Nordic Volcanological Institute 9503
University of Iceland

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Content

ABSTRACT

Excellent exposures along the glacially eroded coast of SE-Iceland reveal 1-2 km deep cross-sections through intrusions within flexured Late Tertiary plateau lavas and hyaloclastite breccias. This report describes the infrastructure of both central volcanoes and regional dyke swarms based on the quantitative results of the measurement of 828 inclined sheets and 877 regional dykes. Field evidence suggests that a central volcano initiates from sills that grow into a shallow magma chamber, from which inclined sheets are injected, and that later acid intrusions are emplaced along the margins of these intrusions. A three-dimensional reconstruction from representative sheet samples ($N \geq 40$) allows one to infer the position and dimension of the ellipsoidal source magma chamber. Three complete profiles across the regional dyke swarms, with moving averages of strike, dip, thickness, and crustal dilation, make it possible to reconstruct the infrastructure of the dyke swarm. Apart from the dominant rift-parallel trend (N047°E), the regional dyke swarms include sub-swarms with oblique (N034°E & N017°E) and orthogonal (N077°W & N055°W) trends. These sub-swarms were probably emplaced during the final activity of the volcanic system, as a result of changes in the regional stress field outside, yet near, the associated central volcano.

INTRODUCTION

The deeper parts of volcanic systems are exposed within the Tertiary lava pile of Iceland (Walker 1974, 1975, Gudmundsson 1983, 1990, 1995, Helgason & Zentilli 1985, Gautneb & Gudmundsson 1992). These systems usually consist of a central volcano, with gabbros, granites, acid-basic composite dykes and centrally inclined sheet swarms, which are associated with elongated swarms of regional dykes (Gudmundsson 1995). Although this type of volcanic system is typical for Iceland, it shares many features with volcanoes and dyke swarms in other areas, such as the Tertiary Igneous Province in Scotland (Speight *et al.* 1982) and in East Greenland (Myers 1985), as well as in the Hawaiian Islands (Walker 1987).

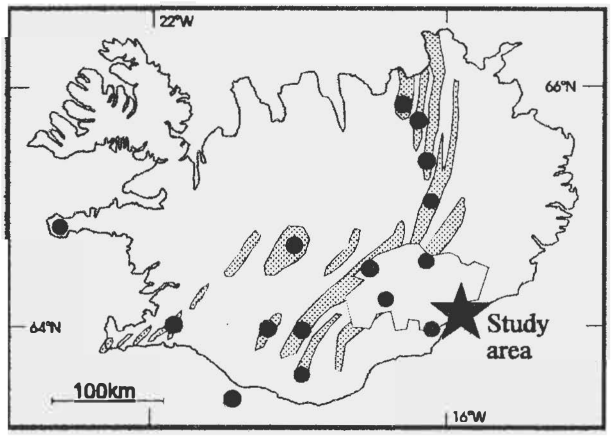

Figure 1: Active volcanic systems in Iceland, with fissure swarms shaded and central volcanoes as ●.

The present study focuses on accurate field measurements of the attitude and thickness of inclined sheets and regional dykes of the Sudursveit area (Fig. 1). These quantitative data are used for statistical reconstructions of the three-dimensional infrastructure of the swarms. The first objective of this study is to provide data on the infrastructure of central volcanoes and volcanic systems in Iceland, with special emphasis on the centrally inclined sheet swarms. The second objective is to test previous models on the overall infrastructure of a regional dyke swarms (Gudmundsson 1990, 1995), focusing on the areas near a central volcano which are known to contain sub-swarms with oblique and orthogonal dykes (Walker 1993b). This study should also contribute to a better understanding of the infrastructure of the active volcanic systems, particular those in that part of the active rift zone of Iceland which presently is mostly covered by the Vatnajökull ice sheet (cf., Fig. 1).

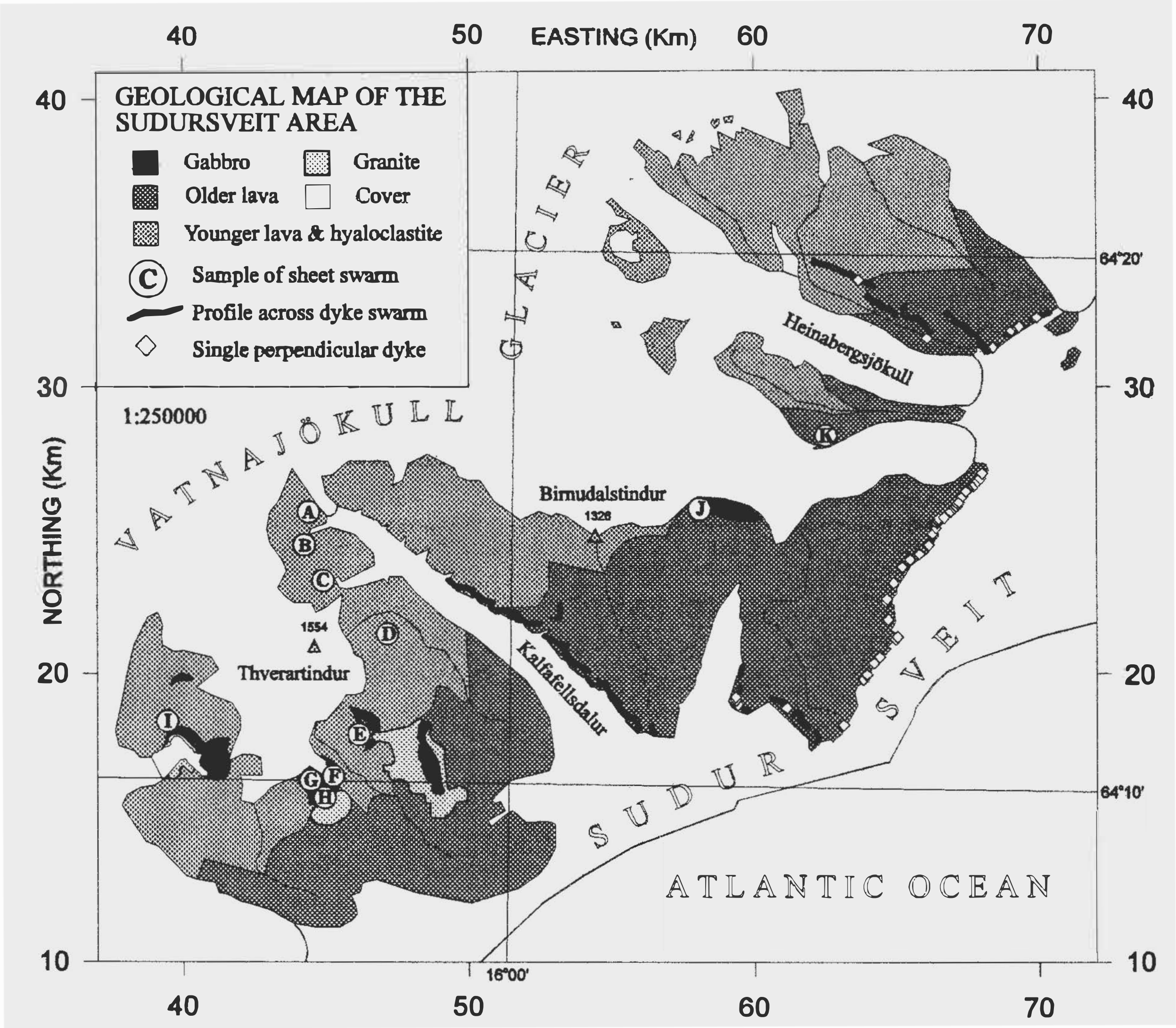

Figure 2: Simplified geological map of the Sudursveit area. The extrusives are dipping towards the northwest. Solid lines define mountain ridges.

GEOLOGICAL SETTING

The Sudursveit area is situated between the Vatnajökull ice sheet and the Atlantic ocean in Southeast Iceland (Figs. 1 & 2). The area is deeply eroded by glaciers and has a topography that reaches from sea level and up to a maximum altitude of 1554 m.a.s.l.. Several deep gullies and long valleys offer 1-2 km deep cross-sections into the Icelandic crust (Walker 1975). The area covers the southernmost continuation of the Lagarfljot flexure zone (Walker 1974), where the Late Tertiary extrusive and intrusive rocks exhibit some of Iceland's steepest regional dips towards the neovolcanic zone (Annels 1967, Saemundsson 1979, Walker 1974, 1975, Torfason 1979).

Stratigraphically up-section, the extrusive pile changes from a ~2.5 km thick pile of Tertiary plateau basalt lavas in the southeast, through a gradual transition across a few hundred metres, to a massive, ~2 km thick, pile of Tertiary hyaloclastite breccias in the northwest (Torfason 1979, Fig. 2). Along the coast, however, the volume of inter-bedded hyaloclastite decreases towards the northeastern parts of the Sudursveit area. In other parts of Iceland, a similar transition from lava to hyaloclastite breccia is generally regarded as the stratigraphic marker between a sub-aerial Tertiary and a sub-glacial Pleistocene environment, but in SE-Iceland the glaciation probably started earlier because of the high precipitation in and elevation of this part of Iceland, as indicated by the present Vatnajökull ice sheet (Saemundsson 1979). True Pleistocene palagonite breccias lie discordantly on top of the Tertiary extrusives in the inner parts of the area, near the Vatnajökull ice sheet, at roughly 1000 m.a.s.l.

Few intrusions cut the Pleistocene palagonite breccias, but numerous different types of intrusions cut the extrusives from the Late Tertiary. Gabbros, granites, acid-basic composite dykes, and inclined basic sheets, are the common types of intrusions in a central volcano. In the Tertiary area of SE Iceland, there are four distinct central volcanoes that lie roughly along the general trend of the presumed rift zone (Torfason 1979). The central volcanoes of Geitafell (Annells 1967, near Hoffellsjökull in Walker 1975, Fridleifsson 1983) and Kollumuli (near Dalsheidi in Walker 1975, Torfason 1979) have been mapped and studied in detail by these authors. The central volcanoes of Thverartindur and Birnudalstindur (near Hvannadalur and Thormodarhnuta, respectively, in Walker 1975) have not been identified as central volcanoes before this study. Outside the central volcanoes in SE Iceland, regional dykes are generally emplaced in sub-vertical swarms that strike sub-parallel with the eastern rift zone in South Iceland. Characteristic dykes referred to as "brown dolerites" (Annels 1967, Newman 1967, Walker 1974, Torfason 1979, Fridleifsson 1983) cut all other intrusions in SE Iceland and strike slightly oblique to the presumed regional trend of the extinct rift zone (Torfason 1979).

CENTRAL VOLCANOES

A central volcano is characterised by having a significant proportion of silicic rocks, in addition to basaltic rocks, and contains also rocks of intermediate composition (Saemundsson 1979, Walker 1993a). There is a caldera associated with many central volcanoes which indicates the existence of a shallow magma chamber. In more deeply eroded areas (e.g., the Vesturhorn and Austurhorn central volcanoes), the shallow magma chamber is exposed as ≤20 km^2 large gabbroic and granitic intrusions (Gudmundsson 1995). Acid and basic parts are often mixed in net-veined complexes. Basic sheets are common and form dense swarms that normally are inclined towards the centre of the volcano (Gautneb & Gudmundsson 1992).

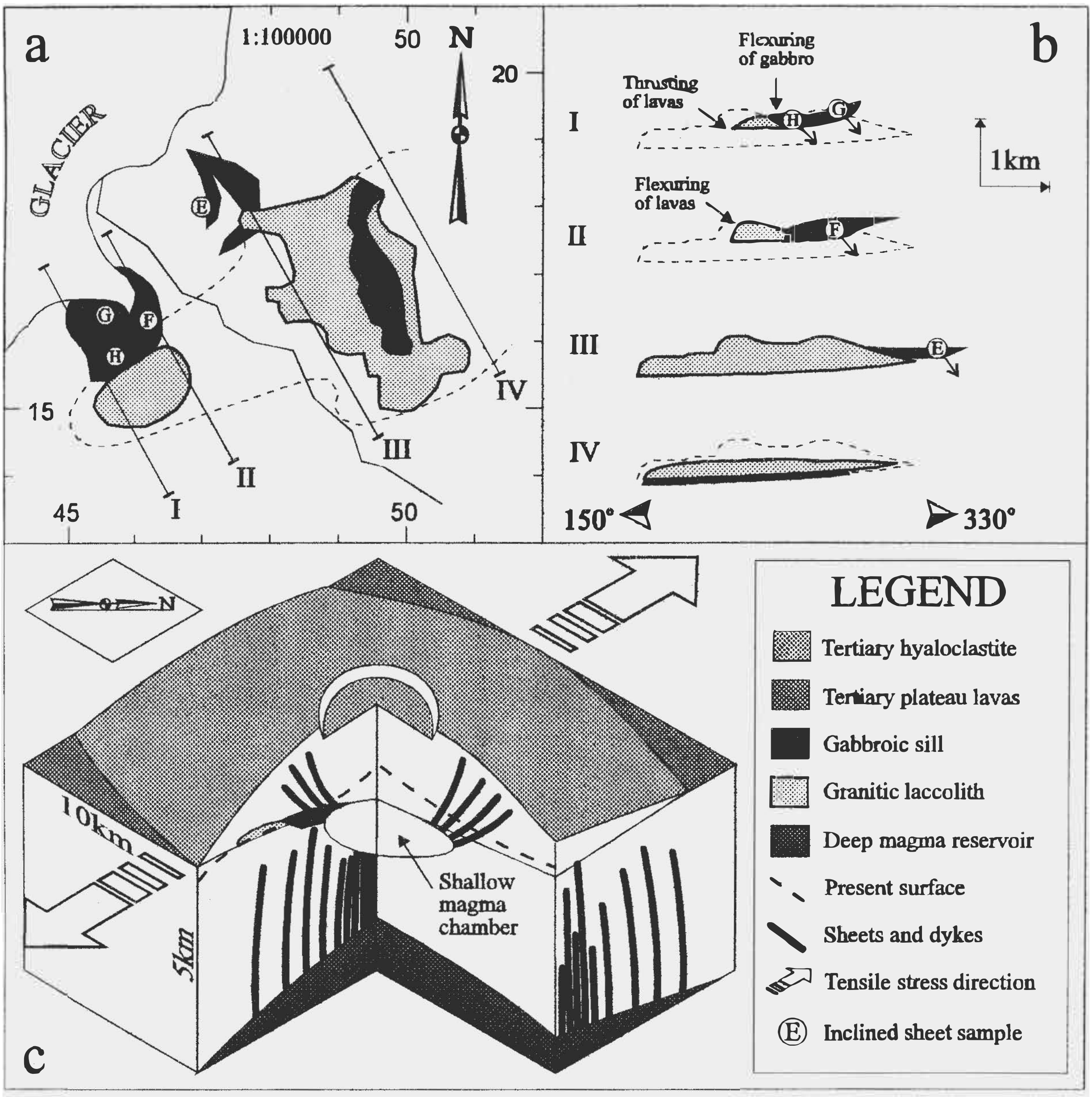

Figure 3: (a) Map and (b) cross-sections through gabbro and granite intrusions. (c) Simple isometric reconstruction of the Thverartindur central volcano.

Acid-basic composite dykes occur as late intrusions near the granites.

Of the two central volcanoes in the Sudursveit area, that of Thverartindur is much better exposed, and thus more easily studied, than that of Birnudalstindur. Structural field data on all the main types of magmatic intrusions from these central volcanoes are presented separately in the following subsections, with an emphasis on the quantitative data from the centrally inclined sheet swarms.

Gabbro intrusions

The gabbros are generally of the melanocratic or the leucocratic type. The most common leucocratic type consists of a large variety of pegmatitoidal sub-types. Modal layering is rare, but ≤100 m thick and shallowly inclined layers of different gabbro sub-types, occur inside several hundred metres thick intrusions. A correction for the regional dip in the area gives these layers an original sub-horizontal attitude, which suggests that they were emplaced as large sills. All gabbros at the southeastern margin of the Thverartindur and Birnudalstindur central volcanoes are situated at roughly the same stratigraphic level where there is a transition from older plateau lavas to younger lavas and hyaloclastite breccias. This location is probably due to the porous and less dense hyaloclastite breccias acting as a density barrier to the vertically propagating basic dykes. The proportion of other intrusions that are cut by the gabbros is unknown, but because the granites and the inclined sheets cut the gabbros the sills were presumably emplaced at a relatively early stage in the evolution of the central volcanoes.

The difficult terrain prevented much field work to be done on the gabbros inside the presumed caldera of the Thverartindur central volcano, but there are indications that these intrusions were not emplaced as sills. There is no sign of layering or sub-horizontal contacts in the large gabbro in the western part of the Thverartindur area (Figs. 2 & 6). Instead, this intrusion appears to be the exposed top of the shallow magma chamber (cf., the subsection on inclined sheets). North of this gabbro, there is a 50 m wide, coarse grained, and zoned gabbro body that is inclined sub-parallel with the surrounding sheets.

Granite intrusions

Two separate granite intrusions are exposed in the Thverartindur central volcano, one being the Hvannadalur intrusion (Walker 1975). An acid dyke swarm and a negative aeromagnetic anomaly indicate the presence of a granite intrusion northeast of the Birnudalstindur central volcano (cf., Fig 7). A characteristic feature of the granites in the Sudursveit area is the occurrence of an ≤30 m thick, basic, and very fine grained intrusion, which surrounds the granite as a shell. This basic shell is probably formed by a mechanism similar to that of the composite dykes, where the acid magma uses the preexisting basic magma as a pathway (Gudmundsson 1985). The coexistence of acid and basic magma is supported by the common occurrence of typical net-veined textures and large amount of rounded basic inclusions. In addition, the granites have internal zones which may be related to repeated crystallization fronts (i.e., centimetre-thick zones which are sub-parallel with the outer boundary of the granite), or to successive injections of acid melt (i.e., ≤20 m thick zones with variably chilled margins).

Like the gabbroic sills, the granite intrusion exposed at the southeastern margin of the Thverartindur central volcano seems to have intruded at the stratigraphic level where older plateau lavas are replaced by younger lavas and hyaloclastite breccias. However, the general

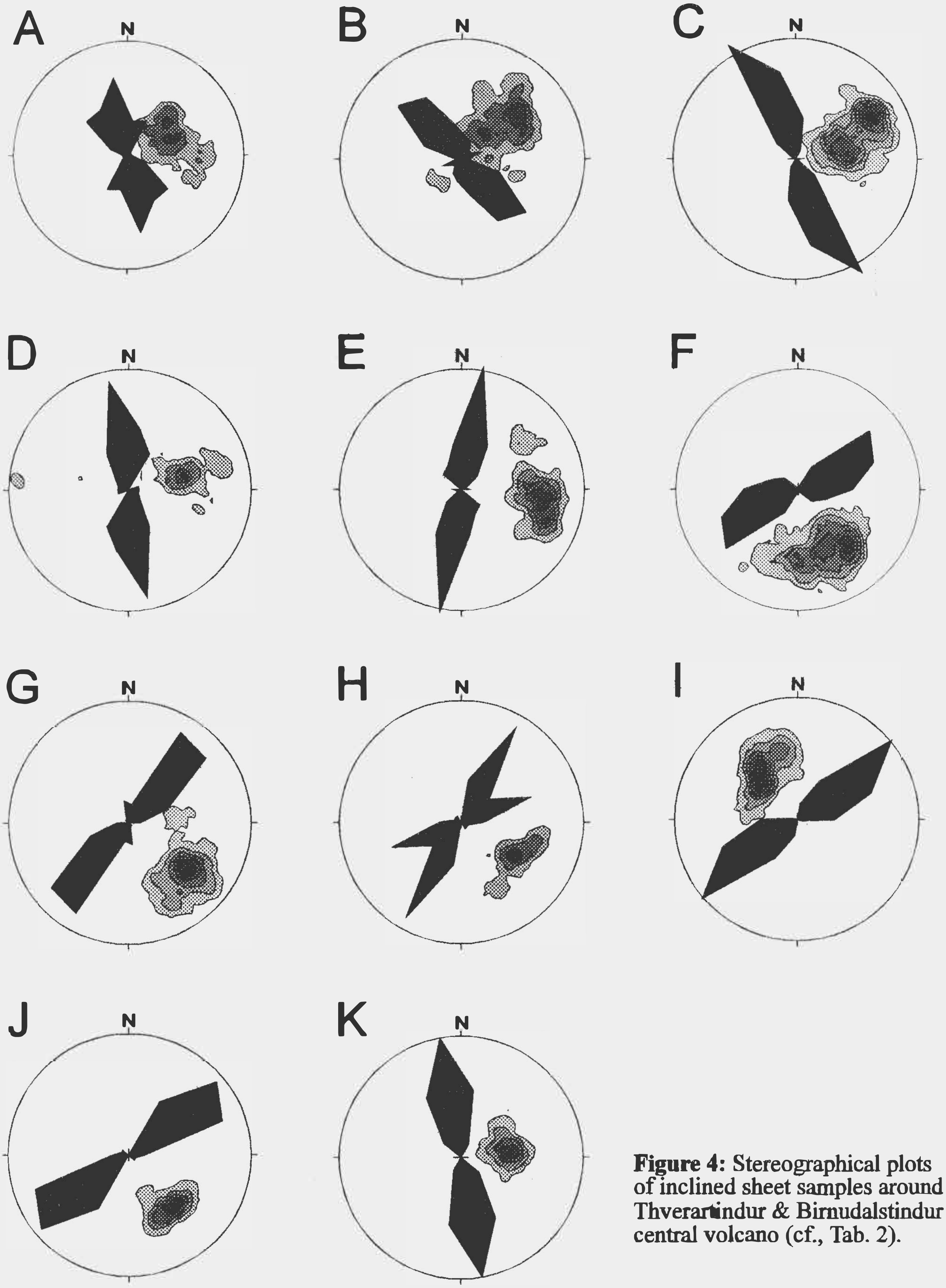

Figure 4: Stereographical plots of inclined sheet samples around Thverartindur & Birnudalstindur central volcano (cf., Tab. 2).

shape of this granite, as well as the indication of local up-bending and perhaps thrusting, of the lavas and gabbros, suggest that the acid magma intrusion grew forcefully into an elongated laccolith rather than a sill (Fig. 3). The estimated volume of acid magma that produced this laccolith is 2-3 km^3, judging from the areas of the exposed granite. This shape and size corresponds well with that of other granite intrusions in Iceland (Gudmundsson 1995), and can be related to the typical mode of emplacement of acid magma (Corry 1988).

Acid (composite) dykes

Like the granites in the area, the acid dykes are commonly with basic margins. The acid part is normally fine to medium grained, while the basic part is very fine grained and fresh compared with the inclined sheets and regional dykes. Together with the cross-cutting relationships, these observations indicate that the acid dykes and their basic counterparts were injected subsequent to the major hydrothermal alteration. The heterogeneous acid-basic contacts are sharp to gradual, indicating variable mixing between the intruding acid melt and the partially solidified basic dyke.

The acid dykes occur mainly at the margins of the central volcanoes, near the granites. The dominant strike of 110 measured acid dykes coincides with the regional basaltic dyke trend, indicating that the emplacement of the acid dykes was partly controlled by the regional stress field. The average thickness of the acid parts of the composite dykes is greater than that of the basic margins, and also greater than the average thickness of the inclined sheets and regional dykes (Table 1). The thickness of one acid dyke was measured to decrease from around 30 m to 2 m over a distance of only 400 m. That acid dykes are both shorter and wider than basic sheets and dykes probably reflects the greater internal flow resistance and higher magmatic pressure of the acid magma (Wada 1994).

Intrusive type	N	T ± 1σ (m)
Acid dykes	108	4.56 ± 0.57
Basic margins	134	0.72 ± 0.08
Inclined sheets	1278	0.96 ± 0.04
Regional dykes	828	2.55 ± 0.11
Orthogonal dykes	49	1.75 ± 0.16

Table 1: Average thickness (T) of all sheets and dykes in the Sudursveit area. Basic margins belong to the composite acid-basic dykes. N: number of measurements.

Inclined sheets

At the margins of the two central volcanoes in the Sudursveit area, the inclined sheets occur mainly in very dense swarms. In these swarms, the sheets commonly constitute 50% to 100% of the rock, but there is a rather sharp transition to ≤10% sheets at a certain distance from the central volcano. This transition from areas of high to areas of low density of sheets, together with the maximum extent of gabbro intrusions, is used to define the boundary of the Thverartindur central volcano in Figure 6. The outermost sheets that are still inclined towards the central volcano occur roughly 1.5 km outside this transition zone. Little is known about the central parts of the sheet swarms because these parts are largely inaccessible owing to extensive glaciation (cf., Fig. 2).

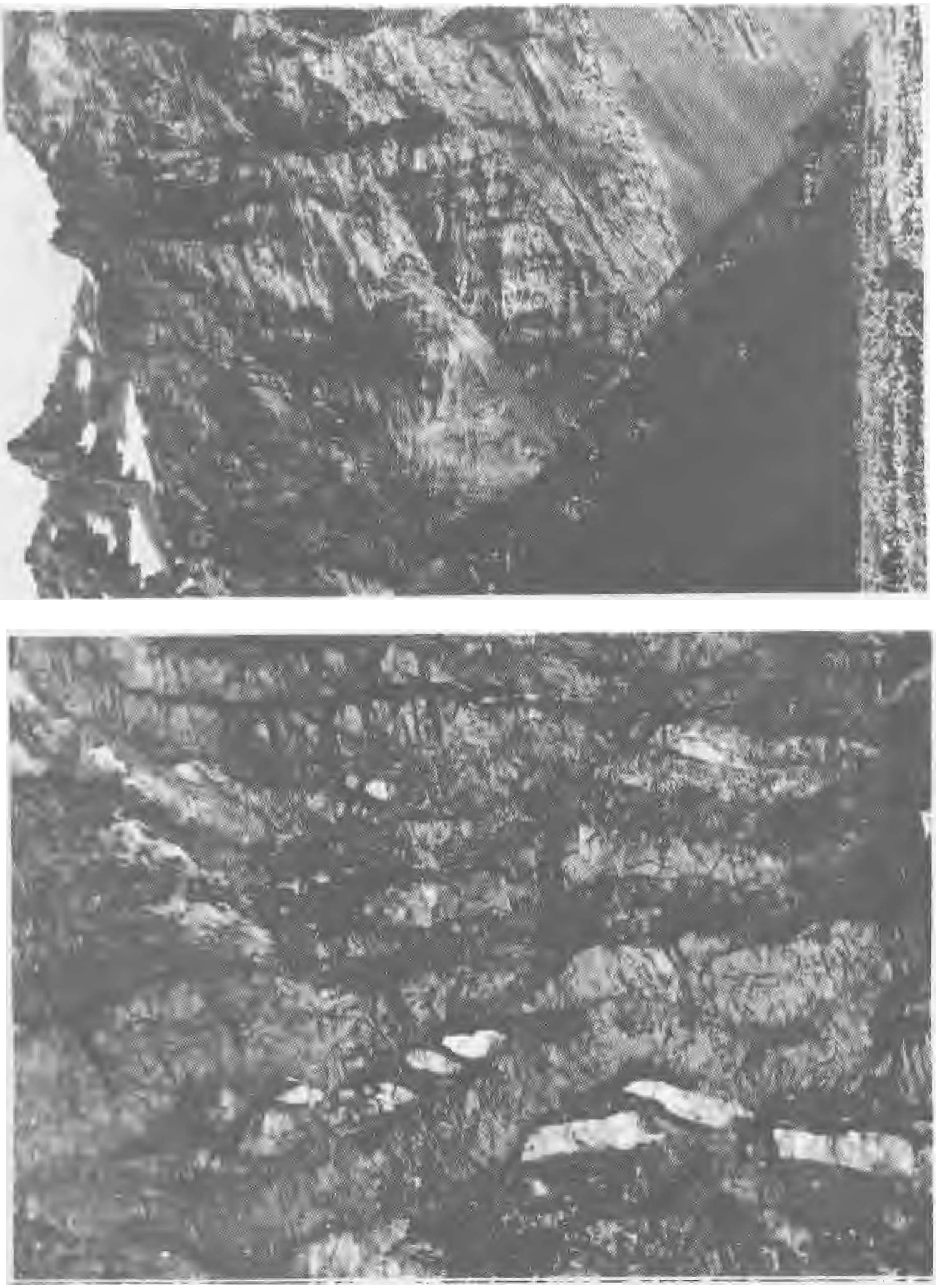

Figure 5: Exposures with very dense swarms of inclined sheets. (**a**) Rjupnadalur (sample C) is the most magnificent, with sheets from the bottom of the valley at ~200 m.a.s.l. to the peaks at ~1000 m.a.s.l.. (**b**) Close-up of sheets in the Thormodarhnuta gabbro (sample J) show cross-cutting relationships. The sheets are on average ~1 m thick.

A total of 1285 inclined sheets were measured in the Sudursveit area. The polymodal strike distribution of the sheets reflects the spatial bias of the measurements (Fig. 4). However, their strike is roughly tangential to the circumference of the central volcano, and the dip is normally distributed around a mode value of 47.2° ± 0.5° towards the centre of the central volcano. The dominant dip varies from ~30° in the outer parts to ~60° in the inner parts of the measured sheet swarms (Table 2), which is similar to the dip variation in the sheet swarm of the Tertiary Reykjadalur central volcano (Gautneb & Gudmundsson 1992).

Inside a particular swarm, the sheets appear sub-parallel when viewed from a distance (Fig. 5a) but are more irregular when observed in detail (Fig. 5b). As illustrated by Figure 5, cross-cutting relationships are common and many earlier sheets are displaced by later sheets and therefore difficult to measure. The basic sheets are generally fine grained, aphyric, and hydrothermally altered. Part of the textural variation in the sheets is related to the difference in the depth of erosion where the sheets are observed; that is the sheets are aphyric and more vesicular in the shallow eroded northwestern parts, and often porphyritic and non-vesicular in the deeply eroded southeastern parts of the Thverartindur central volcano.

THE ORIGIN OF THE INCLINED SHEET SWARMS

The irregular shape of the sheets means that a sufficiently large number of measurements must be made to obtain a statistically significant dip direction for a single swarm. A minimum of 40 measurements for each sample is the chosen lower limit in this study. A total of 828 sheets were measured from eleven samples that satisfy this minimum (Figs. 2 & 6, Table 2). Because the attitude of a sheet also depends on its position in a central volcano, the areal dispersion of measurements in each of these samples has been statistically quantified by spatial standard deviation ellipses. The maximum counted density distribution of the poles to the measured sheets is used to define the dominant dip direction of each sample (Table 2).

These data manipulations are necessary to make the three-dimensional reconstruction of the inclined sheet swarm around the Thverartindur central volcano in Figure 6. From this quantitative reconstruction, it follows that the linearly projected dip directions from the eight sheet samples A-H, along the eastern semi-circumference of the Thverartindur central volcano, all point towards a common source of the inclined sheet swarm. This source is presumably a single shallow magma chamber. Little is generally known about the size and shape of the source of an inclined sheet swarm (Walker 1993a), or how much the source geometry changes with time. The depth contours connecting the linearly projected dip directions suggest that the top of the triaxial ellipsoidal shallow magma chamber may be at 1-2 km below the present sea level (cf., Fig. 6). This conclusion is supported by a good correlation between the depth contours and the positive aeromagnetic anomaly (Jonsson 1991) which probably reflects the distribution of a magnetite-rich cumulate in the crust.

To define the original depth and dimension of the shallow magma chamber, corrections must be made as regards the depth of erosion and the post-intrusive tilting of the area. A uniform correction for a post-intrusive 10° to 15° regional dip of the lava pile will change the present elliptical shape of the depth contours back to an original circular shape. Using an average of 1 km for the estimated depth below the original surface (Walker 1974, 1975, Torfason 1979), it is possible to estimate the maximum depth of a magma chamber, 5 km in diameter, as being roughly 4 km below the original surface. This depth would, however, be less if one allows for an expected curved attitude of the sheets (Gautneb & Gudmundsson 1992). A reconstruction of rotated sheet swarms is not illustrated because of the large uncertainty related to the estimated amount of post-intrusive tilt of the lava pile and the depth below the original surface.

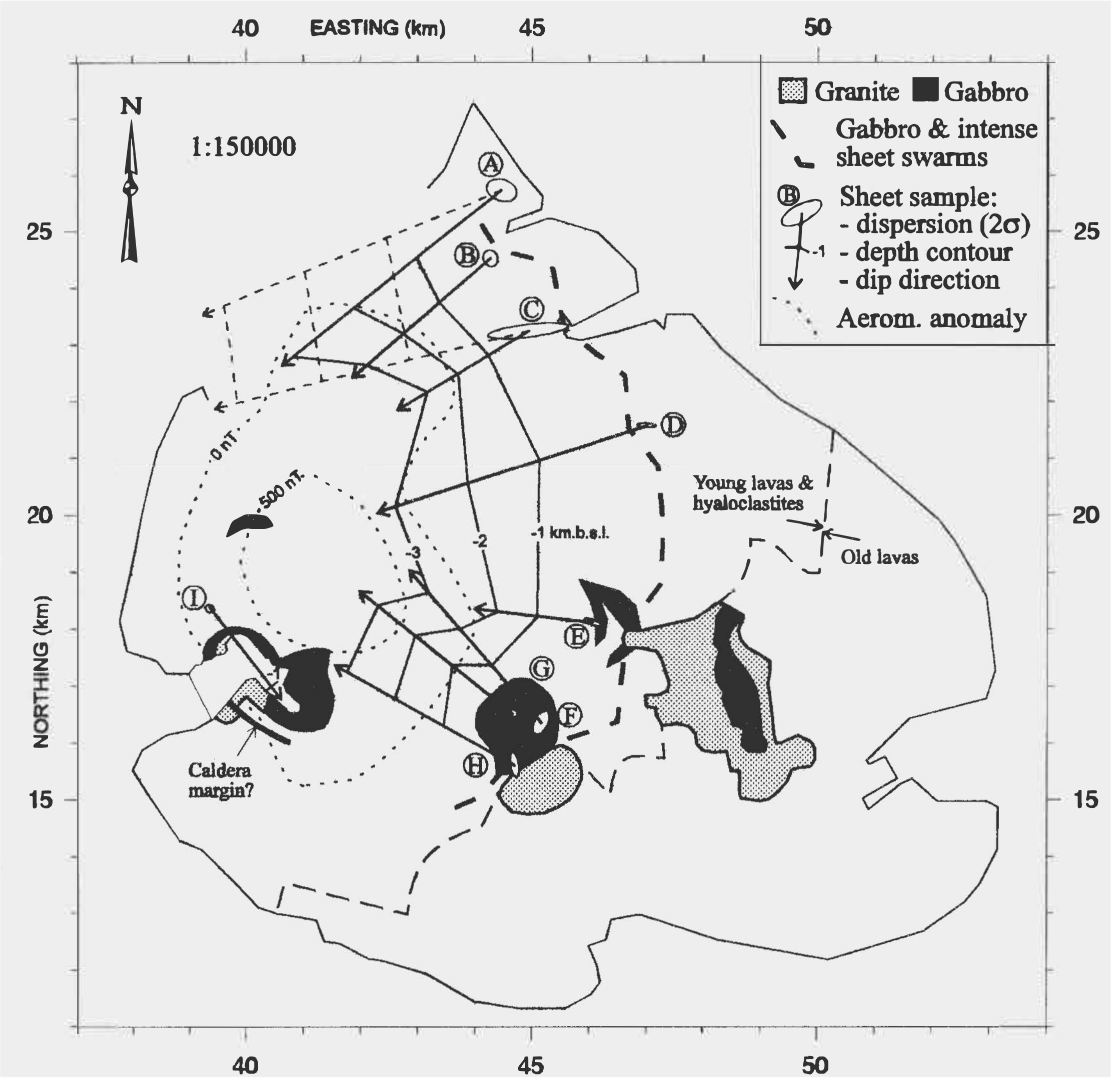

Figure 6: Structural data for the Thverartindur central volcano (cf., Tab. 2). Contoured dip directions give a 3-D image of the infrastructure of the sheet swarm.

ID	N	Mean easting, northing, and altitude (m)	σ_1 (m)	σ_2 (m)	θ (°)	Maximum density distribution of dip direction
A	66	$^{4}44500$, $^{71}25640$, 411	275	192	292	17% on 230/37°*
B	106	$^{4}44310$, $^{71}24450$, 405	127	148	242	11% on 230/50°
C	124	$^{4}44970$, $^{71}23200$, 358	713	110	262	19% on 240/59°*
D	58	$^{4}47020$, $^{71}21550$, 506	171	42	274	15% on 255/37°
E	78	$^{4}46050$, $^{71}18140$, 414	158	52	143	19% on 277/55°
F	118	$^{4}45170$, $^{71}16380$, 607	207	99	289	15% on 320/50°
G	82	$^{4}44670$, $^{71}16520$, 626	48	44	28	21% on 310/50°
H	42	$^{4}44680$, $^{71}15660$, 485	221	77	221	24% on 300/46°
I	74	$^{4}39380$, $^{71}18370$, 554	78	67	119	20% on 144/41°
J	40	$^{4}58060$, $^{71}25704$, 700	75	56	296	18% on 317/45°
K	40	$^{4}62321$, $^{71}27920$, 477	82	21	259	19% on 265/32°

Table 2: Spatial and structural density distribution of inclined sheets in the Sudursveit area. *: secondary peak of 15% on 251/36° for sample A and 14% on 256/33° for sample C. ID: label of identification (cf., Figs. 2, 4, 6 & 7). N: number of measurements. σ_1, σ_2 and θ: major half-axis, minor half-axis, and the orientation of the major axis, respectively, for the standard deviation ellipse; the position of which is given in the preceding column.

Sheet sample I (Table 2 & Fig. 6) is situated inside the proposed caldera fault along the western margin of the Thverartindur central volcano. Its dominant dip direction does not conform to that of the other samples along the eastern margin of the central volcano, but points towards a nearby gabbro. This gabbro might be a copula on the presumed shallow magma chamber (cf., the subsection on the gabbros). An irregularly shaped roof of a shallow magma chamber would result in a less systematic dip direction of the sheet swarms in the central parts of the central volcano, compared with an expected sub-vertical sheet swarm above the top of an ellipsoidal chamber (Gautneb & Gudmundsson 1992). Due to the poor exposure, only two small sheet samples (K-J) were measured along the southeastern margin of the Birnudalstindur central volcano. These samples do not add much information on the general infrastructure of sheet swarms (Fig. 7). The dominant dip directions from the two sheet samples, the exposed gabbros, the positive aeromagnetic anomaly, and the topography are used to constrain the position and dimension of the Birnudalstindur central volcano.

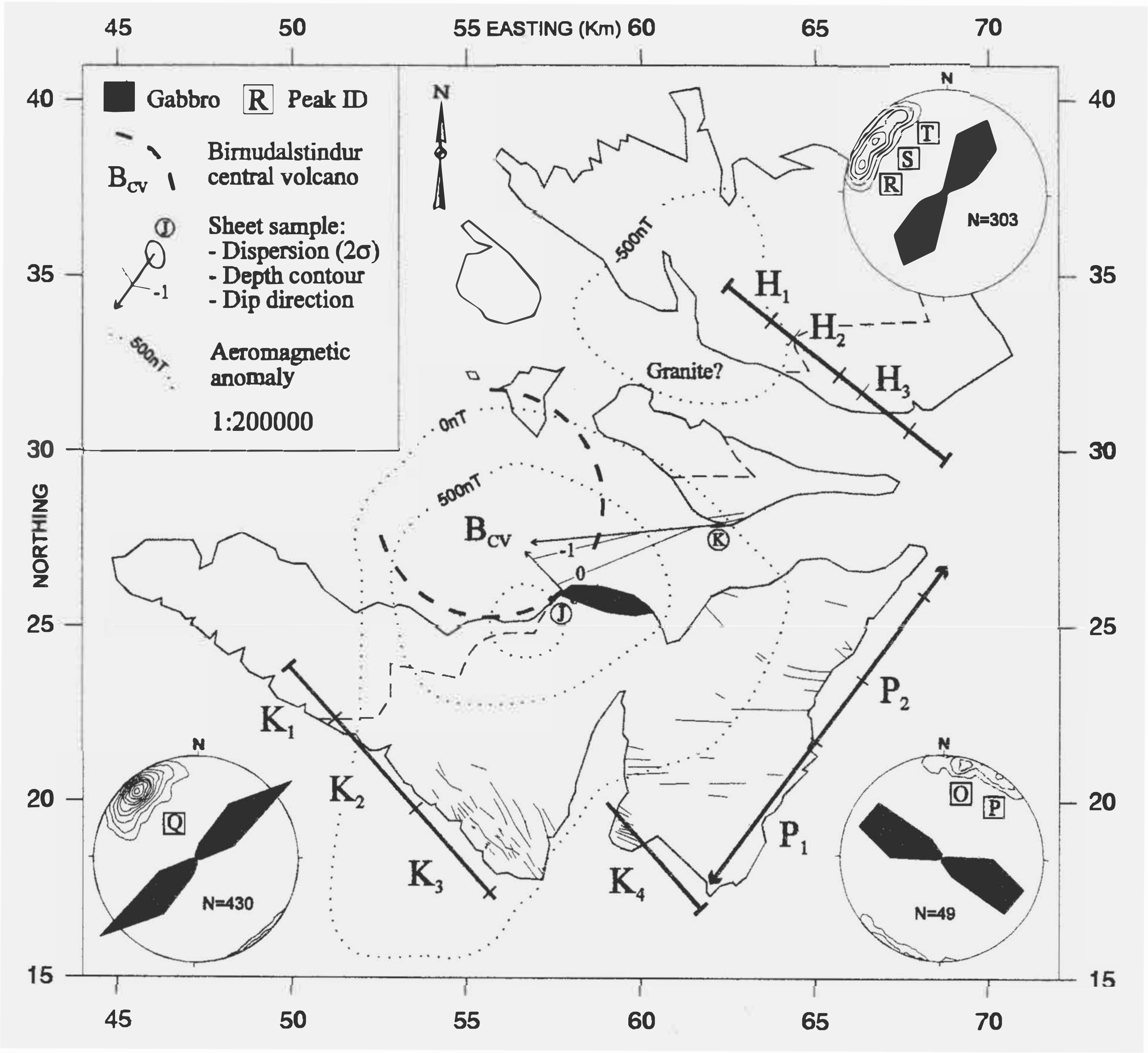

Figure 7: Structural data from the profiles around the Birnudalstindur central volcano. Stereographical plots of regional dykes within each profile (cf., Tab. 3).

REGIONAL DYKE SWARMS

Regional dykes strike roughly parallel to the trend of the extinct rift zone and cut the tilted lava pile at nearly right-angles. The maximum density distribution of the attitudes of 828 measured dykes are summarised in Table 3. The regional dykes are on average more regular and thicker than the inclined sheets (Fig. 8 & Table 1), but minor offsets and local variations in thickness occur. The basic dykes are often fine grained, aphyric, and less altered than the inclined sheets, with variations in grain size being related to the thickness of the dyke. Some dykes contain plagioclase and occasional mafic phenocrysts. By definition, a regional dyke swarm is emplaced outside a central volcano (Gudmundsson 1990, 1995), but a distinct group of so-called "brown doleritic" dykes (Annels 1967, Newman 1967, Torfason 1979) cut through all the intrusions related to the central volcanoes.

Every regional dyke was measured along 13 km and 8 km long profiles in Kalfafellsdalur and Heinabergsdalur, respectively. In addition, 49 dykes, striking roughly perpendicular to the regional dykes, were measured along a 16 km long profile between the two valley profiles (Figs. 2, 7, 9-11). Significant peaks in the density distributions of the poles to the planes of all dykes from each of the three profiles suggest that there is a single swarm (labelled peak Q) in Kalfafellsdalur profile, three overlapping (sub-)swarms (peaks R-T) in Heinabergsdalur profile, and possibly two sub-swarms (peaks O & P) in the perpendicular profile (cf., stereograms in Fig. 7 & Table 3). The maximum density distribution of peaks Q and T represent two samples of dykes that are here referred to as rift-parallel because they are emplaced sub-parallel with the general trend of the volcanic systems in southern Iceland (cf., Fig. 1). The maximum density distribution of peaks R and S are more northerly trending than the rift-parallel dyke swarm and are referred to as oblique sub-swarms. The maximum density distribution of peaks O and P are sub-perpendicular to the oblique sub-swarms R and S, respectively (Table 3), and will be referred to as orthogonal dykes.

ID	N	Maximum density distribution of data
M	95	22% on 60/77°SE
Q	430	24% on 47/76°SE
R	303	18% on 17/76°E
S		17% on 34/74°SE
T		13% on 57/76°SE
Total	828	18% on 48/75°SE
O	49	20% on 103/82°S
P		18% on 125/87°S

Table 3: Structural density distribution of the regional dykes in Sudursveit. ID: label of identification (cf., Fig 7). N: number of measurements.

To study the infrastructure of the regional dyke swarms in greater detail, the positions of all moving averages of the measured strike, dip and thickness of the dykes, and the calculated crustal dilation due to the dykes, are projected onto lines which are perpendicular to the dominant or average strike of the dykes in each profile (Table 3 & Figs. 7, 9-11). The regular shape of the regional dykes compared with that of the inclined sheets allow one to use smaller samples for obtaining significant averages. The minimum number of dykes in a sample has been chosen as 30 for the regional dykes and 7 for the orthogonal dykes. The measured strike and dip were normalised and are referred to as strike$_N$ and dip$_N$, respectively. Dilation is the cumulative thickness of the dykes in a sample divided by the distance from the first dyke to

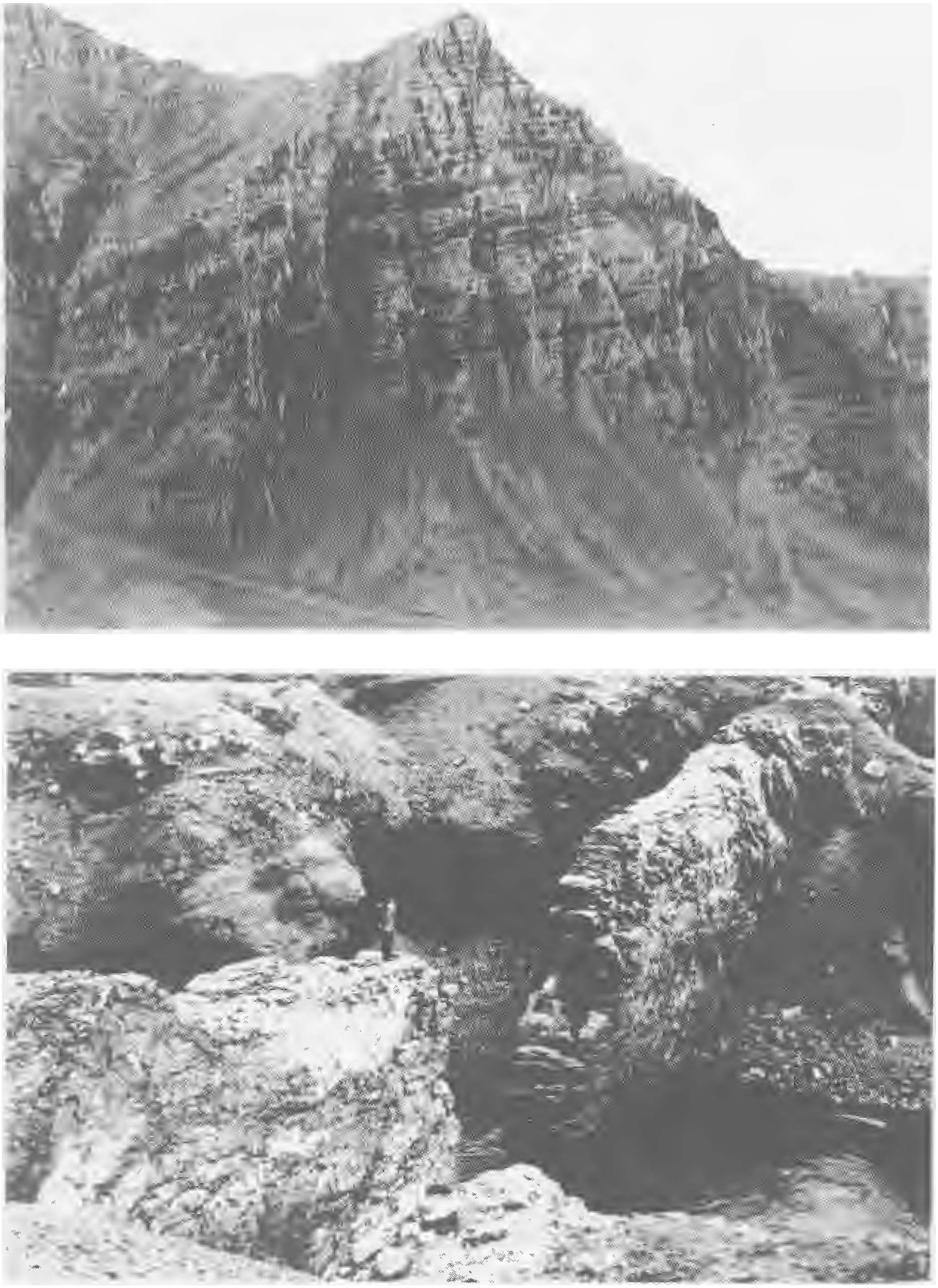

Figure 8: Exposures with regional dykes. (**a**) Dyke swarm cutting the regionally dipping lava pile in Kalfafellsdalur (profile section K_3). The lowest part of the cliff is at ~200 m.a.s.l. and the pointed top of the cliff is at 663 m.a.s.l.. (**b**) Close-up of a nice dyke in Heinabergsdalur. Person provides a scale.

the dyke preceding the last one in the sample section. The dilation does not include the additional dilation due to faulting of the host rock. The three profiles surround the southeastern semi-circumference of the Birnudalstindur central volcano, and provide a quantitative presentation of the infrastructure of a regional dyke swarm outside, yet only ~8-12 km from the centre of, the Birnudalstindur central volcano (Fig. 7). The results from the moving averages of strike_N, dip_N, thickness, and crustal dilation in the three profiles in Figures 9-11 are described separately in the following subsections.

Kalfafellsdalur profile

The regional dyke swarm that dissects the Kalfafellsdalur profile has a narrow spread in strike (cf., peak Q in Figs 7, 12 & Table 3), except for a more easterly moving average strike_N in profile section K_3 (Fig. 9). This anomalous strike_N coincides with a higher moving average crustal dilation in K_3, and might thus be caused by the interference of the more easterly striking sub-swarm, measured southeast of the Thverartindur central volcano (peak M in Table 3). The uniform change in the moving average dip_N of the dykes in K_1-K_3 (from 70°SE to 80°SE, or ~1.2°/km) probably reflects the local flexure in the regional lava pile. Outside the local flexure in K_4, there is a roughly constant moving average dip_N, suggesting that the lava pile has an apparent regional dip of ≤10°NW.

Regarding the major variations in the crustal dilation due to the dykes, there is a distinct quadrupling marking the transition from K_1 to K_2, which is attributed to the termination of dykes, or change of dykes into sills, at the transition from older lavas to younger lavas and hyaloclastite breccias (cf., the subsection on gabbros). The crustal dilation due to the dykes decreases through K_2-K_3 to a constant percentage of dilation in K_4, when disregarding a possible addition of roughly 2% to 5% dilation by the interference of the more easterly trending sub-swarm in K_3. There is an inverse relationship between this decrease in crustal dilation and a gradual ~3.2 m increase in the moving average thickness towards the southeast. The thickness of the regional dykes approaches the average thickness of inclined sheets in the inner northwestern part of the swarm (cf., Table 1).

Heinabergsdalur profile

The Heinabergsdalur profile includes three dyke swarms with different but overlapping trends (i.e., peaks R-T). The variation of the moving averages is more irregular than in Kalfafellsdalur, but three main profile sections (H_{1-3}) are recognised. Generally, the moving average strike_N exhibits a step-like variation through the sections, which is mainly caused by a large fraction of dykes from the more northerly or oblique trending sub-swarms (i.e., peak R) towards the NW (cf., Table 4 & Fig. 12). Cross-cutting relationships suggest that the more northerly striking dykes were emplaced relatively late; their appearance resembles the "brown doleritic" dykes (Annels 1967, Torfason 1979).

The variable moving average dip_N of the dykes in the three sections defines a slight anticlinal flexure (~1.5°/km) in H_1, a slight synclinal flexure (~0.8°/km) in H_2, and a distinct synclinal flexure (~5.7°/km) in H_3. Furthermore, these sections are separated by a 2°-decrease in dip_N marking the transition from H_1 to H_2, and a 5°-increase in dip_N marking the transition from H_2 to H_3. These abrupt changes in dip of the dykes occur at corresponding changes in crustal dilation, but ~700 m further to the southeast of the major changes in the average strike_N. Field observations indicate that each of the two abrupt changes in the dip of the dykes coincide with an unconformity in the extrusive pile.

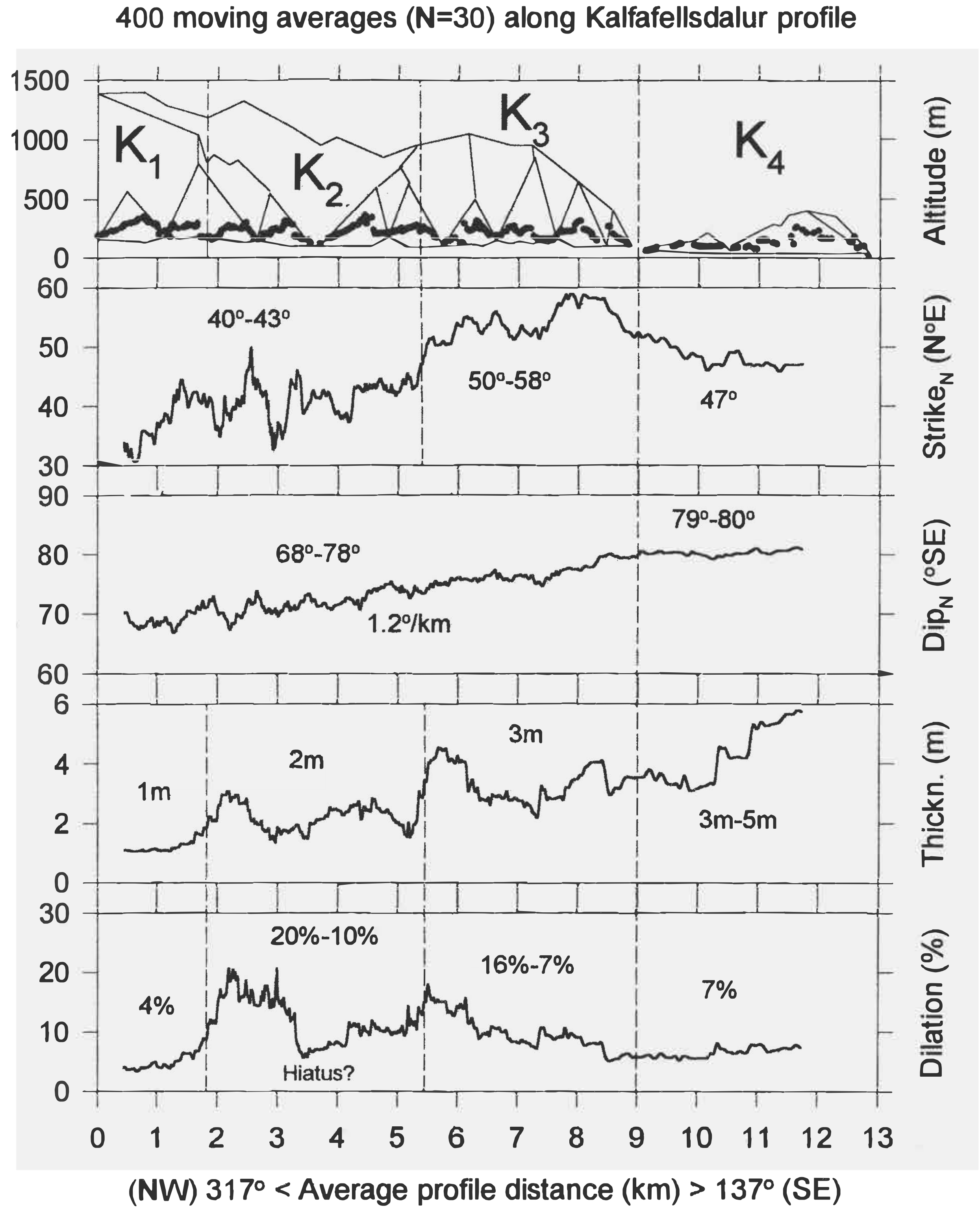

Figure 9: Moving averages (N=30) of 430 measurements along Kalfafellsdalur.

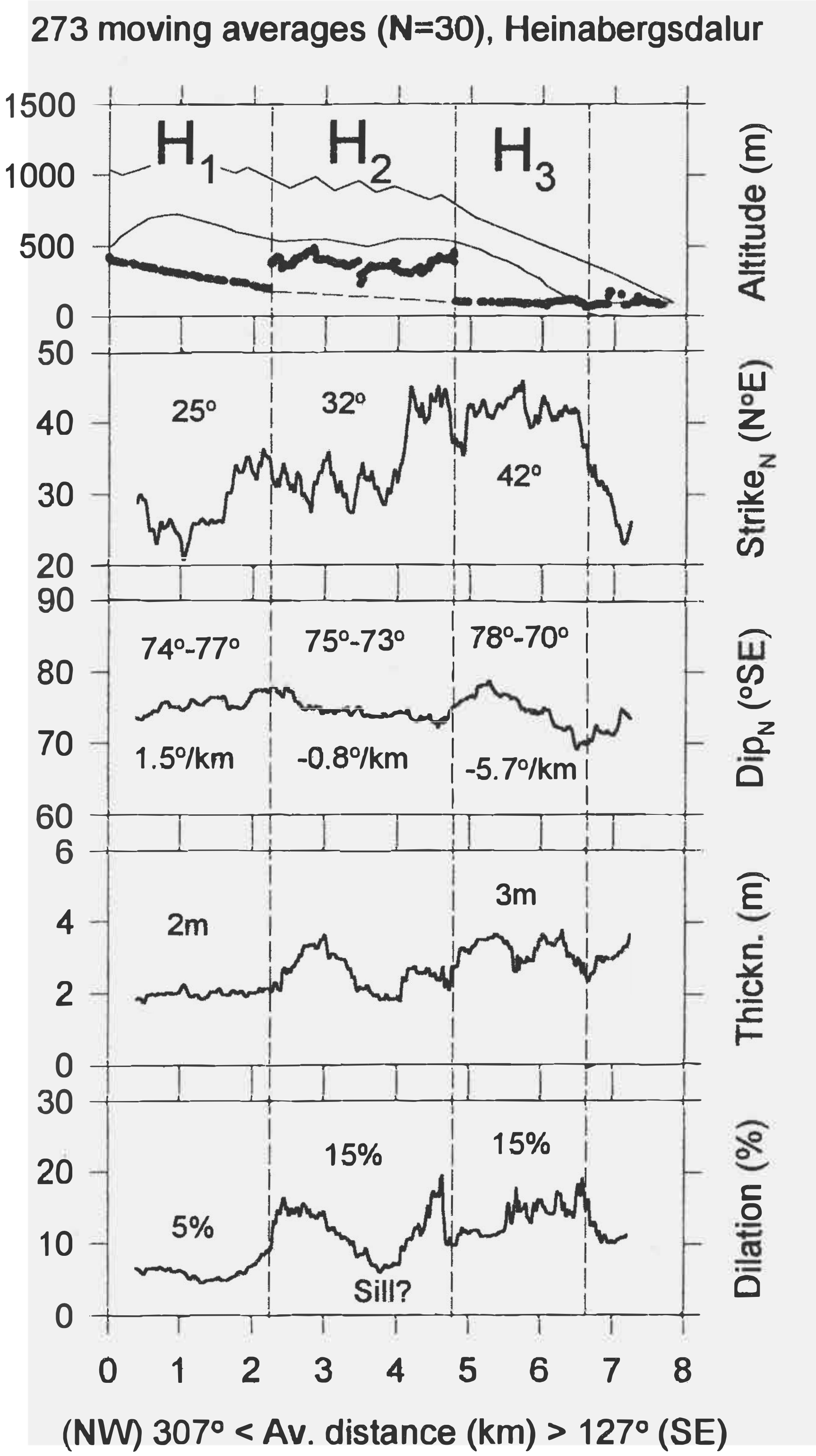

Figure 10: Moving averages (N=30) of 303 measurements along Heinabergsdalur.

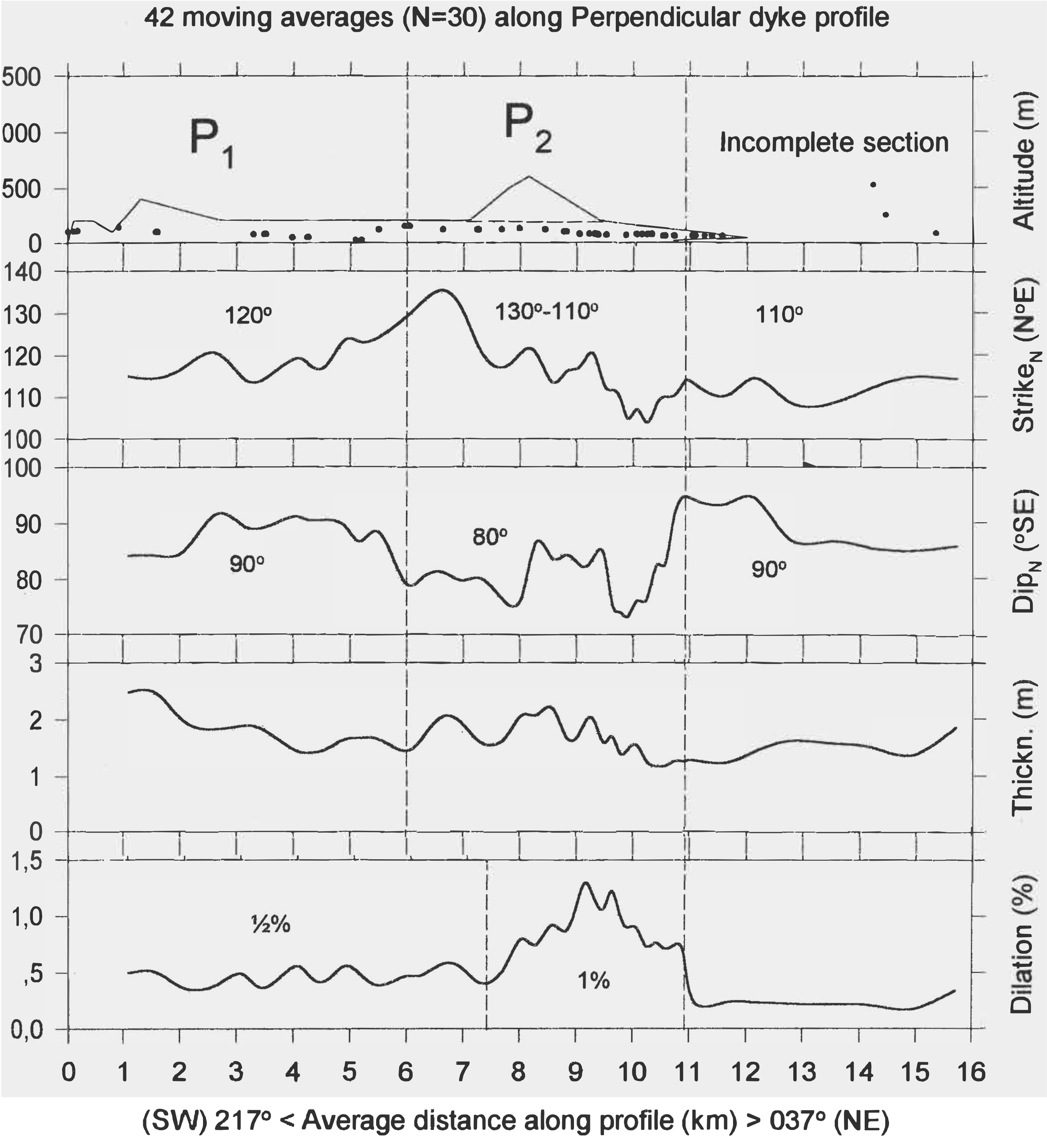

Figure 11: Moving averages (N=7) of 49 measurements along the perpendicular profile.

Profile section	N	Maximum density distribution at peak R	Maximum density distribution at peak S	Maximum density distribution at peak T
H_1	65	30% on 16/75°SE	20% on 36/71°SE	10% on 62/78°SE
H_2	100	19% on 16/75°SE	19% on 28/77°SE	18% on 60/75°SE
H_3	114	13% on 18/75°SE	23% on 39/72°SE	15% on 55/76°SE

Table 4: Variations in the structural density distribution of three (sub-)swarms across the profile in Heinabergsdalur (cf., Figs. 7, 10 & 13). Peaks refer to maximum counted density distributions similar to those defined in Table 3. N: number of measurements.

The crustal dilation due to the dykes more than doubles when going from H_1 to H_2, which supports the previous explanation of the change of dykes into sills upon entering the younger lavas and hyaloclastite breccias (cf., subsection on the gabbros). Unlike the Kalfafellsdalur profile, however, the dilation remains roughly constant through the rest of the profile, disregarding a distinct negative anomaly at ~4000 m along the profile as being caused by measuring dykes along a young sill instead of an old lava flow. This lack of a gradual change in dilation along the regional dyke swarm might be related to the existence of three (sub-) swarms (i.e., peaks R-T) and/or the irregular flexure of the lava pile. The moving average thickness across the Heinabergsdalur profile indicates a ~1.4 m increase from southeast to northwest, which is slightly less than that in Kalfafellsdalur.

Perpendicular profile

Both the moving average attitude and the amount of crustal dilation are relatively constant through P_1, exhibit much variation in P_2, and return to relatively constant values further to the north (cf., Fig. 11). The significant variations in P_2 are (1) a gradual ~20° rotation in strike, suggesting that the dykes are somewhat radiating from the Birnudalstindur central volcano, (2) a sudden uniform ~80°S dip_N of the dykes, suggesting an apparent ~10°N dip of the lava pile, and (3) a doubling in the crustal dilation due to the dykes.

The following observations indicate a relationship between the orthogonal sub-swarms and the oblique sub-swarms. First, the maximum density distribution of strike for the orthogonal and oblique dyke swarms are both very close to being perpendicular to each other (i.e., peak O is 86° to R, and peak P is 91° to S, in Table 3). Secondly, the orthogonal dykes resemble the "brown doleritic" dykes in appearance (i.e., distinct reddish-brown weathered surfaces, columnar jointing, and vesicular margins). Thirdly, both the oblique and the orthogonal dykes have been observed to cut the sheet swarms in Birnudalstindur central volcano, and are therefore younger than the sheets. Fourthly, there is a vague tendency for the oblique and orthogonal dykes to be restricted to the area that lies east of Birnudalstindur central volcano and a series of distinct N-S trending topographical depressions. Other sub-orthogonal lineaments, identified from aerial photographs and added to Figure 7, do not correspond to the measured orthogonal dykes. Some lineaments west of the distinct N-S trending valley and east of Kalfafellsdalur have been identified in the field as joints and faults, devoid of any dykes.

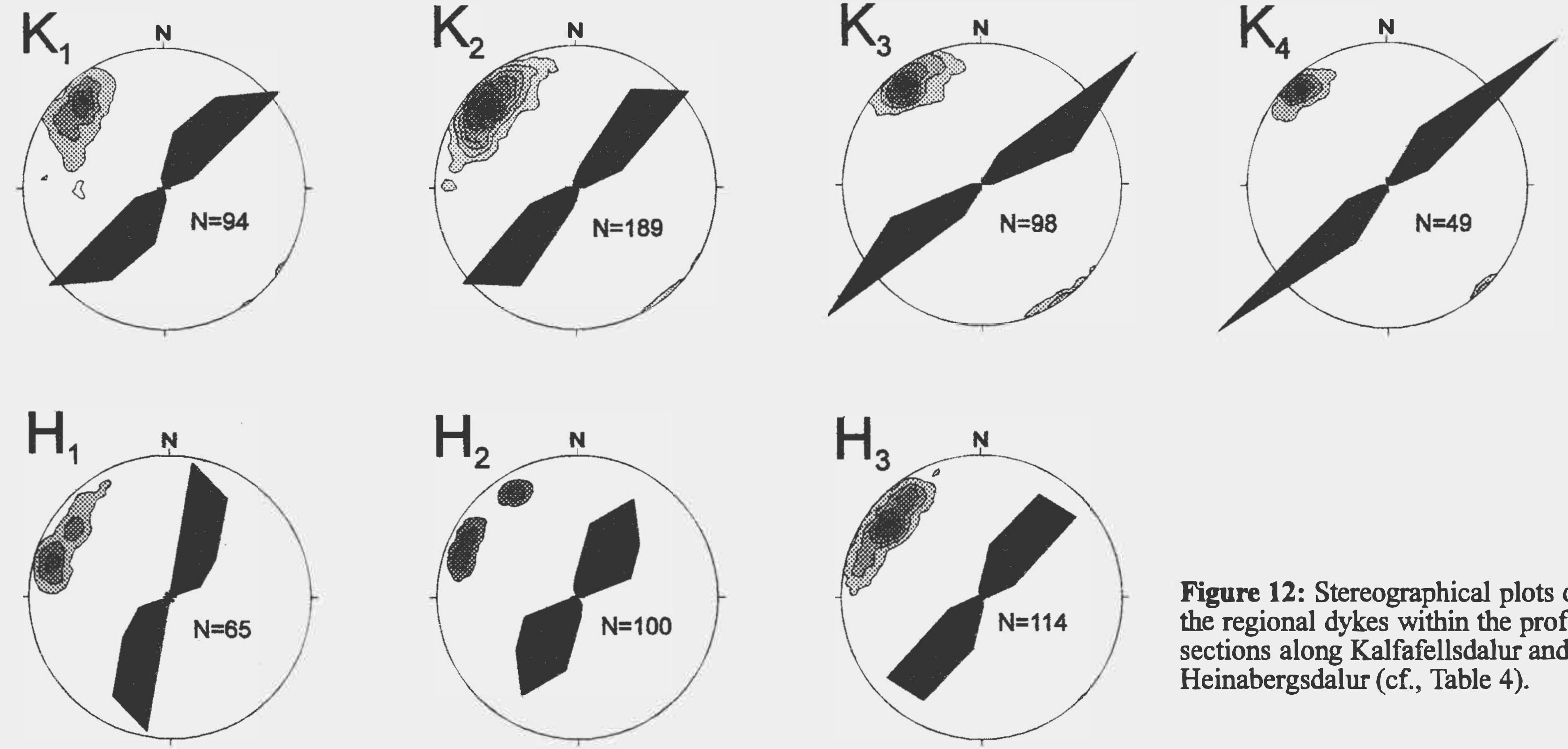

Figure 12: Stereographical plots of the regional dykes within the profile-sections along Kalfafellsdalur and Heinabergsdalur (cf., Table 4).

THE ORIGIN OF THE REGIONAL DYKE SWARMS

In the three profiles described above, and around Thverartindur central volcano, it has been possible to distinguish a dominant regional swarm, including some minor sub-swarms with distinctly different trends. It is therefore necessary to discuss the origin of (1) the dominant rift-parallel swarm, (2) the oblique sub-swarms, and (3) the orthogonal dykes in separate subsections.

Rift-parallel swarm

The spreading vector in Iceland trends N103°E, and cannot through pure dilation produce the regional trend of N047°E for the rift-parallel dyke swarm in Sudursveit. This trend has, however, been the general trend in southern Iceland since its formation. During the initiation of the North Atlantic this trend was sub-perpendicular to, but since -26 Ma it has been oblique to, the spreading vector (e.g., Nunns 1983). Elongated magma reservoirs probably exist at the bottom of the crust and trend sub-parallel with the stable trend of these rift zones. One such deep magma reservoir probably acts as the source for a rift-parallel dyke swarm and partly controls its infrastructure (Gudmundsson 1995).

The extent of the volcanic system towards the northwest is unknown due to the cover of the Vatnajökull ice sheet. However, the Thverartindur and Birnudalstindur central volcanoes are assumed to lie slightly en échelon along the centre of the rift-parallel dyke swarm (Fig. 13). Thus, the increased crustal dilation due to the dykes towards the inner parts of Kalfafellsdalur might reflect the variation in dilation towards the centre of the rift-parallel dyke swarm, disregarding any variation related to an unknown amount of change in the depth of erosion (Walker 1974, Gudmundsson 1983, Helgason & Zentilli 1985). The inverse relationship between crustal dilation and dyke thickness towards the centre of the swarm may correlate with an increased magma supply and tensile stress concentration towards the top of the reservoir. A similar decrease in the average thickness of dykes towards the central volcano has been documented along strike of dyke swarms in other areas (Sleight *et al.* 1982, Walker 1992). Consequently, there may be a general rule of increased intensity of dykes with decreasing average thickness of dykes towards the centre of a regional dyke swarm, or towards the central volcano.

The moving averages suggest that the rift-parallel and oblique dykes cut the regionally dipping and flexured lava pile at nearly right-angles. The dykes may have been emplaced sub-vertically prior to any tilting of the lava pile. Alternatively, they may have been emplaced inclined along the sub-perpendicular cooling joints in the lavas subsequent to the regional tilting and local flexuring of the lava pile. The two abrupt changes in the moving average dip$_N$ of the dykes in the Heinabergsdalur profile (Fig. 10) seem to coincide with primary unconformities in the jointed lava pile, which suggests that the dykes followed cooling joints in the lavas. Additionally, there is no difference in dip between the rift-parallel swarm and the later oblique sub-swarms (Table 3), which would be expected if some tilting of the lava pile had occurred during their sub-vertical emplacement. The gradual change in the dip of the dykes and the scarcity of faults suggest that the flexure was created through bending, rather than by domino-like block rotations as inferred for other areas in Iceland (e.g., Villemin *et al.* 1994). This may be a consequence of the number of faults decreasing with depth (Forslund & Gudmundsson 1992), and possibly also the increased magmatism relative to the amount of extension, as one approaches the central part of the rift zones in Iceland.

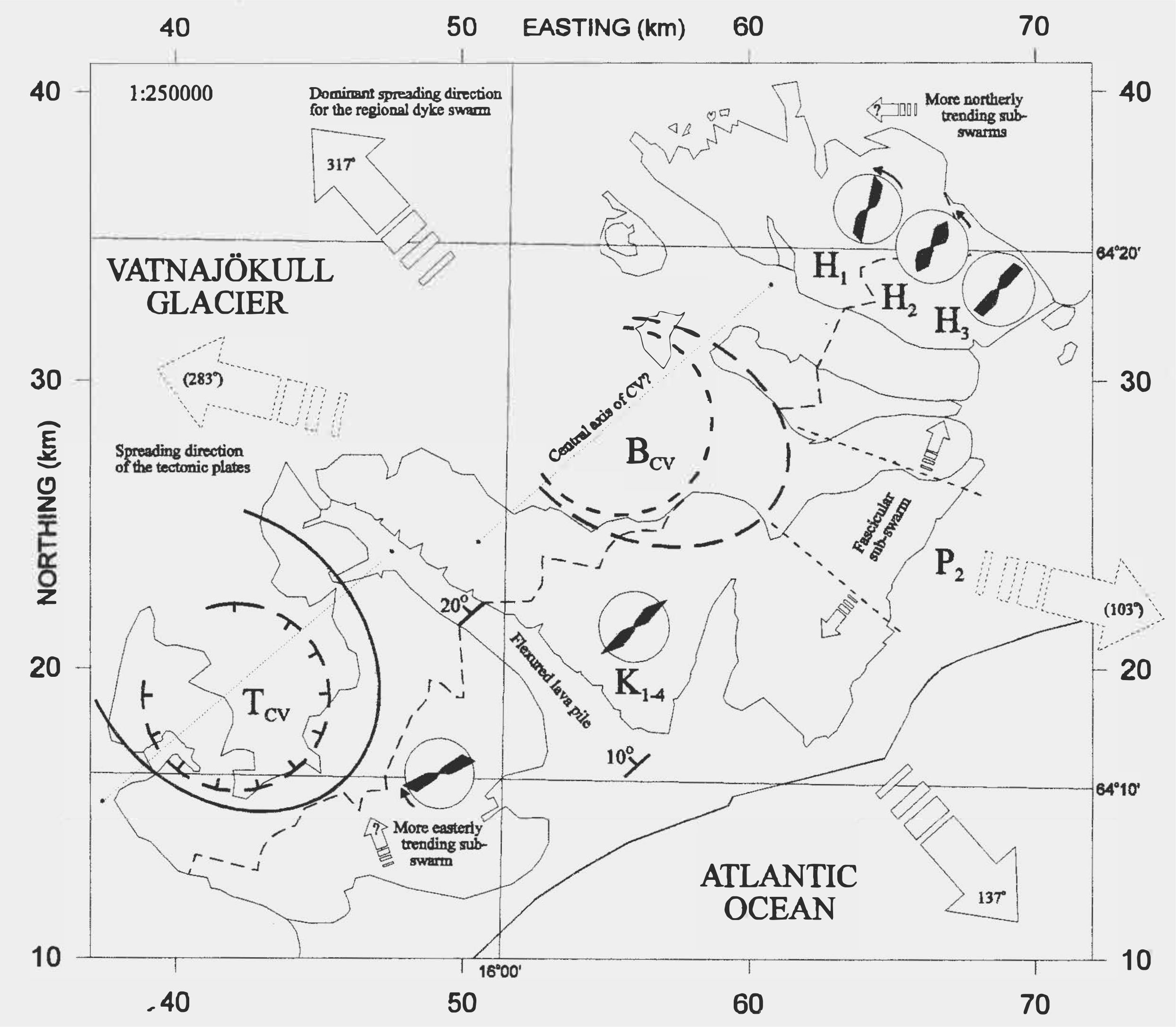

Figure 13: Structural features of Sudursveit. Large and small arrows indicate tensile stress components for main- and sub-swarms, respectively.

Oblique sub-swarms

During the end stages of a volcanic system, a diminished influence from the deep magma reservoir might allow the emplacement of northerly trending dykes in a regional stress field that is sub-perpendicular to the spreading vector in Iceland. The localized distribution of the oblique sub-swarms could then be explained by the existence of a remaining magma source at the Birnudalstindur central volcano. Alternatively, the oblique sub-swarms might belong to an even later rifting episode that was similar to the presumed active off-rift zone further to the west (Saemundsson 1979). However, no other evidence for the existence of an extinct off-rift zone has hitherto been identified in SE Iceland. These explanations of regional changes in the stress field subsequent to the emplacement of the rift-parallel dyke swarm are rather *ad hoc*, and the following suggestion for a local change in the regional stress field is favoured.

A similar group of oblique trending dykes are found south of the inferred centre of the Kailua caldera (outcrops 22-30 in Walker 1987), and Annels (1967) suggests that a similar variation in the strike of the regional dykes occurs around the Geitafell central volcano. Thus, it seems that the regional stress field may become modified near a central volcano, yet outside the local stress field generating the centrally inclined sheet swarms (cf., Fig. 13). Because of the relatively late emplacement of the oblique sub-swarms in this study, such a stress component might be related to a larger flexure of the crust near the Birnudalstindur central volcano. Torfason (1979) elaborates on this idea by relating both northerly trending fractures and "brown dolerites" to an en échelon arrangement of locally flexured zones around all four central volcanoes along this extinct rift zone in SE Iceland (cf., section on geological setting). However, most of Torfason´s "brown dolerites" were measured around the Kollumuli central volcano and may belong to the northern rift zone of Iceland. Further studies on the proposed local flexures around the central complexes, as well as the extent of the oblique dykes, are needed to verify this explanation for the origin of the oblique sub-swarms.

Orthogonal dykes

Sub-swarms, trending sub-perpendicular to the regionally trending swarms in the Tertiary Province of the British Isles, have been observed around the margins of central complexes on the Isles of Skye, Rhum, and Arran (Sleight *et al.* 1982, Walker 1993b). According to Sleight *et al.* (1982) orthogonal dykes cause up to 1½% crustal dilation on Skye, which is a little higher than the dilation measured in this study. Furthermore, they tend to be slightly radiating (or fascicular according to Walker 1993b), which can be inferred from the strike variation through profile section P_2 (Fig. 11). Related features, such as orthogonal rift zones occur on some Hawaiian volcanoes (Walker 1992). These similarities between the fascicular sub-swarms in Scotland, orthogonal rift zones in Hawaii, and the orthogonal dykes in the present area suggest a general mechanism for their emplacement which is related to the tensile stress field near a central volcano; in this case Birnudalstindur.

Consider a simple wedge-shaped regional dyke swarm (cf., Walker 1992) that is 10 km wide and 50 km long (Gudmundsson 1995), which generates a uniform increase in crustal dilation from the tips of the swarm to a maximum of 10% at the central cross-section (roughly the average crustal dilation through Kalfafellsdalur and Heinabergsdalur). Ideally, such a differential dilation in a regional dyke swarm would only cause 0.1% of perpendicular dilation at the central flanks of the swarm, which is a factor less than measured in this study. This deficiency must therefor be compensated by an asymmetrical growth of the rift zone (Walker 1992), and/or an additional crustal dilation by the Birnudalstindur central volcano.

CONCLUSIONS

The exposed infrastructure of the magmatic intrusion in Sudursveit present most features related to volcanic systems in Iceland. This study confirms that extinct volcanic systems are composed of central volcanoes and regional dykes swarms (Gudmundsson 1995), but indicates that there are also oblique and orthogonal sub-swarms in the volcanic systems.

Field evidence suggests that a rift-zone central volcano is initiated from sills which gradually build up to become a shallow magma chamber (Gudmundsson 1986). Elongate granite laccoliths and acid dykes are emplaced along the margins of the central volcano. They are relatively young and commonly with a regional trend, which indicates that they were emplaced outside the local stress field of the central volcano. Dense sheet swarms, defining the extent of the central volcano, are centrally inclined along and outside the margins of a presumed ellipsoidal shallow magma chamber. The dominant dip of the centrally inclined sheets decreases from the inner (~60°) to the outer (~30°) parts of the swarms. There is, however, a distinct difference between the centrally inclined sheet swarms and the surrounding regionally trending dyke swarms, and therefore no gradual transition between these swarms as proposed for other volcanic systems (e.g., Walker 1992, 1993b). Above the magma chamber not all sheet swarms are necessarily centrally inclined or sub-vertical, but may be inclined towards minor copulas in the roof of the chamber. This infrastructure of the sheet swarms agrees with the model presented in Gautneb & Gudmundsson (1992), where a shallow ellipsoidal magma chamber controls the local stress field.

It is assumed that the Thverartindur and Birnudalstindur central volcanoes represent the centre of the regional dyke swarm in Sudursveit. The regional dykes are emplaced sub-perpendicular to a flexured lava pile which dips from ~10°NW to ~20°NW towards the centre of the swarm in Kalfafellsdalur. The dip of the regional dykes is probably controlled by the cooling joints in the lavas rather than being tilted with the lava pile to their present attitude. Complete profiles show a decrease in the dyke intensity (≤20% to ≥5%) and an increase in the thickness of the dykes (≥1 m to ≤5 m) towards the margin of the swarm. The systematic increase in the number of dykes towards the centre of a regional dyke swarm is expected above a deep-seated magma reservoir, acting as the source of the dykes (Gudmundsson 1995). Additional sub-swarms with dykes that strike oblique (N017°E & N034°E) and perpendicular (N077°W & N055°W) to the dominant strike of the regional dykes (N047°E) are spatially related to the Birnudalstindur central volcano. The oblique sub-swarms were probably a group of late regional dykes that were rotated by an additional stress component, caused by a larger amount of flexure around the margins of the central volcano. The orthogonal sub-swarms cannot only be generated along the wide margins of a wedge-like shaped regional dyke swarm, during differential growth (Walker 1992), but additional expansion of the central volcano is necessary to produce the measured amount of crustal dilation.

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