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

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We welcome an independent assessment by Fjäder *et al.* (1994) of an area encompassed by our previous work (Young *et al.* 1985). We believe it is productive that alternative viewpoints be available when assessing complex, fracture-dominated deformation such as exists along the Tjörnes Fracture Zone (TFZ) of Iceland.

Fjäder *et al.* (1994) described dikes, minor faults and mineral veins mostly observed along parts of the western and northern coasts of the Flateyjarskagi peninsula in north-central Iceland. Particularly in the northern part of this peninsula, Tertiary basalts contain structural elements formed and deformed by right-lateral transform-fault activity near the southern boundary of the TFZ (Jancin *et al.* 1981). The stratigraphy, K/Ar ages and structure of the Flateyjarskagi peninsula and adjacent area have been discussed by Jancin *et al.* (1985) and Young *et al.* (1985). From south to north along the western half of Flateyjarskagi, as one approaches the TFZ, lava bedding and dikes display a progressive 0–110° clockwise change of trend, and lava dip angles steepen from ~15–45° NW (Young *et al.* 1985). We noted that this structural curvature is accompanied by a generally progressive increase in fault, vein and (locally) dike intensity, and an elevated paleogeothermal gradient as inferred from vein and amygdule minerals.

Fjäder *et al.* (1994) largely confirmed the structural observations generalized above, although they gathered structural data along only one relevant traverse (their fig. 5, profile C) within the *interior* of the peninsula. However, they disagreed with the previous interpretation of these structures by Young *et al.* (1985) on a significant point: Fjäder *et al.* (1994) did not concur that significant tectonic rotations have occurred along northern Flateyjarskagi. We believe that some of their disagreement stems both from a misunderstanding of key points in Young *et al.* (1985) and an areally incomplete study of the attitudes of structural elements within the interior of the peninsula, as discussed below.

In Young *et al.* (1985), we demonstrated that the 0–110° clockwise change in the strike of lavas and dikes occurs over an 11-km wide zone immediately south of the Flatey fault. This zone trends WNW, approximately parallel to the TFZ boundary. The Flatey fault passes within 1 km of the north coast of Flateyjarskagi, and is one of a series of left-stepping, right-oblique faults comprising the Húsavík–Flatey fault system (HFFS) (Voight *et al.* 1983). The HFFS is considered to be the present southern boundary to the TFZ. Contrary to the depiction of the Húsavík–Flatey fault in Fjäder *et al.* (1994) (fig. 1), there is no structural or bathymetric evidence indicating a single, through-going right-lateral fault passing from Húsavík westnorthwest to near the north coast of Flateyjarskagi (Thors 1983).

Young *et al.* (1985) evaluated three hypotheses regarding the aforementioned 0–110° structural curvature in the northern Flateyjarskagi peninsula: (1) formation of dikes associated with radial or circumferential stress trajectories near the Flateyjarskagi central volcano: (2) dike intrusion during lava pile formation in a transform-influenced curved stress field; and (3) flow and dike reorientation by clockwise tectonic rotations, about roughly subvertical axes, due to TFZ-related, right-lateral heterogeneous, approximated simple shear. As explained in that paper, the weight of the data favored the third interpretation. We therefore referred to the 11-km wide zone of pronounced structural curvature as the Flateyjarskagi shear zone. The southern limit to the Flateyjarskagi shear zone was tentatively defined by the Gil-Látur line, a TFZ-subparallel hypothetical boundary separating dikes to the south, having distinct mean NNE trends, from dikes to the north which progressively swing clockwise and ultimately attain WNW mean trends along the north coast (Fig. 1, after Young *et al.* 1985, figs. 5 and 7). The Gil-Látur line also divides lavas with SW–WSW dips, to the south, from flows to the north which progressively swing clockwise in strike, and which dip steeply to the NW along the north coast (Fig. 2, after Young *et al.* 1985, figs. 3 and 5). In western Flateyjarskagi, both dikes and flows show roughly similar amounts of clockwise curvature to the north of the Gil-Látur line.

line is not surprising, given the data of Young *et al.* (1985, fig. 7), and is certainly an insufficient logical basis for claiming the absence of regional crustal rotations to the north of this line.

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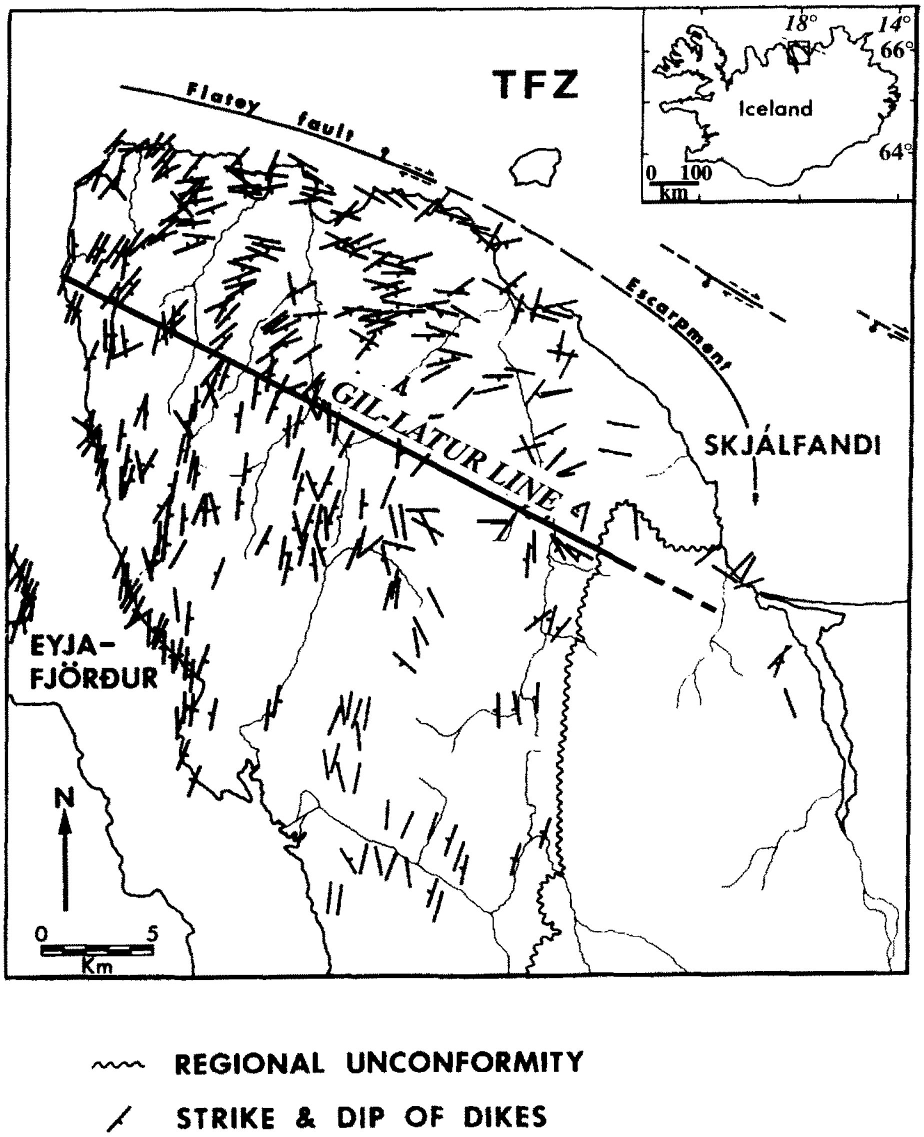

Fig. 1. Basaltic dike orientations in Flateyjarskagi. The Gil-Látur line is the hypothetical southern boundary to the Flateyjarskagi shear zone. Note the abundance of ENE–WNW-trending dikes near the TFZ and the lack of dikes in the post-unconformity lavas (younger than ~6.5 Ma) on the east side of the peninsula. We interpret the curvature in dike trends as largely due to tectonic rotations, with some superposition of younger, non-rotated WNW-trending dikes near the north coast. The intensities of dikes shown here do not rigorously reflect the actual intensities observed in the field. After Young *et al.* (1985, figs. 5 and 7).

mation involving veins, faults and tectonic breccias (Young *et al.* 1985). Fjäder *et al.* (1994) recognized this same intensively deformed zone of about 3–5 km width, bounded along the north coast, but did not define their basis for delineating a southern boundary to this zone. They did not recognize any regional crustal deformation to the south of this zone, and did not support our interpretation of clockwise regional crustal tectonic rotations in northern Flateyjarskagi. They interpreted the WNW dike trends along the north coast as primary (original) and indicative of NE–SW extension across the TFZ.

However, the distribution of dikes throughout western Flateyjarskagi (Fig. 1) well illustrates the progressive clockwise swing in dike trends to the north of the Gil-Látur line. With only the single relevant interior site north of the road-accessible Dalsmynni valley, Fjäder *et al.* (1994) (fig. 5) have not shown sufficient areal distribution to their dike observations to have gleaned (or tested) the progressive pattern shown in Young *et al.* (1985) (fig. 7).

In Young *et al.* (1985) we considered two hypotheses (1 and 2 listed earlier) encompassing the notion that northern Flateyjarskagi dike trends might be largely primary. We considered the hypothesis of a transform-ridge stress reorientation producing a curved-stress field that in turn controlled the dike trends, requiring no subsequent rotation. This hypothesis was similar to that presented in Fjäder *et al.* (1994) but its test incorporated the full, regionally complete, areal distribution of dike trends throughout Flateyjarskagi. One reason we tentatively rejected this hypothesis was because the clockwise swing in dike trends thus implied a former rift-zone and transform junction requiring right-lateral offset of the rift zones, with left-lateral slip along the transform. There is no evidence for significant present or former

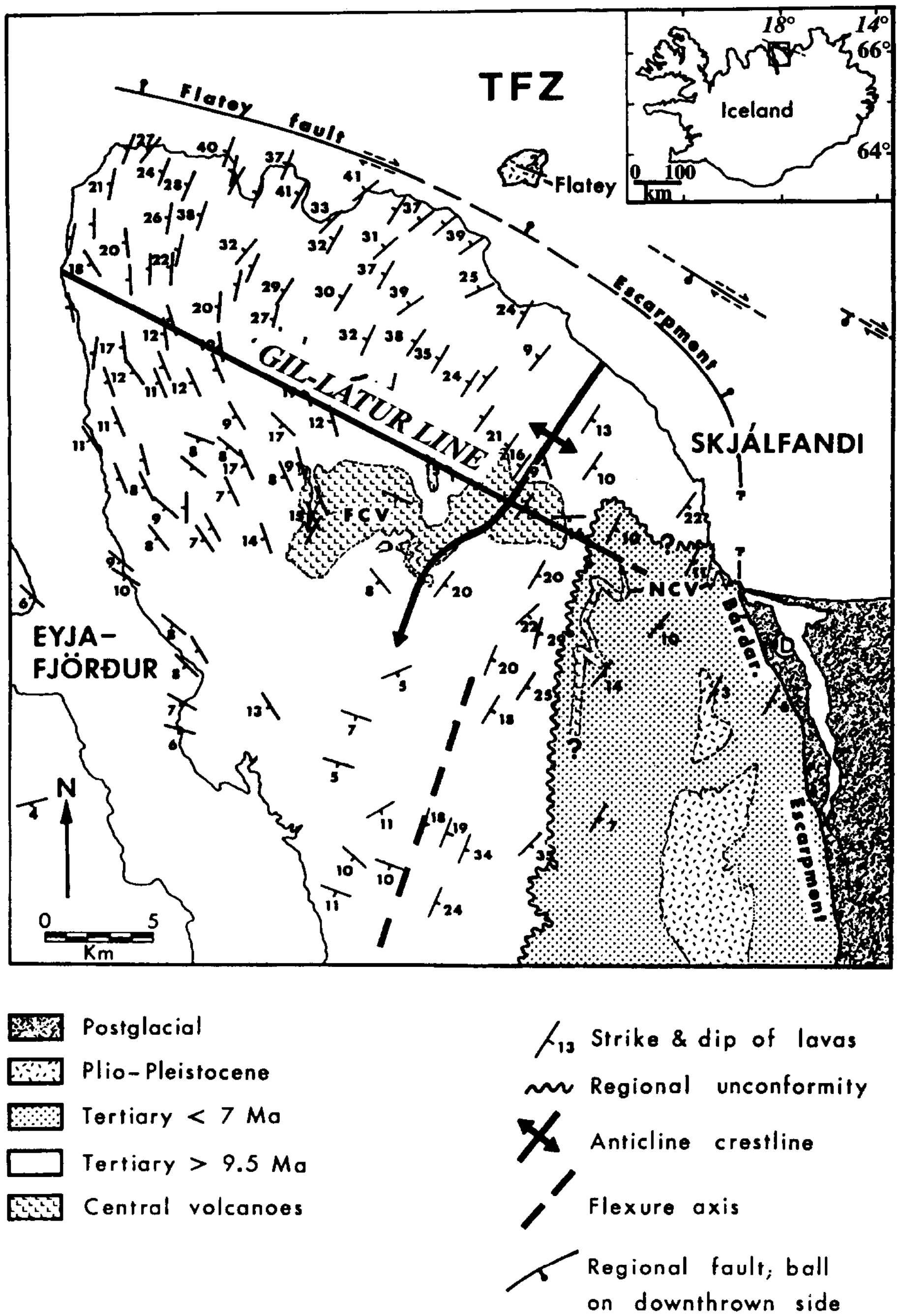

Fig. 2. Lava flow orientations in Flateyjarskagi. The Gil–Látur line shown was first determined by inspection of the dike orientations and then transferred to this figure. Note the progressive change in strike and increase in dip angle for flows in the north and northwest parts of the peninsula. The NNE-trending, heavy dashed line in the south marks the hingeline of a monoclinal flexure. FCV, Flateyjardalur central volcano; NCV, Náttfaravík central volcano. After Young *et al.* (1985, figs. 3 and 5).

displacements along the TFZ other than right-lateral, consistent with the 100-km left-lateral offset of the northeast Iceland rift zone from its offshore continuation along the Kolbeinsey Ridge.

Fjäder *et al.* (1994) (pp. 113 and 115) noted that along the western coast from Grenivík to Látur (their subprofiles F to H), from south to north, dike trends swing only 4° clockwise, while associated lava strikes swing about 30° clockwise. Young *et al.* (1985) (figs. 3, 5 and 7) had documented and interpreted these same observations. Fjäder *et al.* (1994) interpreted these observations as indicating that in this locality the change in lava strikes was primary and not due to subsequent tectonic rotations. However, they concluded that the 0–110° clockwise reorientation of structural elements in the northern peninsula is also primary. We emphasize that their 17-km long profile between Grenivík and Látur is entirely to the south of the Gil-Látur line and thus is outside of the Flateyjarskagi shear zone proposed by Young *et al.* (1985). The lack of rotated dikes south of the Gil-Látur line is not surprising, given the data of Young *et al.* (1985), (fig. 7), and is certainly an insufficient logical basis for claiming the absence of regional crustal rotations to the north of this line.

We also disagree with statements of Fjäder *et al.* (1994) that there is no crustal deformation in rocks along their same 17-km profile, and inland from there. In their fig. 5, profile C shows subparallel, NE mean trends of dikes and lavas—these lavas dip about 28° NW. These rocks have undergone crustal deformation involving, *at a minimum*, rotation components about subhorizontal axes that tilted both the flows and dikes. Also, inland between Grenivík and Látur, the lava amygdules locally contain chalcedony laminae tilted from 4–15° to the west (Young *et al.* 1985, fig. 11). Both the lava and chalcedony-laminae dip angles increase from south to north, as do the total normal-fault separations in any transect. These tilts occurred during rotations about subhorizontal axis components accompanying NNE-trending, rotational normal faulting to the south of the Gil-Látur line. North of this line, chalcedony-laminae strikes swing clockwise along with their flows, with maximum laminae dips of about 37° NW. All of this data proves significant regional crustal deformation.

The aforementioned 30° clockwise change in flow strikes, south of the Gil-Látur line, does not appear to be primary. While the dikes and chalcedony laminae demonstrate that no significant subvertical-axis rotations have occurred in this region, the change in lava strike is likely a manifestation of rotation about subhorizontal axes during rotational normal faulting. These rotations about N–NNE-trending, subhorizontal axes have had different effects on planar markers with different initial orientations. Given an original, roughly WNW-strike to the flows here, the northward increase in the amount of normal-fault induced rotations has effectively rotated the flow strikes progressively clockwise, while causing only minor changes in the trends of originally N–NNE-striking, subvertical dikes. Consistent with this interpretation of rotational normal faulting is the statistically significant, ~5° difference in mean dip angles for dikes between subprofiles F and H cited in Fjäder *et al.* (1994, p. 113).

Along the north coast, a handful of cross-cutting relations consistently showed the ENE–WNW-trending dikes are older than a subordinate, NNE–NE-trending dike set. This NE set is roughly normal to bedding, suggesting both dike sets may have been injected prior to the steep NW-tilting of the lavas. We described the presence of some WNW-trending dikes that are very fresh and non-tectonized, but we emphasized that these fresh WNW-trending dikes, and the NE-trending dike set, are a small component of the total coastal dike volume. A few of the WNW-trending dikes show unaltered tachylitic chill margins and clearly post-date deformation and alteration. However, the rest of the dikes show the pervasive effects of burial alteration: glassy chill margins show cryptocrystalline alteration to iron oxides and (typically) zeolites; olivine invariably is partly or completely altered to iron oxides and/or iddingsite; and vugs are filled with zeolites, quartz, chalcedony, and/or calcite. Most dikes show a similar degree of veining to contiguous flows, while a few do not. This could represent a variable mechanical response to the deformation as a result of, for example, grain size, or the influence of well developed columnar joints. By far, most dikes show a similar degree of faulting and alteration, and in many cases veining, to that in contiguous flows. Most of the northern Flateyjarskagi dikes appear to have been tilted and tectonized along with the lavas. Nevertheless, roughly northeast–southwest directed extension across some WNW-trending structures certainly has occurred; an impressive large-scale example of such movements is the sediment-filled graben located just off the peninsula's north coast (Thors 1983, Flóvenz & Gunnarsson 1991).

While Fjäder *et al.* (1994) repeatedly stated that they do not favor our rotation hypothesis for rocks in northern Flateyjarskagi, on p. 116 they stated, "The irregularity in attitude of lavas in the 3–5 km wide fault zone suggests that rotational deformation played a part in its tectonic evolution. Apparently, however, the magnitude of the rotation, about steeply inclined axes, varied considerably along the Húsavík–Flatey fault. In some areas the inferred rotation is over 100°; in others it is only 40°". This statement seems inconsistent with others in their paper, and they certainly did not address these rotations in their subsequent interpretation of stress directions and stress history. It also is unclear whether their paleostress analysis accounted for the steep lava dips in the northern peninsula.

The key test of whether northern Flateyjarskagi rocks have been significantly rotated about subvertical axes resides in paleomagnetic sampling and analysis. We have reported (Orkan *et al.* 1984) preliminary paleomagnetic results strongly supportive of maximum clockwise rotations of 110–120° based on core samples from north of the Gil-Látur line (Lutur, Ygla, and Laekjarvík-Víkurbakka) and using a sampled section from south Flateyjarskagi as a control on the reference direction of the paleomagnetic field. On the basis of this work, we are confident that any further paleomagnetic work in northern Flateyjarskagi will generally confirm these rotations. The northern Flateyjarskagi and Tjörnes localities comprise the only known regional occurrences of ENE–WNW-striking Tertiary dikes in Iceland, and this orientation exists because the rock masses that contain the dikes have undergone large clockwise rotations during TFZ-related shear. Paleostress field directions determined from structural elements in northern Flateyjarskagi, and ignoring such rotations, are likely to be incorrect.

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