle plume (e.g. Lawver and Müller, 1994; Wolfe et al., 1997; Allen et al., 2002). The rift zones in and around Iceland are dominated by various volcanic systems of different extents and activities (Thordarson and Larsen, 2007; Jóhannesson and Sæmundsson, 1998). Induced by the hotspot the plumbing of the volcanic systems is extended compared to a usual divergent plate boundary (Allen et al., 2002). As the plate boundary crosses the hotspot, it breaks up into a complex series of segments. Purely divergent segments are the Northern Volcanic Zone (NVZ) in North Iceland, and the sub-parallel Western and Eastern Volcanic Zones (WVZ, EVZ) in South Iceland which are generally assumed to be the expression of a ridge jump (Sæmundsson, 1979; Einarsson, 1991; Einarsson, 2008). In the South, the South Iceland Seismic Zone (SISZ) is the connecting segment between the Reykjanes peninsula and the Eastern Volcanic Zone (Sæmundsson, 1974; Sæmundsson, 1979; Einarsson, 1991; Stefánsson et al., 2008). In the North the Tjörnes Fracture Zone (TFZ) connects the NVZ to the southern

http://dx.doi.org/10.1016/j.tecto.2016.02.008

end of the submarine Kolbeinsey Ridge (Sæmundsson, 1974; Sæmundsson, 1979; Einarsson, 1991; Stefánsson et al., 2008). The WVZ and NVZ are joined by a transverse E–W zone across central Iceland. Outside of the immediate plate boundary, volcanism occurs in the South Iceland Volcanic Zone, the Snæfellsnes Volcanic Zone and the Öræfajökull Volcanic Zone (e.g. Jakobsson, 1979; Sæmundsson, 1978; Sæmundsson, 1986).

This volcano-tectonic setting has received a particular attention in the first compilation of the present-day crustal stress by Hast (1969). Since then, several researchers investigated the state of stress in different parts of Iceland. An extensive campaign of in-situ stress measurements from shallow overcorings was carried out by Haimson and Rummel (1982) conducted hydro-fracturing experiments in six onshore boreholes. Furthermore, extensive field campaigns to collect geological fault slip data provide information on the current and palaeo-stress field in Iceland as well as its temporal evolution (Gudmundsson et al., 1996; Bergerat and Angelier, 1998; Garcia and Dhont, 2005; Angelier et al., 2008; Plateaux et al., 2012). In total, the compilation of stress data records in the World Stress Map (WSM) database 2008 resulted in 38 data records of the contemporary S_{Hmax} orientation and the stress regime (9 focal mechanism solutions, 5 hydro-fracturing orientations, and 24 overcoring measurements, (Heidbach et al., 2008; Heidbach et al., 2010)). However, this small data set is not sufficient to reveal the presumably high variability of the stress field pattern of Iceland. This is especially important since Iceland's peculiar location causes extensive interactions between tectonic and volcanic

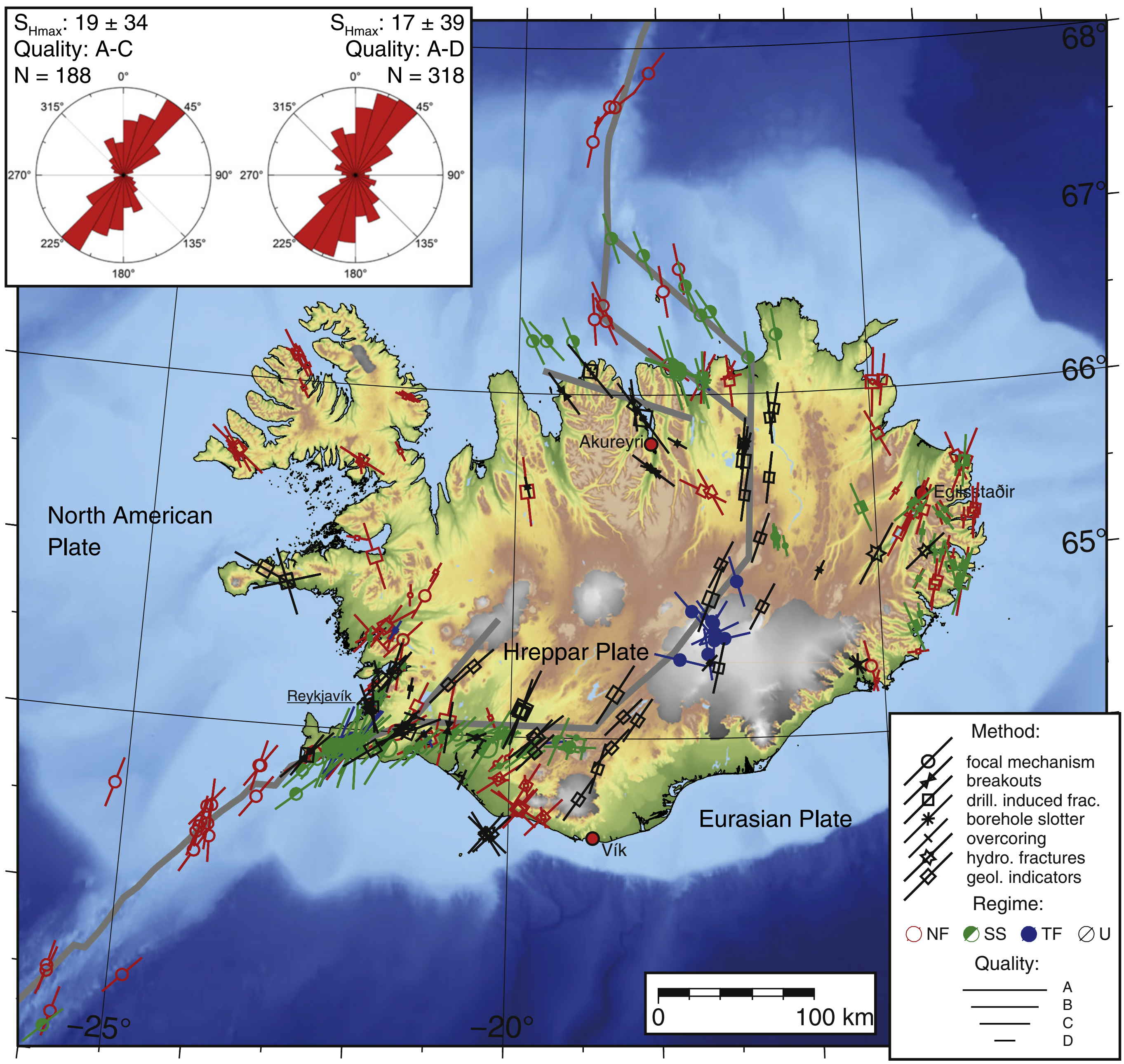

Fig. 1. The first comprehensive stress map of Iceland with 318 data records with A–D quality according to the World Stress Map quality criteria (Sperner et al., 2003; Heidbach et al., 2010). Lines represent the orientation of maximum horizontal stress S_{Hmax} with the length proportional to quality. The symbols in the middle of the lines display the method used for stress determination. The colour coding is according to the stress regime with red indicating normal faulting, green indicating strike slip faulting, blue indicating thrust/reverse faulting, and black for unknown regimes. The plate boundaries according to Bird (2003) and Einarsson (2008) are indicated in grey. Two rose diagrams display the unweighted frequency distribution of the A–C and A–D quality data respectively. Mean S_{Hmax} orientations and their standard deviations are calculated with the circular statistics of bi-polar data (Mardia, 1972).