Reviewed research article

Mapping of Holocene surface ruptures in the South Iceland Seismic Zone

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Abstract — *The South Iceland Seismic Zone is a transform zone marking the southern boundary of the Hreppar microplate. It is the source area of some of the most destructive earthquakes in Iceland's history. The surface formations of the zone are ground moraines, alluvial plains and Postglacial lava flows, and show widespread evidence of Holocene faulting. The fractured area is 15 km wide and 70 km long. A project to map by GPS-instruments all recognizable Holocene fault structures in this zone is described here. A large majority of fractures strike NNE to NE and form left-stepping, en echelon arrays with a northerly trend. They are associated with right-lateral faulting at depth. Right-stepping arrays also exist, apparently associated with faulting on conjugate faults with ENE strike, but they are an order of magnitude less frequent and mostly of a secondary nature. Other fault trends also occur, but are rare. Push-up structures are prominent in association with the en echelon arrays, sometimes reaching heights of several meters. Fractures active during a few of the large, historical earthquakes in this region have been identified and traced, e.g. the 1630, 1784, 1896, and 1912 events. The fractures are found within narrow, N-S trending zones crossing the seismic zone. Thus the large-scale, left- lateral transform motion across the plate boundary is accommodated by right-lateral slip on a series of transverse faults arranged side by side within the zone and by slight rotation of the blocks between them, a process sometimes called "bookshelf tectonism". Fractures formed during the earthquakes of June 17 and 21 (M_w=6.5) in 2000 and May 29 in 2008 (M_w=6.3) follow this pattern and confirm this general model of faulting along the transform zone. The size of push-up structures gives a clear indication of relative sizes of the earthquakes. The push-ups formed in 1630 and 1912 are an order of magnitude larger than the ones formed in the 2000 and 2008 earthquakes.*

INTRODUCTION

The mid-Atlantic plate boundary separating the Eurasia and North-America plates crosses Iceland from the SW at the tip of the Reykjanes Peninsula to the NE where it joins the Kolbeinsey Ridge north of Iceland. The crust here is abnormally thick due to the enhanced magmatism of the Iceland hotspot (e.g. Bjarnason *et al.*, 1993a, Menke and Levin, 1995). Furthermore, the movements of the two major plates relative to the hotspot lead to frequent ridge jumps as the plate boundary seeks to relocate itself above the center of the underlying mantle plume (e.g. Einarsson, 1986, 1991, Pálmason and Sæmundsson, 1974). The thick crust and the unstable configuration of the plate boundary makes the structure of the boundary segments more complex in Iceland than elsewhere along the Mid-Atlantic Ridge. Most of the segments are oblique to the plate spreading vector and in some areas spreading is divided between two or more branches of the boundary. Each branch of the plate boundary has its own characteristics with respect to obliqueness, volcanism, type of faulting and pattern of fault systems (Einarsson, 2008). In this paper the tectonic fault pattern in one of these branches, the South Iceland Seismic Zone (Figure 1), will be described. This branch is a transform zone and takes up the transform motion between the oblique Reykjanes Peninsula rift and the Eastern Volcanic Zone. A long-term project has been conducted in this zone since 1977 to map all surface faulting structures. This paper is based on results of that project.

TECTONIC FRAMEWORK OF THE SOUTH ICELAND SEISMIC ZONE

The complexity of the Icelandic plate boundary is particularly apparent in South Iceland where a microplate has been defined between two sub-parallel rift zones, the Western and the Eastern Volcanic Zones (Einarsson, 2008, Sinton *et al.*, 2005, Einarsson *et al.*, 2006). This microplate, the Hreppar Microplate, is considered to have formed when the Eastern Volcanic Zone began propagating away from the center of the hotspot at about 3 Ma. This crustal block is gradually being transferred from the Eurasia Plate to the North America Plate as the Eastern Volcanic Zone takes over from the Western Volcanic Zone as the main rift in South Iceland. The spreading rates across the Western and Eastern Volcanic Zones are estimated from GPS-measurements to be 1–5 mm/a and 14–19 mm/a, respectively, varying along the zones (LaFemina *et al.*, 2005). The rate increases southwards along the western zone but decreases southwards along the eastern zone. This leads to rotation of the microplate with the pole of rotation slightly north of the end of the Western Volcanic Zone in West-central Iceland (Einarsson, 2008). The total spreading rate between the two major plates is consistent with the rate estimated from the pole of rotation of the Nuvel-1A model of DeMets *et al.* (1994) for the Eurasia and North America Plates, about 19 mm/a (Geirsson *et al.*, 2006, Árnadóttir *et al.*, 2009).

The South Iceland Seismic Zone is the source area of most destructive earthquakes in Historic Time in Iceland (Einarsson *et al.*, 1981, Tryggvason *et al.*, 1958, Thoroddsen, 1899, 1905). This zone is a 70 km long branch of the plate boundary, has an E-W orientation and separates the Hreppar Microplate from the Eurasia Plate. The relative plate movement across the zone is left-lateral transcurrent motion, at a rate of about 15 mm/a. Volcanism in this zone is minimal so one must assume only a small amount of divergence across the zone. The only expression of recent volcanic activity is the late Pleistocene activity at Hestfjall (Kjartansson, 1943) and the Grímsnes volcanic system, a group of monogenetic lava and cinder cones at the northern boundary of the zone (Jakobsson, 1966, Sinton *et al.*, 2005) from the early Holocene.

The South Iceland Seismic Zone as defined by destruction areas of historical earthquakes, Holocene surface ruptures and instrumentally determined epicenters (Einarsson *et al.*, 1981, Stefánsson *et al.*, 1993) is 10–15 km wide. Destruction areas of individual earthquakes and surface faulting indicated rather early on that each event is associated with faulting on N-S striking planes, perpendicular to the main zone (Einarsson *et al.*, 1981, Einarsson and Eiríksson, 1982a,b). The over-all left-lateral transform motion along the zone, i.e. between the Hreppar Microplate to the north and the Eurasia Plate to the south, thus appears to be accommodated by right-lateral faulting on many parallel, transverse faults and counter-clockwise rotation of the blocks between them, "bookshelf faulting" (Einarsson *et al.*, 1981, Sigmundsson *et al.*, 1995).

Earthquakes in South Iceland tend to occur in major sequences in which most of the zone is affected. These sequences last from a few days to a few years. Each sequence typically begins with a magnitude 6.5–7 event in the eastern part of the zone, followed by similar or smaller events farther west. Sequences of this type occurred in 1896, 1784, 1732–1734, 1630–1633, 1389–1391, 1339 and 1294. Apart from the historic gap between 1391 and 1630, the sequences thus occur at intervals that range between 45 and 112 years (Einarsson *et al.*, 1981), and it has been argued that a complete stress release of the whole zone is accomplished in about 140 years (Stefánsson and Halldórsson, 1988). The long time since the last sequence led to a long-term forecast published in 1985 (Einarsson, 1985), later refined by Stefánsson *et al.* (1993), of a

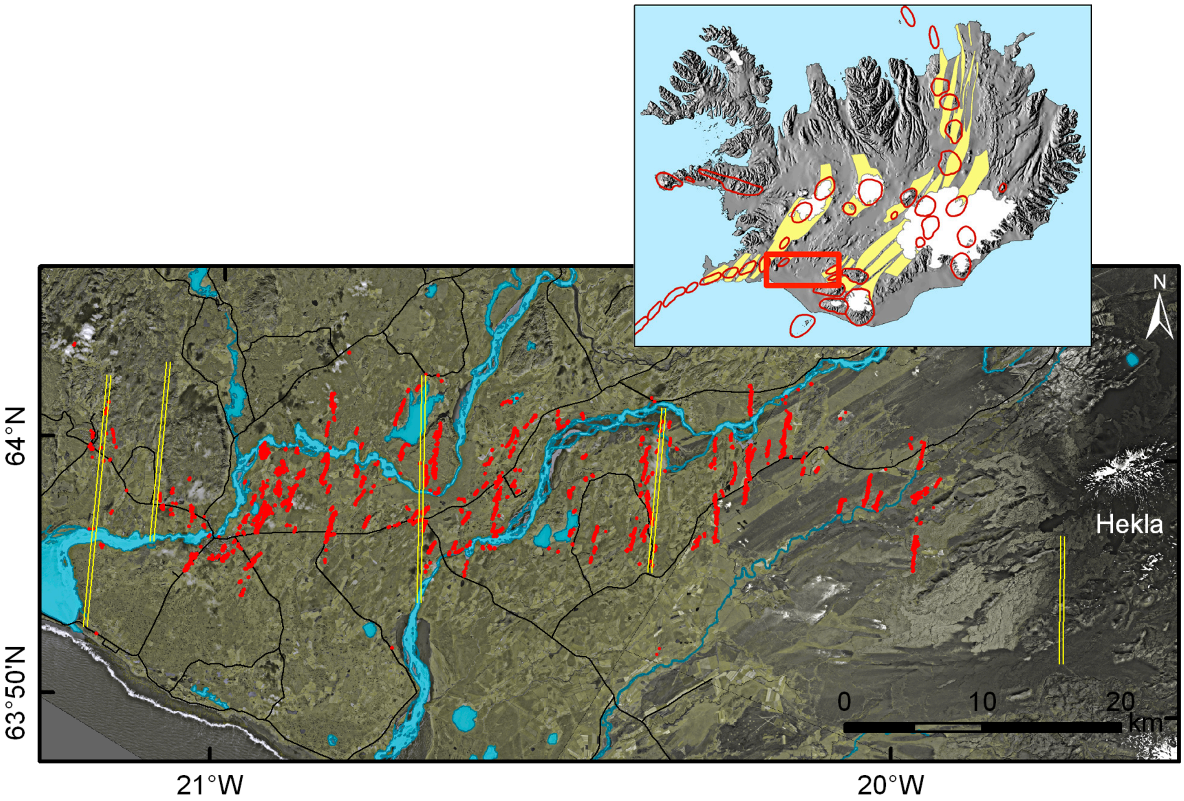

Figure 1. Index map of the plate boundaries in Iceland and volcanic systems is adapted from Einarsson and Sæmundsson (1987). Rectangle shows the study area. Lower image: Surface fractures in the SISZ, exposed in Holocene formations, shown with red lines. Double yellow lines show the source faults of the 1987 (Bjarnason and Einarsson, 1991), 2000 (Hjaltadóttir, 2009) and 2008 (Decriem *et al.*, 2010) earthquakes. Background is from SPOT Image. – *Yfirlitskort af eldstöðvakerfum og flekaskilum á Íslandi. Rauður ferhyrningur afmarkar rannsóknasvæðið. Neðri mynd: Yfirborðssprungur á skjálftasvæði Suðurlands, sem sjá má ummerki um í jarðmyndunum frá Nútíma, kortlagðar með GPS-tækni. Gular línur sýna upptakamisgengi skjálfta við Vatnafjöll 1987, skjálfta í júní 2000 og maí 2008.*

major earthquake sequence within the next decades. The original forecast gave a 80% probability for the occurrence of a major earthquake sequence within the next 25 years (i.e. within the 1985–2010 time window). This forecast was fulfilled in 2000 when two magnitude 6.5 (M_w) events occurred, accompanied by several triggered magnitude 5 events along the SISZ and the adjacent plate boundary branch on the Reykjanes Peninsula (e.g. Einarsson, 2001, 2002, Stefánsson *et al.*, 2001, Árnadóttir *et al.*, 2004). A double event occurred again in 2008 that appears to have consisted of subevents of magnitude 5.9 and 6.1, respectively, on two parallel faults in the western part of the zone (Decriem *et al.*, 2010, Halldórsson *et al.*, 2009, Hreinsdóttir *et al.*, 2009). The sequence may not be over yet at the time of writing (Sept. 2010) as only part of the potential seismic moment accumulated since 1896 has been released (Decriem *et al.*, 2010).

FORMER INVESTIGATIONS

Thoroddsen (1899, 1905) collected written documentation of historic earthquakes in Iceland and described the effects of the 1896 earthquakes, the latest sequence in the SISZ before the current episode of 2000–2008. His work contains a wealth of information, including numerous descriptions of surface fractures associated with the earlier earthquakes, in many cases detailed enough to make them identifiable in the field today. T. Einarsson (1967, 1968) observed and mapped fractures in two parts of the zone and concluded correctly that they were the result of strike-slip faulting although he failed to see their significance within the larger tectonic framework of Iceland.

Einarsson and Eiríksson (1982a,b) reported on the first results of a systematic effort to map all the recognizable surface fractures of the seismic zone. The main faults of the eastern part of the zone were identified and their structural features described. Further work was reported by Einarsson *et al.* (1981).

Bjarnason *et al.* (1993) studied the fracture system of the 1912 earthquake in more detail than had been done earlier by Einarsson and Eiríksson. Further work on this fracture system concentrating on the push-up structures was done by Angelier *et al.* (2004).

Erlendsson and Einarsson (1996) demonstrated that the system of transverse and parallel strike-slip faults extended westward along the plate boundary, beyond the Hengill triple junction. Subsequent work, e.g. by Clifton *et al.* (2003), Clifton and Kattenhorn (2007), Árnadóttir *et al.* (2004), and Einarsson (2008), has shown that plate movements across the oblique rift of Reykjanes Peninsula are partly taken up by bookshelf faulting.

A group led by J. Angelier and F. Bergerat has conducted several studies of fractures in the SISZ and their tectonic significance (e.g. Angelier and Bergerat (2002), Angelier *et al.* (2004, 2008), Bergerat and Angelier (2000, 2003), Bergerat *et al.* (1998, 2003).

The importance of recent surface fracturing for planning and the assessment of seismic hazard has been recognised and several studies have been made at the request of the Selfoss municipality (Imsland and Einarsson, 1995, Imsland *et al.*, 1997, 1998a,b). Furthermore, Þjórsá river, a major source of hydropower in Iceland, flows across the South Iceland Seismic Zone. Several power projects are planned on this river in the near future, requiring detailed information about the location of active faults and their hydrological properties. Several studies have been conducted to this end in the seismic zone (e.g. Einarsson *et al.*, 2002, Khodayar and Einarsson, 2002, Khodayar *et al.*, 2007a,b, 2008). Similarly, the importance of the active fractures in conducting hot water to feed geothermal areas has been demonstrated (e.g. Khodayar *et al.*, 2004, 2010).

METHODS

In this paper I summarise the results of a systematic effort that began in 1977 to map surface ruptures within the South Iceland Seismic Zone. Most of these structures are exposed in Holocene formations and have therefore been active in the last 10 000 years. The area was used as a training ground for students in courses at the University of Iceland, s.a. Tectonics, to identify active faults and map structures at a large scale in the field. Field trips were made to the area every year since 1977 with groups of 5–20 students, covering new areas and fracture systems every time. In the beginning the tools were aerial photographs, tape measure and compass. After about 1995 differential GPS-receivers were used. All structures were located and mapped by walking along and around them. Accurate GPS- maps at a resolution of less than 1 m were made of all the structures, including the areas that had been mapped previously by hand.

The usual procedure was to study available aerial photographs of the area to identify potential fractures and fault structures. Then the potential sites were visited and fractures and fracture systems were identified in the field and traced further. The field investigation usually revealed a much more extensive system than was visible on the photographs. The opposite also happened, that long, linear structures seen on the photographs turned out to be old bridle paths, ditches, wind erosion streaks etc. Interviews with the local inhabitants were frequently useful. They often had knowledge of fault structures when they were described to them, e.g. sinkholes in the fields where tractor wheels tended to get stuck repeatedly, pits where animals had perished, and holes that were useful for trash disposal.

The surface in the SISZ is mainly of two different types. A good part of the zone is covered by a single lava flow, the Þjórsá lava with an estimated volume of 15 km^3 (Hjartarson, 1988), that issued from the Eastern Volcanic Zone ~8000 years ago. Other parts of the zone have basalts of the Plio-Pleistocene Hreppar formation as bedrock, covered by thin ground moraines left by the last glaciation. The Þjórsá lava generally preserves the fracture structures rather well and they are easily traced in spite of considerable vegetation and soil that covers parts of the lava. An open fracture tends to maintain a sinkhole in the soil cover above for a long time after its formation. Tracing fractures in the Hreppar formation and the moraine material is much more difficult. The surface erodes faster and therefore fracture manifestations tend to get erased. There is, however, no noticeable difference in the appearance of the structures if they are exposed. This was clearly demonstrated in the surface effects of the earthquakes of 2000 (Clifton and Einarsson, 2005).

STRUCTURES ASSOCIATED WITH THE SURFACE FAULTS

The seismogenic faults of South Iceland are clearly exposed at the surface in numerous places and can be identified by characteristic structures. The best exposures are in areas where the Þjórsá lava forms the surface bedrock layer, also where it is covered by a thin soil layer. The characteristic structures are also found in areas where the lava is lacking and glacial deposits form the surface layer but they are not as well preserved there.

En echelon fracture arrays constitute one of the most characteristic features of surface ruptures of strike-slip faults. The surface trace is marked by a deformation zone of obliquely trending fractures. Left-lateral faults are marked by right-stepping extensional fractures and right-lateral faults have left-stepping fractures associated with them. In South Iceland most of the identified fault ruptures are associated with right-lateral faulting. Left-lateral faults occur but almost always in a subordinate role. The en echelon structure shows up on many different length scales. The largest scale is measured in kilometers. Fault segments of one to a few km length are offset with respect to each other. This scale can be clearly seen in the faults in Figure 1. The offset between the segments is of the order of a few hundred meters to a kilometer. This offset determines the width of the fractured zone associated with the underlying fault. Each segment then displays en echelon structure. Individual fractures of lengths up to tens of meters are offset with respect to each other, forming en echelon fracture arrays. The pattern is sometimes repeated on a meter scale within these arrays. During the recent earthquakes of 2000 and 2008 this pattern was observed on a finer scale yet (Clifton and Einarsson, 2005), to centimeters and millimeters in soil surfaces (Figure 2).

Push-up structures are frequently found within en-echelon fracture arrays, usually bridging the gap between the tips of adjacent extensional fractures. They have the form of small hillocks, a few tens of centimeters to a few meters in height. The horizontal dimensions and shape are quite variable. Some push-ups are almost round in shape, others are quite elongated. The tops of the hillocks are usually heavily fractured, sometimes to the extent of looking crushed. When fracture systems can be discerned there appear to be two separate kinds of fractures, longitudinal and transverse. The longitudinal fractures are sub-parallel to the adjacent extensional fractures and thus form a part of the en echelon pattern of the over-all fracture array. There may be several of these crossing the push-up (Figure 3) resembling a sliced loaf of bread, often rotated slightly with respect to the adjacent pattern. In a left-stepping, N-S trending array the longitudinal fractures would thus have slightly more easterly strike than the adjacent extensional fractures.

The transverse fractures usually follow the crest of the push-up and are extensional in nature. In lava surfaces that are not affected by other processes it can be seen how the transverse fractures occupy the crest of folded antiforms. The push-up is then seen as a miniature fold with axis perpendicular to the maximum horizontal principal stress. This structure was demonstrated well in the surface ruptures associated with the

Figure 2. Photograph of fine-scale, en echelon fracture pattern in the source area of the SISZ earthquake of June 17, 2000. – *Skástígar sprungur í moldarflagi á upptakamisgengi jarðskjálftans 17. júní 2000.*

South Iceland earthquake of June 17, 2000 (Clifton and Einarsson, 2005). Small push-ups were seen in the surface vegetation cover as small folds, twisted clockwise by the right-lateral displacement across the fault (Figure 4).

Small conjugate fractures are sometimes found in association with push-up structures. They typically occupy positions extending from the outer side of the push-up hillock, i.e. the side facing away from the main fracture system.

The size of a push-up hillock gives an indication of the displacement across the fault. Bjarnason *et al.* (1993), Angelier *et al.* (2004), and Bergerat *et al.* (2003) develop this idea quantitatively from the assumption that the shortening across the hillock is a direct result of and geometrically related to the strike-slip displacement. This concept should not be taken too literally. The size of push-ups is highly variable along the fracture arrays. This would imply that the displacement may vary by orders of magnitude over short distances along the fault trace. Secondly, only a part of the displacement at depth is taken up across a well defined fault at the surface. A considerable part is distributed within a deformation zone around the surface trace of the fault. This was demonstrated in the 2000 earthquakes (Clifton and Einarsson, 2005).

Figure 3. Longitudinal fractures cutting a push-up. This push-up is located on a 1896 fault-break at the farm Þúfa. – *Sprunga og sprunguhóll við Þúfu í Landssveit frá skjálftunum 1896. Hóllinn er allur sundursprunginn.*

Figure 4. The fold-type structures of push-ups, here seen in the turf layer in the source area of the June 17, 2000, earthquake. – *Sprungur og lítill sprunguhóll í túni við Mykjunes í Holtum eftir skjálftann 17. júní 2000.*

In a more general way, however, it is obvious that the size of push-ups depends on the magnitude of the earthquake. The largest push-up formed in the 2000 earthquakes (magnitude 6.5 M_w) was of the order of tens of centimeters. The push-ups formed in the 1912 and 1630 earthquakes are of the order of 2–4 m high. The 1912 event had a magnitude of 7.0 (M_S).

Sinkholes form where soil covers an open fracture in the underlying bedrock. They are funnel-shaped depressions, of the order of meters to ten meters across and tens of centimeters to a few meters deep. The size of the sinkholes is mainly dependent on the thickness of the soil cover, only mildly dependent on the width of the underlying fracture. The hole or depression forms when the soil seeps into the fracture, either by gravity or helped by water. The water is probably mostly precipitation seeping through the soil and into the fracture but fluctuating ground water level in the fracture may also play a part. The holes may be circular in shape but frequently they are elliptical with the major axis aligned with the underlying fracture. A fracture may be expressed at the surface by a linear row of sinkholes. Sometimes the sinkholes merge into a continuous depression above the fracture (Figure 5). In some of them the vegetation is unruptured, in others there may be a breach in the vegetation at the bottom, maintained by flowing or standing water.

Even though the sinkholes are the consequence of surface fault rupturing they do not necessarily acquire their present form at the time of fault movement. A sinkhole will grow in size as long as the underlying fracture can accommodate material. A good example was provided during our studies in the district Skeið where fractures formed in one of the 1896 earthquakes were seen on older aerial photographs. Farmers had then filled in the sinkholes because of the inconvenience of having them in the fields. Animals would fall into them and tractors would get stuck in them. So at the time of our initial study, around 1980, we could not find them. Twenty years later, when we began our GPS-guided mapping of fractures in this part of the zone, all the sinkholes had reappeared and could be mapped.

THE FAULTS, SPECIFIC EXAMPLES

The mapping project has revealed numerous fracture arrays, here shown in Figure 1. The arrays have been grouped into systems that can be taken to represent the surface expressions of underlying strike-slip faults. More than 30 such faults may be defined from the fracture data at hand, arranged side by side within a zone extending from the Hengill triple junction in the west to the eastern end where the zone merges with the Eastern volcanic zone near Hekla. Many more faults may be defined at depth from the relative location of microearthquakes, e.g. by Hjaltadóttir *et al.* (2005a,b), Hjaltadóttir and Vogfjörð (2005), and Hjaltadóttir (2009). Furthermore, Bjarnason and Einarsson (1991) found that the 1987 Vatnafjöll earthquake (M_w= 5.9) originated on a N-S fault at the eastern end of the zone, and Soosalu and Einarsson (1997, 2005) identified two N-S seismic lineaments underlying the Hekla volcano, one of which joins with the Vatnafjöll fault. The separation between neighbouring faults is in the range 1–5 km.

Several of the surface faults can be paired with known historical earthquakes (e.g. Einarsson *et al.*, 1981). Recent revision of research into this was published by Roth (2004) and Richwalski and Roth (2008). Most of the fractures are of unknown age, except that they are exposed in Holocene surface formations and were therefore active in the Holocene. Fracture maps of two areas are presented here as examples of the level of detail in the mapping. The fracture systems in these maps are not associated with known historical earthquakes.

The Hestfjall fault

The Hestfjall fault is marked by a relatively continuous, 4 km long chain of fissures, sinkholes and push-ups exposed in an interglacial lava shield (Figure 6). The system passes slightly west of the apex crater of the shield but otherwise it appears to be unrelated to the structure or the existence of the shield. Several observations of this system are important for the general understanding of the structure of the fracture systems.

1) The system has all the structural characteristics of SISZ fracture systems, including sinkholes, en echelon arrangements, and push-ups. These charac-

Figure 5. Large sinkholes along the 1912 earthquake source fault trace south of Galtalækur. – *Stór niðurföll ofan á sprungum við Galtalæk sem voru virkar í jarðskjálftanum mikla 1912 á Rangárvöllum og Landssveit.*

teristics are therefore not the results or diagnostic of Holocene lavas on top of sediment.

2) The middle part the fracture system crosses an erosional boundary. To the south the fractures are covered by a thick soil layer, whereas this layer is eroded off by wind to the north of the boundary. In the soil-covered part the fractures are primarily visible as deep sinkholes. Push-ups are buried by the sediments, apparently after they were formed. In the un-covered part of the fault segment the push-ups are prominent and form a very regular pattern with the en echelon fractures. The lesson is that push-ups may get obliterated by later sedimentation, but extensional fractures continue producing sinkholes long after their initial formation.

3) The fracture system bifurcates towards its southern end. Both spurs have a N-S trend. Bifurcation is a common feature of the faults. It was described for the 1912 and the 1630 fault traces by Einarsson *et al.* (1981). What is unusual about the

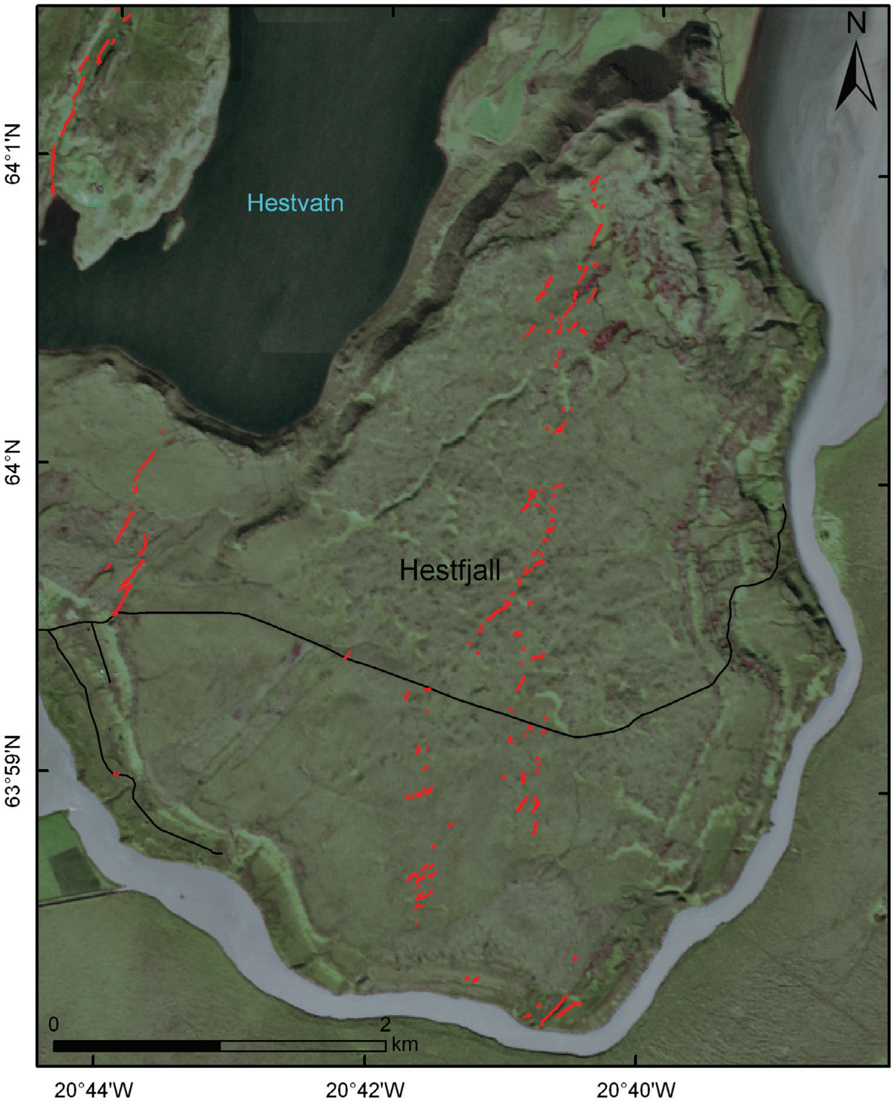

Figure 6. Fault map of the Hestfjall area in the central part of the South Iceland Seismic Zone. The background is aerial photographs by Loftmyndir ehf. – *Sprungukort af Hestfjalli og nágrenni í Grímsnesi.*

Hestfjall case is that the western splay consists of several short conjugate segments, each with a definite right-stepping pattern (Figure 6).

4) The aftershock zone of the second mainshock of the 2000 earthquake sequence, that of June 21, is located directly under the Hestfjall fault (Hjaltadóttir, 2009). Yet no surface faulting was observed on the Hestfjall system. The surface ruptures associated with that event were located 2.5 km to the west (Clifton and Einarsson, 2005). The fault plane active in this event is planar only in its lower part. The shallower parts of the seismically defined fault plane had dif-

ferent dips. The northern part of the fault dips to the east, the southern part dips to the west (Hjaltadóttir, 2009). The tear in the surface ruptures is bridged by a conjugate surface fault at Bitra (Clifton and Einarsson, 2005), which, by the way, does not show up in the hypocentral distribution of aftershocks.

The Réttarnes, Leirubakki, and Tjörvafit faults

Unusually clear fault segments are exposed in a flat lava flow near the farm Leirubakki in the eastern part of the seismic zone (Figure 7). Three parallel fault segments can be distinguished, here named by the nearest place names, Réttarnes, Leirubakki, and Tjörvafit. The first two were discovered and described by Einarsson and Eiríksson (1982a), the third one was identified later. The Leirubakki fault was the subject of a study by Bergerat *et al.* (2003). The distance between the parallel faults is 1–2 km.

The Réttarnes fault is exposed in a rather rough aa-lava and is traceable primarily by its push-up hillocks for about one kilometer. Faint trace of it can be followed for longer distances. The Leirubakki fault is beautifully exposed for about 1.5 km in a smooth pahoehoe-lava. This section perhaps provides the best examples of strike-slip structures anywhere. The fault can be traced further in both directions, a total of about 4 km, but it becomes obscured in the rough lava to the north and the alluvial deposits to the south. The Tjörvafit fault is mainly traceable by its push-ups and pressure ridges. It is clearly traced for 1.5 km. Conjugate structures are prominent in its southern part.

It is not known with certainty when these faults were last active. At least two of the large historical earthquakes originated in this general area, in 1294 and 1732. Skálholts-annal states (Thoroddsen, 1899) for an earthquake in the year 1294: "the earth was fractured in the district Rangárvellir and Rangá river was forced out of its bed and broke people’s houses". The Rangá river crosses the seismic zone in this area and only very few farms are close enough to the river that such damage could be done. The most likely farm is Svínhagi (Figure 7). The most probable fault is therefore the Leirubakki fault although the other two faults cannot be excluded. The 1732 earthquake caused extensive damage in the Land district and the damage zone as mapped by Björnsson (1978) is centered on the farms Leirubakki and Svínhagi. One of the three faults shown in Figure 7 must be regarded as likely source of this earthquake.

A somewhat contrary view on historical activity is expressed by Bergerat *et al.* (2003). They argue that the surface structures of the Leirubakki fault are formed in one single earthquake. The evidence they quote is mainly a comparison with the 1912 earthquake fault and the events of 2000. In both quoted examples the earthquakes took place on an old fault with pre-existing fault structures (Clifton and Einarsson, 2005). It is therefore by no means certain that the structures visible along the Leirubakki fault are due to one single event. In fact, it appears more likely that more than one event are responsible. Their magnitude estimate of 7.1 must therefore be regarded as the absolute upper limit. They furthermore argue (Bergerat *et al.*, 2003) that such a large earthquake would probably have been recorded in the historical accounts, which it is not. Therefore it must be pre-historic. This argumentation does not hold if the structures are due to more than one event.

DISCUSSION

Conjugate faulting

In the beginning of the mapping project it was generally accepted that the South Iceland Seismic Zone was a transform zone and thus a zone of horizontal shear (e.g. Stefánsson, 1967, Ward, 1971). A major E-W fault had not been identified in spite of a clear alignment of earthquake sources in that direction. A system of conjugate faults was to be expected. It soon became evident, however, that a large majority of recognizable surface fracture systems had northerly trends and that the conjugate trend of ENE was poorly represented (Einarsson and Eiríksson, 1982a,b). This was consistent with the observation of Björnsson (1978) and Einarsson and Björnsson (1979) that damage zones of individual historical earthquakes were elongated in a N-S direction. The data presented here confirm this finding. Fracture arrays indicating left-lateral faulting on ENE-striking faults exist but they are an order of magnitude less common in the SISZ than fracture arrays showing right-lateral displacement on

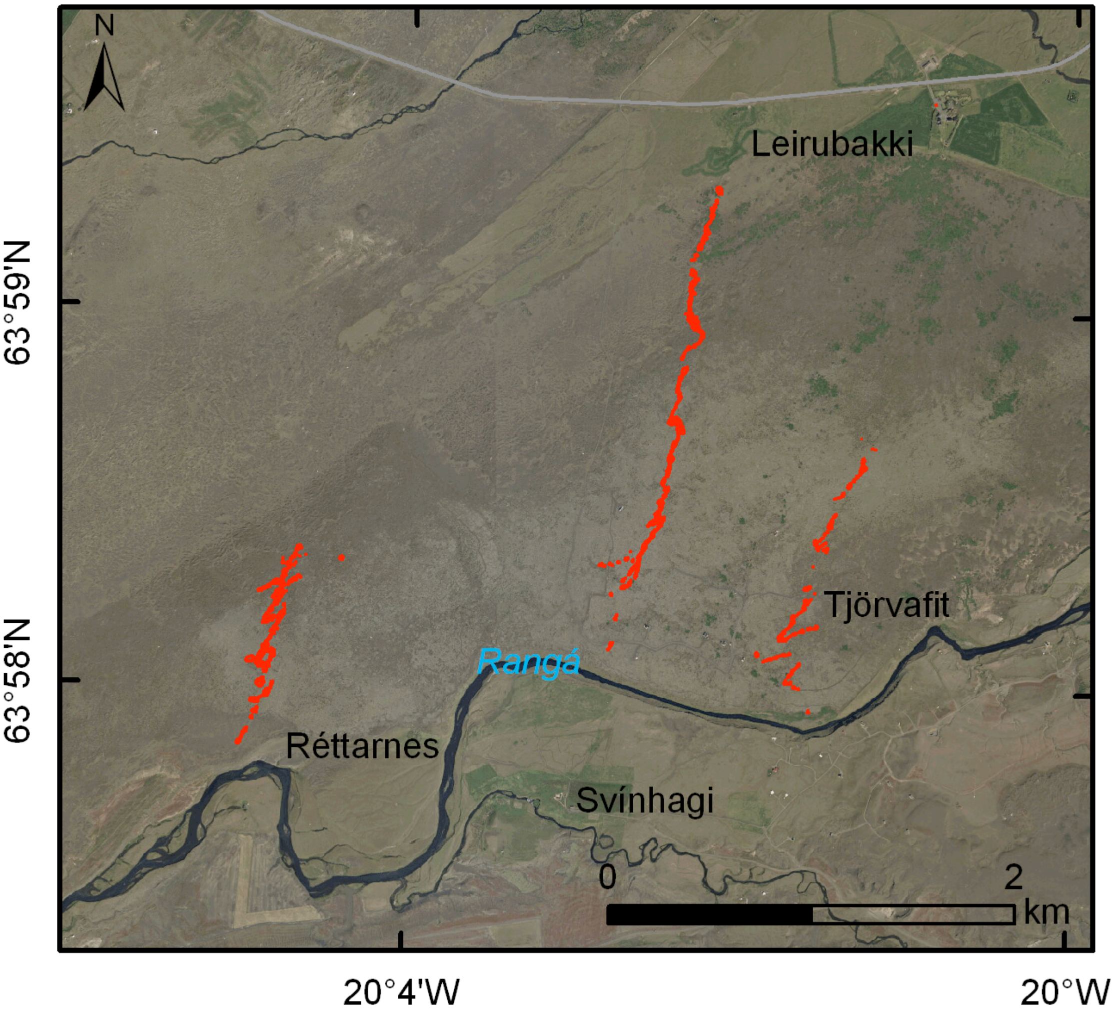

Figure 7. Map of surface ruptures in the Réttarnes-Leirubakki area in the eastern part of the South Iceland Seismic Zone. Background is aerial photographs from Loftmyndir ehf. – *Kort af yfirborðssprungum við Réttarnes og Leirubakka í Landssveit.*

N-S striking faults. Most of the left-lateral cases are found in a subordinate role, bridging gaps between offset tips of right-lateral fault strands or in connection with push-up structures within the deformation zones of N-S faults. This was demonstrated for the surface ruptures of the 1912 earthquake at Selsund (Einarsson and Eiríksson, 1982b (Figure 4), Bjarnason *et al.*, 1993) and for the earthquakes of June 2000 (Clifton and Einarsson, 2005).

By far the most prominent example of conjugate faulting was found in the faulting zone of the earthquake of June 21, 2000, at the Bitra segment (Clifton and Einarsson, 2005, Angelier *et al.*, 2002). A 2 km long zone of left lateral faulting was found along Highway #1, disrupting the road in several places. Several investigators have attached undue importance to this fault segement in the tectonic synthesis of the zone, seemingly not realizing how exceptional this segment is (e.g. Angelier and Bergerat, 2002, Bergerat and Angelier, 2003). Other, much less conspicuous examples of conjugate faulting are found in the southern part of the Selfoss township (Imsland *et al.*, 1998 a, b), at the Litlu-Reykir fault zone, where it crosses Highway #1, and in the fracture system active in the 1912 earthquake near the farm Haukadalur.

Length of faults

Since the largest seismogenic faults trend transversely to the seismic zone, the width of the zone should give an indication of the length of the faults. The zone of mapped fault structures, as seen e.g. in Figure 1, concides very well with the zone of background seismicity. This width is about 20 km, almost uniformly along the zone. The lengths of the source faults of recent large earthquakes in the zone are consistent with this. Modeling of surface deformation fields of the two M_w 6.5 earthquakes of June 2000 gives fault lengths of 15 km (e.g. Pedersen *et al.*, 2001, 2003) and the two faults responsible for the double event of May 2008 were 11 and 17 km long (Decriem *et al.*, 2010). The mapped surface ruptures of the 1912 earthquake (M_S7.0) are 11 km long (Einarsson and Eiríksson, 1982) and Bjarnason *et al.* (1993) suggest that the original rupture may have been as long as 30 km. It has been argued that the length of the destruction zones of historical earthquakes in South Iceland as shown by e.g. Einarsson and Björnsson (1979) and Björnsson and Einarsson (1981) may be taken as a proxy for fault length (e.g. Guðmundsson, 1995, 2000, Angelier *et al.*, 2008) and therefore may be as long as 50 km. This is not so. Assuming a simple model where earthquake intensity is a function of only the distance to the nearest segment of the source fault, it is easy to show that the fault length should be equal to L-W, where L is the length and W the width of the destruction zone. This would give a fault length of about 30 km for the largest earthquakes with known destruction zones, i.e. those of 1784 and 1912.

Strike of the faults

All the larger faults, that are reasonably known, strike almost due N-S. This is clearly seen in the 1912 mapped fault traces, the 1896 second event fault traces (Einarsson *et al.*, 1981), the aftershock distribution of the 1987 Vatnafjöll event (Bjarnason and Einarsson, 1991) and the earthquakes of 2000 (Hjaltadóttir, 2009). Modeling of the deformation fields of the 2000 and 2008 earthquakes shows the same results (Pedersen *et al.*, 2001, 2003, Decriem *et al.*, 2010). Yet there is frequent reference in the literature to a strike of NNE for the major faults (e.g. Gudmundsson, 1995, Gudmundsson and Brynjólfsson, 1993, Bergerat and Angelier, 2000). The reason for this misconception appears to be the en echelon arrangement of the fault structures. The first order en echelon is on the scale of a kilometer. One may therefore see a kilometer long strike-slip segment with a NNE strike (see e.g. Figure 7) but fail to see that it is a part of a larger structure with a strike of N-S. Detailed studies of the hypocentral distribution of the earthquake sequence of 2000 and modeling of the deformation field confirms that the en echelon fracture arrays at the surface are underlain by a continuous, near-vertical fault plane with a northerly strike. This relationship is to be expected where a strike-slip fault, initiated at depth, propagates towards the free surface.

The Grímsnes volcanic system

A population of NE-SW striking fractures in Grímsnes, at the northern border of the SISZ is identified as belonging to a fissure swarm associated with the Grímsnes Volcanic System. The GVS is placed unconformably on top of older crust (Jakobsson, 1966) and judging from the lack of long, continuous structures, its fissure swarm is immature. The fractures are expressed as rows of sinkholes and depressions in the Holocene surface. They are mostly extensional and rarely exhibit a normal component. Their widths are implied to be of the order of 1–2 m and lengths are generally less than 1 km. En echelon arrangements are hardly seen at all, and push-ups are not known here. The fractures are fairly evenly distributed in a 6×20 km swarm. Total dilatation in the Holocene is estimated to be of the order of 10–20 m. Fractures judged to belong to the GVS are not included in Figure 1.

CONCLUSIONS

An overview is given of a project to map in detail structures associated with Holocene faults in the South Iceland Seismic Zone. Mapping has been accomplished with GPS-instruments with a resolution of 1 m.

Holocene faults in South Iceland follow an E-W zone that coincides with the SISZ as defined by epicenters of earthquakes. The zone is about 15 km wide.

The majority of fractures strike NNE-ENE and form left-stepping arrays with northerly trend. This implies right-lateral strike-slip faulting on northerly striking faults. Push-up structures confirm strike-slip faulting and the sense of slip.

Conjugate sets of ENE-striking, left-lateral fault segments also exist, but they are less common by an order of magnitude. Most of them are in a subordinate role, bridging gaps between right-lateral segments.

Large earthquakes in the South Iceland Seismic Zone thus seem to occur mostly by right-lateral faulting on faults that are transverse to the zone. The earthquakes of 2000 and 2008 occurred by right-lateral faulting on N-S faults and confirmed the above findings.

The source faults of most of the largest historical earthquakes since 1630 have been tentatively identified.

Kinematically, the model of "bookshelf faulting" can explain how the over-all left-lateral movement across this branch of the plate boundary is accommodated by slip on numerous parallel transverse faults and rotation of the blocks between them. This model implies an unstable plate boundary configuration. The rotation of the blocks will eventually lock the faults and new faults are required to take up the motion.

The fissure swarm of the Grímsnes Volcanic System partly overlaps with the SISZ, but its fissure swarm has characteristics different from those of the SISZ faults. En echelon fracture arrays are not prominent and push-up structures are absent.

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ÁGRIP

Víða á skjálftabelti Suðurlands má finna merki um nýlegar sprunguhreyfingar. Skjálftabeltið er um 15 km breitt og 70 km langt (1. mynd) og er hluti af flekaskilum Atlantshafsins sem liggja gegnum Ísland. Beltið markar suðurjaðar smáfleka, Hreppaflekans, sem liggur milli gliðnunar- og gosbeltanna tveggja á Suðurlandi. Á þessu belti eiga upptök margir mestu tjónaskjálftar Íslandssögunnar. Tvenns konar jarðmyndanir koma einkum fyrir á skjálftasvæðinu. Annars vegar er jökulmótað landslag, jökulöldur og jökulsorfin hraun, mótað fyrir lok síðasta jökulskeiðs, og hins vegar hraun, Þjórsárhraun, sem huldi stóra hluta láglendisins fyrir um 8000 árum. Vísbendingar um nýlegar sprunguhreyfingar, þ.e. frá síðustu 10000 árum, varðveitast nokkuð vel í báðum tegundum landslags, einkum þó í Þjórsárhrauninu. Gögnum um sprungur og sprunguhreyfingar á svæðinu hefur verið safnað kerfisbundið í meira en þrjá áratugi og hafa nemendur í jarð- og jarðeðlisfræði við Háskóla Íslands komið þar mjög við sögu. Sprungur og sprungutengd fyrirbrigði hafa verið kortlögð með GPS-tækni. Hér er gerð grein fyrir helstu niðurstöðum þeirra rannsókna. Langflestar sprungur stefna í NNA til ANA og þær mynda skástígar sprunguraðir eða sprungufylki (2. mynd) með norðlægri stefnu. Í hverju sprungufylki hliðrast sprungurnar til vinstri miðað við aðliggjandi sprungur í fylkinu. Þessi röðun bendir til þess að sprungufylkið sé tengt hægri handar sniðgengishreyfingu á undirliggjandi misgengi. Sprungufylki með öfugri hreyfingarstefnu eru þekkt á svæðinu en eru mun sjaldgæfari. Í þeim hliðrast sprungurnar til hægri, sem bendir til undirliggjandi vinstri handar sniðgengis. Strikstefna þessara misgengja er oftast ANA. Þessi sniðgengi eru vensluð þeim fyrrnefndu og eru orðin til í sama spennusviði. Aðrar sprungustefnur koma fyrir á Suðurlandi en eru miklu sjaldgæfari. Fyrirbrigði sem tengjast sprunguhreyfingunum er víða að finna, svo sem niðurföll og sprunguhólar. Sprunguhólar verða til milli sprunguenda þar sem sprungur hliðrast til innan sprungufylkis (3. og 4. mynd). Hæð hólanna getur verið allt að fáeinir metrar og er tengd stærð misgengisfærslunnar og þar með stærð skjálftans sem hún olli. Sprunguhólar sem mynduðust í skjálftunum 1630 og 1912 eru heilu stærðarþrepi hærri en þeir sem urðu til í skjálftunum 17. og 21. júní 2000 og 29. maí 2008. Niðurföll myndast oft í yfirborðslögum þar sem opnar sprungur eru undir. Þau geta verið margir metrar á dýpt og tugir metra í þvermál (5. mynd). Borin hafa verið kennsl á og kortlögð ummerki og upptakamisgengi nokkurra sögulegra jarðskjálfta, t.d. 1630, 1784, 1896 og 1912. Þessir skjálftar urðu allir vegna hægri handar sniðgengishreyfinga á misgengjum með N-S strikstefnu, þ.e. ef staðið er á bakka misgengisins virðist andstæður bakki hreyfast til hægri. Heildarhreyfing jarðskorpunnar yfir flekaskilin skýrist með svokölluðu bókahillulíkani. Flekaskilin snúa í austur-vestur en Hreppaflekinn norðan skilanna færist í vestur miðað við Evrasíuflekann sem er sunnan þeirra. Sprungurnar snúa þvert á skilin og hreyfingin veldur vinstri snúningi á spildunum milli þeirra en hægri handar sniðgengishreyfingu um sprungurnar sjálfar. Sprungur og mæld aflögun í tengslum við skjálftana á Suðurlandi 2000 og 2008 eru í góðu samræmi við þetta hreyfilíkan.

REFERENCES

Angelier, J. and F. Bergerat 2002. Behaviour of a rupture of the June 21st, 2000, earthquake in South Iceland as revealed in an asphalted car park. *J. Struct. Geol.* 24, 1925–1936.

Angelier, J., F. Bergerat, M. Bellou and C. Homberg 2004. Co-seismic strikeslip displacement determined from push-up structures: The Selsund Fault case, South Iceland. *J. Struct. Geol.* 26, 709–724.

Angelier, J., F. Bergerat, R. Stefansson and M. Bellou 2008. Seismotectonics of a newly formed transform zone near a hotspot: Earthquake mechanisms and regional stress in the South Iceland Seismic Zone. *Tectonophysics* 447, 95–116.

Árnadóttir, Th., H. Geirsson and P. Einarsson 2004. Coseismic stress changes and crustal deformation on the Reykjanes Peninsula due to triggered earthquakes on June 17, 2000. *J. Geophys. Res.* 109, B09307, doi:10.1029/2004JB003130.

Árnadóttir, Th., B. Lund, W. Jiang, H. Geirsson, H. Björnsson, P. Einarsson and T. Sigurdsson 2009. Glacial rebound and plate spreading: Results from the first countrywide GPS observations in Iceland. *Geophys. J. Int.* 177, 691–716, doi:10.1111/j.1365-246X.2008.04059.x.

Bergerat, F. and J. Angelier 2000. The South Iceland Seismic Zone: tectonic and seismotectonic analyses revealing the evolution from rifting to transform motion. *J. Geodynamics* 29, 211–231, doi:10.1016/S0264-3707(99)00046-0.

Bergerat, F. and J. Angelier 2003. Mechanical behaviour of the Árnes and Hestfjall Faults of the June 2000 earthquakes in Southern Iceland: inferences from surface traces and tectonic model. *J. Struct. Geol.* 25, 1507–1523.

Bergerat, F., A. Gudmundsson, J. Angelier and S. Th. Rögnvaldsson 1998. Seismotectonics of the central part of the South Iceland Seismic Zone. *Tectonophysics* 298, 319–335.

Bergerat, F., J. Angelier, A. Gudmundsson and H. Torfason 2003. Push-ups, fracture patterns, and palaeoseismology of the Leirubakki Fault, South Iceland. *J. Struct. Geol.* 25, 591–609. doi:10.1016/S0191-8141-(02)00051-2.

Bjarnason, I. Th. and P. Einarsson 1991. Source mechanism of the 1987 Vatnafjöll earthquake in South Iceland. *J. Geophys. Res.* 96, 4313–4324.

Bjarnason, I. Th., W. Menke, Ó. G. Flóvenz and D. Caress 1993a. Tomographic image of the Mid-Atlantic plate boundary in Southwestern Iceland. *J. Geophys. Res.* 98, 6607–6622.

Bjarnason, I. Th., P. Cowie, M. H. Anders, L. Seeber and C. H. Scholz 1993b. The 1912 Iceland earthquake rupture: Growth and development of a nascent transform system. *Bull. Seismol. Soc. Am.* 83, 416–435.

Björnsson, S. 1978. Large Earthquakes in South Iceland. In: *Report of Working Group to the Civil Defence of Iceland.*, (in Icelandic).

Björnsson, S. and P. Einarsson 1981. Jarðskjálftar - "Jörðin skalf og pipraði af ótta." *Náttúra Íslands.* Almenna bókafélagið, Reykjavík. 121–155.

Clifton, A. and P. Einarsson 2005. Styles of surface rupture accompanying the June 17 and 21, 2000 earthquakes in the South Iceland Seismic Zone. *Tectonophysics* 396, 141–159.

Clifton, A. E. and S. A. Kattenhorn 2007. Structural architecture of a highly oblique divergent plate boundary segment. *Tectonophysics* 419, 27–40.

Clifton, A. E., C. Pagli, J. F. Jónsdóttir, K. Eythorsdóttir and K. Vogfjörð 2003. Surface effects of triggered fault slip on Reykjanes Peninsula, SW Iceland. *Tectonophysics* 369, 145–154.

Decriem, J., T. Árnadóttir, A. Hooper, H. Geirsson, F. Sigmundsson, M. Keiding, B. G. Ófeigsson, S. Hreinsdóttir, P. Einarsson, P. LaFemina and R. A. Bennett 2010. The 2008 May 29 earthquake doublet in SW Iceland. *Geophys. J. Int.* 181, 1128–1146, doi:10.1111/-j.1365-246X.2010.04565.x

DeMets, C., R. Gordon, D. Argus and S. Stein 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophys. Res. Lett.* 21, 2191–2194.

Einarsson, P. 1985. Jarðskjálftaspár (Earthquake prediction, in Icelandic). *Náttúrufræðingurinn* 55, 9–28.

Einarsson, P. 1986. Seismicity along the eastern margin of the North American Plate. In: P. R. Vogt and B. E. Tucholke, (eds.). *The Geology of North America, Vol. M, The Western North Atlantic Region*. Geol. Soc. Am., 99–116.

Einarsson, P. 1991. Earthquakes and present-day tectonism in Iceland. *Tectonophysics* 189, 261–279.

Einarsson, P. 2001. Suðurlandsskjálftar 2000: Orsakir og atburðarás (South Iceland earthquakes of 2000: Their cause and course of events, in Icelandic). *Goðasteinn, Héraðsrit Rangæinga* 37, 195–217.

Einarsson, P. 2002. Jarðfræðileg umgjörð Suðurlandsskjálfta og áhrif þeirra á land. Í: Suðurlandsskjálftar 2000 (Geological framework of the South Iceland earthquakes and their effects on land, In: Á. Bernharðsdóttir and S. Þorvaldsdóttir (eds.). *The South Iceland Earthquakes of 2000*, (in Icelandic). The Icelandic civil defense, report, 69–77.

Einarsson, P. 2008. Plate boundaries, rifts and transforms in Iceland. *Jökull* 58, 35-58.

Einarsson, P. and S. Björnsson 1979. Earthquakes in Iceland, *Jökull* 29, 37-43.

Einarsson, P., S. Björnsson, G. Foulger, R. Stefánsson and Þ. Skaftadóttir 1981. Seismicity pattern in the South Iceland seismic zone. In: D. Simpson and P. Richards (eds.). *Earthquake Prediction – An International Review.* Am. Geophys. Union, Maurice Ewing Series 4, 141–151.

Einarsson, P. and J. Eiríksson 1982a. Jarðskjálftasprungur á Landi og Rangárvöllum (Earthquake fractures in Land and Rangárvellir, in Icelandic). In: *Eldur er í norðri.* Sögufélag, Reykjavík, 295–310.

Einarsson, P. and J. Eiríksson 1982b. Earthquake fractures in the districts Land and Rangárvellir in the South Iceland Seismic Zone. *Jökull* 32, 113–120.

Einarsson, P. and K. Sæmundsson 1987. Earthquake epicenters 1982–1985 and volcanic systems in Iceland. In: Þ. I. Sigfússon (ed.). *Í hlutarins eðli.* Festschrift for Þorbjörn Sigurgeirsson. Menningarsjóður, Reykjavík (map).

Einarsson, P., M. Böttger and S. Þorbjarnarson 2002. *Faults and fractures of the South Iceland Seismic Zone near Þjórsá.* The Icelandic Power Company, Landsvirkjun, report LV-2002/090, 8 pp.

Einarsson, P., F. Sigmundsson, E. Sturkell, Th. Árnadóttir, R. Pedersen, C. Pagli and H. Geirsson 2006. Geodynamic signals detected by geodetic methods in Iceland. In: C. Hirt (ed.), *Festschrift for Prof. G. Seeber*, Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik der Universität Hannover, 258, 39–57.

Einarsson, Tr. 1967. The Icelandic fracture system and the inferred causal stress field. In: S. Björnsson (ed.) *Iceland and Mid-Ocean Ridges.* Soc. Sci. Islandica, 38, 128–141.

Einarsson, Tr. 1968. Submarine ridges as an effect of stress fields. *J. Geophys. Res.* 73, 7561–7575.

Erlendsson, P. and P. Einarsson 1996. The Hvalhnúkur Fault, a strike-slip fault mapped within the Reykjanes Peninsula oblique rift, Iceland. In: B. Thorkelsson *et* *al.*, (ed). *Seismology in Europe.* European Seismological Commission, Reykjavík, 498–504.

Geirsson, H., Th. Árnadóttir, C. Völksen, W. Jiang, E. Sturkell, T. Villemin, P. Einarsson, F. Sigmundsson and R. Stefánsson 2006. Current plate movements across the Mid-Atlantic Ridge determined from 5 years of continuous GPS measurements in Iceland. *J. Geophys. Res.* 111, B09407, doi:10.1029/2005JB-003717.

Gudmundsson, A. 1995. Ocean-ridge discontinuities in Iceland. *J. Geol. Soc.* 152, 1011–1015.

Gudmundsson , A. 2000. Dynamics of volcanic systems in Iceland: example of tectonism and volcanism at juxtaposed hot spot and mid-ocean ridge systems. *Ann. Rev. Earth Planet. Sci.* 28, 107–140, doi:10.1146/annurev.-earth.28.1.107

Gudmundsson, A. and S. Brynjolfsson 1993. Overlapping rift-zone segments and the evolution of the South Iceland Seismic Zone. *Geophys. Res. Lett.* 20, 1903–1906.

Halldórsson, B. and R. Sigbjörnsson 2009. The M_w6.3 Ölfus earthquake at 15:45 UTC on May 29 2008 in South Iceland: ICEARRAY strong-motion recordings. *Soil Dyn. Earthq. Eng.* 29, 1073–1083, doi:10.1016/-j.soildyn.2008.12.006.

Hjaltadóttir, S. 2009. *Use of relatively located microearthquakes to map fault patterns and estimate the thickness of the brittle crust in Southwest Iceland.* MSc. thesis, Univ. Iceland, 109 pp.

Hjaltadóttir, S. and K. S. Vogfjörð 2005. *Subsurface fault mapping in Southwest Iceland by relative location of aftershocks of the June 2000 earthquakes.* Icelandic Meteorological Office, publ. 21.

Hjaltadóttir, S., K. S. Vogfjörð, Th. Árnadóttir, P. Einarsson and P. Suhadolc 2005a. *A model of the release of the two June 2000 earthquakes based on all observations.* Icelandic Meteorological Office, report, 05020, VÍ-ES-09.

Hjaltadottir, S., K. S. Vogfjord and R. Slunga 2005b. Fault patterns in the South Iceland Seismic Zone revealed by double-difference mapping of microearthquakes. *Eos Trans. AGU* 86 (52), Fall Meet. Suppl., abstr. S32B-03.

Hjartarson, Á. 1988. The great Þjórsá lava, the largest postglacial lava of the Earth (in Icelandic). *Náttúrufræðingurinn* 58, 1–16.

Hreinsdóttir, S., Th. Árnadóttir, J. Decriem, H. Geirsson, A. Tryggvason, R. A. Bennett and P. LaFemina 2009. A complex earthquake sequence captured by the continuous GPS network in SW Iceland. *Geophys. Res. Lett.* 36, L12309, doi:10.1029/2009GL038391.

Imsland, P. and P. Einarsson, 1995. *Bráðabirgðaskýrsla til Selfossbæjar um sprungur í jörð á bæjarstæðinu og nágrenni þess* (Preliminary Report on Ground Fractures within the Town Limits of Selfoss, in Icelandic). Science Inst., Univ. Iceland, prelim. report 2 pp.

Imsland, P., P. Einarsson, D. Þorbjörnsson, S. Jónsson and P. Bjarnason 1997. *Kortlagning jarðskjálftasprungna í landi Selfossbæjar vegna byggðarskipulags – Áfangaskýrsla* (Mapping of Earthquake Surface Ruptures in Selfoss, interim report in Icelandic). Science Inst., Univ. Iceland report RH-05-97, 52 pp.

Imsland, P., P. Einarsson and P. Bjarnason 1998a. *Könnun á tilvist jarðskjálftasprungna í Þjórsárhrauni við Selfoss með skurðgreftri* (Investigation by trenching on the existence of fractures in the Þjórsá lava at Selfoss, in Icelandic). Report, 29 pp., Reykjavík.

Imsland, P., P. Einarsson and P. Bjarnason 1998b. *Frekari greining byggingarlands á svokölluðum Lækjarengjum og Fjárhúsengjum við Selfoss* (Further analysis of ground conditions in the Lækjarengi and Fjárhúsengi areas by Selfoss, in Icelandic). Report, 17 pp., Reykjavík.

Jakobsson, S. P. 1966. The Grímsnes lavas SW-Iceland. *Acta Naturalia Islandica II*, 6, 30 pp.

Khodayar, M. and P. Einarsson 2002. *Structural analysis of the Núpur area, Gnúpverjahreppur, South Iceland.* Landsvirkjun, report LV-2002/101, 16 pp., 2 maps.

Khodayar, M., S. H. Gunnarsdóttir, P. Einarsson and H. Franzson 2004. *GPS-mapping of geothermal areas in South Iceland. Phase 1: Reykjanes in Grímsnes, Þorlákshver and Laugarás in Biskupstungur. – An overview.* Iceland geosurvey report ÍSOR-04001, 6 pp.

Khodayar, M., H. Franzson, P. Einarsson and S. Björnsson 2007a. *Hvammsvirkjun. Geological investigation of Skarðsfjall in the South Iceland Seismic Zone.* Iceland geosurvey report ÍSOR-2007/017; LV-2007/065, 40 pp. and 2 maps.

Khodayar, M., P. Einarsson, S. Björnsson and H. Franzson, 2007b. *Holtavirkjun – Memorandum: Preliminary map of fractures and leakages in Akbraut in Holt and Laugar in Landssveit.* Iceland geosurvey report ÍSOR-2007/010, 8 pp. and 6 maps.

Khodayar, M., P. Einarsson, S. Björnsson and H. Franzson 2008. *Fractures and leakages at the Holtavirkjun project sites, South Iceland Seismic Zone.* The Icelandic Power Company, Landsvirkjun, report LV-2008/088, 52 pp. and maps.

Khodayar, M., S. Björnsson, P. Einarsson and H. Franzson 2010. Effect of tectonics and earthquakes on geothermal activity near plate boundaries: A case study from South Iceland. *Geothermics* 39, 207–219, doi:10.1016/j.geothermics.2010.06.003

Kjartansson, G. 1943. *Árnesingasaga* (The Saga of Árnessýsla, in Icelandic). Árnesingafélagið, Reykjavík, 268 pp.

La Femina, P. C., T. H. Dixon, R. Malservisi, Th. Árnadóttir, E. Sturkell, F. Sigmundsson and P. Einarsson 2005. Geodetic GPS measurements in south Iceland: Strain accumulation and partitioning in a propagating ridge system. *J. Geophys. Res.* 110, B11405, doi:10.1029/2005JB003675.

Menke, W. and V. Levin 1994. Cold crust in a hot spot. *Geophys. Res. Lett.* 21, 1967–1970.

Pálmason, G. and K. Sæmundsson 1974. Iceland in relation to the Mid-Atlantic Ridge. *Ann. Rev. Earth Planet. Sci.* 2, 25–50.

Pedersen, R., F. Sigmundsson, K. Feigl and Th. Árnadóttir 2001. Coseismic interferograms of two M_s=6.6 earthquakes in the South Iceland Seismic Zone, June 2000. *Geophys. Res. Lett.* 28, 3341–3344.

Pedersen, R., S. Jónsson, Th. Árnadóttir, F. Sigmundsson and K. L. Feigl 2003. Fault slip distribution of two June 2000 M_w 6.5 earthquakes in South Iceland estimated from joint inversion of InSAR and GPS measurements. *Earth Planet. Sci. Lett.* 213, 487–502.

Richwalski, S. M. and F. Roth 2008. Elastic and viscoelastic stress triggering in the South Iceland Seismic Zone due to large earthquakes since 1706. *Tectonophysics* 447, 127–135.

Roth, F. 2004. Stress changes modelled for the sequence of strong earthquakes in the South Iceland Seismic Zone since 1706. *Pure Appl. Geophys.* 161, 1305–1327, doi:10.1007/s00024-004-2506-5.

Sigmundsson, F., P. Einarsson, R. Bilham and E. Sturkell 1995. Rift-transform kinematics in south Iceland: Deformation from Global Positioning System measurements, 1986 to 1992. *J. Geophys. Res.* 100, 6235–6248.

Sinton, J., K. Grönvold and K. Sæmundsson 2005. Postglacial eruptive history of the Western Volcanic Zone, Iceland. *Geochem. Geophys. Geosyst.* 6, Q12009, doi:10.1029/2005GC001021.

Soosalu, H. and P. Einarsson, 1997. Seismicity around the Hekla and Torfajökull volcanoes, Iceland, during a volcanically quiet period, 1991–1995. *Bull. Volcanol.* 59, 36–48.

Soosalu, H. andP. Einarsson, 2005. Seismic characteristics of the Hekla volcano and its surroundings, Iceland. *Jökull* 55, 87–106.

Stefánsson, R. 1967. Some problems of seismological studies on the Mid-Atlantic Ridge. In: S. Björnsson (ed.), *Iceland and Mid-Ocean Ridges.* Soc. Sci. Islandica, Rit 38, 80–90.

Stefánsson, R. and P. Halldórsson 1988. Strain release and strain build-up in the South Iceland Seismic Zone. *Tectonophysics* 152, 267–276.

Stefánsson, R., R. Böðvarsson, R. Slunga, P. Einarsson, S. S. Jakobsdóttir, H. Bungum, S. Gregersen, J. Havskov, J. Hjelme and H. Korhonen 1993. Earthquake prediction research in the South Iceland seismic zone and the SIL project. *Bull. Seismol. Soc. Am.* 83, 696–716.

Thoroddsen, Th. 1899 and 1905. *Landskjálftar á Íslandi* (Earthquakes in Iceland, in Icelandic). Hið Íslenska Bókmenntafélag, Kaupmannahöfn.

Tryggvason, E., S. Thoroddsen and S. Þórarinsson, 1958. Greinargerð jarðskjálftanefndar um jarðskjálftahættu á Íslandi (Report of the Earthquake Committee on seismic risk in Iceland, in Icelandic with English summary). *Tímarit Verkfræðingafélags Íslands*. 43, 81–97.

Ward, P. L. 1971. New interpretation of the geology of Iceland. *Geol. Soc. Amer. Bull.* 82, 2991–3012.