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Dikes, minor faults and mineral veins associated with a transform fault in North Iceland: Reply

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We welcome the opportunity to discuss further our results on the structure and formation of the Tjörnes fracture zone, a transform fault that comes onto land in North Iceland (Fjäder *et al.* 1994). The main points in the Discussion of Jancin *et al.* are: (1) that a dextral transform fault cannot generate the stress field needed to explain the curvature of the dikes observed near the Husavik–Flatey fault, the main structural element of the Tjörnes fracture zone; (2) that there was widespread horizontal block rotation on the Flateyjarskagi peninsula which is responsible for the change in dike strike on approaching the Husavik–Flatey fault; (3) that the dikes on the north cost of the Flateyjarskagi peninsula belong to the same swarm as those on its western coast; (4) that Fjäder *et al.* (1994) do not define the southern boundary of the 3–5 km wide zone of intense crustal deformation at the north coast of the Flateyjarskagi peninsula; and (5) that the Husavik–Flatey fault is not a single fault. In this Reply, we will briefly discuss these points.

STRESSES AT RIDGE–TRANSFORM JUNCTIONS

The Tjörnes fracture zone is just one of hundreds of oceanic fracture zones, many of which have been studied in detail. Although it is partly exposed on land, the Tjörnes fracture zone does not seem to differ in any fundamental way from other such zones or be formed by a different mechanism. It follows that a general model that is supposed to explain the structures associated with the Tjörnes fracture zone should explain similar structures associated with other fracture zones as well. In this Reply, however, the focus is on the data from the Tjörnes fracture zone, in particular the data from the Flateyjarskagi peninsula.

Structural and seismic evidence indicate a limb, buried by younger lava flows, at the eastern end of the Husavik–Flatey fault, and also at its western end. At the time of emplacement of the dikes on the Flateyjarskagi peninsula, the structure of the Husavik–Flatey fault may thus have been similar to that in Fig. 1. Ridge-transform angles at oceanic fracture zones are normally between 50 and 90°, but most commonly 80–90° (Atwater & Macdonald 1977); that of the Kolbeinsey ridge–Husavik–Flatey fault is 65°. In Fig. 1 the ridge-transform angle is 90°.

In their Discussion, Jancin *et al.* assume that the curvature of the stress trajectories, as indicated by the change in dike trend, requires an earlier sinistral (left-lateral) displacement along the Tjörnes fracture zone. Figure 2 represents boundary-element results, using the BEASY (1991) analysis program, on the stress field associated with the ridge-transform junctions in Fig. 1. The results show that the trajectories of the maximum compressive principal stress, curve in two directions at the ridge-transform junctions. Most dikes are pure extension fractures and follow the trajectories of the maximum compressive stress. In Fig. 2, dikes in box A would curve to the left, whereas those in box B would curve to the right. These results show that the assumption of Jancin *et al.* (1995) is incorrect; a dextral (right-lateral) transform fault can easily generate the stress field needed to explain the curvature of dikes observed on the Flateyjarskagi peninsula.

The dike swarm on the western coast of the Flateyjarskagi peninsula (here referred to as the Grenivik swarm), represents a fossil volcanic system which formed a part of the rift zone in North Iceland. Most of the dike measurements in the northernmost part of the Flateyjarskagi peninsula are to the east of the Grenivik dike swarm and would thus correspond roughly to box B in Fig. 2. According to the model of Jancin *et al.*, which is the same as that of Young *et al.* (1985, fig. 14), the dikes in box B would require sinistral (left-lateral) strike-slip along the Tjörnes fracture zone, whereas those in box A would require dextral (right-lateral) strike slip, which shows that their model is mistaken.

HORIZONTAL BLOCK ROTATION

Jancin *et al.* and Young *et al.* propose that the dike swarm on the northern coast of Flateyjarskagi

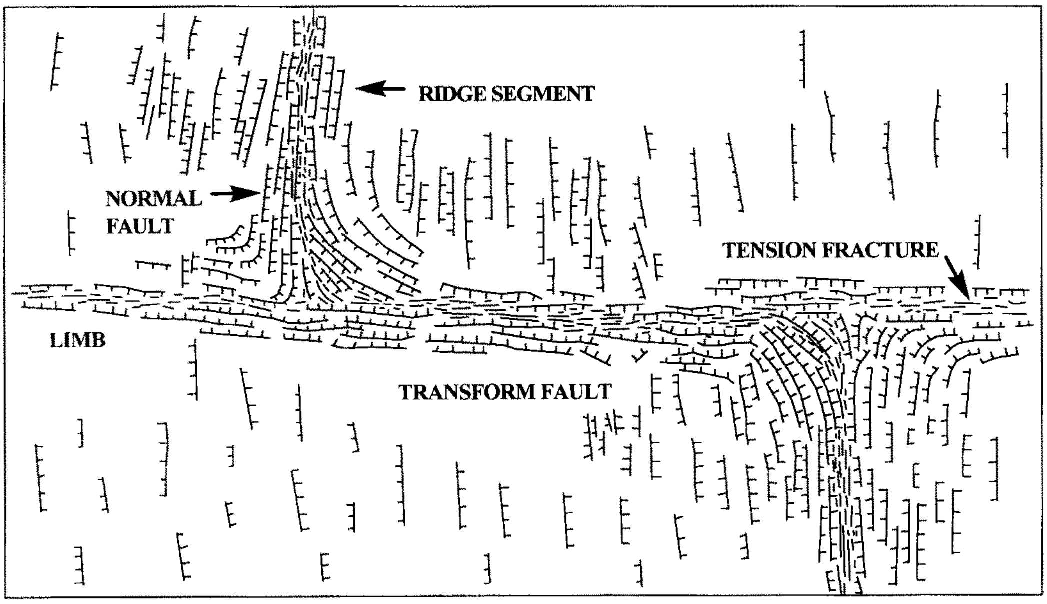

Fig. 1. Schematic illustration of the main structural elements associated with oceanic transform faults. These include transform-parallel tension fractures, normal faults, grabens and (mostly) aseismic limbs (e.g. Fox & Gallo 1986, Barth *et al.* 1994). These observations show that ridge-transform junctions are normally characterised by a curved fabric, such as occurs on the Flateyjarskagi peninsula. The dimensions of the graben offshore the Flateyjarskagi peninsula are similar to those of a typical rift-zone valley. There is evidence that the Tjörnes fracture zone had limbs that are now mostly covered by lava flows and sediments.

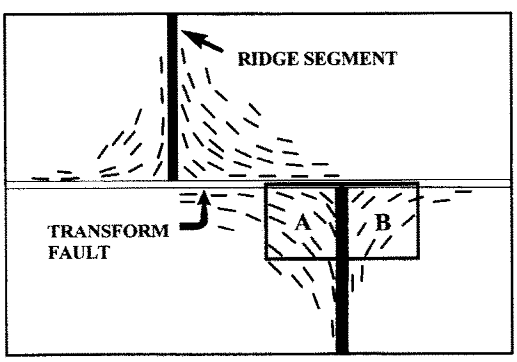

Fig. 2. Trajectories (ticks) of the maximum compressive principal stress at the ridge-transform junctions in Fig. 1. Dikes that follow these trajectories would curve to the left in box A and to the right in box B. The graben structure of oceanic transform faults indicates that, in addition to the transform-parallel loading, there is tensile loading perpendicular to the transform fault (Gudmundsson 1993). The ridge segments and the fracture zone are modelled as mode I (opening mode) cracks with internal springs of stiffness 0.01 MPa, and the lithosphere as a semi-infinite elastic plate loaded in biaxial tension at its margins. Using the uppermost kilometre of the Icelandic crust as representative for a young oceanic crust, Young's modulus of the elastic plate is 10 GPa and Poisson's ratio is 0.25. The biaxial tensile loading is 6 MPa, equal to the maximum in situ tensile strength of the uppermost part of the crust in Iceland (Haimson & Rummel 1982).

(here referred to as the Flatey swarm) is a clockwise-rotated part of the Grenivik swarm. Young *et al.* (1985) estimated most dike thicknesses by the eye or by pacing (Fjäder *et al.* (1994) measured them with tape) and, apparently, did not recognise a significant difference in dike thicknesses in these two swarms. The arithmetic mean thickness of 226 dikes in the Grenivik swarm is 5.4 m, whereas that of 144 dikes in the Flatey swarm is only 4 m (Fjäder *et al.* 1994, figs. 8 & 9). This thickness difference indicates that these are two separate swarms derived from different sources and formed in different stress regimes, as is suggested by Fjäder *et al.* (1994).

The northern end of the 17-km-long continuous profile of Fjäder *et al.* (1994) is at the margin of the Grenivik dike swarm; a different dike swarm, the Hrisey swarm, takes over further to the north (Långbacka & Gudmundsson 1995). The average thickness of the dikes in the Hrisey swarm is 6.2 m. Young *et al.* (1985) studied only a part of the 17-km-long profile and, apparently, did not distinguish between the Grenivik dike swarm and the Hrisey swarm.

There are many NE-trending dikes in the swarm at the north coast of the Flateyjarskagi peninsula (Jancin *et al.* fig. 1; Fjäder *et al.* 1994, fig. 5). Young *et al.* (1985, fig. 18) omit these dikes in their calculations of the "average strike" of the dikes "as they likely represent synshear zone intrusions emplaced subsequent to the majority of strain". We know of no evidence that all these dikes are younger than the WNW-trending dikes. In the Fjäder *et al.* (1994) model, the NE-trending dikes at the north coast form in a direction that is perpendicular to the direction of the spreading vector (cf. Gudmundsson 1993).

Many dikes shown in Young *et al.* (1985, figs. 7 & 18) are not located within the dike density traverses presented in their fig. 9, and it is not clear how these dikes were selected. The change in "average strike" of dikes, as proposed for the dikes approaching the northern coast of the Flateyjarskagi peninsula (Young *et al.* 1985, fig. 18), can be misleading. For example, if most dikes in a set strike either north or east the "average strike" of that set is northeast. The number of dikes used to infer each "average strike" is not given; the only information provided in the caption to fig. 18 of Young *et al.* (1985) is that these averages are "based on a more complex data set than shown in fig. 7". Clearly, rose diagrams or histograms of the dike strike in each set would have been more informative than a single tick giving the "average strike".

Jancin *et al.* state that "we had noted that the northernmost part of the Flateyjarskagi shear zone shows the greatest intensity of deformation involving veins, faults and tectonic breccias" and that "Fjäder *et al.* (1994) recognized this same intensively deformed zone of about 3–5 km width, bounded along the north coast (they did not define their basis for delineating a southern boundary to this zone)". Our basis for delineating the southern boundary of this zone is, of course, that there the intensity of the deformation diminishes abruptly; there is, indeed, "little evidence for a regional crustal deformation south of the 3–5 km wide on-land fault zone". (Fjäder *et al.* 1994, p. 115).

Fjäder *et al.* (1994, p. 116) state that the "irregularity in the attitude of the lavas in the 3–5 km wide fault zone suggests that rotational deformation played a part in its tectonic evolution". As regards the dip of the lavas in the fault zone, the rotational deformation is obvious because "the tilting of the lavas (in excess of the regional tilting in this part of Iceland) ranges from 15 to 35°". (Fjäder *et al.* 1994, p. 117). Horizontal rotation may have played a part in the evolution of the fault zone, particularly during its early stage of development, but the "absence of rotated dike segments suggests that no great rotation of crustal blocks occurred subsequent to the dike emplacement" (Fjäder *et al.* 1994, p. 117). Young *et al.* (1985) maintain that block rotation was widespread south to the Gilsa–Latur line, and now Jancin *et al.* suggest that block rotation affected the lavas on the western coast of the Flateyjarskagi peninsula, at least 20 km south of the fault zone. Jancin *et al.* believe that this horizontal block rotation is responsible for the change in dike strike along the peninsula, whereas Fjäder *et al.* (1994) attribute this change to the curved stress trajectories at the ridge-transform junctions.

In the 17-km-long profile along the western coast of the Flateyjarskagi peninsula, from Grenivik to Latur, Fjäder *et al.* (1994, figs. 4 & 5) measured a 30° clockwise change in the strike of the basaltic lava flows, but no statistically significant change in the strike of the associated dikes, and concluded that the change in strike of the lavas was primary and not related to horizontal block rotation. Jancin *et al.* state that this 30° clockwise change in the lava flow strike "does not appear to be primary" and is "likely a manifestation of rotations about subhorizontal axes during rotational normal faulting". These rotations about N–NNE-trending subhorizontal axes has "effectively rotated the flow strikes progressively clockwise, while causing only minor changes in the trends of originally N–NNE-striking, subvertical dikes".

Jancin *et al.* (1995) do not provide any evidence that the 30° change in the lava strike is not primary. The rotational normal faults that they propose were not found along the 17-km-long profile. This profile has essentially complete exposure along its whole length; part of it was omitted in the studies of Young *et al.* (1985, figs. 7 & 9). Their model for generating horizontal rotation of the lava flows while not rotating the dikes seems to be the one in fig. 13 of Young *et al.* (1985) where they represent a "schematic view of rotational normal faulting". In this model, Young *et al.* (1985) do not specify the loading conditions, crustal elastic properties nor stresses, and show no stress trajectories or areas of shear-stress concentrations. Their model is a cartoon with no indication as to whether or not the associated stress field would fit with their speculations. If there was horizontal block rotation by 30° along the 17-km profile that Fjäder *et al.* (1994) measured, one would expect many strike-slip faults to form, but these are not observed.

If the Jancin *et al.* model were correct, major horizontal rotation might be expected on the Tröllaskagi peninsula, which has a dome-like structure similar to that of the Flateyjarskagi peninsula, but there exists no evidence of such a rotation (Långbacka & Gudmundsson 1995). The dome-like structure, and the associated variation in the strike of the lava pile, on both peninsulas appear to be mostly primary and unrelated to horizontal block rotation.

STRUCTURE OF THE TJÖRNES FRACTURE ZONE

Jancin *et al.* state that "there is no structural or bathymetric evidence indicating a single, through-going right-lateral fault passing from Húsavik westnorthwest to near the coast of Flateyjarskagi (Thors 1983)". The Husavik–Flatey fault runs for 25 km across the south part of the Tjörnes peninsula. Where the fault dissects Tertiary and Pleistocene rocks, it is marked by a very clear fault scarp that, in places, is as high as 200 m (Gudmundsson *et al.* 1993). In the Holocene lava flows in the eastern part of the Tjörnes peninsula, the trace of the Husavik–Flatey fault is also very sharp, as is easily seen on arial photographs and in the field (Gudmundsson *et al.* 1993, figs. 7 & 9).

Offshore the Flateyjarskagi peninsula, the Husavik–Flatey fault is marked by a 5–10 km wide and 3–4 km deep fracture-zone (transform) valley, partly filled with sediments that give rise to a pronounced negative gravity anomaly (Gudmundsson *et al.* 1993). This is recognised by Jancin *et al.* who refer to "the sediment-filled graben located just off the peninsula's north coast". The Husavik–Flatey fault is the main structure of the Tjörnes fracture zone and should be identified with the transform-tectonised zone of a typical oceanic transform fault. Thus, provided a typical transform-tectonised zone can be regarded as a single fault, the Husavik–Flatey fault should be regarded as a single fault as well.

CONCLUSIONS

Jancin *et al.* propose that the WNW-trend of the dikes in the northernmost part of the peninsulas of Flateyjarskagi and Tjörnes "exists because the rock masses that contain the dikes have undergone clockwise rotations during TFZ-related shear". We have shown (Fig. 2) that the curvature of the dikes on Flateyjarskagi is a direct consequence of the general stress field associated with the ridge-transform junctions, that the dikes on the northern coast are different from those on the western coast, and that the evidence of major horizontal block rotation south of the main on-land fault zone is lacking. In our model the transform-parallel graben, normal faults, and dike swarm associated with the Tjörnes fracture zone are explained in terms of a transform–perpendicular tensile stress. This tensile stress, with the ridge-perpendicular tensile stress, gives rise to a stress field that explains the curved fabric and other structural elements at ridge-transform junctions.

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