Supplementary Information

Syn-emplacement fracturing in the Sandfell laccolith, eastern Iceland – implications for rhyolite intrusion growth and volcanic hazards

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The supplementary information includes:

Supplementary Text

S1. Regional geology

S2. Regional faults

S3. Roof pendant

Supplementary Tables

Table S1. AMS measurements (in separate file)

Table S2. Flow indicator measurements (in separate file)

Supplementary Figures

Figure S1. Curie temperature experiment, heating and cooling curves

Figure S2. Map of the Sandfell laccolith with AMS data (in separate file)

Supplementary Video

Video S1. 3D model of the magma flow directions in the Sandfell laccolith (in separate file)

S1. Regional geology

The fjords of Iceland's eastern coast expose a 10 to 12 km thick succession of some of the oldest rocks on Iceland, the Neogene lava pile and related volcanic systems (Walker, 1974; Watkins and Walker, 1977; Saemundsson, 1979; Torfason, 1979; Mussett et al., 1980; Einarsson, 1991). The volcanic systems in the East fjords became extinct due to jumps of the rift-axis, which eventually ended volcanic activity in the area (Helgason, 1984). The extinct central volcanoes and associated fissure swarms are considered direct analogues to the active rift zones on Iceland today (Thordarsson and Höskuldsson, 2002).

The Reydarfjörður central volcano was active between 12.2 to 11.3 Ma ago in the area of Fáskrúðsfjörður, Stödvarfjörður and Reydarfjörður in eastern Iceland (Eriksson et al., 2011; Martin et al., 2011), with its main eruptive center in the middle of Reydarfjörður (Gibson, 1963) (Figure 1). The Reydarfjörður central volcano had six phases of felsic volcanic activity, each with a slightly different eruptive center (Gibson, 1963). An eruptive phase generally commenced with the eruption of an explosive felsic tuff that was followed by effusive felsic, intermediate and basaltic eruptions. The Sandfell laccolith formed in the fourth felsic eruptive phase and intruded the lava and silicic pyroclastic flank succession of the Reydarfjörður central volcano, approximately 10 km south of the volcanoes main eruptive center (Gibson, 1963; Gibson et al., 1966) (Figure 1B). Several vesicular dolerite dikes of the Reydarfjörður fissure swarm cut the Sandfell laccolith (Hawkes and Hawkes, 1933).

S2. Regional Faults

Three major regional faults transgress the Sandfell laccolith, the Heljara, Grákullor and Lambaskarð faults. The Heljara and Grákullor faults have been traced across Fáskrúðsfjörður on the Hafnarnes and Vattarnes peninsulas (Gibson, 1963). The Heljara fault intersects the main body of the laccolith between Upper and Lower Sandfell visibly displaces the laccolith by 120 m (Gibson, 1963). The Víkugerðisá River valley transgresses the laccolith along the proposed scarp of the Grákullor fault. The Grákullor fault has a maximum displacement of 120 m observed in the lava pile north of the laccolith. Together the Heljara and Grákullor faults down-faults the central part of the Sandfell laccolith by about 80 to 120 m (Wilson and Wright, 1958; Gibson, 1963). The third fault, which we call the Lambaskarð fault, is clearly visible in the Neogene lava pile above the Upper sill and down throw Rauduhnausar and part of the Upper sill between 30 to 50 m in the easternmost part of the laccolith. Gibson (1963) therefore proposed that the Upper sill and Rauduhnausar is 'up-faulted' continuations of the main body of the Sandfell laccolith. The central graben is suggested to have formed by either unloading due to erosion or emptying of a magma reservoir below Sandfell (Gibson, 1963).

Whether the Heljara and the Grákullor faults formed pre-, syn- or post-emplacement is not clear, since no exposures exist in the laccolith along the proposed fault lines. The Heljara fault was, however, likely active during laccolith emplacement, because the fault has its maximum displacement at Sandfell (Gibson, 1963). The Heljara fault cut the center of the main body of the laccolith. This indicate that the fault may have acted as the feeder to the Sandfell laccolith. The Grákullor fault, on the other hand, displaces lavas younger than the Sandfell laccolith, and is therefore assumed to have formed after the emplacement of the laccolith (Gibson, 1963). Where the Lambaskarð fault cuts the Upper sill, the laccolith is brecciated, and thins abruptly from ~50 to 15 m, which indicates syn-emplacement activity on the fault.

S3. Roof pendant

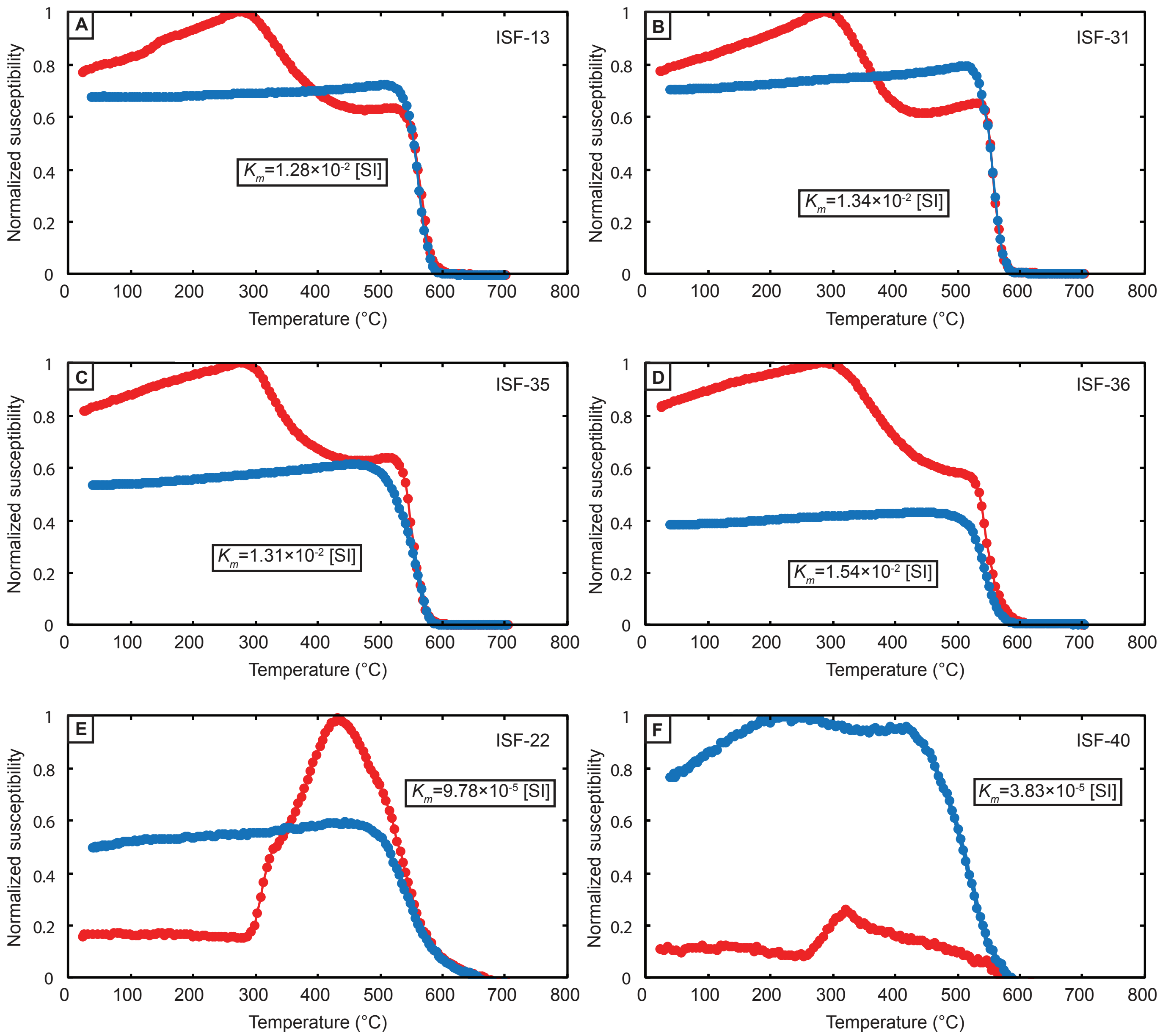
On the eastern slopes of Lower Sandfell an angular slab of basalt (250 m long × 125 m wide × 50 m thick) surrounded by the rhyolite of the Sandfell laccolith is exposed. The contact between the basalt and the laccolith is sharp and vertical in the upper part of the slab, while elsewhere the contact is parallel to the slope of the mountain (dipping ~40° NE). Hawkes and Hawkes (1933) interpreted this basalt mass as a separated part of roof, while Gibson et al. (1966) suggested that the basalt slab was a dolerite intrusion and that felsic veins in the pendant were a result of net-veining. We observed that the slab consists of aphyric dark basalt and a phyric green basalt and that the basalts are hornfelsed close to the contact with the rhyolite (see also Hawkes and Hawkes 1933). Dikelets of rhyolite magma (cm to dm thick) have sometimes intruded fractures in the basalt pendant. Joints in the basalt pendant exhibit an inverted funnel arrangement that seems to cross-cut the indistinct, slope-parallel, layering of the basalt. This joint pattern may indicate that the block was sufficiently heated to generate new cooling joints, but it is more likely only an effect of up-doming and outcrop conditions. The joint pattern, the layering, lithological variation and alteration strongly suggest that the laccolith partially punched the host rock, and that the slab is a subsided and detached roof block, which is supported by the sharp and steep (fault-like) upper contact of the pendant. This implies that the basalt roof pendant can be used as a wall contact for the 3D reconstruction of the Sandfell laccolith.

Supplementary Figures and Tables

Supplementary Table S1. Average AMS tensor measurements and including sample location and type of flow indicator for each sample. See method section for details on the AMS analysis.

Supplementary Table S2. Flow indicator measurements collected during field work.

Supplementary Figures



Supplementary Figure S1, Heating and cooling curves. A-F) Normalized plots of bulk magnetic susceptibility that show Curie temperatures of the mineral phases in selected representative samples from the Sandfell laccolith (sample name is given in the upper right corner of each figure panel). The red and the blue line represent bulk magnetic susceptibility (K_m) during heating and cooling, respectively. The less altered rhyolite samples display Curie temperatures of between 520 to 540°C. The main contributor to the magnetic susceptibility in the rhyolite is probably magnetite (Butler, 1992). However, the heating experiments also show an increase in susceptibility to between 280 to 300°C, which is an indication of growth of low temperature oxides, and thereafter a decrease in bulk susceptibility that could indicate the presence sulfides, such as pyrrhotite, pyrite or paramagnetic minerals (biotite or hornblende) (cf. de Boer et al., 2001). In the altered samples, the magnetic susceptibility curve change between heating and cooling, which is probably caused by oxidation during heating (cf. Böhnel et al., 2002).

Supplementary Figure S2. Map of the Sandfell laccolith with southern hemisphere projections of AMS tensors.

Supplementary Video S1. 3D model of the magma flow directions in the Sandfell laccolith interpreted using the magmatic and magnetic fabric. Red arrows represent magma flow directions interpreted from magmatic fabric measurements and AMS measurements, and orange arrows represent the magma flow directions inferred form oblate fabrics, the shape of the magma body and attitude of emplacement related features. The gray line on the laccolith roof surface defines the present-day contact with the host rock.

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