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Tectonics of the Thingvellir fissure swarm, SW Iceland

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Abstract—The Thingvellir fissure swarm dissects 9000 year-old pahoehoe lava and contains about 100 fractures of average orientation N29.3°E. The average length of fractures is 620 m, the minimum being 57 m and the maximum 7.7 km. The maximum width and throw on a single fracture are 68 m and 40 m, respectively. Most fractures are vertical at the surface and must be the result of an absolute tensile stress. The geometry and arrangement of the fractures indicate that they have grown by coalescence of initially offset small fractures. It is concluded that most fractures attain depths of the order of several hundred meters or less, but that the largest faults attain depths of many kilometers. Comparison with the Vogar fissure swarm on the Reykjanes Peninsula suggests that the Thingvellir swarm may have the greater rate of dilation; the total maximum postglacial dilation of the Vogar swarm is only 15 m, whereas the corresponding figure for the Thingvellir swarm is about 100 m.

INTRODUCTION

THE PURPOSE of this paper is to provide data on the geometry of fractures of the Thingvellir fissure swarm, SW Iceland, and to discuss their formation and development. The question of whether the primary cause of fracture formation is regional stress (plate movements or gravity gliding) or magmatic pressure (dyke intrusion or uplift of the area), however, is not addressed in this paper. The Thingvellir fissure swarm dissects 9000 year-old (Kjartansson 1964) basaltic (pahoehoe) lava north of Lake Thingvellavatn (Fig. 1). This swarm, which is a part of the Pleistocene Hengill fissure swarm (Saemundsson 1978) contains the largest postglacial fractures of the rift zones in Iceland (Fig. 2), and this thus of major importance in the process of rifting.

In recent years, various attempts have been made to determine the present rate of horizontal deformation in the Thingvellir area (Gerke 1974, Brander *et al.* 1976, Decker *et al.* 1976). The results indicate that horizontal movement is irregular; parts of the swarm are contracting while others are dilating, but the net result is dilation at the rate of about 3 mm a^{-1}. Attempts have also been made to measure the rate of vertical deformation, and the results indicate that the average rate of subsidence of the graben, relative to the area west of it, is 0.4 mm a^{-1} (Tryggvason 1974, 1982). The rate of subsidence thus appears to be an order of magnitude less than the rate of dilation, but Tryggvason (1982) emphasized that the subsiding zone may be wider than the graben, and that the absolute rate of subsidence may thus be much higher than the quoted figure.

In order to provide accurate geometrical data, the width and throw of fractures were measured in the field, at intervals of 25 or 50 m. Width was measured with a tape, and throw with a tape or estimated by hand levelling, using a clinometer. Most width measurements on the major fractures Almannagja and Hrafnagja were made on aerial photographs at the scale of 1 : 13,000 and 1 : 8500, respectively, and the accuracy tested by several field measurements.

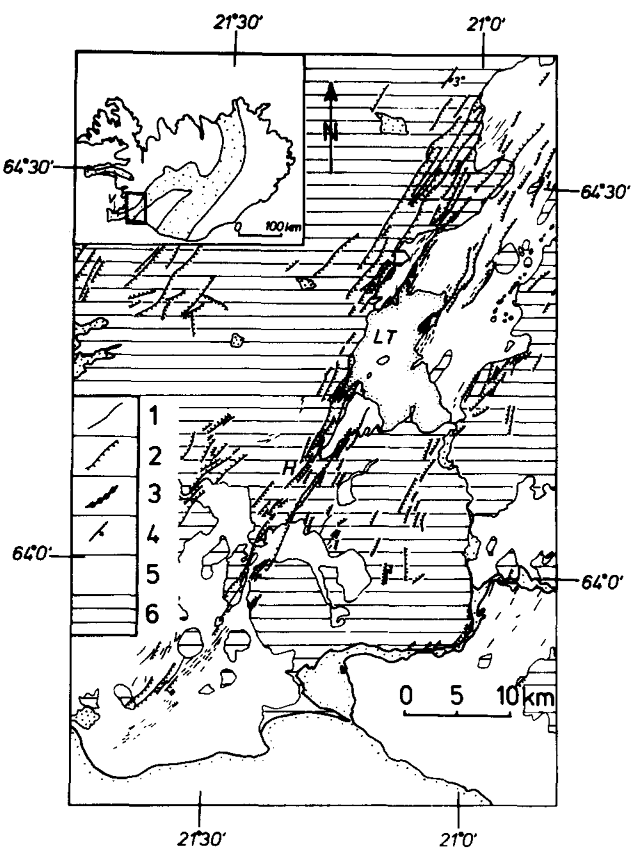

Fig. 1. A map of the Pleistocene Hengill fissure swarm, Iceland, a part of which is the Holocene Thingvellir fissure swarm. H, Hengill central volcano; LT, Lake Thingvallavatn; V (on the inset map of Iceland), Vogar fissure swarm, 1, tectonic fissure; 2, normal fault; 3, volcanic fissure; 4, strike and dip; 5, Holocene lavas; 6, Pleistocene rocks (lavas and hyaloclastites) or alluvium. Based on a map by K. Saemundsson and S. Einarsson.

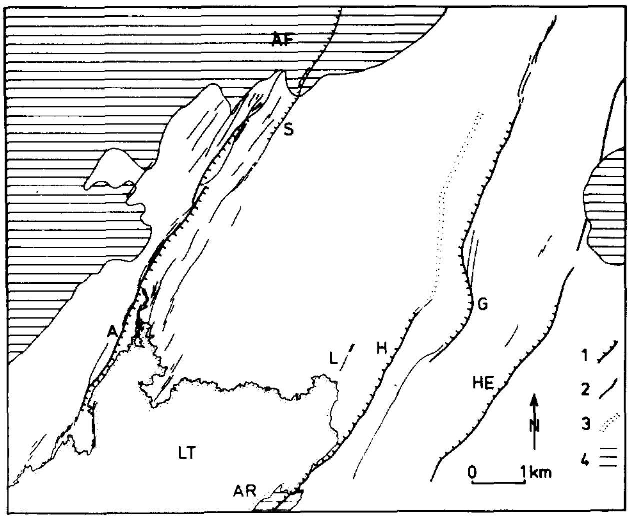

Fig. 2. A map of the Thingvellir fissure swarm. A, Almannagja; S, Sledaasgja; AF; Armannsfell; LT, Lake Thingvallavatn; AR, Arnarfell; L, Litlagja; H, Hrafnagja; G, Gildruholtsgja; HE, Heidargja. 1, normal fault (only those with throws of several meters are thus indicated); 2, tectonic fissure (with a small or no throw); 3, deformation zone; 4, Pleistocene rocks (basaltic lavas or hyaloclastites) or alluvium.

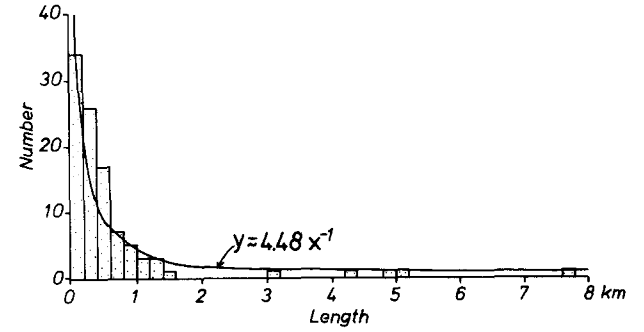

Fig. 4. Length distribution of 101 fractures of the Thingvellir fissure swarm. The mean length is 620 m and the cumulative length is 62642 m.

FRACTURE GEOMETRY

Fractures of the Thingvellir swarm are of two types: extension fractures and normal faults. Most small fissures are extension fractures (Fig. 3), here defined as fractures having throws of less than 0.5 m, but the large ones are normal faults which, however, often grade into extension fractures at their ends (Fig. 2). The Icelandic word "gja", which forms a part of the names of many large fractures (such as Almannagja), means "gaping fracture" (a fissure) and refers both to faults and extension fractures.

Strike

The average strike of fractures, referring to linear orientation between fracture ends, is N29.3°E, with a standard deviation of 11.1°. Individual fractures are sinuous, and some depart much from the average strike, along part or the whole of their length. For instance, Gildruholtsgja, a large fault in the east part of the swarm, is notably curved where its throw is largest (Fig. 2). The strikes of most fractures are, however, similar throughout the swarm.

Length

The determination of fracture length depends on interpretation. Most fractures are discontinuous, and it is sometimes unclear which parts belong together. In this paper, fracture length is the distance a fracture can be traced as a continuous fissure or fault. All small fractures, whether or not associated with large fractures, are regarded as separate fractures. Because the analysis is restricted to the postglacial Thingvellir swarm, no attempt is made to associate individual fractures with old faults of the Hengill fissure swarm. Thus, the length refers to length of fractures inside the postglacial lava flow at Thingvellir.

The average length of 101 measured fractures is 620 m (Fig. 4). Lengths range from 57 m to about 7.7 km (Almannagja), but the minimum length depends on the scale of aerial photographs. Although photographs at a larger scale are available, photographs at 1 : 33,300 were used for length measurements to facilitate comparison with the fractures of the Vogar swarm (Gudmundsson 1980), and to exclude all minor fractures and joints of non-tectonic origin.

Comparison of Figs. 2 and 5 shows that fractures have different lengths on different scales. On small-scale photographs, very narrow fractures that connect wider fractures are invisible; thus, some fractures that are discontinuous in Fig. 2 are continuous in Fig. 5. Conversely, some fractures that are continuous in Fig. 2 turn out to be composed of several small, nearly collinear fractures in Fig. 5. Although the scale is thus important in deciding lengths of individual fractures, the length distribution would probably be similar to that in Fig. 4, even if the scale were larger. This type of distribution seems to be the rule for geological fractures on many scales. For instance, lengths of joints in the Sierra Nevada (Segall & Pollard 1983), lengths of fissures and faults of the Vogar swarm in Iceland (Gudmundsson 1980), and lengths of tens of kilometers long tensile fracture lineaments (Nur 1982) all follow a similar distribution.

The length distribution in Fig. 4 shows that most fractures are short relative to the average length, and that a few fractures are very long. The approximate least-squares power function

$$y = 4.48x^{-1} \qquad (1)$$

fits the data reasonably well (Fig. 4). This function overpredicts the number of fractures of length less than 200 m and underpredicts the number of fractures of length 200–600 m. The overprediction is as expected because it is known, from field observations and observations on aerial photographs at a larger scale, that the swarm contains many more short fractures. The underprediction is partly due to class limits, so chosen to agree with the class limits for the Vogar swarm (Gudmundsson 1980). For instance, if the interval of the first class was 0–250 m, instead of 0–200 m, the fit would be better. But as it is, the fit is reasonably good.

Width and throw

Width and throw of many fractures were measured in the field at intervals of 25 or 50 m (Fig. 5). The results (Figs. 6–8) show that width and throw are variable, but that they often attain maximum values somewhere near the middle of fractures and decrease towards their ends (Figs. 7 and 8).

The determination of both width and throw depends on interpretation. Slumping has generally negligible effects on the measured width, but many of the fractures, especially the large ones, are of graben-like structure (Figs. 9 and 11). The separation of the fracture walls at right angles to the fracture strike may thus be significantly less than the measured width at the surface. For many fractures, however, it is virtually impossible to decide what fraction of the width is due to the graben structure and what to the separation. Thus, in this paper, fracture width is the measured width at the surface, irrespective of how it came into being. Fracture throw is here considered to be difference in altitude between the edges of the fracture walls.

The maximum measured width of a single fracture, 68 m, is on Hrafnagja (Fig. 8b). The maximum measured width of Almannagja is 64 m (Fig. 8a), but both these figures were obtained from measurements on aerial photographs. The maximum measured width in the field, 60 m, is on Hrafnagja.

All large fractures are normal faults, and many small fractures have significant throws on parts of their lengths (Figs. 6–8). Most fault walls are vertical; on some faults they are closed, but usually they are wide apart (Fig. 9).

Referring to the edges of fault walls, the maximum measured throw on a single fault is on Almannagja, 28 m (Fig. 8a). In places, however, the east fault wall stands 10–20 m above the area immediately to the east (Fig. 9), so that the total maximum throw on Almannagja is about 40 m (Saemundsson 1965). Referring to the lowest ground inside the Thingvellir graben, at the location of Tryggvason's (1974) profile, the throws of Almannagja and Hrafnagja are 30–35 m. On the closed fault Gildruholtsgja throw reaches 25 m in many points of measurement (Fig. 6g). The maximum throws on most faults are, however, only a few meters (Figs. 6 and 7).

ALMANNAGJA AND HRAFNAGJA

These two large fractures occur at each side of the main postglacial graben, and are its major faults. Both are gaping normal faults, but they are notably different in appearance. A detailed discussion of them is thus appropriate.

Almannagja

This normal fault, roughly elliptical in horizontal section, is 7.7 km long and up to 64 m wide. Being composed of a number of smaller, initially offset, fractures, Almannagja has clearly formed by coalescence, as a result of continuing tension, of these smaller fractures (Figs. 2 and 5).

In the south, Almannagja grades into a set of en échelon extension fractures (Figs. 2 and 10), the orientation of which is notably different from the main orientation of Almannagja. Individual en échelon fractures, however, have the same orientation as Almannagja. This indicates that an old weakness, perhaps a Pleistocene fault beneath the postglacial Thingvellir lava, is responsible for the location of the en échelon fractures. The fractures themselves formed in a direction perpendicular to the postglacial maximum tensile stress. In the north, Almannagja grades into a number of small extension fractures, of parallel arrangement, that end short of the hyaloclastite mountain Armannsfell.

In places, Almannagja is split into several more or less parallel fractures (Figs. 2 and 5) and, commonly, the strip of land in between has subsided several meters. Evidently, most fractures that make up Almannagja are graben-like faults, mostly of rectangular profiles (Fig. 9), formed by subsidence of the strip of land between parallel fractures.

The ground surface east of the fault of Almannagja slopes some 11° to the east (Fig. 9). There has thus been some tilting of the postglacial lava flow during the formation of Almannagja.

Hrafnagja

This normal fault is 11 km long, the south end being outside Fig. 2, and up to 68 m wide. The width varies from 0 to 68 m, but the throw varies from 0 to 14 m (Fig. 8b). Like Almannagja, Hrafnagja is composed of a number of graben-like faults, partly grown together (Fig. 11), but, unlike Almannagja, they have an en échelon arrangement. These graben-like faults are shallow compared with those of Almannagja.

Near its south end, which is in Lake Thingvallavatn, Hrafnagja is split into a number of parallel fractures which do not have an en échelon arrangement, however. In the north, Hrafnagja widens, becomes shallower, and grades into numerous very small, parallel extension fractures; that is, a deformation zone (Fig. 2). The ground surface west of the fault slopes to the west so there has, as in the case of Almannagja, been some tilting of the lava flow during the formation of Hrafnagja.

FORMATION AND DEVELOPMENT

Growth

Most fractures of the Thingvellir swarm are vertical at the surface. Because the earth's surface is free of shear

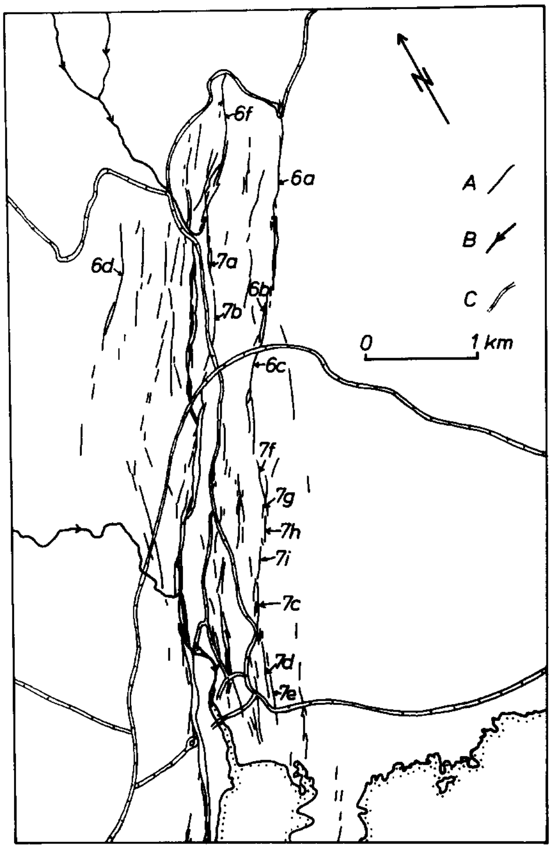

Fig. 5. Location of fractures measured in the west part of the Thingvellir swarm. The width (W) and throw (T) in meters of the numbered fractures, measured from north to south, is shown in Figs. 6–8. A, Tectonic fracture; B, river; C, road; 6a, fracture a in Fig. 6, etc. A part of Lake Thingvallavatn occupies the lower right part of the figure.

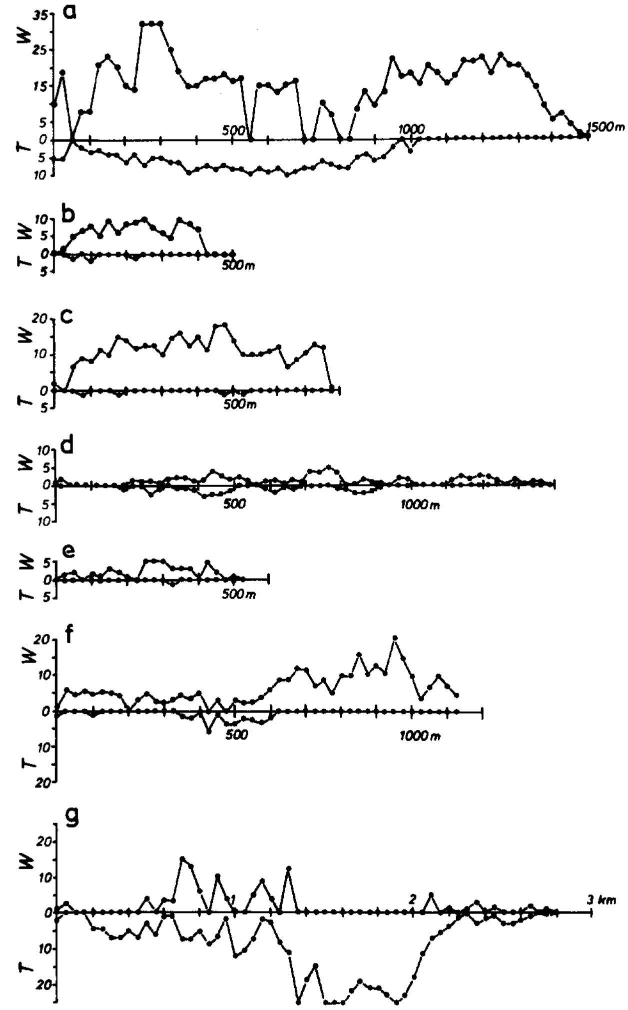

Fig. 6. The width and throw of seven fractures shown in Figs. 2 and 5. Note that the fracture at the bottom, Gildruholtsgja (Fig. 2), is at a different scale. Fracture e is Litlagja, and fractures a, b and c together from Sledaasgja, shown in Fig. 2.

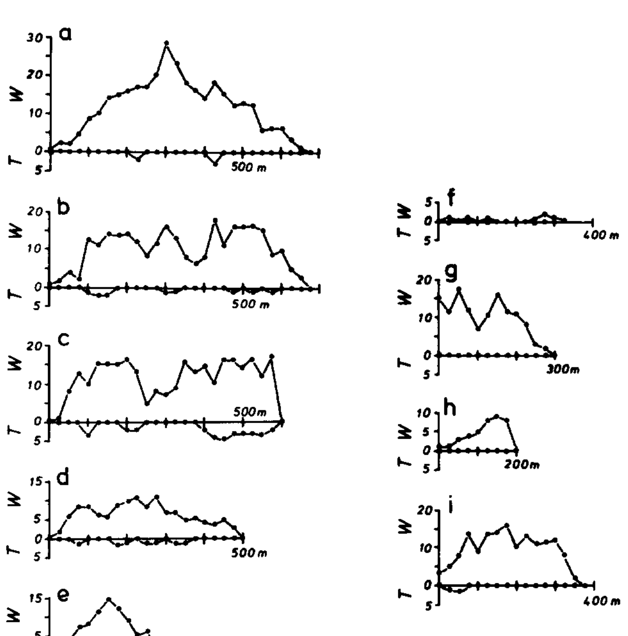

Fig. 7. The width and throw of nine fractures shown in Fig. 5.

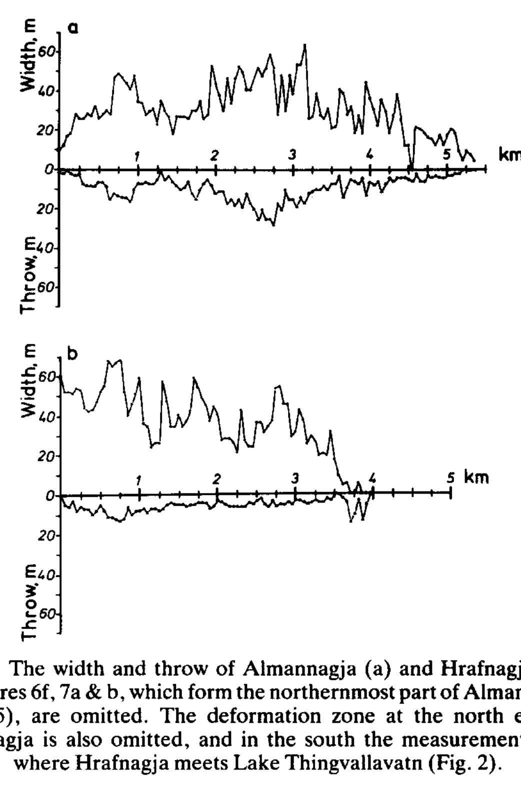

Fig. 8. The width and throw of Almannagja (a) and Hrafnagja (b). Fractures 6f, 7a & b, which form the northernmost part of Almannagja (Fig. 5), are omitted. The deformation zone at the north end of Hrafnagja is also omitted, and in the south the measurements end where Hrafnagja meets Lake Thingvallavatn (Fig. 2).

Fig. 3. A water-filled extension (tension) fracture near the north shore of Lake Thingvallavatn. Next to the observer the fracture is about 10 m wide. The view is to NNE.

Fig. 9. The east fault wall of Almannagja, dipping 11° to the east, and a part of the Thingvellir graben. The background is the hyaloclastite mountain Armannsfell (Fig. 2) in the NNE. (The people, walking along Almannagja, and a bus, near the centre of the photograph, indicate the scale.)

Fig. 10. An aerial view to SW of the en échelon fractures, surrounded by summerhouses, at the south end of Almannagja. The fractures are pure extension fractures; next to the road on the left they are 5 m wide and on the right 12 m.

Fig. 11. An aerial view of the narrow en échelon graben-like fractures of which Hrafnagja is composed. Looking E, the offset is about 40 m. Fracture width is 60 m to the left of the road and 36 m to the right.

stress, vertical planes just beneath the surface must also be principal stress planes. The Thingvellir fractures must thus have formed along a principal stress plane. As there is no evidence for a fluid pressure that could drive the fractures open at the surface, these extension fractures must be true tension fractures (Seçor 1965).

The geometry and arrangement of the fractures indicates that they have grown by coalescence of smaller fractures. This kind of growth is common on all scales in rock; from microcracks (Peng & Johnson 1972), through macroscopic joints (Segall & Pollard 1983, Granier 1985), to fractures many kilometers long (Segall & Pollard 1980). It is likely that the columnar joints in the postglacial Thingvellir lava served to initiate fractures because a rock fails, when subject to uniform tensile stress, where its tensile strength is least.

The crack extension 'force' or strain energy release rate per crack tip, G, is given for plane stress (Parker 1981, p. 24) by

$$G = \partial U/\partial a = \pi\sigma^2 aE^{-1}, \quad (2)$$

where U is the elastic strain energy released per unit thickness of rock due to crack propagation, a is the half-length of the crack, σ is the applied external tensile stress (or internal fluid pressure) and E is Young's modulus. This equation shows that, for constant σ, G increases linearly with increasing crack length. This indicates that long fractures are favored. Figure 4 however shows that relatively short fractures are much more common than long fractures. Similar length distributions have been obtained from measurements on joints, which are up to tens of meters long (Segall & Pollard 1983), and from measurements on tensile fracture lineaments, which are up to tens of kilometers long (Nur 1982).

For the Thingvellir fractures I propose the following explanations of the length distribution.

(1) Long fractures are favored in homogeneous materials subject to homogeneous stress fields. But the upper part of the crust beneath Thingvellir is probably heterogeneous as regards distribution and orientation of joints, contacts, and other weaknesses; hence as regards tensile strength. Much higher tensile stress is needed to propagate a fracture across transverse joints than to propagate a fracture along joints arranged parallel to the developing fracture. Transverse joints may thus be able to stop the propagation of fractures (Pollard 1973, Weertman 1980, Hertzberg 1983, p. 357). The spatially variable tensile strength caused by transverse joints may be one reason why short fractures are common.

(2) The location and length of the surface fractures may be controlled by old fractures in the Pleistocene rocks below the postglacial lava flow. Where these old fractures are oblique to the orientation of the postglacial maximum tensile stress, a number of short offset or en échelon fractures develop instead of a single long fracture. Each short fracture develops perpendicular to the direction of the present maximum tensile stress, but the set of such fractures follows the direction of the older fracture (Figs. 2 and 10).

(3) Long fractures 'shield' short fractures (Nur 1982, Segall & Pollard 1983). This means that a single long fracture relaxes so much tensile stress that it stops the propagation of many other fractures in its neighborhood. Consequently, many fractures that happen to be near to a long fracture fail to develop and remain short.

(4) There is some evidence that the fracture toughness, which is a measure of resistance to fracture propagation, of rock containing joint-sized fractures increases with increasing crack length (Schmidt & Rossmanith 1983, Ingraffea 1985). This may also apply to rock containing large-scale fractures such as those of the Thingvellir swarm.

Offsets

Offset fractures, some arranged en échelon, are common in the Thingvellir fissure swarm. Some large fractures grade into numerous small tension fractures at their ends (Figs. 2 and 5). Such offsets, common in dykes and fractures in other areas (e.g. Watterson 1968, Pollard *et al.* 1975, Gudmundsson 1980, Delaney & Pollard 1981), are analogous to the 'steps' on microcracks in materials such as glass and metals. Lawn & Wilshaw (1975) propose three mechanisms to explain fracture surface steps or offsets.

(1) The main crack may experience a local disturbance at its front, whereby it breaks up into several nearly parallel cracks.

(2) The main crack may form by coalescence of smaller cracks, where the smaller cracks initially are offset.

(3) Fast-running cracks may bifurcate because of dynamic crack-tip distortion, initiation of secondary cracks, or stress-wave branching.

The mechanism for fracture growth proposed in this paper is the second mechanism for surface steps on microcracks. Initially, fractures are offset because the tensile stress exceeds the tensile strength of the lava simultaneously in many places within a zone of high tensile stress. These offset fractures enlarge and finally coalescence to form the main fractures.

Depth

The results of Lachenbruch (1961) indicate that, in evolving tension-crack systems, crack depth should be of the same order of magnitude, or less, than crack spacing. Also, provided the applied tensile stress increases with depth, Nur (1982) concluded that spacing between tension cracks of a given depth should be roughly of the order of their depth and, furthermore, that the length of the cracks should usually be equal to or greater than their depth. Using these results as a basis, one may estimate the depth of the Thingvellir fractures.

Figure 2 shows that lateral spacing of major fractures is most commonly of the order of several hundred meters. This indicates that the depth of the fractures is, on average, of the order of several hundred meters. Also, the length distribution (Fig. 4) and the average length, 620 m, indicate that the depth of the fractures should most commonly be of the order of 600 m or less.

Both considerations lead to the conclusion that the depth of the Thingvellir fractures is of the order of several hundred meters.

Major faults such as Almannagja and Hrafnagja, however, may reach to the depth of the magma layer (low-resistivity layer) which, beneath the Thingvellir swarm, is at the depth of about 8 km (Hersir *et al.* 1984).

COMPARISON WITH THE VOGAR SWARM

Fissure swarms, similar to the Thingvellir swarm, are common in other parts of the volcanic zone of Iceland (Saemundsson 1978), as well as in other volcanic areas such as Hawaii (Duffield 1975). The only fissure swarm in Iceland that has been studied in a similar way is the Vogar swarm (Fig. 1) on the Reykjanes Peninsula in SW Iceland (Gudmundsson 1980, 1983). This swarm is the NE part of the Reykjanes fissure swarm (Tryggvason 1982). It is the largest swarm of the peninsula that lies completely within a single lava flow and is thus not obscured by younger lavas. Also, detailed precision levelling measurements of the Vogar swarm have been carried out over many years (Tryggvason 1982). All data on the Vogar swarm are taken from Gudmundsson (1980).

Both swarms are located in early postglacial pahoehoe lava flows; the Thingvellir swarm in a 9000 year-old lava and the Vogar swarm in a 10,000 year-old lava. Both swarms are of similar area; the width is up to several kilometers and the length about ten kilometers. The maximum subsidence is also similar, being 70 m for the Thingvellir swarm and 50 m for the Vogar swarm. The average length of fractures is essentially the same, 620 m for the Thingvellir swarm and 611 m for the Vogar swarm, and the length distribution is also similar. In both swarms the fractures are vertical, or nearly so, at the surface.

There are however some dissimilarities between the two swarms. First, the mean strike of the Thingvellir fractures is about N29°E as compared with N54°E for the Vogar fractures. Second, the maximum combined width of the Thingvellir fractures is over 100 m, whereas the corresponding figure for the Vogar swarm is only 15 m. Third, the fractures of the Thingvellir swarm tend to have larger throws and greater widths. For instance, most of the Thingvellir faults are gaping fractures whereas most of the Vogar faults are closed at the surface. Also, the maximum measured width on a single fracture is 68 m for the Thingvellir swarm (Hrafnagja) but only 8 m for the Vogar swarm. The maximum throw on a single fault (Almannagja) is 40 m for the Thingvellir swarm as compared with only 10 m for the Vogar swarm.

These results may indicate that the Thingvellir swarm dilates at a significantly greater rate than the Vogar swarm. However, many of the large fractures of the Thingvellir swarm are of graben-like structure. It is well known that the dilation needed for the formation of grabens, or graben-like fractures, is only a fraction of the measured width of the grabens. Consequently, the true total dilation of the Thingvellir swarm may be significantly less than the combined width of the fractures at the surface. Furthermore, geodetic measurements indicate that the Reykjanes swarm, of which the Vogar swarm is a part, dilates at the rate of 21 mm a^{-1} (Wood 1982) as compared with the rate of 3 mm a^{-1} for the Thingvellir swarm. However, neither of these figures agrees with the average spreading half-rate in Iceland (10 mm a^{-1}), and the direction of dilation in the Reykjanes swarm is far from being perpendicular to the strike of the fractures (Wood 1982). The results of geodetic measurements over a period of only 5–10 years may thus be misleading as regards the average rate and direction of dilation within any particular fissure swarm over much longer periods of time.

Another explanation for the apparent difference in dilation rates is that the Vogar swarm may take up only a fraction of the total dilation of the volcanic zone on the Reykjanes Peninsula. On this peninsula, the neovolcanic rift zone is split up into four (Saemundsson 1978) or five (Jakobsson *et al.* 1978) volcanic and tectonic fissure swarms, arranged en échelon, of which the Reykjanes swarm is the westernmost and the Hengill swarm (which includes the Thingvellir swarm) the easternmost. The total maximum postglacial dilation of all these swarms is not known, but, extrapolating the results from the Vogar swarm, it may be at least 60–75 m and thus comparable with the dilation of the Thingvellir swarm.

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