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Three-dimensional geometry of concentric intrusive sheet swarms in the Geitafell and the Dyrfjöll volcanoes, eastern Iceland

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[1] Sheet intrusions (inclined sheets and dykes) in the deeply eroded volcanoes of Geitafell and Dyrfjöll, eastern Iceland, were studied at the surface to identify the location, depth, and size of their magmatic source(s). For this purpose, the measured orientations of inclined sheets were projected in three dimensions to produce models of sheet swarm geometries. For the Geitafell Volcano, the majority of sheets converge toward a common focal area with a diameter of at least 4 to 7 km, the location of which coincides with several gabbro bodies exposed at the surface. Assuming that these gabbros represent part of the magma chamber feeding the inclined sheets, a source depth of 2 to 4 km below the paleoland surface is derived. A second, younger swarm of steeply dipping sheets crosscuts this gabbro and members of the first swarm. The source of this second swarm is estimated to be located to the SE of the source of Swarm 1, below the present-day level of exposure and deeper than the source of the first swarm. For the Dyrfjöll Volcano, we show that the sheets can be divided into seven different subsets, three of which can be interpreted as swarms. The most prominent swarm, the Njardvik Sheet Swarm, converges toward a several kilometers wide area in the Njardvik Valley at a depth of 1.5 to 4 km below the paleoland surface. Two additional magmatic sources are postulated to be located to the northeast and southwest of the main source. Crosscutting relationships indicate contemporaneous, as well as successive activity of different magma chambers, but without a resolvable spatial trend. The Dyrfjöll Volcano is thus part of a complex volcanic cluster that extends far beyond the study area and can serve as fossil analog for nested volcanoes such as Askja, whereas in Geitafell, the sheet swarms seem to have originated from a single focus at one time, thus defining a single central volcanic complex, such as Krafla Volcano.

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1. Introduction

[2] The understanding of the internal structure of active volcanoes was pioneered by fundamental studies of extinct volcanoes in northwest Scotland [*Harker*, 1904; *Richey and Thomas*, 1930; *Anderson*, 1936] and *Walker*'s [1962] study of the Breiddalur Volcano, which laid the foundation for a series of studies on extinct and eroded volcanoes in Iceland [e.g., *Walker*, 1959, 1962, 1974; *Carmichael*, 1964; *Blake*, 1966; *Annels*, 1967, 1968; *Newman*, 1967; *Torfason*, 1979; *Fridleifsson*, 1983a; *Klausen*, 1999, 2004, 2006] and elsewhere [e.g., *Schmincke*, 1967; *Schirnick et al.*, 1999; *Geshi*, 2005; *Donoghue et al.*, 2010].

[3] One of the basic constituents found in the cores of extinct volcanoes worldwide are swarms of 'cone sheets' or centrally inclined sheets that are thought to dip toward a common magmatic source [*Anderson*, 1936]. These inclined sheets record much of the intrusive activity of a volcano during its lifetime, feed sill intrusions [*Burchardt*, 2008] and flank eruptions, and together constitute large volumes of magma. Hence, they contribute significantly to the growth of a volcanic edifice and the hosting crustal segment [*Le Bas*, 1971; *Klausen*, 2004; *Siler and Karson*, 2009]. Additionally, they record the local stress field surrounding their source during their time of emplacement [*Anderson*, 1936; *Nakamura*, 1977; *Gautneb and Gudmundsson*, 1992; *Chadwick and Dieterich*, 1995].

[4] Since exposure of the interior of volcanoes is usually limited in lateral and vertical extent, the geometry of inclined sheets at depth has to be inferred. Based on the original model by *Anderson* [1936], two end-member geometries of cone sheet swarms exist: *Phillips*'s [1974] model of the geometry of inclined sheet swarms allowed for concave-downward ('trumpet-shaped') sheet geometries with increasing sheet dip closer to the magmatic source. The second end-member geometry is characterized by decreasing sheet dip with depth that result in a concave-upward ('bowl-shaped') geometry [*Chadwick and Dieterich*, 1995; *Gudmundsson*, 1998]. Previous studies usually use either of these two geometries [*Klausen*, 2004], or assume a planar geometry of cone sheets measured at the surface in eroded volcanoes to deduce depth, shape, and size of the feeding magma chamber [e.g., *Schirnick et al.*, 1999; *Ancochea et al.*, 2003; *Geshi*, 2005; *Siler and Karson*, 2009].

[5] The eroded Tertiary volcanoes of eastern Iceland represent excellent examples to study the geometry of inclined sheet swarms. Within two of these, the 5–6 Ma old Geitafell Volcano in Southeast Iceland and the 12–13 Ma old Dyrfjöll Volcano in Northeast Iceland, detailed structural mapping of intrusive swarms was carried out to reconstruct their geometry. For this purpose, structural field data was analyzed statistically and used to model sheet geometries. This was achieved by projecting the outcrop data in three dimensions to determine the location, depth, and size of their source magma chambers and to evaluate the relevance of different end-member geometries.

2. Geological Setting

[6] The superposition of the Mid-Atlantic Ridge and the Iceland Mantle Plume has formed the Iceland Plateau, with oceanic rifting processes now occurring above sea level in the active rift zones of Iceland [*Saemundsson*, 1979]. Within these rift zones, magmatic and tectonic processes occur within en echelon volcanic alignments (rift segments) that are characterized by fissure swarms including normal faults and eruptive fissures, as well as central volcanoes [*Saemundsson*, 1979]. Crustal extension is of approximately 18 mm per year in ESE-WNW direction [*DeMets et al.*, 1990]. The relative movement of the plate boundary across the quasi-steady Iceland Mantle Plume results in relocation of the rift zone, i.e., a rift jump [*Helgason*, 1985]. The overall direction of rift jumps on a large scale (jumps of 100 to

200 km, every approximately 6 to 7 Ma) is eastward and characterized by temporal and spatial overlaps, such as the present-day configuration of the rift zones [*Johannesson*, 1980]. On a small scale (jumps of 20 to 40 km), rift jumps occur approximately every 2 Ma, but do not follow a linear pattern, i.e., activity may relocate eastward or westward. The reason for this is still unknown and subject to discussion [*Helgason*, 1985]. As a consequence of rift jumps, volcanic systems become extinct and magmatic activity relocates, so that extinct volcanic systems are concentrated e.g., in the Tertiary and Plio-Pleistocene parts of the island (Figure 1) [*Johannesson*, 1980; *Helgason*, 1985].

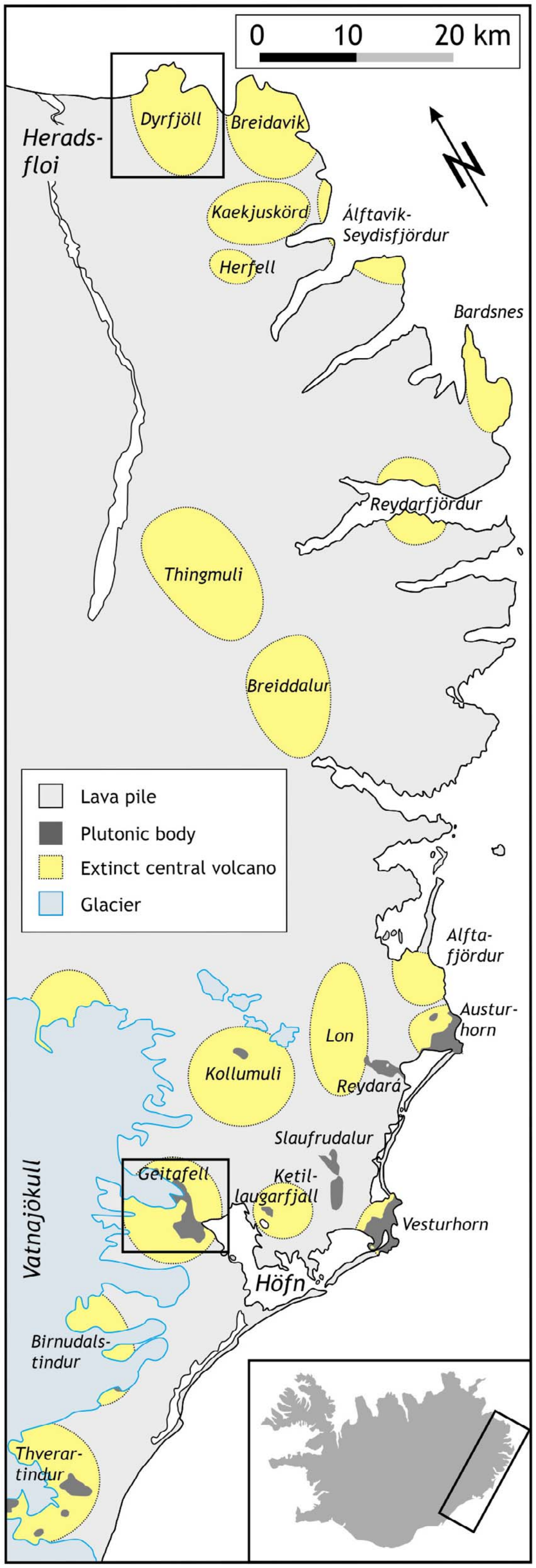

Figure 1. Schematic map of eastern Iceland that illustrates the distribution of extinct central volcanoes embedded in the Tertiary lava pile (according to *Walker* [1974] and *Gustafsson* [1992]). The depth of glacial erosion decreases northward so that the volcanoes in the south are exposed at deeper levels, including plutons that represent parts of their magma chambers.

[7] The Tertiary lava pile of eastern Iceland comprises basaltic lavas that make up a total thickness of up to 12 km [*Walker*, 1974; *Torfason*, 1979], which erupted from fissures in the Tertiary rift zone. The lava pile is characterized by a regular tilt toward the active rift zone with an increasing dip with depth [*Saemundsson*, 1979]. Consequently, the oldest exposed rocks with ages of approximately 14 Ma occur along the eastern coast of Iceland [*Gale et al.*, 1966; *Moorbath et al.*, 1968]. In addition to the regular tilt toward the rift zone, a monoclinal flexure zone that runs N-S through eastern Iceland, is characterized by increased dips of up to 20° toward the active rift zone in the west [*Walker*, 1974].

[8] The glaciations of the Plio-Pleistocene carved deep fjords that expose sections through the crust, the eroded depth of which has been determined by the combination of three separate approaches [*Walker*, 1960, 1974]: (i) the extrapolation of the altitude of zero dip of the lavas that is assumed to correspond to the original top of the lava pile based on the observation of an increase in dip of the lavas with depth, (ii) regional metamorphic zeolite zonation that represents fossil geothermal isotherms subparallel to the original land surface, and (iii) the extrapolation of the altitude of zero dyke density. As these three methods give consistent results with a maximum deviation of 200 m, erosion depths range from up to 2 km below the former Tertiary land surface in Southeast Iceland [*Walker*, 1960, 1974] to about 1.1 km in Northeast Iceland [*Gustafsson*, 1992].

[9] This also exposes the extinct volcanic edifices of central volcanoes (Figure 1). These are charac-

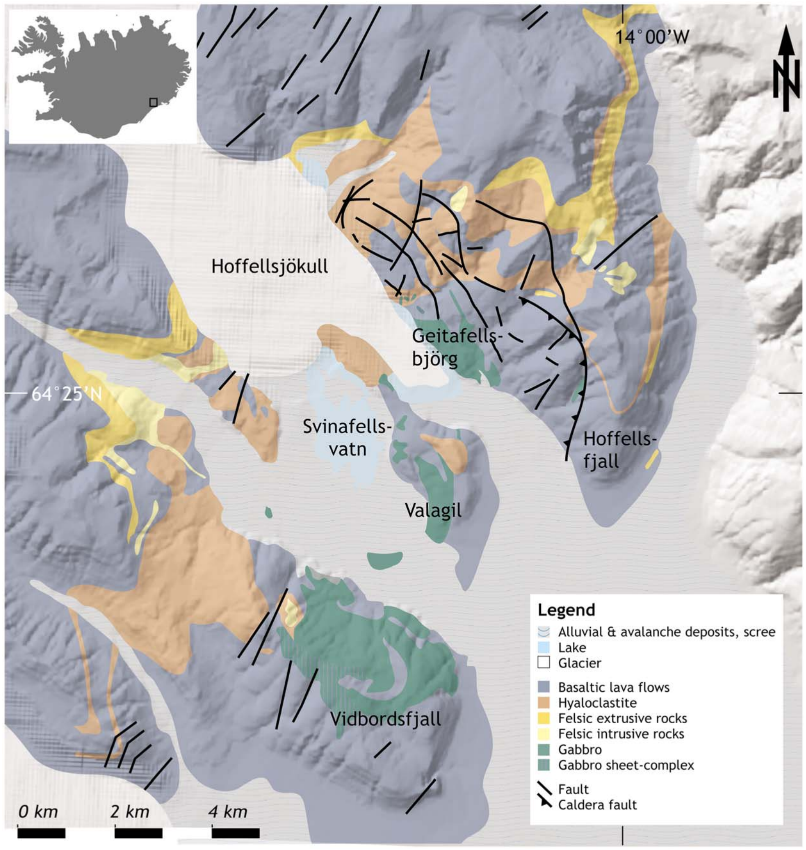

Figure 2. Geological map of the Geitafell Volcano (location indicated in Figure 1), modified after *Fridleifsson* [1983a]. Note that due to the regional dip to the northwest, deeper levels of the volcano are exposed in the southeast. The highest peak (north of Geitafellsbjörg) reaches an altitude of 1275 m a.s.l.

terized by (1) the occurrence of acid rocks that are restricted in Iceland to volcanic centers [*Walker*, 1966], (2) inclined sheet swarms [*Anderson*, 1936], (3) plutons composed of gabbro and/or granophyre [e.g., *Emeleus and Bell*, 2005], (4) disturbances of the regional metamorphic zones and local occurrence of alteration zones from volcanic high-temperature geothermal systems [*Walker*, 1974; *Fridleifsson*, 1984; *Holness and Isherwood*, 2003; *Donoghue et al.*, 2008], (5) deviations from the regional dip of the surrounding country rock as a consequence of uplift and/or subsidence of the center of the volcano [*Walker*, 1962, 1964; *Troll et al.*, 2002; *Holohan et al.*, 2009; *Petronis et al.*, 2009], and (6) associated swarms of vertical dykes that represent the feeders of fissure eruptions [*Walker*, 1974].

2.1. Geological Setting of the Geitafell Volcano

[10] The 5 to 6 Ma old Geitafell Volcano [*Fridleifsson*, 1983a] in Southeast Iceland is located northwest of the town Höfn, in the area with the deepest glacial erosion in Iceland (2 km) [*Walker*, 1974]. Glacial valleys related to Hoffellsjökull and other outlet glaciers of the Vatnajökull Ice Sheet cut the center of the volcano and expose sections that reach from its flanks down to the roofs of several gabbro plutons (Figures 2 and 3). The plutons are surrounded by dense swarms of inclined sheets and remnants of a high-temperature geothermal system that features propylitic and calcitic zones [*Fridleifsson*, 1983b, 1984].

[11] Previous studies by *Annels* [1967], *Newman* [1967], and *Fridleifsson* [1983a] give an overview of the petrology, structure, and geothermal alteration of the Geitafell Volcano. The flanks of the volcano comprise a succession of basaltic lava flows, shallow silicic intrusions, silicic extrusive rocks (Figure 3d), as well as hyaloclastites; the latter bear evidence of repeated glaciations of the volcano [*Fridleifsson*, 1983a]. *Fridleifsson* [1983a] was the first to describe a steeply outward dipping caldera fault in the northeastern sector of the volcano.

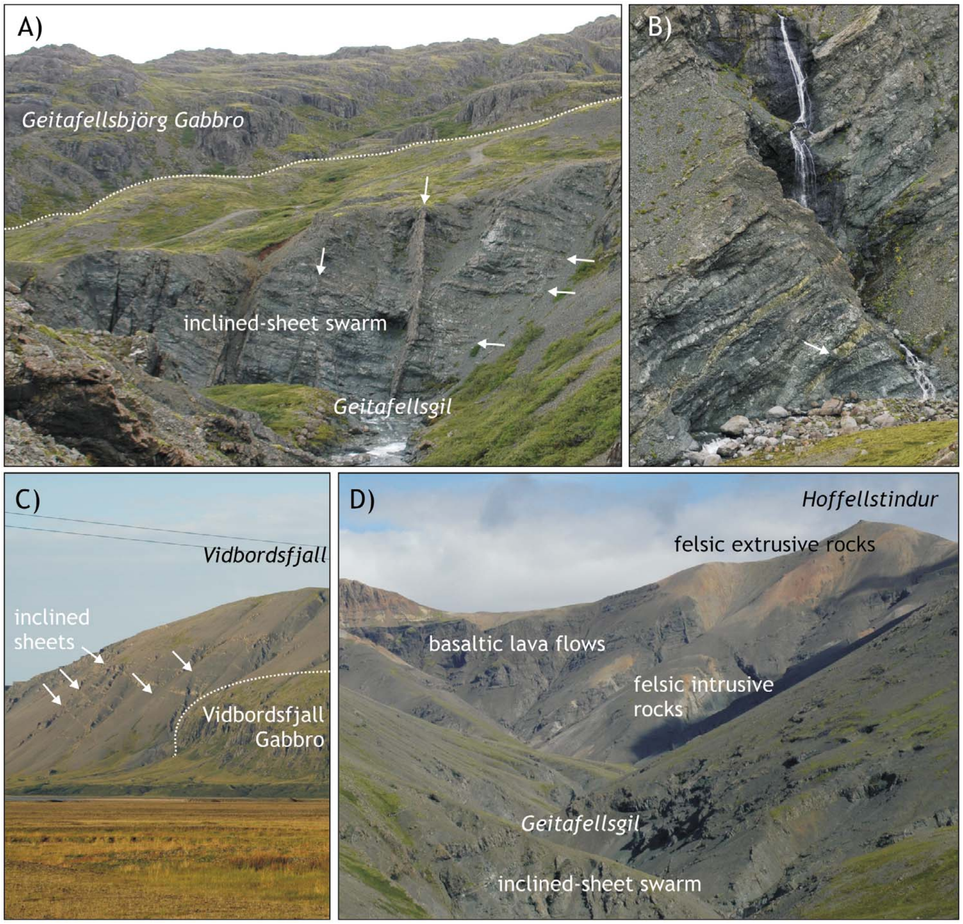

Figure 3. (a) View SW along the canyon of Geitafellsgil where inclined sheets are exposed to the adjacent Geitafellsbjörg Gabbro. The approximate location of the margin of the gabbro is indicated by a dotted line. Canyon wall is approximately 30 m high and mainly composed of shallow dipping inclined sheets cut by steeply dipping sheet intrusions (examples of both groups indicated by arrows). (b) Canyon wall in Geitafellsgil composed of inclined sheets. Yellowish sheets are felsic in composition. The sheet marked by the arrow is ca. 1.2 m thick. View NW. (c) View SSW from Hoffellsfjall to Vidbordsfjall. The Vidbordsfjall Gabbro is distinguishable by differences in relief and vegetation. Around the gabbro, inclined sheets (indicated by arrows) form a bowl-shaped swarm. Altitude of Vidbordsfjall is ca. 500 m from the river plain in the foreground. (d) View NE from Geitafellsbjörg across the inclined sheet swarm in Geitafellsgil toward the flank area of the Geitafell Volcano, composed of basaltic lava flows and felsic intrusive and extrusive rocks. Scale varies with distance.

[12] In the core of the volcano, several, mainly gabbroic plutons are exposed. Geophysical evidence suggests that these plutons are connected below the level of exposure [*Schönharting and Strand Petersen*, 1978]. The close relation to the surrounding swarms of inclined sheets (Figure 3a) indicates that the plutons may be parts of the magmatic source that fed sheet intrusions and surface eruptions. Inclined sheets are exposed along several deep canyons in the vicinity of the gabbros and comprise probably 10,000s, mainly basaltic, sheet intrusions. *Burchardt and Gudmundsson* [2009] suggest that the inclined sheet swarm of the Geitafell Volcano is probably bowl-shaped (i.e., concave upward), based on field observations of the geometry of sheets in vertical exposures, such as Vidbordsfjall (Figure 3c). Three-dimensional modeling of the inclined sheet swarm presented in this study is based on the data set of sheet intrusions in the vicinity of the Geitafellsbjörg Gabbro (Figures 2 and 3).

2.2. Geological Setting of the Dyrfjöll Volcano

[13] Dyrfjöll Volcano is located between the river plain Heradsfloi and the fjord Borgarfjördur eystri in Northeast Iceland (Figures 1 and 4), in an area characterized by the abundance of unusually large volumes of felsic rocks (mainly rhyolite and dacites) for Icelandic volcanoes [*Gustafsson et al.*,

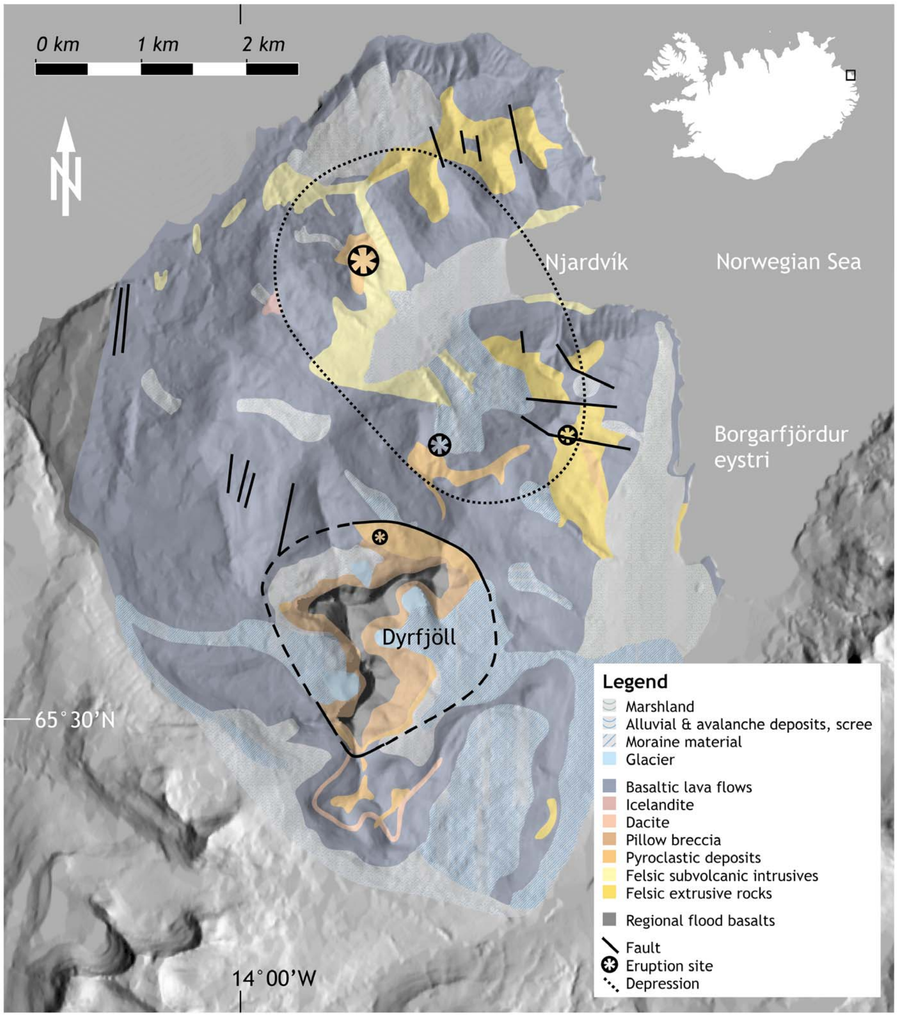

Figure 4. Geological map of the Dyrfjöll Volcano (location in Figure 1), modified after *Gustafsson* [1992]. The highest peaks (Dyrfjöll) reach an altitude of 1100 m a.s.l.

1990]. With an age of 12.5 to 13.1 Ma [*Martin and Sigmarsson*, 2010], it is one of the oldest volcanoes exposed in eastern Iceland and probably belongs to a suite of central volcanoes located between Heradsfloi in the north and Seydisfjördur in the south (Figure 1).

[14] As a consequence of strong glacial erosion, the interior of the Dyrfjöll Volcano is exposed in the cove of Njardvik down to a maximum depth of about 1100 m below the original land surface. The highest peaks surrounding Njardvik, as well as the Dyrfjöll Mountains, are part of the summit area, whereas parts of the flanks of the volcano are preserved on the slopes west of Borgarfjördur eystri, south of the Dyrfjöll, and northwest of northern Heradsfloi. Probably as a result of its remote location, the absence of recent geothermal activity, and the lack of opportunity to exploit hydropower, the area has not been the focus of geological investigations, except for *Gustafsson* [1992].

[15] Based on *Gustafsson* [1992], the geological history of the Dyrfjöll Volcano can be summarized as follows: The main volume of the volcano was built up by basaltic lava flows, the extrusion of which dominated during the early evolution of the volcano (Lower basaltic group). Toward higher structural levels, the occurrence of some intermediate and acid lava flows (rhyolites, dacites, and icelandites), intercalated with the basaltic lavas, indicates the progressive maturation of the magma chamber system underlying the volcano. This culminated in the emplacement of a subvolcanic intrusive complex, the Njardvik Silicic Complex (NSC), at shallow levels in the central area of the volcano. At the surface, this was accompanied

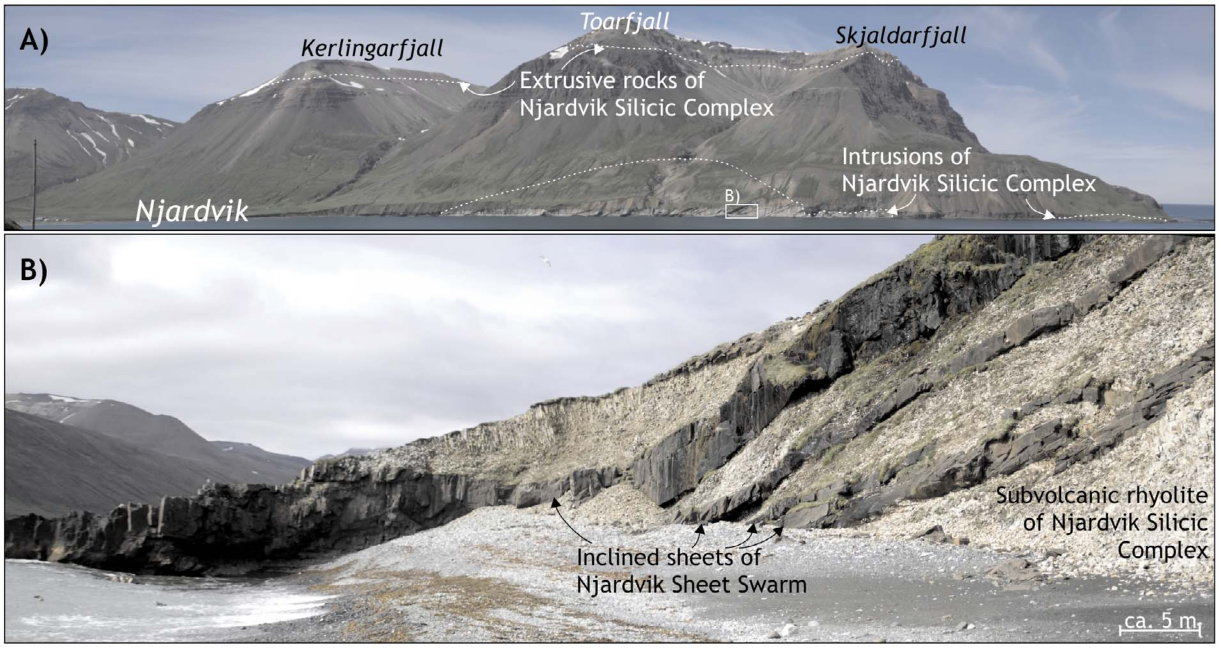

Figure 5. (a) Panoramic view of the northwestern shore of the cove of Njardvik. Outcrops of felsic rocks of the Njardvik Silicic Complex (NSC) can be distinguished from the basaltic lava flows of the Dyrfjöll Volcano by their light colors. The NSC comprises subvolcanic intrusions at low elevations and extrusive rocks on the peaks of the mountains. (b) Outcrop photograph of basaltic inclined sheets emplaced into the intrusive part of the NSC. Location marked in Figure 5a. View W. Scale varies with perspective.

by explosive and effusive activity concentrated around the volcano's center, approximately located in Njardvik Valley. During the next phase of the evolution of the volcano, activity shifted toward the southwest, where a major explosive eruption led to the formation of the Dyrfjöll Caldera. During the final stages of the Dyrfjöll Volcano, the caldera depression, then occupied by a lake, was filled with basaltic hyaloclastites and pillow breccias and later with some lava flows. Finally, after the volcano became extinct it was buried by regional flood basalt lavas.

[16] The NSC is exposed near sea level in the cove of Njardvik, on the summits of the surrounding mountains (Figures 4 and 5), and in a few canyons in the northern and southern part of the Dyrfjöll Volcano (Figure 3). At lower structural levels, it displays intrusive contacts to its host rock. However, as shown in detail by *Gustafsson* [1992], toward higher levels, the felsic rocks of the NSC increasingly exhibit extrusive features. In addition, some of the exposed eruption sites are clearly connected to the underlying intrusive felsic rocks through dykes and inclined sheets [cf. *Holohan et al.*, 2009]. The occurrence of several subunits indicates that the formation of the NSC occurred through episodic magma supply. The overall shape of the intrusive part of the NSC resembles a broad dome with an inferred culmination in the valley of Njardvik, where a maximum of 200 m of intrusive thickness is exposed. Basalt lavas that form the roof rock of the intrusive part of the NSC on the slopes surrounding Njardvik, dip concentrically toward Njardvik Valley, thus forming a depression. According to *Gustafsson* [1992], this structure is a result of subsidence following the intrusion and subsequent extrusion of magma belonging to the NSC [cf. *O'Driscoll et al.*, 2006, 2007].

[17] As can be observed in the impressive outcrops of the NSC at the coast in Njardvik (Figure 2b), the interior of the volcano is crosscut by a large number of basaltic dykes, inclined sheets, and sills [*Burchardt*, 2008]. These represent a shift back to predominantly basaltic magmatism, which postdates the felsic phase of the Dyrfjöll Volcano. *Gustafsson* [1992] reported that the inclined sheets are arranged in a concentric pattern around the center of the Volcano in Njardvik Valley, whereas the dykes strike dominantly NNE.

3. Data Sets and Methods of Analysis

[18] The intrusive swarms of the Geitafell and the Dyrfjöll Volcano were studied mainly along gullies.

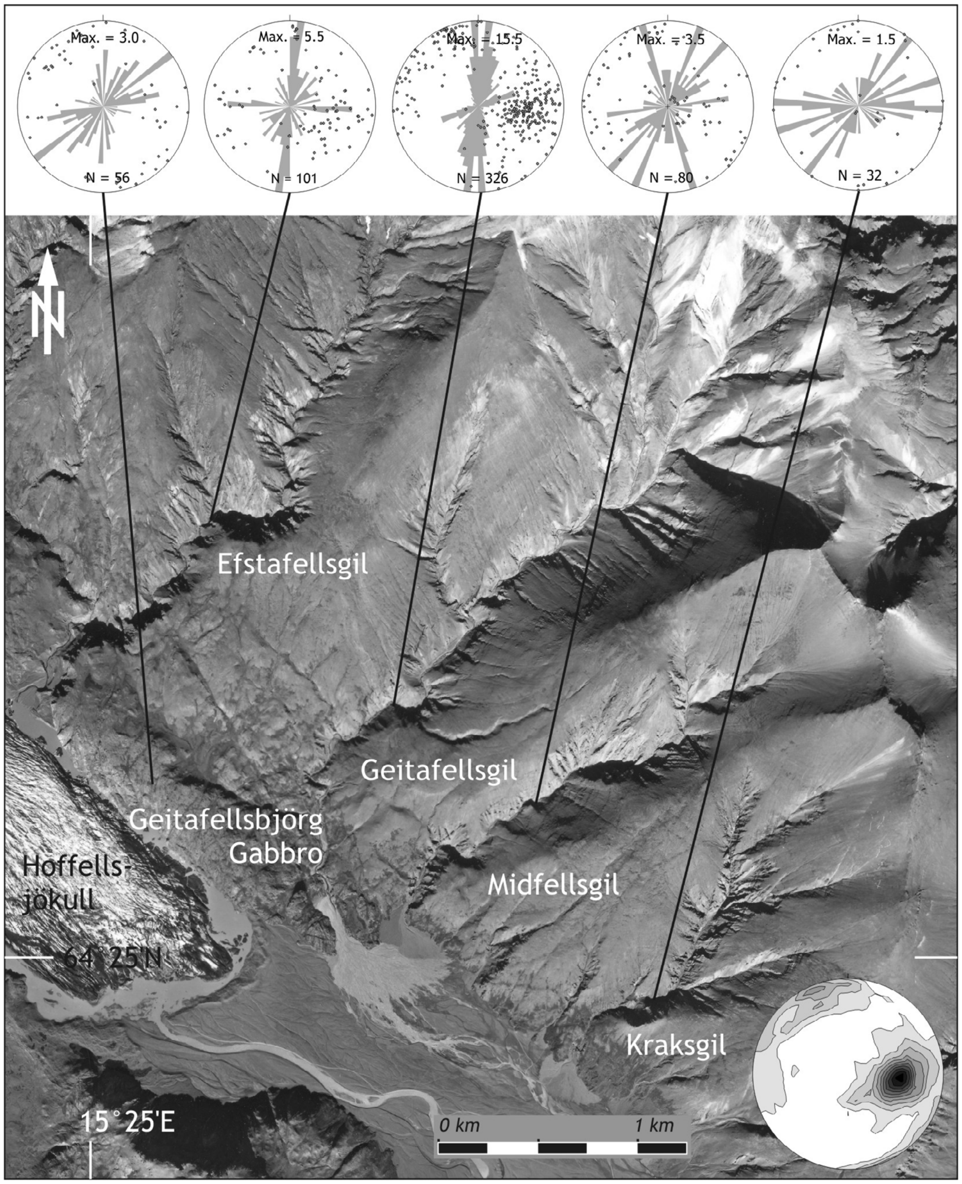

Figure 6. Orientation of sheet intrusions within the Geitafellsbjörg Gabbro and in the four canyons in the Geitafell Volcano displayed as stereographic projection of poles to planes (equal area, lower hemisphere) and rose diagrams of the strike direction (gray, background of plots, 5° classes). Inset density plot displays poles to planes of the full data set with a contour spacing of 0.7 and a maximum density of 7.14.

Representative sheet orientations were recorded for respective outcrops and measured to avoid small-scale irregularities. The inclined sheets of the Geitafell Volcano are best exposed in the four canyons in the northern part of the volcano close to the Geitafellsbjörg Gabbro (Figure 6), namely Efstafellsgil, Geitafellsgil (Figures 3a, 3b, and 3d), Midfellsgil, and Kraksgil. These canyons represent NE-SW striking sections that reach, in the case of the first three canyons, from close to the gabbro at the lowest-exposed altitude toward the flanks of the volcano. The intensity of sheet intrusion decreases with distance from the gabbro from 100% adjacent to the gabbro (Figures 3a and 3b) to only a few percent toward the flanks. Since Kraksgil is located at some distance from the center of the volcano (Figures 2 and 6), it is characterized by the lowest intrusive density. In addition, exposure quality generally decreases upstream in the canyons where the incision by water creates more gently dipping walls that are more scree covered.

[19] According to *Burchardt and Gudmundsson* [2009], individual sheets are usually basaltic, between

1 cm and 11.25 m thick, and characterized by variable degrees of alteration, crystal content, vesicularity, and chilling against neighboring sheets. As a base for three-dimensional modeling of the sheet swarm geometries, we used the data set described by *Burchardt and Gudmundsson* [2009] that includes orientation, thickness, and location, as well as a description of macroscopic features of 539 sheet intrusions (Figure 6). In addition, *Burchardt and Gudmundsson* [2009] report the orientation of 56 sheet intrusions that cut the Geitafellsbjörg Gabbro.

[20] At the Dyrfjöll Volcano, measurements were carried out along coastal sections, river valleys, and canyons mainly in the areas with the lowest altitudes since they represent deeper structural levels of the Dyrfjöll Volcano and are characterized by a higher intrusion density. Together with the orientation, we recorded thickness, type, and – for the intrusions – lithology of 93 faults and 464 sheet intrusions.

[21] We subdivided sheet intrusions according to their dip into subvertical dykes (dip >70°) and inclined sheets (dip ≤70°), following the approach of e.g., *Annels* [1967] and *Gautneb et al.* [1989]. This distinction was used because dykes are assumed to have a more regional source located at considerable depth beneath the shallow magma chambers that feed the inclined sheets [*Walker*, 1966; cf. *Grosfils*, 2007]. Evidence for a generic difference is provided by a bimodal dip distribution with a gap between sheet intrusions dipping <70° and those dipping ≥70° for both volcanoes (Figure 8i) [*Burchardt and Gudmundsson*, 2009, Figure 5c]. Sheet orientations of the complete data sets of both volcanoes were plotted and categorized according to their location, and employing stereographic projections to assess spatial variations. In case of the Dyrfjöll Volcano, the orientations of dykes and faults were also plotted on stereographic projections to assess regional trends. In general, the regional tilt of the lava pile that postdates the lifetime of the two volcanoes [cf. *Walker*, 1974], has not been considered during data evaluation. In case of the Geitafell Volcano, we therefore did not account for postvolcanic rotation of the measured sheets due to regional or local tilting. The amount of tilt seems to vary within the area of the volcano, however, we discuss below implications for data interpretation that could arise from tilting. Furthermore, the orientations of steeply dipping sheet intrusions were subsequently compared to the results of three-dimensional models of inclined sheets.

[22] To model the sheet swarm geometries in three dimensions, 436 inclined sheets in the Geitafell Volcano and 321 inclined sheets in the Dyrfjöll Volcano were taken into consideration. Location (as UTM XYZ coordinates), orientation, and number of each of these sheets were included in two ASCII data files. Each sheet was then projected along its strike as a 100 m long strike line to transform the point of measurement into a line. This line was then linearly projected downdip, using the software 3DMove, to create surfaces with the defined sheet orientations. In case of the Geitafell sheets, the distance of downdip projection was 1000 m, since the sheets are proposed to be located close to the magmatic source, exposed as gabbro bodies [*Burchardt and Gudmundsson*, 2009]. Since the exact location and depth of the source of the inclined sheets in the Dyrfjöll Volcano was not known, we used a projection distance of 5000 m. As a base map, we used parts of the Digital Elevation Model (DEM) of Iceland with a cell size of 25 m, provided by the National Land Survey of Iceland. The projected sheets typically converge toward common foci and this allowed them to be grouped accordingly. Grouping was done manually, taking into consideration sheet orientation, location, and relationship to other sheets. In contrast to e.g., *Siler and Karson* [2009], we defined foci as clusters of inclined sheet projection surfaces, because we expect magmatic sources to have a certain volume, as opposed to point sources defined by intersection of all sheet trajectories in one point. For each group, a potential source location/depth/size was defined, the accuracy of which depend on the number of sheets that belong to each focus and their spatial distribution.

4. Results

4.1. Sheet Swarms in the Geitafell Volcano

[23] Stereographic projection of sheet orientations by their location in the four canyons (Figure 6) does not show a clear systematic spatial variation. In the data from all four canyons, sheets appear to belong to two main groups or swarms: (1) N-S striking sheets that dip mainly toward the W at shallow to moderate angles and (2) NE-SW to ENE-WSW striking sheets that dip SE to SSE at moderate to steep angles.

[24] Three-dimensional planar projection of the 436 inclined sheets offers the opportunity to analyze the relation between location and orientation of each inclined sheet in more detail, because the results clarify the relationship between location and orientation for an individual sheet, as well as the

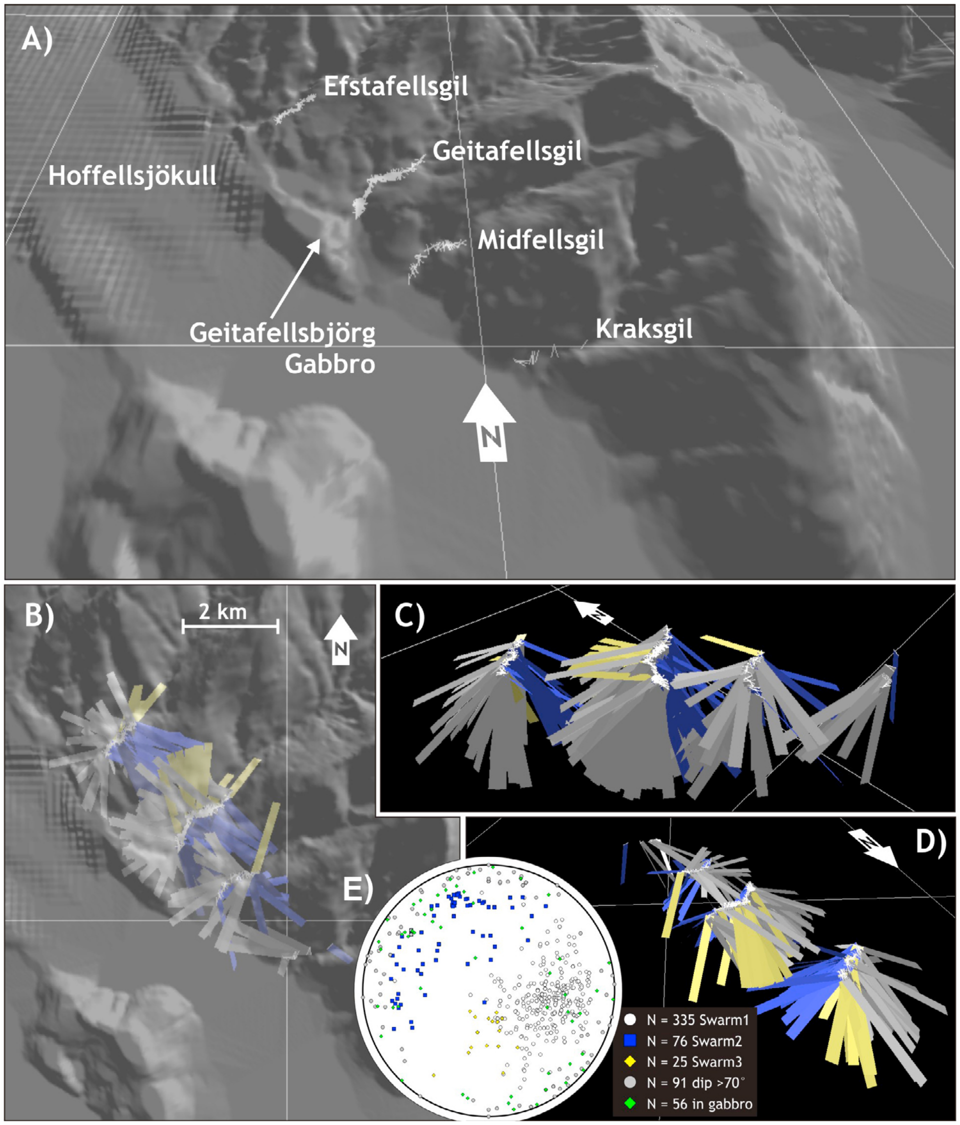

Figure 7. Results of planar projection of inclined sheets of the Geitafell Volcano in 3DMove. (a) Perspective view of the DEM with 100 m long strike lines (white lines) of 436 inclined sheets. Grid size 5 × 5 km^2. DEM with a cell size of 25 m provided by the National Land Survey of Iceland. (b) Map view of the projected sheets, color coded according to swarm affiliations defined by location and orientation, beneath the translucent DEM surface. (c and d) Perspective views of the projected inclined sheets. Grid size is 5 × 5 km^2. (e) Stereographic projection of poles to planes (equal area, lower hemisphere) of the orientation of 583 sheet intrusions.

spatial relationships between the sheets. The results support the above mentioned classification in two swarms and suggest the existence of a third swarm of inclined sheets striking E-W and dipping at shallow angles to the N. The three likely swarms were color coded in 3DMove to better visualize the groups (Figure 7 and Animation S1 in the auxiliary material) and analyzed separately to derive information about their magmatic sources.[1] Swarm 1 comprises 335 of the projected sheets. Members of this swarm occur in all four canyons without significant variations among the canyons. Dip directions cover a continuum from NW to SW, while dips cover the full spectrum from ca. 20 to 70°, giving Swarm 1 the shape of a downward facing fan. Swarm 2 comprises 76 steeply SSW to SSE dipping sheets that occur in all canyons, while only 25 inclined sheets belong to Swarm 3. The latter is distinguished from Swarm 1 by its shallow N to NNE dip. Swarm 3 sheets appear to become more abundant toward the NW, however.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GC003527.

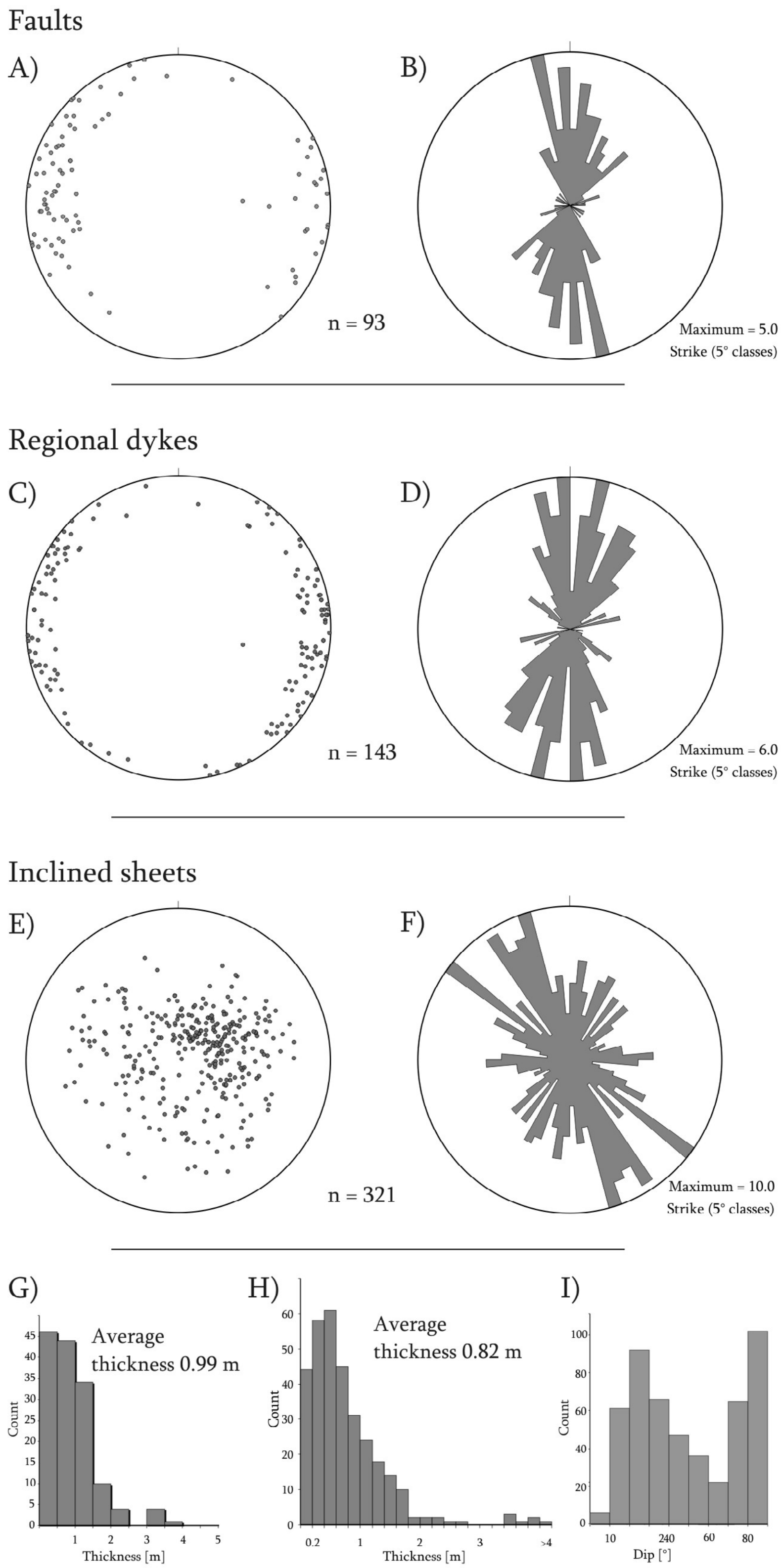
Faults
A)
B)
n = 93
Maximum = 5.0
Strike (5° classes)
Regional dykes
C)
D)
n = 143
Maximum = 6.0
Strike (5° classes)
Inclined sheets
E)
F)
n = 321
Maximum = 10.0
Strike (5° classes)
G)
Average thickness 0.99 m
Count
Thickness [m]
H)
Average thickness 0.82 m
Count
Thickness [m]
I)
Count
Dip [°]

Figure 8

[25] A comparison of the orientation of inclined sheet swarms identified in the three-dimensional model, where the sheets dip >70°, indicates that many of the steep sheets can be defined as members of Swarm 2 (Figure 7). In this context, the majority of the 56 sheets that cut the Geitafellsbjörg Gabbro can be assigned to Swarm 2, even though *Burchardt and Gudmundsson* [2009] showed that most of them follow cooling joints in the gabbro. Only nine of the sheets that cut the gabbro can be safely defined as belonging to Swarm 1.

[26] Crosscutting relationships between sheets observed in the field (e.g., Figure 3a; we recorded 21 cases where sheets of Swarm 2 crosscut gully walls formed by Swarm 1. No cases where Swarm 2 sheets were cut by members of Swarm 1 were observed) and the preferential occurrence of Swarm 2 sheets within the Geitafellsbjörg Gabbro indicate that Swarm 2 postdates Swarm 1. Crosscutting relationships of Swarms 1 and 3, however, were not that frequently recorded, which we attribute to their similarity in orientation, so that their intersections would be at highly acute angles.

4.2. Sheet Swarms in the Dyrfjöll Volcano

[27] Of the 464 sheet intrusions measured in the area of the Dyrfjöll Volcano, 93 were classified as dykes (dip >70°). These are mainly basaltic and tend to be thicker (0.99 m on average) than sheet intrusions, dipping ≤70° (0.82 m thick on average). Dykes exhibit NNE to NNW strikes (010° on average) which coincide with the orientation of faults in the area (Figure 8). Faults are located in virtually all stratigraphic units of the Dyrfjöll Volcano, where they are predominantly characterized by normal displacement (only three of the faults show reverse sense). Fault throw, where possible to estimate, was in the range of a few centimeters up to approximately 10 m. Faulting probably occurred throughout the lifetime of the Dyrfjöll volcano, as indicated by crosscutting relationships with sheet intrusions.

[28] The orientation of shallow dipping intrusive sheets (inclined sheets) is characterized by a small-circle distribution (Figure 8) that might indicate a common magmatic source. However, sheet orientations plotted as a function of location (Figure 9) demonstrate that there is a strong variation that cannot be attributed to one common center. Three-dimensional, planar projection of 321 inclined sheets indicates that they belong to more than one swarm. As a consequence, sheets which obviously deviate from the orientation of the main swarm (as proposed by *Gustafsson* [1992]) were marked and subsequently grouped according to their location and orientation. The selection resulted in the differentiation of three major swarms, as shown in Figure 10 (see also Animation S2), as well as four minor swarms or subsets.

[29] The largest subset, Swarm 1 (marked purple in Figure 10), comprises 221 sheets that are distributed all over the studied area. The swarm has a radius of a minimum of 3 km and is traceable in its central area in the upper Njardvik Valley. Its outer part is constrained by sheets in all profiles and represents more than 240° of a circle in the area north of Borgarfjördur Valley and the Dyrfjöll (Figure 11). Sheet dips vary from around 10° to 70° in all profiles and therefore do not show a systematic variation in dip. A second subset (Swarm 2, marked blue in Figure 10) consists of 39 sheets exposed in the southeast of the study area. They represent the northwestern segment of a circular swarm with a radius of around 3 km. The sheets vary in dip between 10° and 70°. The rest of the swarm is not exposed, but we expect them to lie offshore in the fjord of Borgarfjördur eystri and below the sedimentary cover of Borgarfjördur Valley. The third largest subset (Swarm 3, marked light yellow in Figure 10) comprises 32 sheets located in the north and northeast of the Dyrfjöll Volcano. The inclined sheets of Swarm 3 dip toward a center located to the north-northeast, off the coast (Figure 11). A reconstructed swarm would have a radius of at least 5 km. Furthermore, there are four minor subsets: 11 sheets of subset 4 (marked yellow in Figure 10) are located in the northeastern part of the studied area and dip to the northwest. They are possibly associated with Swarm 3. Five sheets marked orange (subset 5) that are located in the westernmost part of the study area converge to a common focal point northwest of the Dyrfjöll Mountains. Another subset (subset 6, marked green in Figure 10) consists of three inclined

Figure 8. Illustration of all data of sheet intrusions (dykes and inclined sheets) and faults measured in the Dyrfjöll Volcano. (a) Stereographic projection of poles to 93 fault planes (equal area, lower hemisphere). (b) Rose diagram of the strike direction of faults in Figure 8a. (c) Stereographic projection of poles to planes of 143 dykes (equal area, lower hemisphere). (d) Rose diagram of the strike direction of dykes in Figure 8c. (e) Stereographic projection of poles to planes of 321 inclined sheets (equal area, lower hemisphere). (f) Rose diagram of the strike direction of inclined sheets in Figure 8e. (g) Thickness frequency distribution of 93 dykes. (h) Thickness frequency distribution of 321 inclined sheets. (i) Dip frequency distribution of regional dykes and inclined sheets in Figures 8c–8f.

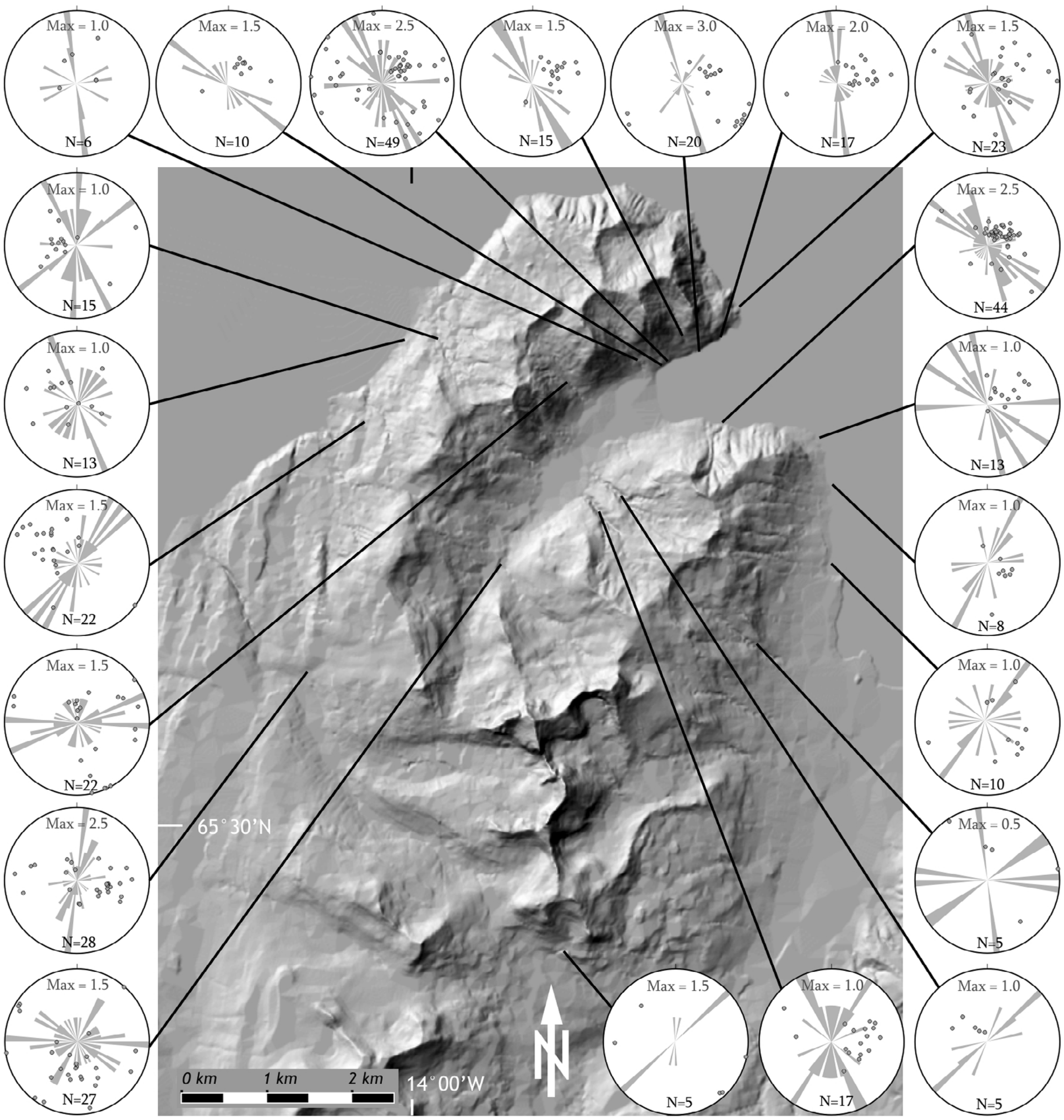

Figure 9. Orientation of inclined sheets in different locations around the Dyrfjöll Volcano, displayed as stereographic projection of poles to planes (equal area, lower hemisphere) and rose diagrams of the strike direction (gray, background of plots).

sheets in the northwest of the study area. Their main dip direction is WNW. Finally, one felsic inclined sheet was measured south of the Dyrfjöll Mountains (marked in pink in Figure 10). It does probably not belong to one of the centers of the Dyrfjöll Volcano as it appears to originate from the south.

[30] To assess the relationships between the individual swarms the following questions were posed:

[31] (1) Which stratigraphic units of the Dyrfjöll Volcano were intruded by each swarm?

[32] (2) What do crosscutting relationships of individual sheets reveal about the relative age of each swarm?

[33] (3) Is there a connection between the lithology of individual sheets and their affiliation to one of the swarms?

[34] Analysis of the host rocks of the inclined sheets does not show any differences between the swarms. Instead, all swarms intrude the Lower basaltic units of the Dyrfjöll Volcano and the NSC. Thus, all

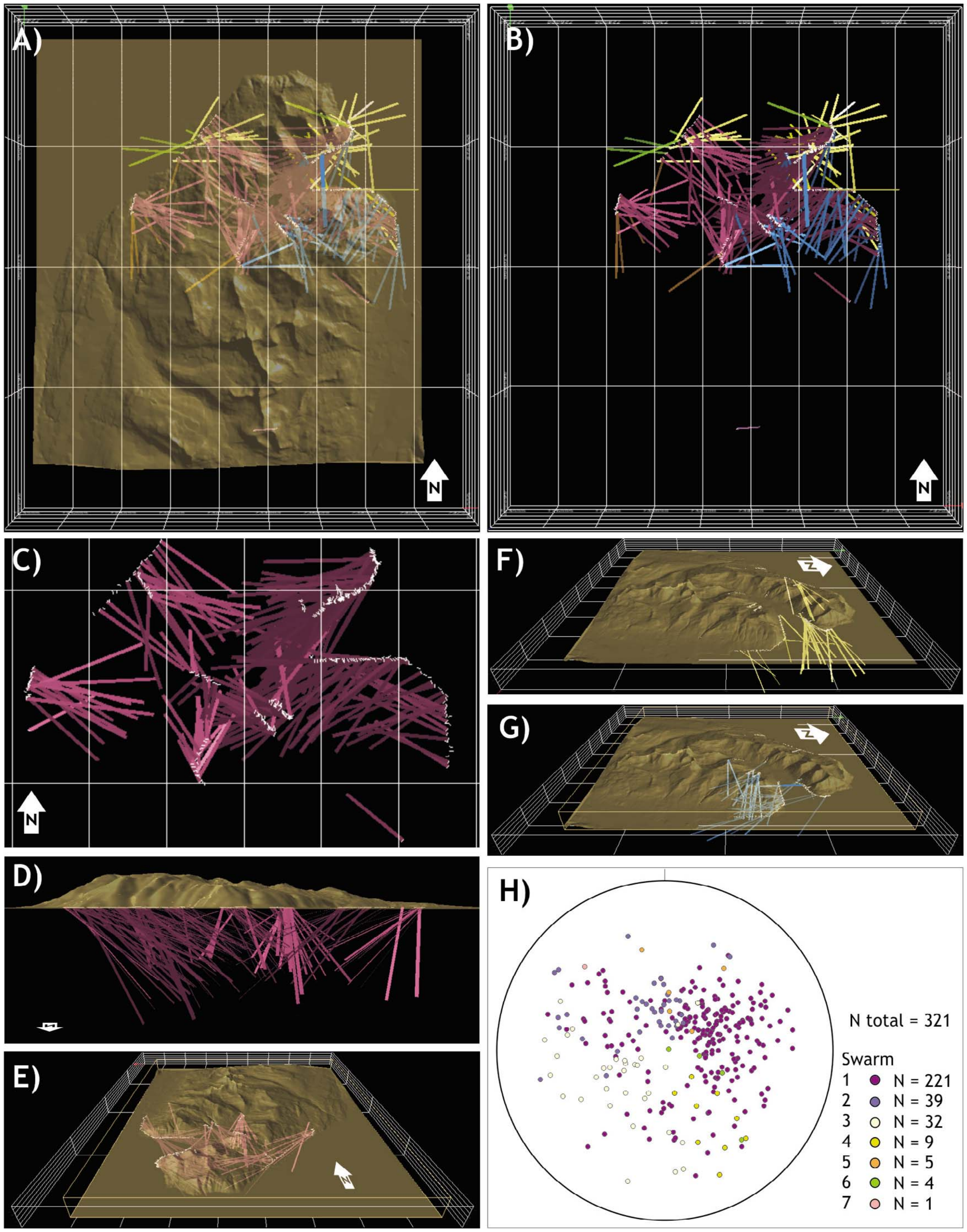

Figure 10. Results of three-dimensional, planar projection of 321 inclined sheets in the Dyrfjöll Volcano. (a) Map view of projected inclined sheets below the translucent surface of the DEM. Short white lines represent 100 m long, projected strike lines of the inclined sheets. Color coding was carried out manually according to location and attitude of individual sheets. Projection distance 5000 m. (b) Map view of all projected sheets. (c) Map view of Swarm 1. (d and e) Perspective view of Swarm 1. (f) Perspective view of Swarm 2. (g) Perspective view of Swarm 3. (h) Projection of poles to planes of inclined sheet orientations (equal area, lower hemisphere) color coded by subset. Background grid is 2 and 5 km in E-W and N-S directions in Figures 10a–10g.

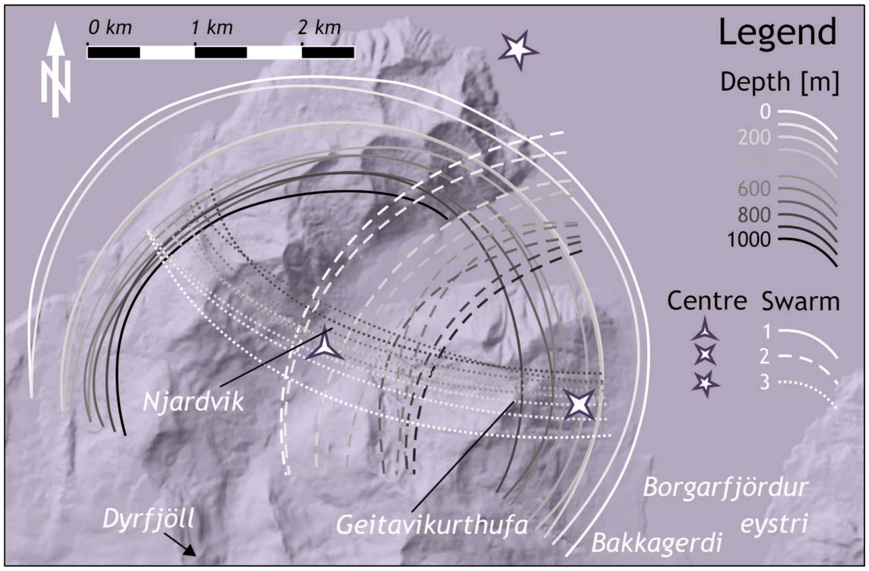

Figure 11. Depth contours of the outline of the three most prominent inclined sheet swarms in the Dyrfjöll Volcano. Each contour represents a smoothed envelope of the respective swarm at the given depth interval. Star symbols mark the locations of possible swarm centers.

swarms are either younger than the felsic magmatic phase represented by the NSC, or their time of formation extends beyond the felsic phase. Crosscutting relationships of all sheet intrusions reveal that regional dykes tend to be younger than the inclined sheets (in 12 of 14 recorded cases). Furthermore, Swarms 1 and 3 were contemporaneous (two cases of Swarm 1 cutting Swarm 3, one case of Swarm 3 cutting Swarm 1), whereas Swarm 4 is younger that both Swarm 1 and 3 (four cases of Swarm 4 cutting Swarm 1, one case cutting Swarm 3). Unfortunately, only few crosscutting relationships were found in the field, so the statistics of the results are rather poorly constrained. For Swarm 2, not one single crosscutting relationship was recorded. An analysis of the sheet lithology of the swarms reveals that there is no detectable correlation, i.e., all swarms comprise predominantly basaltic sheets. Of 321 sheets measured, only 25 are of felsic composition (7.8%). They form part of all the identified subsets without any clear tendency toward a higher felsic component in any particular swarm.

5. Discussion

5.1. Three-Dimensional Projection of Different Sheet Geometries

[35] Three-dimensional projection of inclined sheets allows on the one hand to visualize more clearly the spatial distribution of different sheet orientations, for instance compared to stereographic projection. On the other hand, it helps to deduce information about the depth, shape, and size of the magmatic source feeding the sheets [e.g., *Klausen*, 2004; *Siler and Karson*, 2009]. All techniques used so far assume simplified sheet geometries at depth, because the geometry and exact orientation of inclined sheets and sheet swarms at depth is still uncertain [*Anderson*, 1936; *Phillips*, 1974; *Chadwick and Dieterich*, 1995; *Gudmundsson*, 1998] and appears to vary from volcano to volcano [e.g., *Schirnick et al.*, 1999; *Klausen*, 2004]. Therefore, sheets are usually projected as planar trajectories [*Siler and Karson*, 2009]. However, this assumption results in considerable deviations of the results when compared to a projection of curved sheet geometries. This is demonstrated here by comparing the results of projection of the Geitafell sheets along three different paths (Figures 12 and 13). Idealized, concave-upward sheet geometries produce a bowl-shaped sheet swarm (Figure 13e) [cf. *Klausen*, 2004] and lead to a shallow source depth, as sheet dips decrease with depth. Concave-downward sheet projection produces a trumpet-shaped swarm (Figure 13f), with a deeper focal point, since sheet dip increases downward. By comparison, planar sheet projection results in intermediate source depths (Figure 13d). This difference in the derived source depth is in the range of several hundred to even a few thousand meters, depending on the swarm size and the defined sheet geometry the projection is applied to. Comparatively well-exposed swarms of inclined sheets with well-distributed profiles allow an estimate

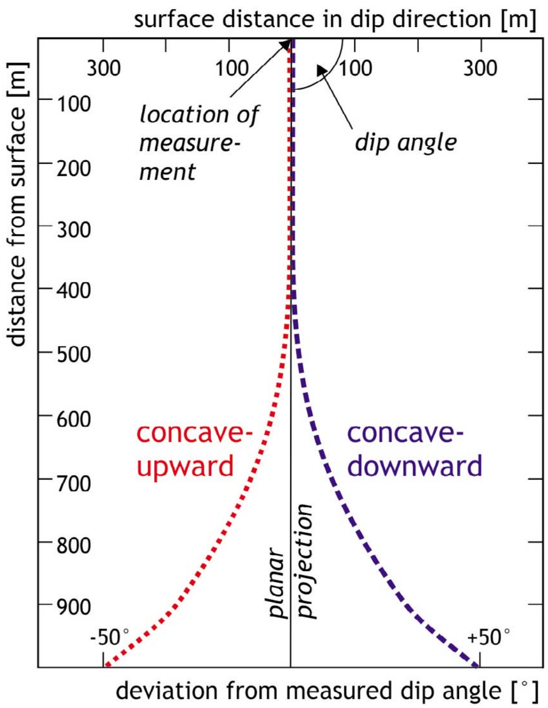

Figure 12. Curves defining the geometry of inclined sheet projections for the Geitafell data set in 3DMove. The curves deviate from the straight line equivalent to a change in the dip angle by 50° at the maximum depth of 1000 m.

of true sheet geometries e.g., from spatial variations in sheet dips [e.g., *Gautneb et al.*, 1989; *Klausen*, 2004]. In case of the Geitafell Volcano, field observations of the overall appearance of the inclined sheet swarm in the slope of Vidbordsfjall (Figure 3c) suggest that the geometry of sheets is predominantly bowl shaped with a decrease in dip of about 7°/km horizontal distance from the source [*Burchardt and Gudmundsson*, 2009]. Therefore, we used the Geitafell data set to test the implications of assuming different sheet geometries, i.e., (1) planar, (2) concave-downward (trumpet shape), and (3) concave-upward (bowl shape) (Figure 12). The results demonstrate significant differences in the overall swarm shape (Figure 13). This is particularly evident since all sheets were projected along the same curve (blue curve = concave-downward and red curve = concave-upward in Figure 12) without adjustments to account for dip variations and projection distance of sheets. Generally, sheet projection along a concave-upward ("bowl-shaped") path results in a fanning out of sheets with depth (Figure 13c). When deriving information about the magmatic source from intersection clusters of sheets from opposite ends of the swarm, a depth of more than one kilometer above that of the planar and convex-downward ("trumpet-shaped") sheet projection is derived. The trumpet-shaped arrangement is characterized by clustering of sheet trajectories from one side of a swarm with depth (Figure 13e). Even though inclined sheets in the Geitafell Volcano compose a bowl-shaped swarm, their exact concave-upward geometry at depth cannot be constrained with certainty. For this reason we derived source depths estimates and locations from the planar projections (see Section 5.2).

[36] In the Dyrfjöll Volcano, there is no systematic variation in dip with distance from the center for any of the swarms. Furthermore, the studied profiles do not cover a sufficient range of elevations to deduce significant variation in dip with elevation. Consequently, the geometry of inclined sheets at depth was only projected along planar paths.

5.2. Depths, Sizes, and Shapes of Magmatic Sources

[37] In case of the Geitafell Volcano, the distribution of the sheet intrusions studied does not allow a determination of the exact location, depth and size of their source magma chambers [cf. *Klausen*, 2004]. The inclined sheets studied in Geitafell are all located in the northwestern sector of the volcano along four NE-SW striking profiles. To determine the depth of the magmatic source from intersection points [cf. *Klausen*, 2004; *Geshi*, 2005; *Siler and Karson*, 2009], measurements from other sectors of the volcano are needed. In turn, the studied sheets in the Geitafell Volcano have the advantage that the exposed gabbro bodies represent parts of their magmatic source [*Burchardt and Gudmundsson*, 2009], so that the source location is not a completely unconstrained parameter. The inclined sheet swarm is in direct contact with the Geitafellsbjörg Gabbro and decreases in spatial density away from it. Moreover, most of the inclined sheets do indeed converge toward the Geitafellsbjörg Gabbro, toward the Valagil Gabbro in the west (Figure 2), as well as toward the northwest and north of Geitafellsbjörg (Figure 7). This semi-continuous spread of dip directions indicates that the Geitafellsbjörg and the Valagil Gabbros are most likely linked and probably continue to the northwest and north below the current level of exposure. In this respect, Swarm 3 may be interpreted as a continuation of Swarm 1, reflecting the potential extent of the source toward the north. Moreover, the wide range of dip directions of sheets shows that the size of the source magma chamber is in the range of at least 7 km in NW-SE direction and more than 4 km in NE-SW direction. Assuming that the distance to the magmatic source is the distance to the Geitafellsbjörg Gabbro, the wide range of dips of the inclined sheets of Swarm

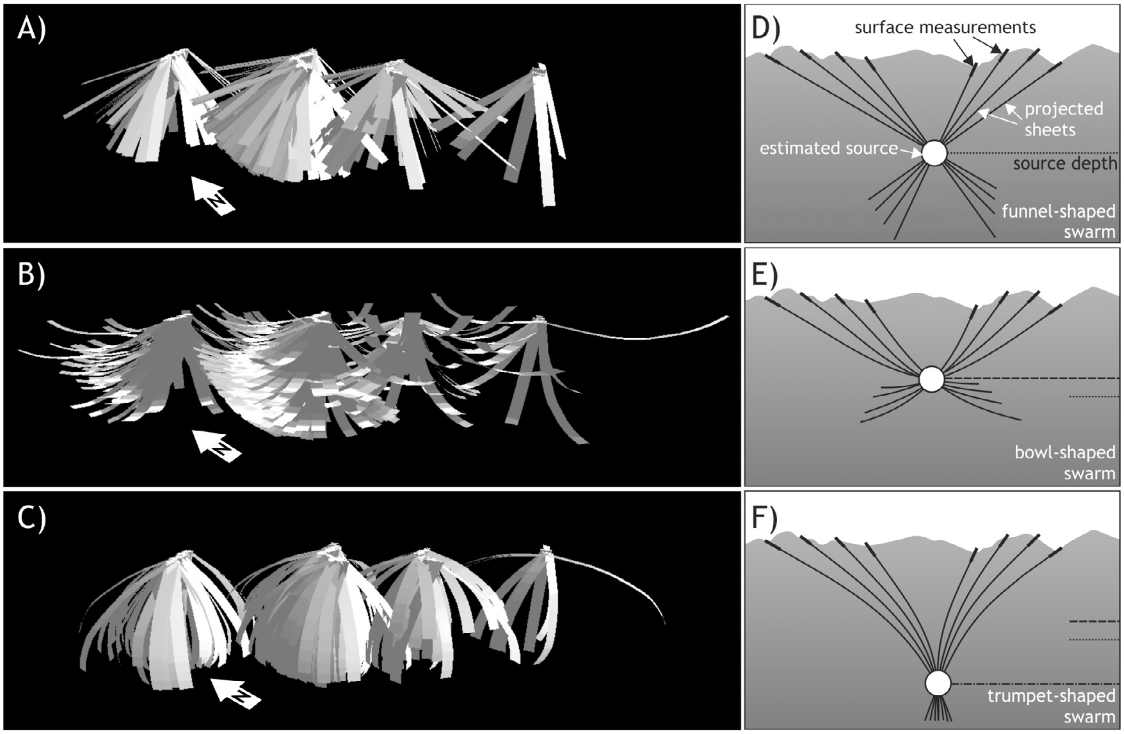

Figure 13. Illustration of the significance of different sheet geometries for the determination of the depth and location of focal points. Results of sheet projection of inclined sheets of the Geitafell Volcano in 3DMove along different projection paths (see Figure 12): (a) planar, (b) concave-upward, and (c) concave-downward projection. Projection distance downdip is 1000 m. Note that the Geitafell data set contains only one sector of the swarm. Scale varies with perspective. (d-f) Schematic sketches illustrating the different source depths (indicated by dashed and dotted lines) and locations that will be derived from assuming different sheet geometries.

1 indicates that the depth of the gabbro ranges from the current sea level to approximately 2 km (assuming planar sheet geometries). This corresponds to a source depth of between 2 to 4 km below the Tertiary land surface [cf. *Walker*, 1960, 1974].

[38] Members of Swarm 2 are characterized by intermediate to steep eastward dips. Taking into account the regional westward tilt in this area [*Walker*, 1974], one could expect that the original dips were up to 20° steeper. The magmatic source of the inclined sheets of Swarm 2 was located only a few hundred meters east of the Geitafellsbjörg Gabbro below the current level of exposure. However, the small number of sheets of this swarm does not allow a precise localization. Consequently, the source depth cannot be constrained accurately. Crosscutting relationships between swarms show Swarm 2 crosscut the presumable source pluton of Swarm 1, the Geitafellsbjörg Gabbro. Also, the lack of a continuous overlap in sheet orientations of Swarms 1 and 2 indicate that the inclined sheets of Swarm 2 represent a newer phase of activity with a newly established and deeper magma chamber, rather than a gradual transition. Possibly, Swarm 2 represents a phase of activity that was dominated by regional tectonic forces, as has been proposed for Geitafell by *Annels* [1967] and *Fridleifsson* [1983a] and for the Hafnarfjall Volcano in Western Iceland [*Gautneb et al.*, 1989], or was simply caused by a new intrusion originating from the Geitafellsbjörg Gabbro (e.g., a magmatic finger).

[39] At the Dyrfjöll Volcano, three major and four minor subsets or swarms of inclined sheets were distinguished (Figure 10); for three of them, source locations can be estimated (Figure 11). The most prominent of the inclined sheet swarms (Swarm 1) corresponds to the concentric Njardvik Sheet Swarm described by *Gustafsson* [1992]. Projection surfaces of sheets of this swarm cluster between 0.5 and 3 km depth below present-day sea level in a 3.5 km (E-W) × 5 km (N-S) area, indicating a depth of the magmatic source of at least 1.5 km below the summit area of the eroded Dyrfjöll Volcano. This magmatic source is located in the Njardvik Valley (Figure 11), approximately on the western margin of the intrusions and depression

associated with the NSC that predates the Njardvik Sheet Swarm (Figure 4). Since crosscutting relationships show that the Njardvik Sheet Swarm (Swarm 1) postdates the NSC, the sheet swarm documents a renewed phase of activity fed by a mafic magma chamber that was located to the west of the NSC center.

[40] The small number of members of other identified inclined sheet swarms at the Dyrfjöll Volcano allows a rough, or in the case of very small amounts of sheets no estimate at all, of the location and depth of their magmatic sources. Swarms 2 and 3 indicate the existence of at least two further magma chambers, one (feeding Swarm 2) located ca. 2.5 km to the ESE near Geitavikuthufa, the other (feeding Swarm 3) ca. 4 km NW of the center of Swarm 1 (Figure 11). In case of Swarm 2, the source is estimated to lie at a depth of 0.5 to 3.5 km b.s.l. and to cover an area of at least 4 km (N-S) × 4 km (E-W). Further evidence of the existence of a magmatic center at Geitavikuthufa is given by an eruption site southeast of the summit (Figure 4).

[41] Crosscutting relationships show that the magma chamber feeding Swarm 3 was active at the same time as that of Swarm 1. Inclined sheets belonging to Swarm 4 are evidence of a subsequent shift of activity toward the northeast. There is, however, no spatial trend of activity with time. Remarkably, no inclined sheets associated with the Dyrfjöll Caldera and no evidence of a shift of activity toward the Dyrfjöll Caldera has yet been found.

5.3. Comparison With Eroded and Active Volcanoes in Iceland and Elsewhere

[42] Our results are in good agreement with results from inclined sheet swarms in other extinct volcanoes in the Tertiary and Plio-Pleistocene lava pile of Eastern and Western Iceland and elsewhere. The inclined sheet swarms in the Geitafell Volcano show similarities with a bowl-shaped swarm with an outward fanning geometry that was identified in the Thverartindur Volcano, Southeast Iceland [*Klausen*, 2004] (for location see Figure 1), except that in the case of Swarm 1, a downward fanning geometry occurs. The Thverartindur swarm shows a considerable decrease in dip of sheets with distance from the source, a feature also observed in several other eroded central volcanoes in Iceland, such as the Reykjadalur Volcano [*Gautneb and Gudmundsson*, 1992] and the Stardalur Volcano [*Pasquarè and Tibaldi*, 2007] and elsewhere, e.g., the western Cuillin Centre of Skye, Scotland [*Hutchison*, 1966], the Vallehermoso Volcano, La Gomera, Canary Islands [*Ancochea et al.*, 2003], and the Otoge Volcano, Japan [*Geshi*, 2005]. In contrast, neither the Njardvik Sheet Swarm in the Dyrfjöll Volcano, nor the inclined sheet swarms in the Vatnsdalur area show dip variations [*Siler and Karson*, 2009]. In case of the Vatnsdalur area, the lack of dip variation might be due to insufficient spatial variation in the studied profiles, whereas in case of the Njardvik Sheet Swarm, a wide spectrum of dips is evident in all studied sections, independent of the distance to the estimated center of the swarm. This, in turn, is in agreement with observation of sheets in the Tejeda Volcano, Gran Canaria [*Schirnick et al.*, 1999; *Donoghue et al.*, 2010].

[43] Remarkably, most of the studied swarms of inclined sheets in eroded volcanoes can be ascribed to spatially confined and thus probably single magma chambers [e.g., *Schirnick et al.*, 1999; *Klausen*, 2004; *Pasquarè and Tibaldi*, 2007]. In contrast, *Siler and Karson* [2009] showed that inclined sheets in the Vatnsdalur Volcano converge toward two different magma sources at different depths and locations. Furthermore, the nested inclined sheet swarms of Ardnamurchan and Mull, Scotland, bear evidence for changes in source location with time [*Bailey et al.*, 1924; *Richey and Thomas*, 1930; *Kerr et al.*, 1999; *Upton*, 2004; *Emeleus and Bell*, 2005]. In both cases, three successive phases of activity are illustrated by three swarms of inclined sheets that converge toward focal points at shallow depth. In analogy to the Dyrfjöll Volcano, activity of individual centers in Mull and Ardnamurchan partly overlapped in time, and did not follow a linear spatial sequence [*Bailey et al.*, 1924; *Richey and Thomas*, 1930].

[44] In determining the position of the magmatic bodies at the foci of the cone sheet swarms, we are able to trace the timing and 3D spatial migration of the sources over time, which is relevant to understand crustal construction in Iceland [*Siler and Karson*, 2009] and other magmatic rifts. Our results indicate that the Geitafell and Dyrfjöll volcanoes are different in their internal structure and temporal evolution. The Geitafell Volcano represents a typical Icelandic central volcano, with a collapse caldera [*Fridleifsson*, 1983a] and long-lived magma chamber at 2 to 4 km depth. This chamber fed 10 000s of inclined sheets at depth (Swarm 1), as well as numerous eruptions at the surface. In the context of crustal growth, this means that crustal growth by intrusion and extrusion was locally confined. Late activity, as documented by the sheets of Swarm 2, was perhaps influenced by regional tectonic stresses. Geitafell is therefore comparable, and may serve as a fossil analogue, to active Icelandic volcanoes, such as

Krafla in Northern Iceland that has a main magma chamber at approximately 3 km depth [*Björnsson et al.*, 1979; *Tryggvason*, 1989; *Ewart et al.*, 1991] and Eyjafjallajökull in Southern Iceland [e.g., *Sturkell et al.*, 2003; *Pedersen and Sigmundsson*, 2004]. In the latter case, ground deformation preceding the 2010 flank eruption has been explained by the intrusion of a "tilted dyke" [*Sigmundsson et al.*, 2010] and underlines the significance of inclined sheets as feeders to flank eruptions.

[45] By comparison, the Dyrfjöll Volcano was part of a volcanic cluster with several contemporaneous, as well as successive activity centers distributed within and beyond the studied area. *Gustafsson et al.* [1990] and *Gustafsson* [1992] proposed a genetic correlation between the Dyrfjöll Volcano and volcanic centers to the south, namely Kaekjuskörd, Breidavik, Herfell, and the Álftavik-Seydisfjördur Volcano (Figure 1). Together, this area represents the second largest exposure of felsic rocks in Iceland and comprises at least two collapse calderas [*Gustafsson et al.*, 1990; *Gustafsson*, 1992]. The fjord of Borgarfjördur eystri dissects this volcanic cluster. However, the existence of the sheet swarm around Geitavikurthufa (Swarm 3) suggests continuation toward the south. The Dyrfjöll Volcano and the surrounding area are therefore a possible fossil analogue of the Torfajökull Volcano in Southern Iceland that contains the largest volume of exposed silicic rocks in Iceland. Multiple coeval and successive magmatic sources, as well as recycling of older volcanic material, may in both cases be responsible for the formation of large volumes of silicic rocks [cf. *Gunnarsson et al.*, 1998] and thus widely distributed crustal growth. The Dyrfjöll Volcano may be compared to the active Askja Volcano in Northern Iceland that is characterized by three nested calderas. The youngest, Lake Öskjuvatn, has an active magma chamber at approximately 1.5 to 3.5 km depth [*Tryggvason*, 1989; *Sturkell and Sigmundsson*, 2000].

6. Conclusions

[46] The results of our study of inclined sheets of the Geitafell Volcano in Southeast Iceland and the Dyrfjöll Volcano in Northeast Iceland can be summarized as follows:

[47] Most inclined sheets in the 5 to 6 Ma old Geitafell Volcano belong to a swarm that was fed from a magma chamber with a diameter of at least 4 to 7 km, located to the NW, W and SW of the studied sheets. Assuming that the gabbro bodies that are exposed within this focal area and which are partly in direct contact with the inclined sheet swarm represent parts of the magmatic source of the inclined sheets, their source depth can be derived at 2 to 4 km below the Tertiary land surface. A second swarm of younger and more steeply dipping inclined sheets is evidence for a later and deeper magma source located a few hundred meters to the southwest of the Geitafellsbjörg Gabbro that may represent an independent pulse of activity.

[48] Inclined sheets in the 12 Ma old Dyrfjöll Volcano in Northeast Iceland can be grouped into three major and four minor swarms, the existence of the latter four are indicated by a few inclined sheets only, however. The most prominent of these swarms is the Njardvik Sheet Swarm, the magmatic source of which is located in Njardvik Valley at a depth of 1.5 to 4 km below the paleoland surface and has a diameter of approximately 3.5 to 5 km. At least two additional magma chambers can be identified from the sheet swarms, one to the south and one to the northeast of the Njardvik Sheet Swarm. Crosscutting relationships between sheets indicate contemporaneous, as well as successive activity of different magma chambers. The Dyrfjöll Volcano was part of a volcanic cluster that extends considerably beyond the volcano itself.

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