Holocene displacement field at an emerged oceanic transform-ridge junction: the Husavik-Flatey Fault - Gudfinnugja Fault system, North Iceland

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Abstract

Our research focuses on Holocene tectonics in a broad area surrounding the junction between the active NW-SE trending Husavik-Flatey transform fault (HFF) and the N-S Gudfinnugja normal fault (GF), an exceptional example of onshore transform-ridge intersection. We mapped 637 minor and major faults, and measured the dip-slip and strike-slip offset components on the major faults. We also mapped 1016 individual fissures, as well as opening directions on the most reliable ones. The results indicate that this portion of the HFF comprises major right-stepping segments, with both normal and right-lateral strike-slip components, linked by local normal faults. The entire GF always shows pure dip-slip normal displacements, with a strong decrease in offset at the junction with the HFF. Fissure opening directions are in the range N45°-65°E along the HFF, N90°E along the GF, and N110°E within the area south of the HFF and west of the GF. Fault kinematics and fissure openings suggest a displacement field in good agreement with most of present-day GPS measurements, although our data indicate the possible long-term Holocene effects of the

superimposition of magma-related stresses on the regional tectonic stresses. The HFF and the GF work together as a structural system able to accommodate differential crustal block motion, and possibly past dyke intrusions.

Keywords: Gudfinnugja fault; Husavik-Flatey fault; transform fault; normal fault; fissure; Iceland.

1. Introduction

The active Iceland rift zone runs NNE-SSW across the entire island and, in its northern sector, it is connected with the Kolbeinsey mid-ocean ridge (Fig. 1). This connection is expressed by the parallel right-lateral strike-slip Grimsey, Husavik-Flatey, and Dalvik faults, which make up the 120-km-long Tjörnes transform fault zone (Ward, 1971; Saemundsson, 1974). Most of these faults are offshore, whereas the south-eastern segment of the Husavik-Flatey Fault (HFF) is very well expressed on-land, where the fault has a length of 25 km, strikes NW-SE across the southern part of the Tjörnes peninsula and connects to a set of approximately N-S-striking normal faults and fissures known as the Theystareykir fissure swarm (TFS), part of the North Volcanic Zone of Iceland. Most earthquakes along the rift zone are <M4 (Einarsson and Björnsson, 1979; Gudmundsson, 1999), whereas transform zones such as the Tjörnes are characterised by destructive events with the greatest magnitudes in Iceland (M 6-7), although taking place mostly offshore (Fig. 1) (Tryggvason, 1973; Halldorsson et al., 1996). The on-land HFF shows several indicators of Holocene movement but limited seismicity in comparison to its offshore counterpart (Einarsson, 1991). Four major earthquakes have occurred along the HFF in the past 200 yrs, all offshore. In 1755, an estimated M 7 earthquake took place in Skjalfandi Bay, and in 1838 a M 6.5 event occurred near the westernmost end of the HFF (Metzger et al., 2011). The latter earthquake was followed, in 1872, by two major M 6.5 earthquakes with epicentres close to the towns of Flatey and Husavik (Fig. 1). In particular, Husavik lies directly above the trace of the HFF; Metzger et al.

(2011) and, assuming that seismic energy has been accumulating since the two large earthquakes of 1872, suggests that the seismic potential of the fault is equivalent to a $M_w 6.8 \pm 0.1$ event.

Given the high seismic potential of the HFF, detailed field investigations along its trace have been carried out on major faults, dykes, mineral veins (Saemundsson, 1974; Young et al., 1985; Gudmundsson et al., 1993; Fjader et al., 1994; Magnusdottir and Brandsdottir, 2011) and major and minor striated faults (Angelier et al., 2000; Bergerat et al., 1990, 2000; Garcia et al., 2002; Garcia and Dhont, 2005; Bergerat and Angelier, 2008). Previous research suggested that the HFF ends against the Gudfinnugja normal fault (GF in Fig. 2) (Gudmundsson et al., 1993); although recently Hjartardottir et al. (2012) suggested a possible subsurface continuation of the HFF towards the SE on the basis of earthquake epicentres, and fracture distribution at the Krafla fissure swarm. Detailed field work may aid in shedding new light on the intersection of the TFS with the HFF, an exceptional example of a ridge-transform intersection, and a setting that is hardly ever exposed on land.

The main purpose of our research has been to assess the tectonic features and long-term (Holocene) kinematics that characterize a broad area centred on the junction between the HFF and the TFS, in order to contribute to understanding the mechanical and kinematic consistency of these structures, and to evaluate the previously hypothesised prolongation of the HFF towards the SE. Our approach has consisted of mapping all minor and major faults and fissures in the area, augmenting previously published work. Moreover, for the first time we have assessed the dip-slip and strike-slip offset components of the main faults, and determined the opening directions of the more reliable fissures. We have mapped 637 faults and 1016 individual tension fractures, at a metric to kilometric scale. Using these data, we have been able to shed new light on fault geometry and provide, for the first time, fault offset differences in space, fissure geometry and extension directions for the last few thousand years. We have also compared the above with present-day GPS vectors.

2. Geologic-tectonic framework

The North Volcanic Zone (NVZ), active since 8-9 Ma (Saemundsson, 1974; Young et al., 1985; Bergerat and Angelier, 2008), is made up of five, approximately N-S-striking rift zones, namely, from west to east: the Theystareykir, Krafla, Fremri-Namur, Askja, and Kverkfjöll volcanic systems (Fig. 1) (Gudmundsson, 2000; Hjartadóttir and Einarsson, 2012). Each of these volcanic systems is made up of 5-20 km-wide and 60-100 km-long fracture swarms and a main volcano (Saemundsson, 1974). The swarms are composed of normal faults, eruptive fissures and tension fractures that strike parallel to the rift direction. Most of the research in this area has focused on the Krafla fissure swarm (e.g., Angelier et al., 1997; Acocella et al., 2000; Dauteuil et al., 2001; Hjartardottir et al., 2012). The TFS is a 10 km-wide stretch of terrain that is dissected by N-S-striking normal faults, eruptive fissures and marked by the presence of the Theystareykir central lava shield (Opheim and Gudmundsson, 1989; Garcia and Dhont, 2005). Within the TFS, the most prominent structure is the Gudfinnugja Fault (GF), a Holocene normal fault that represents the western edge of the rift system (Fig. 2).

Emission of lava flows from the Theystareykir shield was constrained to about 14.5 ka BP in the study area (Slater et al., 2001; Stracke et al., 2003). The latest eruption occurred about 2.4 ka BP, when the ‘Theystareykjahraun’ lava flows were emplaced, between the central shield and the HFF (Saemundsson et al., 2012). Active vertical deformation at Theystareykir was measured using GPS-based methods (Metzger et al., 2011). The latest major event in the area was the rifting episode that took place within the nearby Krafla volcanic system between 1975 and 1984 (Bjornsson, 1985). During that period, several volcano-tectonic episodes produced consistent displacements marked by horizontal (several meters) and vertical (a few metres) offsets (Tryggvason, 1980, 1984, 1986). The extension was associated with M 5–6.5 earthquakes (e.g., Tryggvason, 1980, 1984; Bjornsson, 1985).

The HFF strikes 25 km through the Tjörnes peninsula (Fig. 1), as far as the western border of the Holocene rift zone. It is composed of en-échelon, dominantly right-stepping, dextral strike-

108 slip fault segments (Gudmundsson 1993, 2007). Near the town of Husavik, the HFF separates
109 Tertiary rocks to the north from Upper Pleistocene rocks to the south (Saemundsson, 1974; Garcia
110 et al., 2002). The fault, first described by Einarsson (1958) and mapped by Saemundsson (1974),
111 displays at the surface vertical offsets reaching 200 m at many sites (Gudmundsson, 1993). Its total
112 vertical displacement may amount to as much as 1400 m (Gudmundsson, 1993), which is in
113 agreement with the 1100 m vertical displacement off the coast of the Flatey fault estimated by
114 Thors (1982). Saemundsson (1974) suggested a right-lateral displacement of as much as 5-10 km,
115 and Young et al. (1985) suggest it may amount to 20 km. Garcia and Dhont (2005) subdivided the
116 HFF into three parallel fault traces and, in agreement with Gudmundsson (1993), identified two
117 major sag ponds along the fault trace, interpreting them as pull-apart basins generated by
118 transtensive displacement.

119 As mentioned above, the HFF connects with N-S-striking normal faults belonging to the
120 TFS (Gudmundsson, 1993); the most spectacular of these interactions is visible where the HFF
121 joins the GF, at an angle of about 60° (Gudmundsson et al., 1993). Near the intersection of the GF
122 and HFF, Gudmundsson et al. (1993, 2007) describe zones of transpression and transtension. The
123 former are marked by fragmented lava blocks forming hills and irregular ridges, while the latter
124 result in pure tensional fractures and small collapse structures. Figure 2 illustrates faults and tension
125 fractures as mapped during previous research efforts in the area, summarized in Saemundsson et al.
126 (2012). Rose diagrams are included, depicting the main strike of faults and fractures: Fault strike
127 ranges from NW to NNE, with a dominant orientation around N-S and NNE; fracture strike ranges
128 from NNW to NNE, with a dominant N-S strike.

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130 **3. Results**

131 In the following sections we describe the data we gathered by field mapping, aided by high-
132 resolution satellite imagery. Overall, we recognise 1016 tension fractures, some hundreds of which
133 were also mapped in the field. In measuring their opening directions, we measured only those

fractures that were distant from fault scarps and that are at least 200 m long, thus avoiding possible local gravity effects on the opening vectors. We selected the most reliable tension fractures (120 in total) and measured in the field their strike and opening direction. We also mapped and measured in the field the fault swarms that make up the GF and HFF (including at their junction), by determining their strike, dip, dip-slip and strike-slip displacement components, kinematics, block rotation and amount of tilting.

Although the area has been mapped in the past, our fieldwork enabled us to collect a large amount of new data that can usefully be integrated with the results of previous research efforts. In particular, neither the offsets along the whole length of the GF, nor the opening directions of tension fractures, had previously been assessed in any detail. We describe the area in terms of different kinematics and deformation patterns affecting three sub-areas: 1) the studied section of the HFF, marked by strike-slip deformation structures, 2) the GF, with dip-slip deformation patterns, and 3) the block located south of the HFF and west of the GF (SW-block in Fig. 3).

The geological-structural map and rose diagrams of Figure 3 refer to all the structures mapped through both field work and interpretation of high-resolution satellite images, whereas the following figures and graphs show exclusively the structures and data measured directly in the field. As can be observed in the rose diagrams of Figure 3, the overall strike of tension fractures and faults ranges from NW-SE to NNE-SSW, with a principal N-S orientation for fractures and a dominant N-S to NNE-SSW orientation for fault scarps. In more detail, the 784 tension fractures we recognised along the HFF strike in the NNW-SSE to N-S range, with a dominant NNW-SSE strike. The 79 faults strike from NW-SE to NNE-SSW, with a main NW-SE strike and a subsidiary N-S one. Along the rift zone, the 564 tension fractures and 433 faults mostly strike from NNW-SSE to NNE-SSW. However, the dominant strike of the fractures is N-S. In the SW block, the 268 tension fractures and 125 faults strike from N-S to NNE-SSW, with a dominant NNE-SSW orientation. In the next chapters we describe in further detail the data collected in the field in the three sub-areas.

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161 *3.1 The Husavik-Flatey Fault*

162 The stretch of the HFF that we surveyed in the most detail in the field is made up of three
163 main, WNW-ESE-striking segments (I, III and V in Fig 3). These are made up of single faults
164 linked by two NNW-SSE-striking segments (II and IV in Fig. 3). From Segment II eastwards, the
165 2.4-ka-old lavas are mostly confined to the downthrown block, although they locally onlap the fault
166 scarps and are involved in the younger deformation events. The 14.5-ka-old lavas crop out on the
167 relatively uplifted block north of the faults.

168 Segment I strikes N123°E and is represented by a rectilinear fault mostly covered by active
169 scree deposits, along which three main landslides of post-LGM age are aligned. At the south-eastern
170 termination of this segment an abrupt change in the structural architecture can be observed: the
171 single, N123°E-striking fault is replaced by a set of faults that strike from N154°E to N180°E
172 (Segment II in Figs. 3 and 4). In its northern part, this fault swarm is 125 m wide and marked by
173 seven, mainly dip-slip fault planes, five of which dip towards the WSW and two in the opposite
174 direction. To the south these faults gradually take on an en-échelon arrangement and eventually
175 form a 20-m wide deformation zone marked by fault scarps facing towards the WSW, with a total
176 dip-slip offset of a few metres. About 110 m west of these faults the footwall block is characterised
177 by the presence of NNW-SSE-striking fissures. In the southernmost portion of the area in Figure 4A
178 the 20-m wide fault zone widens into a fan-shaped fault swarm that extends southwards into a N-S-
179 to NNE-SSW-striking fault zone.

180 East of this fan shaped fault zone, a single surface fault trace marks the HFF that here strikes
181 N114°E (segment III in Fig. 3). It shows evidence of a major right-lateral strike-slip component,
182 plus a normal dip-slip component with the downthrown block to the south. Segment III is 1-km
183 long and disappears in correspondence of another NNW-SSE-striking fault swarm (Segment IV),
184 which is made up of four, approximately 150-m long fault scarps striking from N153°E to N180°E,
185 facing towards the WSW. To the south this fault swarm is abruptly interrupted by Segment V (Fig.

186 3), comprising a series of slightly offset fault traces, which will be described from west to east. The
187 first fault strikes N123°E and bears evidence of both right-lateral strike-slip and normal dip-slip
188 components, with the downthrown block to the south. This fault trace is relatively straight up to the
189 point where a left-stepping jump occurs with some overlap (Fig. 5A). Here, another N124°E-
190 striking fault shows clear evidence of right-lateral strike-slip displacement. Further to the SE, a
191 right-stepping geometry, partially overlapping, is clearly observed with a new fault striking
192 N130°E. The area where the left-stepping is observed is marked by domed structures that can be
193 interpreted as push ridges generated by transpressional deformation (contractional overstep),
194 consistent with right-lateral kinematics. By comparison the area where the right-stepping jump
195 occurs is characterised by a depression that can be interpreted as the expression of transtensional
196 deformation (extensional overstep, Fig. 5). Further east, Segment V, although showing a rectilinear
197 surface trace on satellite images and aerial photos, on closer examination in the field is
198 characterised by the presence of systematic en-échelon fractures striking N130°E-140°E. Most of
199 these fractures show pure extension, but some have a right-lateral strike-slip component. Hence,
200 they can be considered as en-échelon, left-stepping fissures and Riedel faults associated with a
201 shear zone. Farther eastwards, Segment V splits into three main fault planes that gradually bend to a
202 N-S strike. Along with the change in fault orientation, the strike-slip component fades away and the
203 dip-slip component takes over as the faults link to the N-S-striking GF.

204 We have also carried out a detailed field survey southeast of the junction across an area of
205 about 2 km, completed by analysis of high-resolution satellite images. Our investigation did not
206 show any evidence of strike-slip faulting at the surface, nor the presence of fault scarps or open
207 fissures parallel to the HFF strike. The only observation here is a slight local re-orientation of a N-
208 S-striking normal fault located about 750 m east of the GF, where a few NW-striking fissures with a
209 left-stepping geometry were also observed.

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3.2 *The Gudfinnugja Fault (GF)*

We describe the GF, the westernmost structure in the TFS (Fig. 2), subdividing it into three sections: i) north of the junction with the HFF (1.5 km in length), ii) in close proximity to the junction, and iii) south of the junction (4.5 km long). In the northern section, lavas cropping out are 14.5 ka old on both sides. South of the junction, 14.5-ka-old lavas crop out on the eastern block and 2.4-ka-old lavas occur on the western block. The first evidence of the GF to the north is represented by NNE-striking fissures, south of which the actual GF occurs with an initial offset of about 2 to 3 m (Fig. 6A) along the first 100 m of its length, which increases southwards (e.g. Figs. 6B-C). In the whole northern sector of the GF, lavas are displaced by normal faulting along one single fault scarp, either without any rotation of the footwall block, or with very limited rotation ($< 10^\circ$). Assuming an original horizontal topography, as suggested by the surrounding flat area. The deformation style along the GF changes abruptly at the intersection with the HFF, where we observed that the lavas dip about 35° westwards. The dip angle becomes steeper to about 65° a few tens of metres south of the triple junction (Fig. 6D). This “monoclinal deformation style”, characterised by the hanging-wall block dipping in the same direction as the fault plane, was observed along the whole southern sector of the GF (from the triple junction to its southern tip), with dip angles ranging from 40° to 65° (Figs. 6D-F).

3.3 *Vertical offset measurements along the HFF and GF*

We devoted considerable effort to the quantification (with the highest possible instrumental detail) of offset variations along the HFF and GF. With regard to the former, we were able to assess its vertical offset component manually because fault scarps in the whole studied section are always < 17 m, hence enabling us to record offsets by means of a tape measure. However, along the HFF the quantification of the strike-slip offset component was difficult due to the lack of piercing points. Regarding the GF, as its offsets are much greater than those along the HFF, our methodology

238 comprised GPS measurements taken every 100 m as we walked both along the upper surface of the
239 footwall block and the lowermost surface of the hanging-wall block. The GPS altitude data
240 collected were processed to show the variations in offset amounts along the whole length of the GF.
241 Errors are in the order of 5% for tape measurements and 2 m for GPS measurements.

242 In regard to the HFF, within Segment II (Fig. 3), which is made up of a series of parallel
243 faults, the total cumulative fault offset on all the scarps is 22.5 ± 1.125 m. The parallel faults are
244 marked by pure dip-slip kinematics, hence this value represents the net slip. The dip-slip component
245 of fault offset at Segment III is 5 ± 0.25 m. At Segment IV the parallel fault scarps are from 2 ± 0.1
246 to 8 ± 0.4 m high each, totalling 20 ± 1 m of net dip-slip offset. The faults of Segment V have a
247 normal dip-slip component from 4 ± 0.2 m to 7 ± 0.35 m. Near the triple junction, where the HFF
248 splits into three main en-échelon faults, each fault has a dip-slip of about 5 ± 0.25 m, and the total
249 dip-slip offset component is in the order of 15 ± 0.75 m.

250 Along the GF, we recorded (Fig. 7) offset values by GPS along a stretch of almost 6 km;
251 from the southern fault terminastion it is possible to notice a sharp increase in offset up to a
252 maximum value of 27 ± 2 m. Northwards, there is a series of irregular variations in offset with a
253 peak at 33 ± 2 m. Most values are between 15 and 22 m. Near the triple junction there is a second
254 peak of 31 ± 2 m. North of the triple junction, there is a local peak of 28 ± 2 m and then dip-slip
255 offset values decrease with some minor variations, mostly in the range 13-20 m, until the fault fades
256 into a simple fissure with pure dilation.

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258 *3.4 Tension fractures*

259 Tension fractures have been mapped in the whole study area of Figure 3, but were measured
260 directly in the field only in a zone centred on the triple junction with a radius of about 3 km. For
261 each tension fracture, we assessed: 1) fracture strike, by averaging measurements along each 10-m-
262 long segment; 2) the average opening direction, obtained by measuring at several points the

263 azimuth of the line connecting offset piercing points (e.g. in Fig. 8); and 3) the amount of net
264 opening and the along-strike and normal-to-strike components.

265 As shown in Figure 3, the 784 tension fractures in the HFF sub-area strike in the N315°W-
266 N25°E range, with a dominant N315°W strike. In the rift zone sub-area, the 564 tension fractures
267 predominantly strike in a northerly direction. In the SW block, the 268 tension fractures we
268 recognised strike between N0°E and N25°E, with a peak in the N23°E direction. For each of the
269 sub-areas studied we plotted fracture and fault strike vs. longitude (Fig. 9). In Figures 9A and 9B it
270 is possible to observe that all along the HFF fractures strike in the range N120°-215°E, whereas
271 faults tend to have a smaller strike variation and gradually rotate along longitude. In regard to the
272 other two sub-areas it is worth highlighting the similar distribution between fracture strikes and
273 fault strikes. In the GF rift sub-area (Figs. 9C, 9D), fractures and faults are markedly more frequent
274 east of the longitude that corresponds to the junction between the HFF and the GF. Moreover,
275 fractures and faults in this rift sub-area range from N160°E to N220°E along the GF, whereas they
276 tend to peak at a more northerly strike east of the GF. With regard to the SW-block sub-area we
277 highlight the scarcity or absence of tension fractures and faults within the first 2.5 km west of the
278 GF (Figs. 9E, 9F). Although a few fractures do occur near the GF, the wide fracture field described
279 by Garcia and Dhont (2005) corresponds to a set of lava flow structures belonging to a young lava
280 field that flowed northward (Fig. 2). These structures may be erroneously attributed to post-lava
281 deformation but, in fact, they can be interpreted as accommodation zones that form during lava
282 emplacement under a brittle-plastic regime (for details see Tibaldi, 1996).

283 Regarding fracture opening directions (Fig. 10A and related rose diagrams) along the rift
284 they range from N45°E to N112°E, with a clear predominance of N90°-100°E-trending directions
285 and a statistical peak at N90°E. Along the HFF, opening directions show two clusters, one around
286 N50-80°E (less represented) and a predominant cluster from N80°E to N100°E. Finally, in the SW-
287 block, opening directions vary from N80°E to N140°E, with a clear predominance at N100°-110°E
288 and a statistical peak of N112°E. In Figure 10A we also report the trend of GPS spreading vectors,

289 as determined by Jouanne et al. (2006), for the years 1997–1999 and 1999–2002 (trending around
290 N110°E). Also, in order to graphically compare GPS spreading measurements and our field data,
291 we include fracture opening directions and strikes. Figures 10B and C are the result of plotting
292 spreading vector trend and fracture strike vs. latitude and longitude; it is particularly worth noting
293 that opening directions are consistently most frequent in the range N80°-120°E (Fig. 10B), with an
294 increase towards N90°-140°E west of the triple junction.

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296 *3.5 Volcano-tectonic structures*

297 In the studied area we found some structures that can be referred to volcanic and volcano-
298 tectonic processes. In the western part there are a few, still recognizable, vents, some of which are
299 associated with small pyroclastic cones occurring on the summit area of the Hofudreidarmuli
300 volcano (Fig. 3). On top of the edifice there is a set of N-S to ENE-WSW-striking fractures (a few
301 tens of metres in length) and normal faults, departing from the cones' craters. On account of this
302 observation, and their limited length, these structures can be regarded as due to volcano-tectonic
303 processes such as deformation due to magma upwelling and subsequent magma outpouring with
304 shallow deflation. Less than 0.5 km south of the Hofudreidarmuli volcano there are other vents that,
305 together with those described above, comprise a N-S-trending elongated zone of craters
306 (Saemundsson et al., 2012). In the SW block sub-area, the Theistareykjahraun lava field is also
307 characterised by the presence of several effusion points that appear coeval based on the similar
308 stratigraphic level of the outpoured lavas (Fig. 3). Although more detailed investigations are
309 necessary to assess the complete distribution of vents within this lava field, the vents do appear to
310 be concentrated in a general N-S alignment.

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312 **4. Discussion**

313 Through the collection of new detailed field data we are able to determine the Holocene
314 displacement field in the area surrounding the junction between the HFF and the GF. Our analysis

315 of the HFF enabled us to assess that the surface expression of this major transcurrent structure is
316 represented by an en-échelon arrangement of faults rather than a single, continuous, strike-slip fault.
317 We also observed several transtensive and locally transpressive structures, some of which had
318 already been recognized by Gudmundsson (1993). With the purpose of defining how recent
319 tectonics has affected the area, we also quantified in detail for the first time the deformation along
320 the GF and the opening direction of the associated fissures.

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322 *4.1. Fault geometry and kinematics*

323 *4.1.1. The Husavik-Flatøy Fault (HFF)*

324 We found that the portion of the HFF studied is composed of three main, en-échelon
325 arranged, WNW-ESE-striking segments linked by NNW-SSE-striking fault zones (Fig. 11). The
326 latter are characterised by dip-slip faults with scarps mainly facing towards the WSW. The right-
327 stepping arrangement of the WNW-striking segments, and their right-lateral strike-slip component
328 of displacement, are compatible with local extension manifested as asymmetric pull-apart basins.
329 We interpret the observed geometry in terms of the structural inheritance of older, N-S-striking, dip-
330 slip faults that very likely interfered with tectonic movements along the deep-seated HFF wrench
331 fault. In fact, as can be observed in Figure 2, several N-S-striking older faults occur in the Pliocene-
332 Early Quaternary rocks north and south of the studied area. Our interpretation is consistent with
333 previous research elsewhere (Mann, 2007; Mann et al., 2007), which, based on field regional and
334 global case studies of strike-slip faults in complex structural settings, interpreted the formation of
335 restraining and releasing bends as the effect of the interaction between strike-slip fault systems and
336 inherited structures in the basement. In particular, the Jamaican field case discussed in Mann et al.
337 (2007) was interpreted in terms of a left-lateral transcurrent fault interacting with oblique structures,
338 which resulted in the formation of a topographic uplifted area due to local transpression. Based on
339 the model proposed by Mann et al. (2007), we suggest that a major right-lateral structure (as
340 opposed to the Jamaican, left-lateral case) such as the HFF, interacting with older structures, would

341 produce the opposite configuration, i.e. the formation of pull-apart basins associated with
342 transtension in a right-stepping geometrical arrangement. The above interpretation is also consistent
343 with recent research by Curren and Bird (2014) that produced a plane-stress finite-strain physical
344 analogue model proving the effect of pre-existing mechanic discontinuities on the evolution of
345 strike-slip fault systems.

346 At a more local scale, along the easternmost portion of the HFF the presence of en-échelon
347 fissures and Riedel faults in a left-stepping arrangement has been observed (e.g. southeastern zone
348 of Figs. 5A and 11). These may be regarded as the earlier structures that develop along a wrench
349 zone; an interpretation consistent with the fact that, although the HFF is relatively old, the build up
350 of younger lava flows hindered the development of a single, well-defined wrench fault plane at the
351 surface. Hence, the observed en-échelon fissures and Riedel faults may be interpreted as an early
352 stage of development of the wrench fault in the uppermost and younger rocks.

353 With regard to the supposed continuation of the HFF east of the triple junction, Hjartardóttir
354 et al. (2012) suggested the buried prolongation of the HFF as far as the Krafla Fissure System
355 (KFS). The above hypothesis was based on two facts: i) earthquake migration from the KFS
356 towards the HFF was observed during the Krafla rifting episode; ii) the central graben of the KFS
357 widens abruptly at the HFF-KFS intersection, and the maximum fracture density in the KFS is
358 accordingly found in this area. Our field survey and interpretation of detailed satellite images up to
359 2.5 km southeast of the triple junction did not show evidence of strike-slip faulting at the surface
360 and structures parallel to the HFF. This is in agreement with Metzger et al. (2013) who, based on
361 GPS data and back-slip modelling, suggested that the HFF ends at the TFS. Furthermore, Geirsson
362 et al. (2006) and Metzger et al. (2013) pointed out that more than 60% of total relative plate motion
363 of 20.3 mm yr^{-1} (e.g. DeMets et al., 1994) is accommodated by the offshore Grimsey Oblique Rift,
364 and the HFF dissipates only about 30% of it. Therefore, although we cannot rule out the possible
365 prolongation of the HFF at depth, based on our field data and data from the literature, we suggest
366 that either the HFF ends at the TFS or it extends at depth but has not yet affected the surface.

367

368 *4.1.2. The Gudfinnugja normal fault (GF)*

369 Our detailed study of the GF, the westernmost structure of the TFS, allowed us to determine
370 that along the 4 km segment south of the triple junction, the fault offset is consistently greater than
371 20 ± 2 m and peaks at 33 ± 2 m, whereas north of the triple junction, there is a decline in vertical
372 throw with a dominant range of 15-20 m and a peak of 28 m. Moreover, the northern section of the
373 GF affects 14.5-ka-old lavas on both sides, whereas to the south, 14.5-ka-old lavas crop out on the
374 eastern block and 2.4-ka-old lavas on the western block. This suggests that the actual offset south
375 of triple junction is likely to be at least between 28 and 53 m, taking into account the average 20-m
376 thickness of the 2.4-ka-old lavas. Also, recent GPS data (Jouanne et al., 2006), indicate that in the
377 last few decades the area north of the triple junction has been moving westward at a much lower
378 velocity than the area south of the triple junction. Our results suggest that this differential
379 behaviour occurred over a much longer interval, producing a cumulative vertical offset that is lower
380 north of the triple junction than south of it.

381 We also noted that the deformation style dramatically changes across the triple junction: south
382 of it, a steeply-dipping monocline is associated with the GF along the hanging-wall block, whereas
383 no monocline can be observed north of the triple junction. The occurrence of monoclinical structures
384 flanking normal faults in Iceland has been explained in terms of: i) the friction produced along the
385 fault plane at depth (Gudmundsson et al., 1993); ii) the upward fault growth (Grant and Kattenhorn,
386 2004), and iii) the original geometrical attitude of lava beds (Sonnette et al., 2010). Our data
387 indicate that south of the triple junction the younger lavas were, at least in part, emplaced against
388 already existing west-facing fault scarps and this implies that the original dip-direction of the lava
389 beds after emplacement was toward the west. However, field evidence also indicates that lavas
390 within the monocline dip as steeply as 65° , too steep to correspond to their original attitude.
391 Moreover, locally, monocline lavas display flow direction structures that suggest they have been
392 tilted after emplacement. Since surface fault movements also occurred prior to the emplacement of

393 these younger tilted lavas, the model of Grant and Kattenhorn (2004) cannot be applied here
394 because the existence of surface fractures along the GF, earlier than the emplacement of the tilted
395 lavas, is incompatible with the successive upward propagation of a fault plane. Therefore, we
396 suggest that the presence of the monocline here can be interpreted in terms of a combination of the
397 original attitude of the lava beds and post-emplacement deformation.

398

399 *4.2 Tension fracture opening directions*

400 We discuss here our data on tension fracture opening directions as collected in the different
401 sub-areas and attempt a comparison with recent GPS data, although we need to add a note of
402 caution that opening directions derived by tension fracture dilation represent a cumulative offset
403 since 14.5 ka BP or 2.4 ka BP (depending on the affected rock units) and hence can be regarded as
404 representing the long-term displacement field.

405 Starting with the TFS zone, along the whole length of the GF, tension fractures strike mostly
406 N-S (Figs. 3 and 10A) with dominant N90°E-trending opening directions. This geometry does not
407 change north and south of the triple junction, as also shown by Figure 10C. In the sector east of the
408 GF we also observed some northerly-striking fractures, whose geometry does not change across the
409 supposed buried prolongation of the HFF. The Theistareykjahraun lava field is characterised by the
410 presence of several N-S-aligned emission vents that appear to be coeval based on the similar
411 stratigraphic level of the outpoured lavas, suggesting they represent N-S-striking eruptive fissures.
412 This observation, together with the diffuse presence of N-S-striking normal faults and tension
413 fractures along the TFS zone, suggests that this area was fed in the past by N-S-striking dykes,
414 consistent with previous observations by Saemundsson et al. (2012). Observations during episodes
415 of dyke emplacement at volcanic rift zones elsewhere have suggested that there is a relation
416 between dyking and slip increments along existing faults and tension fractures, as well as the
417 opening of new fractures (Abdallah et al., 1979; Bjornsson et al., 1979; Pollard et al., 1983; Wright
418 et al., 2006). This, in turn, provided evidence that faulting and tensional fracturing were triggered

419 by the dyke intrusion (Rubin and Pollard, 1988) and not vice-versa. The stress concentration at the
420 advancing dyke tip produces deformation along fault and fracture planes that strike parallel to the
421 dyke plane. Considering the above, we suggest that the long-term deformation along the studied
422 part of the TFS zone may have resulted from the contribution of multiple pre-historic-Holocene
423 dyke injections. Since dykes were injected in a N-S direction, the resulting fracture openings here
424 trend E-W. The GPS vectors of Jouanne et al. (2006) regarding the horizontal velocity field of
425 1997-1999 expressed in the Eurasia fixed reference frame (Fig. 12A) reveal a WNW-directed
426 escape of our whole study area. These vectors are oblique with respect to the studied GF zone and
427 may represent a short-term velocity field superimposed on the long-term, E-W-directed deformation
428 that we documented through our fracture opening data. In other words, the dominant direction of
429 deformation obtained by regional GPS and plate tectonic data is WNW-ESE (Fig. 12), but the field
430 data of the structures along the GF recorded a more E-W-trending dilatation, which is probably due
431 to repeated N-S dyke intrusions.

432 In the SW-block (south of the HFF and west of the GF) we documented a 2.5-km-wide N-S
433 strip, immediately west of the GF, characterised by the absence of tension fractures. Since this area
434 is adjacent to the active rift zone subjected to magmatic intrusions, we can interpret the observed
435 absence of extensional structures as the possible consequence of local, horizontal compressive
436 stresses induced by dyke intrusions along the rift. Previous studies elsewhere in fact
437 (Gudmundsson, 2003; Gudmundsson and Loetveit 2005; Maccaferri et al., 2013), suggested that the
438 magmatic overpressure of intruding dykes along rift zones induces a local stress field perturbation
439 with lateral horizontal compressive stress.

440 Farther west in the SW-block (at a distance > 2.5 km from the GF) tension fractures do occur,
441 but here they have a dominant $N0^{\circ}$ - 10° E strike and $N110^{\circ}$ E-trending opening direction (Fig. 10)
442 that indicate a small component of right-lateral oblique opening. If we compare the distribution of
443 fracture strikes directly measured in the field in the SW-block (Fig. 10) with fracture strikes shown
444 for the same SW-block in Figure 3, we observe that the latter strike more NNE-SSW. This is due to

445 the fact that the rose diagrams of Figure 3 also include the structures mapped by means of satellite
446 images in the southwesternmost part of the area, where most tension fractures and faults strike
447 NNE-SSW. The long-term opening direction in the SW-block is identical to the average direction
448 derived from short-term GPS data provided by Jouanne et al. (2006) for the years 1999-2002 (Fig.
449 12B). Metzger et al. (2013), studying the present kinematics of the Tjörnes Fracture Zone,
450 suggested that the overall spreading direction ranges from N109.4°E to N115.1°E, which is similar
451 to our average N110°E-trending opening direction. Our long-term opening directions are also
452 consistent with horizontal GPS velocities measured all over Iceland outside the rift zone (Geirsson
453 et al., 2006; Árnadóttir et al., 2009), and with plate motion models such as REVEL (Sella et al.,
454 2002) (Fig. 12D). This may be explained in terms of horizontal, magma-induced compressive stress
455 fading away at distance from the rift zone, where the regional tectonic stress takes over in
456 controlling the opening direction of fractures.

457 Along the HFF, tension fractures strike between N315°W and N-S, mainly N337°W
458 (consistent with Gudmundsson, 1993), and their opening directions are mostly N80°-110°E. In the
459 sector north of the HFF we observed very few northerly-striking fractures. Jouanne et al. (2006)
460 show that the modulus of velocity vector is greater south of the HFF and west of the GF in the fixed
461 European frame. The 1997-2011 GPS horizontal data illustrated in Metzger et al. (2013) indicate
462 (Fig. 11C) that the tectonic block south of the HFF and west of the GF is stable with respect to a
463 fixed North America frame, whereas the block north of the HFF moves towards the ESE.

464 By merging all the data it is possible to illustrate the long-term Holocene displacement field.
465 In Figure 13 all the fracture opening directions have been averaged and plotted as extension
466 directions (dashed white line). The areas of larger measurement frequency have been represented by
467 means of diverging blue arrows, which indicate the local dominant extension direction. The
468 resulting displacement field is characterised by quite homogeneous E-W orientations to the east in
469 block 1, which coincides with the main rift zone. Westwards, the displacement orientations bend to
470 N110°E directions. In order to account for this rotation it is necessary to insert another structural

471 boundary along which a change in the dominant extension direction might occur, separating the
472 SW-block into sub-blocks 3 and 4. This boundary may coincide with the approximately 1-km-wide
473 swarm of Holocene faults and fractures located west of the Theistareykjahraun lava field (Figs. 2
474 and 3). These displacement directions are coherent with the long-term and present-day "escape" of
475 the southwestern portion of the study area bounded to the north by a right-lateral transtensional
476 shear zone, coinciding with the HFF. It is also consistent with the presence of a right-lateral strike-
477 slip component, and a normal dip-slip component, along the N114°-130°E strands of Segments I, III
478 and V of the HFF, as well as with the dominant normal dip-slip motions along Segments II and IV.

479

480 **5. Conclusions**

481 With the purpose of assessing how recent and active tectonics have been working in the area of
482 the junction between the HFF and the TFS, based on our highly-detailed field survey we are able to
483 point out the following:

- 484 - Although most seismicity at the HFF is located in the offshore segment, there is also
485 evidence of recent motion along the on-land segment based on the presence of "fresh"
486 morphologies such as fault scarps and fractures, as well as evidence of offsets in Holocene
487 lavas. Holocene motion of the HFF in the study area is marked by a right-lateral strike-slip
488 component that is difficult to quantify in the field, and a dip-slip component that gradually
489 decreases towards the GF.
- 490 - The studied portion of the HFF is composed of three main, right-stepping WNW-ESE-
491 striking, fault segments. The areas between these segments are subject to extension
492 associated with the presence of releasing bends within NNW-SSE-striking fault zones.
493 These bends are characterised by dip-slip normal faults, mainly (90%) dipping to the
494 WSW. We interpret, in agreement with previous research (Mann, 2007; Mann et al., 2007;
495 Curren and Bird, 2014) the observed geometry in terms of the structural inheritance of older,
496 N-S-striking dip-slip faults that very likely interfered with tectonic motion along a deep-

seated wrench fault. At one location we found a major left-stepping contractional overstep, whereas several small-scale left-stepping Riedel shears are present in the easternmost part of the HFF.

- With regard to the possible continuation of the HFF east of the junction with the GF, we cannot rule out its prolongation at depth but, based on our own field data and data from the literature, we suggest that either the HFF ends at the GF or it prolongs farther east but has not yet affected the surface.
- Our study of the GF along its whole length shows that, south of the triple junction, fault offsets are much greater than north of it, being also in part obscured by the onlap of late Holocene lava flows (total estimation of 28-53 m south vs. 15-24 m north). Additionally, the deformation style along the fault dramatically changes from monocline tilting along the whole length south of the triple junction, to a single fault scarp with no, or very limited, rotation of the hanging-wall block to the north. The geometry and kinematics of the normal faults and tension fractures along the GF indicate long-term E-W-trending dilation compatible with the emplacement of N-S-striking dykes over the Holocene.
- The absence of recent extensional features in a 2.5-km-wide strip west of the GF and south of the triple junction can be interpreted as the possible consequence of local, horizontal compressive stress induced by dyke intrusions along the rift.
- Tension fractures and normal faults do occur farther west of the 2.5-km-wide strip, which might be explained in terms of horizontal, magma-induced compressive stress that fades away at distance from the rift zone. At this distance regional tectonic stress takes over and affects the opening of tension fractures compatibly with present-day motions of the area along a N110°E direction, consistent with recent GPS measurements.
- All these data suggest that the HFF and the GF worked during the Holocene as a structural system able to accommodate differential crustal block motions and possible past dyke intrusions.

523

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529

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676

677

678 **Figure captions**

679

680 **Figure 1.** Tectonic setting of northeastern Iceland. The mid-Atlantic Ridge is here offset by the
681 Husavik-Flatey Fault and the Grimsey Lineament (after Garcia and Dhont, 2005 and Metzger et al.,
682 2013). Yellow stars indicate location of $M_w > 6$ historical earthquakes with indication of magnitude
683 and year (after Stefansson et al., 2008; Metzger et al., 2011; Grünthal and Wahlström, 2012; Stucchi
684 et al, 2012). Orange stripes represent volcano-tectonic rift zones with their names and main surface
685 fault traces (after Rögnvaldsson et al., 1998). Black triangles represent the main Quaternary central
686 volcanoes. Inset shows location of the area and the main volcanic zones of Iceland. Box locates
687 Figure 2. DAL = Dalvik Lineament; FL = Town of Flatey; GRL = Grimsey Lineament; HFF =
688 Husavik-Flatey Fault; KFS = Krafla Fissure Swarm; KR = Kolbeinsey Ridge (segmented line); KR
689 = Krafla volcano (triangle); SB = Skjalfandi Bay; TH = Theistareykir shield volcano; TJ = Tjornes
690 Fracture Zone; HU = Town of Husavik.

691

692 **Figure 2.** Fault scarps and tension fractures as mapped during previous studies in the area, along
693 with their rose diagrams. See text for data description. Location in figure 1. HFF = Husavik-Flatey
694 Fault; GF = Gudfinnugja Fault; Hö = Höskuldsvatn pull-apart; Bo = Botnsvatn pull-apart. Data of
695 earthquakes (1994-today) have been provided by Icelandic Meteorological office
696 (www.en.vedur.is). Inset shows location of Figure 3.

697

698 **Figure 3.** Detailed geological map of the study area (redrawn after Saemundsson et al. 2012) with
699 the faults and tension fractures identified in the present paper by means of both field work and
700 satellite image interpretation. Rose diagrams are provided for all the identified 637 fault scarps and
701 1016 tension fractures. Segments I to V indicate the zones of the Husavik-Flatey fault discussed in
702 the text. The dashed black lines separate the three sub-areas studied. Upper box locates Figure 4 of
703 Segment II, and lower box locates Figure 5 of part of Segment V.

704

705 **Figure 4.** *A.* Detailed map of the normal fault zone of Segment II of the Husavik-Flatey Fault based
706 on field data. *B.* and *C.* Photo looking SE and interpretation of the en-échelon pattern of normal
707 faults. *D.* General view of the westernmost NNW-SSE-striking normal fault. Location shown in
708 Figure 3.

709

710 **Figure 5.** *A.* Detailed map of part of Segment V near the eastern termination of the Husavik-Flatey
711 Fault based on field data. *B.* Examples of pressure ridges. *D.* Example of right-lateral strike-slip

712 motions. *E.* ESE-striking fault segment showing both transtensional and transpressional features in
713 correspondence of slight changes in fault strike, compatible with right-lateral strike-slip kinematics.
714 Location shown in Figure 3.

715

716 **Figure 6.** Examples of different styles of deformation along the Gudfinnugja Fault. Left column
717 shows sites located north of the junction with the HFF, right column south of it. See text for details.

718

719 **Figure 7.** Graph showing fault scarp offsets along the Gudfinnugja Fault. GPS measurements have
720 been taken every 100 m. Error is in the order of ± 2 m.

721

722 **Figure 8.** Examples of fractures measured in the studied area: *A.* Pure extensional offset; *B.*
723 Opening with a subordinate strike-slip component; *C.* Dominant strike-slip component; *D.*
724 Compressional fracture typical of transpressional zones.

725

726 **Figure 9.** Graphs of tension fracture and fault scarp strike vs. Longitude in each of the three sub-
727 areas of Figure 3. Here we plotted only the structures measured directly in the field, the structures
728 seen on satellite images have not been included. See text for details.

729

730 **Figure 10.** *A.* Map of the study area with tension fracture opening directions, main faults, GPS
731 spreading directions (from Jouanne et al., 2006) and average fracture strikes. Rose diagrams show
732 fracture strikes (black) and opening directions (blue) in the three sub-areas. *B.* Graph showing
733 tension fracture opening directions (blue circles) and spreading vector directions (yellow diamonds)
734 vs. longitude. *C.* Graph showing tension fracture opening directions (blue circles) and spreading
735 vector directions (yellow diamonds) vs. latitude.

736

737 **Figure 11.** Sketch map of the main structures identified along the Husavik-Flatey Fault, with an
738 interpretation of their overall kinematics.

739

740 **Figure 12.** *A.* 1997/1999 and *B.* 1999/2002 GPS horizontal velocity fields in NE Iceland calculated
741 in an Eurasia fixed reference frame. Ellipses correspond to a 2σ level (95 % confidence) (modified
742 after Jouanne et al., 2006). *C.* GPS horizontal velocities in a fixed North American frame (95 %
743 confidence). Green lines outline fracture swarms and central volcanoes; blue lines indicate the
744 segments of the interseismic deformation model (modified after Metzger et al., 2013). *D.* GPS
745 horizontal velocity vectors (black arrows) with respect to a local fixed reference frame. The white

746 arrows show the predicted REVEL plate motions. Ellipses represent the 2σ confidence level. Inset
747 shows an enlarged map of the active deformation zone in SW Iceland (modified after Geirsson et
748 al., 2006).

749
750 **Figure 13.** Displacement field reconstructed by averaging the opening directions (dashed lines) of
751 the tension fractures measured in the field and taking into account the kinematics and distribution of
752 the faults. The boundaries of the various blocks (numbered 1 to 4) have been determined based on
753 the location, kinematics and geometry of the main faults. Diverging blue arrows provide average
754 opening direction where there is the maximum density of field measurements. Black arrows provide
755 the vector of rigid body translation applied to the various blocks as derived by the average
756 displacements measured in the field.

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