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Strike-slip fault tectonics and the emplacement of sheet–laccolith systems: The Thverfell case study (SW Iceland)

Alessandro Tibaldi [a,*], Luigina Vezzoli [b], Federico A. Pasquaré [b], Derek Rust [c]

[a] Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, P.za della Scienza 4, 20126 Milan, Italy
[b] Dipartimento di Scienze Chimiche e Ambientali, Università dell'Insubria, Via Valleggio 11, 22100 Como, Italy
[c] School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth PO1 3QL, UK

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Abstract

Fault geometry and kinematics indicate that two different tectonic regimes affected the late Pliocene volcanic succession around the Thverfell magmatic complex (Esja peninsula, SW Iceland): The older phase is characterized by sets of left-lateral strike-slip, E–W- to ESE-striking faults and right-lateral strike-slip, N–S- to NE-striking faults; the younger phase produced normal dip-slip, NNE-striking faults. Stress tensor calculation for the older regime provides a horizontal, NE- to E–W-trending greatest principal stress ($\sigma 1$) and a horizontal NW- to N–S-trending least principal stress ($\sigma 3$), followed by a stress regime change with a vertical $\sigma 1$ and a WNW-trending $\sigma 3$. Structural–stratigraphic analyses of the eroded Thverfell magmatic complex indicate three main systems, namely (i) a centrally-dipping sheet swarm, E–W-elongated in plan view, (ii) a sill-composed laccolith, fed by E–W-striking dikes, and (iii) NNE- to NE-striking dikes offsetting the previous intrusions. These data allow unravelling of a multiphase history of magma-tectonics interaction. First, an excess magma pressure from an underlying magma chamber induced the emplacement of the centrally-dipping sheets; this was accompanied by magma upwelling along dikes that bent to propagate as sills under the influence of stress and rheological barriers induced by the lava overburden. Finally, regional dikes linked to the WNW-trending rift extension were emplaced.

Keywords: Iceland; Esja; Strike-slip fault; Inclined sheet; Sill; Regional dike

1. Introduction

Shallow magma feeding systems in the uppermost crust occur with different geometries, ranging from planar intrusions (vertical dikes, inclined sheets, horizontal sills) to laccolith bodies. Dikes are commonly sub-parallel to each other, occur in elongate (tens to hundreds of kilometres) swarms (Walker, 1992, 1999) and usually are perpendicular to the regional tectonic least principal stress ($\sigma 3$), and parallel to subparallel to the greatest principal stress ($\sigma 1$), which is vertically oriented (Gudmundsson, 1995). The structural conditions for sill emplacement, on the other hand, are more controversial, and have been related to different factors: neutral buoyancy forces (Corry, 1988), discontinuities (Weertman, 1980), rigidity ratio (Kavanagh et al., 2006) and stress barriers (Gretener, 1969; Gudmundsson, 1990). With respect to stress barriers, sill formation occurs at crustal levels where the horizontal compressive stresses are higher than the vertical stress, i.e. $\sigma 1$ should be horizontal (Gudmundsson, 2000). Inclined sheets are frequently arranged into centrally-dipping swarms and considered to be the expression of magmatic stress prevailing over tectonic stress. Their radial pattern as seen under cross-sectional view is formed because of internal overpressure, where stress is concentrated towards the edges of the magma chamber (Walker, 1992; Gudmundsson, 1998, 2002; Klausen, 2004; Gudmundsson and Brenner, 2005). Structural studies of sheet swarms mostly focus on the geometric description of the intrusive features and their associations (Geikie, 1897; Bailey et al., 1924; Muller and Pollard, 1977; Nakamura et al., 1977; Gudmundsson, 1990; Tibaldi, 2003; Gudmundsson and Brenner,

* Corresponding author. Tel.: +39 2 6448 2052; fax: +39 2 6448 2073.
E-mail address: alessandro.tibaldi@unimib.it (A. Tibaldi).

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2005; Klausen, 2006). Only in certain instances have petrochemical analyses been included in the investigation of sheet swarms (Geshi, 2005; Corazzato et al., 2006).

Comparison between intrusive structures and contemporaneous tectonic deformation through detailed field investigation is fundamental in determining whether sub-volcanic emplacement was mainly controlled by magmatic forces or by tectonic forces (e.g. Doubre and Geoffroy, 2003; Pasquarè and Tibaldi, 2007). However, this type of approach is lacking in most studies, although it is necessary in understanding magma propagation into the uppermost crust and of crucial relevance to hazard assessment of active volcanism. Studies conducted at eroded volcanoes can provide new insights into hidden structures within active volcanoes. They are also important because sub-volcanic intrusions play a major role in the growth of volcanoes, both in terms of inner expansion (Annen et al., 2001) and lava extrusion.

Iceland is a natural laboratory for the study of the shallow magma feeding systems and their relationships with regional tectonic and magmatic forces: it is an area where tectonic uplift and glacial erosion on Tertiary–Quaternary magmatic complexes exposed several intrusive sub-volcanic bodies (Fridleifsson, 1977; Gautneb et al., 1989; Gautneb and Gudmundsson, 1992; Gudmundsson, 1990, 1995, 2002; Klausen, 2004, 2006). Located directly upon the Mid-Atlantic Ridge system, Iceland is mainly characterised by extensional tectonics with a vertical $\sigma 1$ (Gudmundsson et al., 1992). This tectonic setting favours dke emplacement, and hinders the formation of sills. However, several sills occur in extinct volcanoes in the rift zone of Iceland (Forslund and Gudmundsson, 1991; Pasquarè and Tibaldi, 2007). Strike-slip faulting has been documented in SW Iceland (Passerini et al., 1997), suggesting that the structural architecture and tectonic regimes of rift zones are quite complicated and worth studying in depth.

This work combines detailed field data on the tectonics and intrusions of the eroded Thverfell magmatic complex, in the southern sector of the Esja peninsula (SW Iceland; Fig. 1), with the purpose of understanding the possible control of strike-slip tectonics on shallow magmatic feeding systems and emplacement history of the investigated intrusive bodies. Tectonic data include the location, geometry and kinematics of meso-scale and major faults, the geometry of veins, and stress tensor calculations; data on the basaltic intrusions are related to the spatial distribution and geometry (strike, dip direction, dip, thickness) of 79 vertical dikes, 251 inclined sheets, and 3 large intrusions, one of which is a complex and thick, multi-phase laccolith made of stacked sills.

2. Geological and tectonic settings

Iceland is believed to have been built from the interaction of a mantle plume with the North Atlantic divergent plate boundary (Schilling, 1973; Gudmundsson, 2000; Jacoby and Gudmundsson, 2007). Its geology is characterized by successions

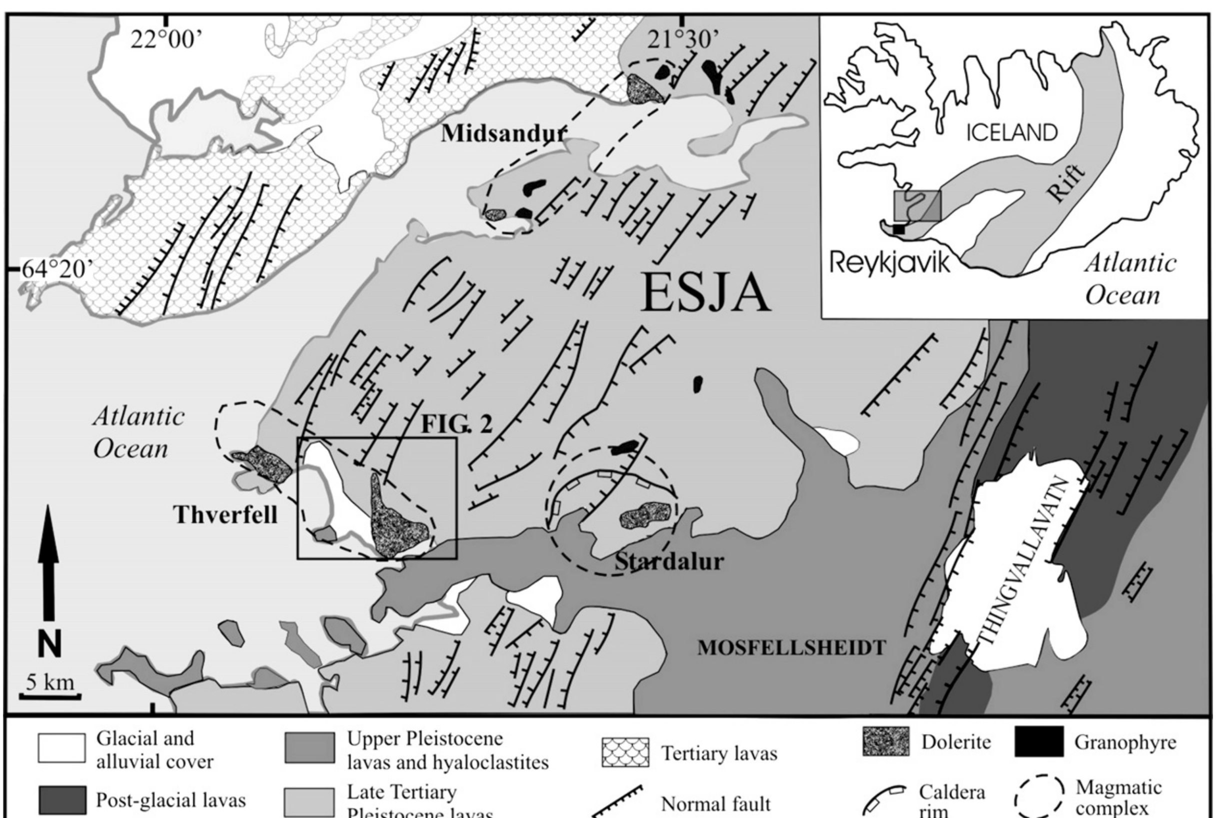

Fig. 1. Geographic location of the study area and regional geological and tectonic framework. Inset shows Iceland with rift zones. Simplified after Johannesson and Saemundsson (1998) and Villemin et al. (1994). Rectangle: location of the study area.

of Tertiary basalts that flank the currently active rift system crossing the island from SW to NNE. These basalts gently dip toward the rift due to the progressive subsidence caused by loading of the rift zone crust, which buried thick piles of rock under high geothermal gradients. This process led to metamorphism of basalt to amphibolite, eventually causing some partial melting that generated rhyolitic magmas (Thordarsson and Hoskuldsson, 2002).

The Esja peninsula (Fig. 1) is located between the western rift zone and Tertiary basalts NW of the rift. This transitional zone incorporates a succession of 3.3–0.8 Ma basaltic lava flows and hyaloclastites (Fridleifsson, 1977), known as the Plio-Pleistocene Formation in the geological map of Iceland by Johannesson and Saemundsson (1998). All the lava units, totalling a thickness of 1300 m and comprising the core of the Esja peninsula, were erupted 2.8, 2.0 and 1.7 Ma ago (Thordarsson and Hoskuldsson, 2002) by the Thverfell, Midsandur and Stardalur magmatic complexes, respectively (Fig. 1; Villemin et al., 1994). During cessation of volcanic activity, the peninsula was dissected by glacial erosion, which exposed the inner structure of the three magmatic complexes (mainly doleritic intrusions). Starting about 0.8 Ma ago, volcanic activity resumed along the SE foothill of the Esja plateau, giving rise to the Mosfellsheidt basaltic shield volcano which erupted lava flows that reached the coastline (Fig. 1).

Five gabbroic intrusions in the Esja peninsula are associated with the above-mentioned Thverfell, Midsandur and Stardalur magmatic complexes. The latest and most detailed map of the Esja peninsula (Fridleifsson, 1972) depicts (Fig. 1) a doleritic body surrounded by lavas and hyaloclastites. This lava-hyaloclastite succession is associated with the Thverfell and Stardalur complexes and is locally intruded by inclined sheets, some of which were already mapped by Fridleifsson (1972). There are no detailed studies on the geometry, thickness and spatial arrangement of the Thverfell sheet swarm, although statistical data on inclined sheets and dikes in the whole Esja peninsula have been presented by Villemin et al. (1994).

The structural features of the area were first described by Fridleifsson (1972) and later in more detail by Villemin et al. (1994). Both reported NE- to NNE-striking normal faults and dikes (Fig. 1), as well as an 8–10° regional tilt towards the SE of the lava succession. Villemin et al. (1994) reported the occurrence of transcurrent faults in the area but noted their minor importance relative to normal faults. About 25 km north of the study area, Passerini et al. (1997) documented several strike-slip faults trending mostly parallel to sub-parallel to the Icelandic Rift.

3. Materials and methods

Lithostratigraphic units and structures in the Thverfell area were mapped at a 1:10,000 scale (Fig. 2) to determine the relationship of tectonic structures, stratigraphy and magmatic intrusions. Majority of the mapping was conducted along an exceptionally well exposed cliff that is parallel to the sea cost. This 7-km-long, NW–SE trending continuous outcrop which on occasion is cut by canyons, provides an excellent three-dimensional view of the geology. Each structure along the outcrop was mapped and located by a handheld GPS (Global Positioning System). Cross-cutting relationships of stratigraphic units, faults and intrusions were carefully observed. The position of the major central intrusion was

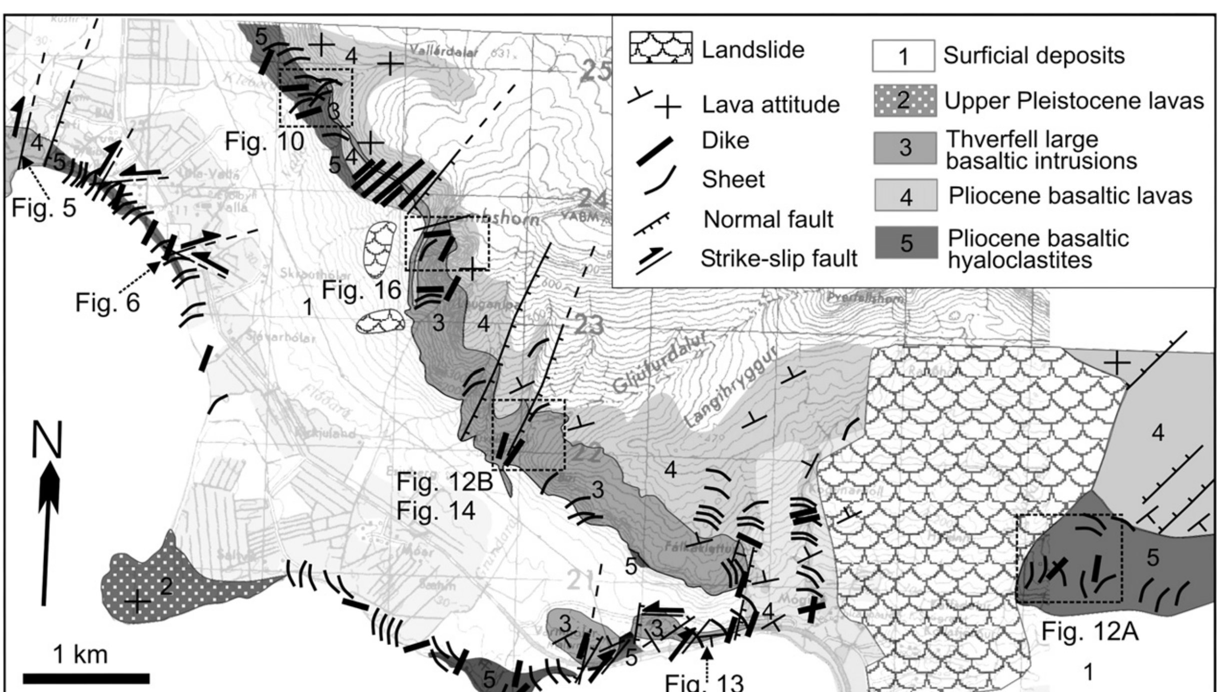

Fig. 2. Geological map of the study area, based on new field surveys by the authors. Original scale of mapping 1:10,000. For the precise location of all dikes and sheets, see Fig. 7.

constrained through systematic observations of intrusion contacts, margin textures and cooling fractures.

We applied an 8°-northwestward backtilting along a N39°E axis to all dip measurements to compensate for the tilting of the rock succession in the Esja peninsula. The backtilting value used is based on our field observations and the work by Villemin et al. (1994) which show that in the Esja peninsula the average dip direction of the layers is N129°, with an average dip angle of 8°. Although it is impossible to determine whether all the sheets and faults were tilted by the same amount, this general assumption may be considered reasonable considering the low degree of tilting of the volcanic successions in the study area.

The configuration of the sheet swarm was determined by measuring each individual sheet (dip direction and amount) at regularly spaced intervals. The thickness of each sheet was also measured at 5-m intervals along the whole exposure. In order to minimize irregularities, the average thickness was taken as a representative value. A strip of about 2 km around the area represented (see Figs. 2 and 7) was also surveyed to check the possible presence and geometry of inclined sheets.

The strike, dip and dip direction of faults were measured in the field; observations included slickenside lineations which were used to determine stress tensors, through classical inversion methods (Carey, 1979, and successive improvements). The criteria of Tibaldi (1996) were used to distinguish slickensides produced by actual tectonic slip from textures induced by lava layers moving at different speeds within a flow. Although the available number of slickensides is limited, due to the fact that they are seldom produced on lavas, these occur on major faults and hence allow us to gain meaningful insights into the tectonic phases that affected the area.

4. Geology of the study area

The mapped lithostratigraphic succession in the Thverfell area is represented by basaltic hyaloclastite deposits, overlain by interlayered basaltic lava flows and thin autoclastic breccias

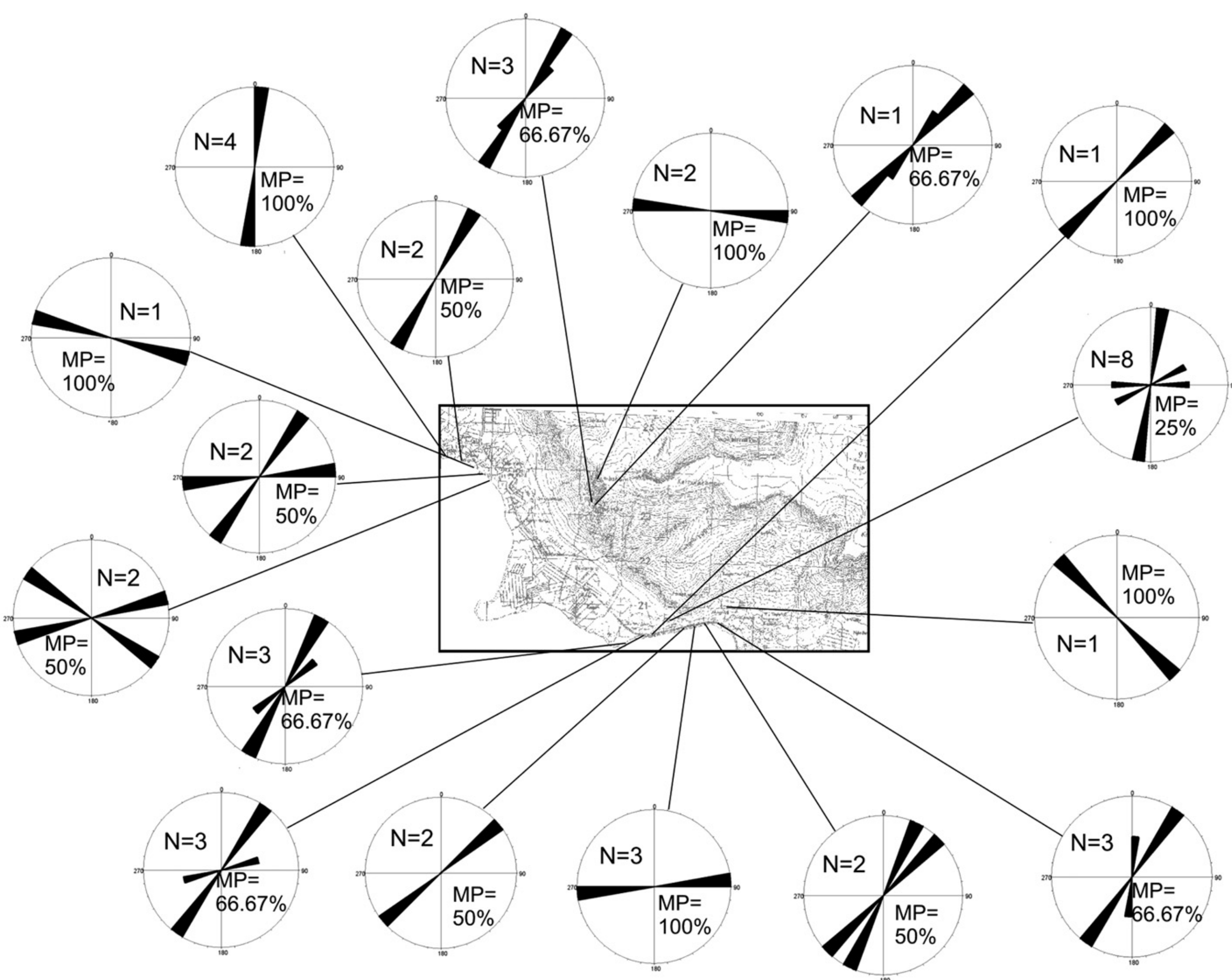

Fig. 3. Rose diagrams of all (both dip-slip and strike-slip) faults at each station. Number of faults (N) is indicated within each rose diagram, as is the maximum percentage (MP) making the perimeter. Sector size is 10°.

(Fig. 2) belonging to the Plio-Pleistocene Formation (Johannesson and Saemundsson, 1998). The hyaloclastite deposits consist of monogenic, angular to subangular glass and lava fragments, centimetre to decimetre in size, with quite homogeneous texture in all the observed outcrops. The basaltic lavas are massive, dark grey to black in colour, with a fine-grained microcrystalline to aphanitic texture. They form 1–5 m-thick continuous and conformable lava flows. Holocene glacial, alluvial and debris deposits are widespread over the volcanic rocks. A huge landslide deposit is also present in the eastern part of the studied area, whereas in the central–western part there are two blocks which are recognized as the result of poorly-developed deep-seated gravity slope deformation, with uphill backtilting of originally layered lava successions. This evidence enabled us to avoid using erroneous attitude measurements of the tilted lava layers.

A swarm of 251 inclined sheets and 3 intrusive bodies compose the Thverfell magmatic complex, intruded almost entirely into the hyaloclastites (Fig. 2). There were also 79 vertical dikes that cut across the Plio-Pleistocene Formation. All these intrusions were the focus of our structural study and are here described in detail.

5. Tectonic structures

We described and analysed 43 faults at 17 stations (Fig. 3) among which are meso-scale (dm-scale offset) and major (metres to tens of metres offset) structures. Continuity of the major faults is difficult to trace in the field, due to the diffuse presence of surface deposits cover. It has been possible to follow these over distances of about 1–2 km. Analysis of satellite images and geological maps (Villemin et al., 1994; Johannesson and Saemundsson, 1998) indicates they are at least 5 km long (Fig. 1).

Among all the studied faults, 22 are recognized as dip-slip faults and 21 are strike-slip faults. The normal faults have a dominant NNE–SSW strike (Fig. 3) with pitches as steep as 80–90°. They cut the strike-slip faults at all locations except in one station where the opposite cross-cutting relationship was observed (station 7 in Fig. 4). The maximum dip-slip offset observed in the field is 5 m. Stress computations on

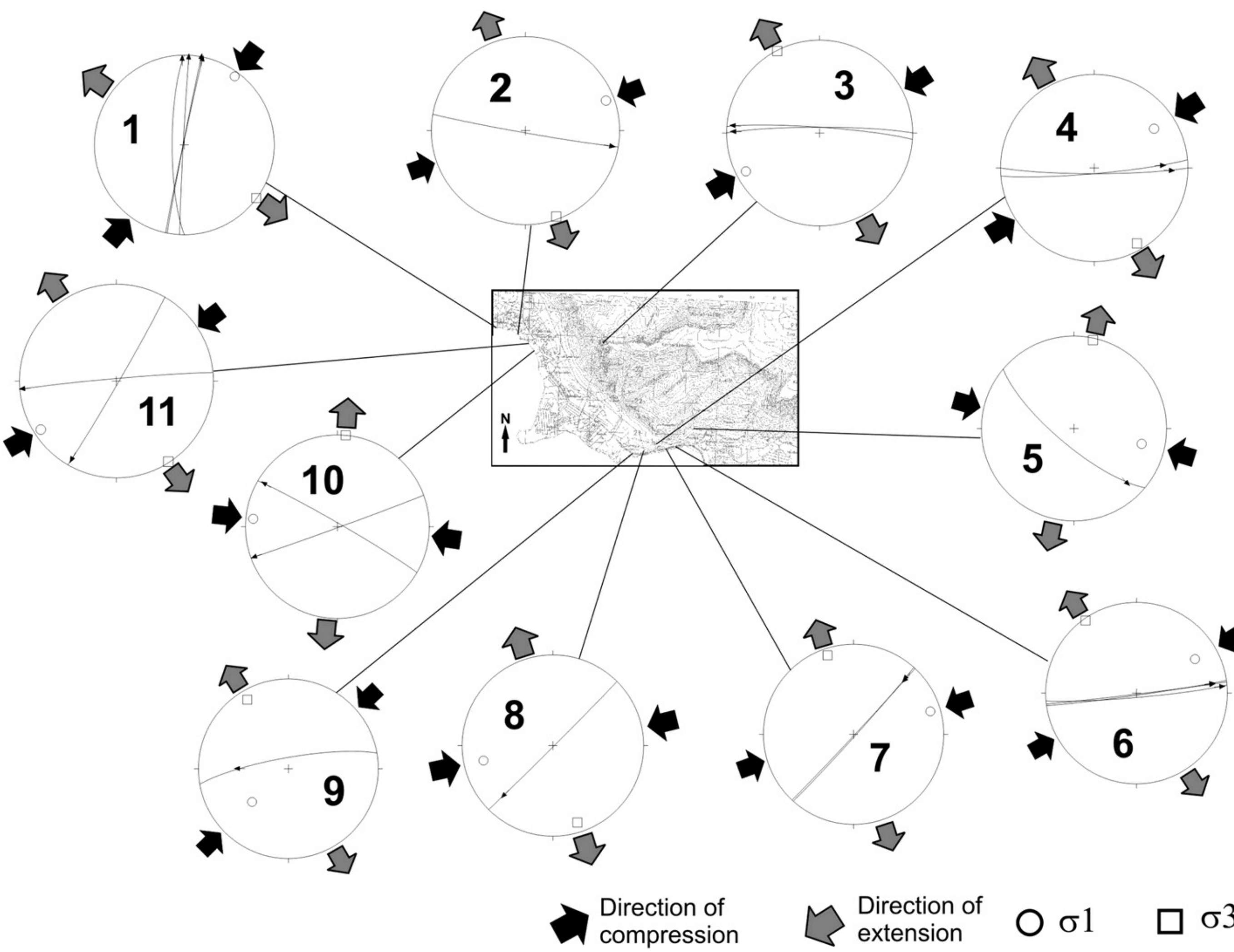

Fig. 4. Lower hemisphere equal-area projections of strike-slip fault orientations at stations numbered from 1 to 11. Kinematic indicators (striations) are drawn as black arrows. Paleostress directions are shown as black and grey arrows.

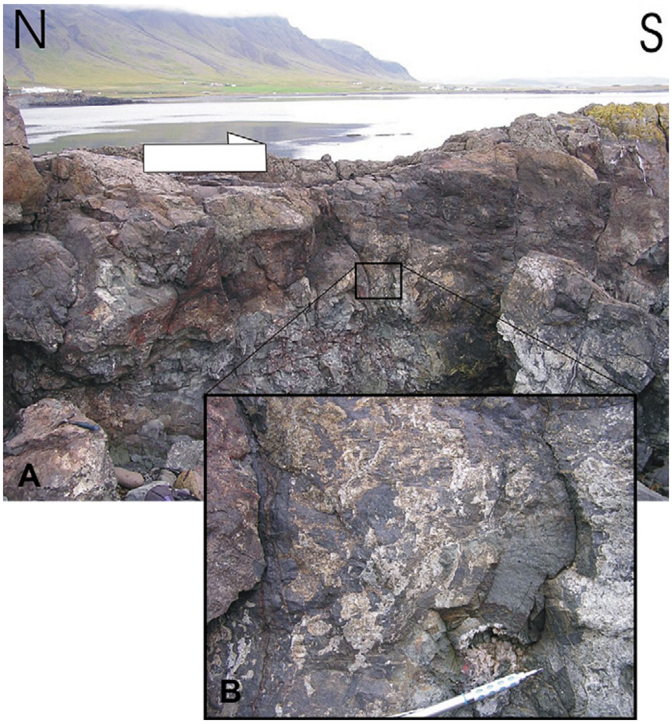

Fig. 5. Example of a major N–S-striking right-lateral strike-slip fault at station 1 of Fig. 4. Inset shows a close-up view of the slickensides.

these faults are the same as those computed by Bergerat et al. (1990) and Gudmundsson et al. (1992) where $\sigma1$ is vertical and $\sigma3$ is WNW-trending.

Transcurrent faults in the area belong to two sets (Fig. 4): (i) right-lateral strike-slip faults, with low pitches (<10°; Fig. 5), that strike N–S to ENE–WSW; and (ii) left-lateral strike-slip faults, also with low pitches (<10°), that strike E–W to ESE–WNW. At station 10 in Fig. 4, two strike-slip faults belonging to the two sets were observed. They form a conjugate set and are characterised by thin (cm-scale) mineralised veins that strike N90° to N105° (Fig. 6). This feature, combined with the analysis of the entire strike-slip data set allowed determination of the $\sigma3$. At this particular outcrop, the $\sigma3$ is N0–15°. The observed strike-slip faults offset stratigraphic markers by a few centimetres to several metres. Some exhibit gouges and long tectonic striations associated with large offsets. These features show their importance in terms of single or cumulative displacements.

In some cases, fault planes show two sets of tectonic striations with different orientations, indicating the presence of multiphase slip with different kinematics. Some observations on NE–SW striking faults suggest that normal motions are younger than strike-slip motions, and hence these transcurrent planes were rejuvenated following the main Icelandic rift geometry. Stress tensor computations (Fig. 4) on strike-slip faults indicate that they were produced by a $\sigma1$ with the following directions: N34° (station 1 in Fig. 4), N46° (station 9 in Fig. 4), N54° (station 11 in Fig. 4), N62° ± 2° (stations 3, 4, 6 in Fig. 4), N68° (station 2 in Fig. 4), N73° (station 7 in Fig. 4), and N90° ± 10° (stations 5, 8, 10 in Fig. 4). The average $\sigma1$ direction is N68°, and the average $\sigma3$ direction is N158°. The transcurrent tectonic phase, that produced the documented right lateral and left lateral sets, was followed by the above-cited, younger dip-slip tectonics that produced normal faults mainly striking NNE–SSW and linked to the present tectonic regime, dominated by a vertical $\sigma1$ and a WNW-trending $\sigma3$. At one station, the occurrence of normal faulting older than transcurrent faulting indicates that another local extensional phase of deformation might have preceded the strike-slip regime.

6. Structure of intrusions

6.1. Inclined sheets

The inclined sheet swarm is made up of 251 inclined sheets (Fig. 7) observed at 25 stations, in outcrops located along the

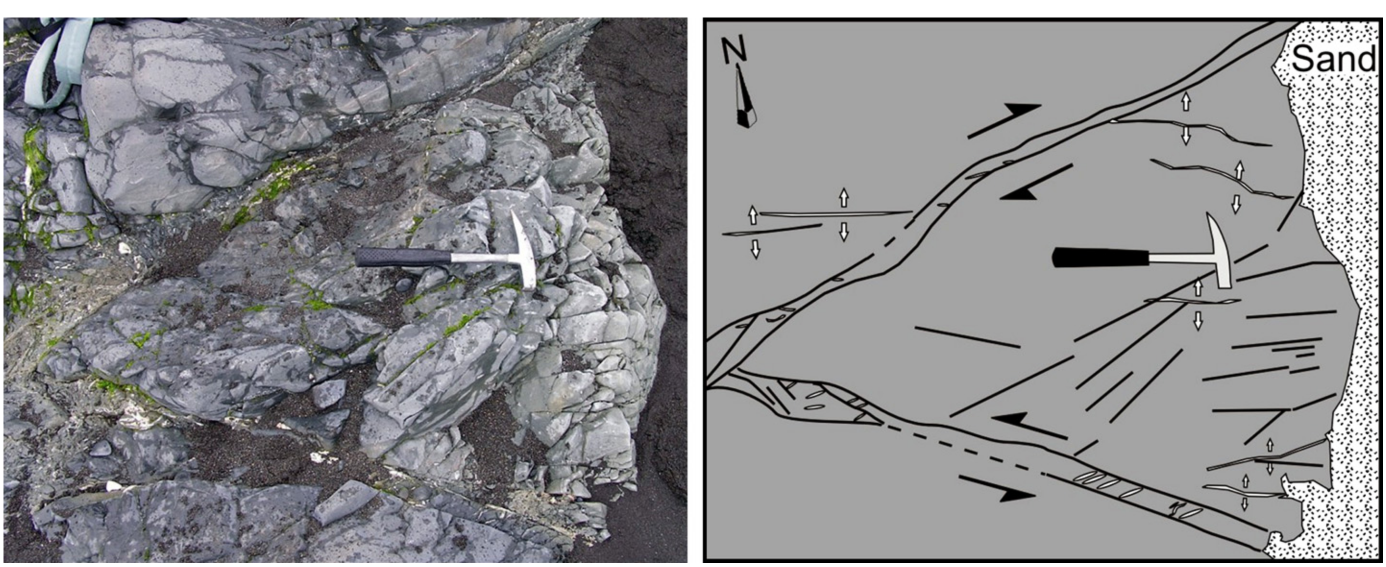

Fig. 6. Photograph (A) and interpretation (B), in plan view, showing the conjugate pair observed at station 10 of Fig. 4. Observe the strike of the veins bisecting the angle formed by the ENE-striking, right-lateral strike-slip fault and the ESE-striking, left-lateral strike-slip fault.

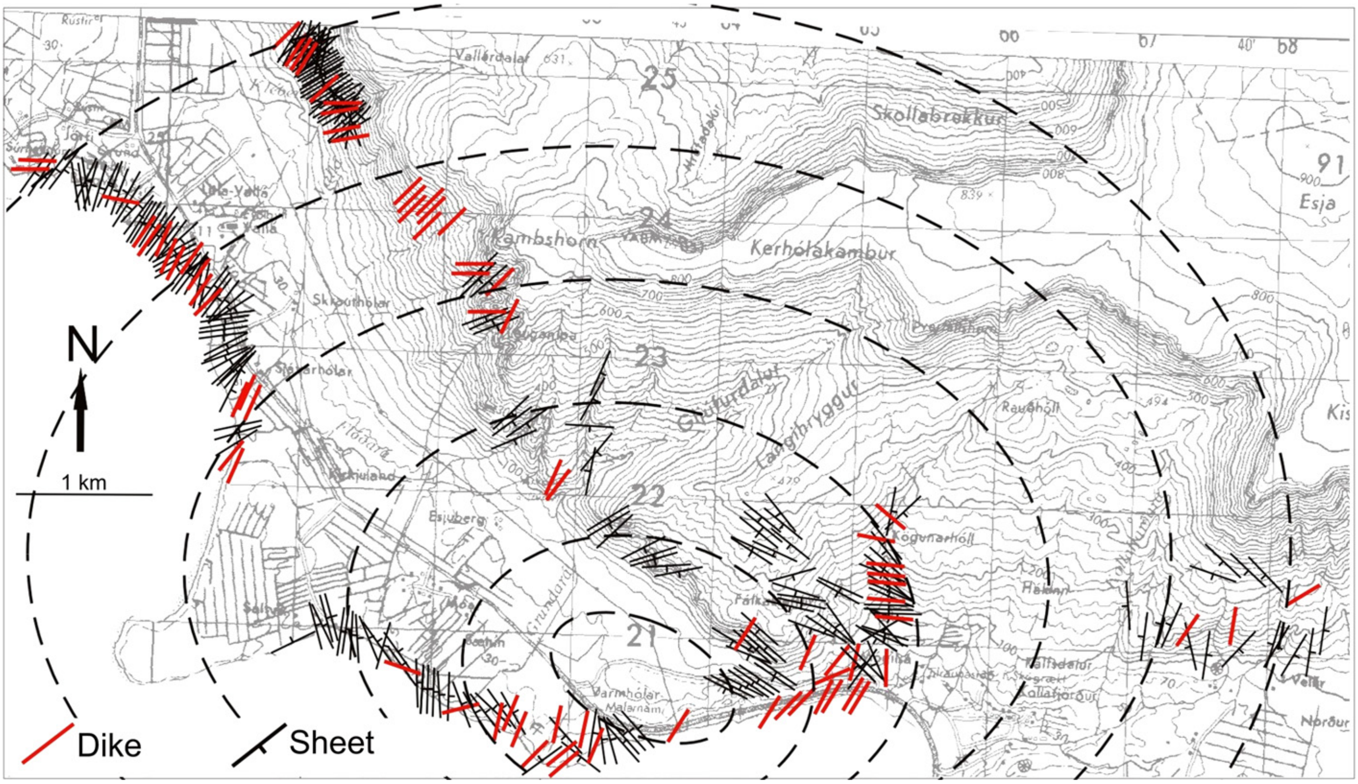

Fig. 7. Location and attitude of all dikes and inclined sheets in the study area. The dashed lines define the general pattern of the sheets which clearly outline an about E–W-elongated ellipse in plan-view.

sea coastline, the Thverfell plateau scarp, and stream valleys (Fig. 8). In terms of sheet spatial arrangement, it has been observed that almost all directions are well represented (Fig. 9), as expected in swarms of conical sheets (Gautneb and Gudmundsson, 1992; Klausen, 2004). The studied swarm has an average sheet dip of 32°, with a peak in dip distribution (152 sheets) between 15° and 35°. This is in agreement with other sheet swarms in Iceland whose average dip is 34° (Gudmundsson et al., 1996) and slightly lower than at Gran Canaria, Canary Islands (average dip of 41°, Schirnick et al., 1999). We plotted all the sheet measurements (Fig. 8), obtaining density contoured plots of poles to the sheets' intrusion planes; the clusters of poles to planes, for each station, are orthogonal to the average dip direction that, being tangential to the depth trajectory of the intrusions, might be called ''sheet trajectory'' as suggested by Klausen (2004). The projected sheet trajectories (drawn as arrows in Fig. 8) point towards the central portion of the study area, defining a centrally-dipping geometry for the sheet swarm. The whole sheet geometric arrangement, in plan view, resembles the shape of an ellipse, with the major axis trending about E–W (Fig. 7).

About 90% of the inclined sheets have been intruded into the hyaloclastite deposits. This observation is not biased by the greater difficulty in distinguishing sheets in the lava succession, as we tracked in the field several sheets up to the contact between the underlying hyaloclastites and the overlying lava flows. In all the investigated cases, a sheet becomes arrested at the contact or assumes a dip parallel to the lava succession. An example of this geometrical arrangement of the sheets within the hyaloclastites is shown in Fig. 10A,B. This preferential distribution in the studied area can also be observed in the geological map (Fig. 2). The inclined sheets tend to have a quite constant dip or bend gradually in the hyaloclastites. An example of the opposite pattern (the sudden and multiple changes of dip and dip direction) is shown in Fig. 11, which documents a thin sheet spreading along preexisting fractures in the intrusive host rock.

The calculated average thickness for each of the 251 sheets is 1.1 m, and is in fairly good agreement with the average sheet thickness calculated in individual swarms, which ranges from 0.1 m to around 1 m (Gudmundsson et al., 1996). Klausen (2004), in his analysis of 1128 sheets in the Thverartindur central volcano, obtained an average thickness of 0.9 m.

Inclined sheets at measurement stations located in the western and eastern portion of the Thverfell area show two systematic and opposite dip directions (Fig. 12A). In some stations where crosscutting relations are appreciable, those dipping in one direction are systematically offset by those with the opposite dip, suggesting that they belong to different emplacement systems. Along a NW–SE cross-section (Fig. 2) in the eastern portion of the area, the sheets dipping eastwards (i.e. outwards from the main magmatic body) tend to decrease in frequency towards the west where they eventually disappear. In the central sector of the Thverfell area, the sheets show a centrally-dipping arrangement, whereas in the western sector the sheets dipping westwards increase in frequency moving towards the west. Based on the above descriptions, we believe that three conical sheet swarms crosscut each other in the study area.

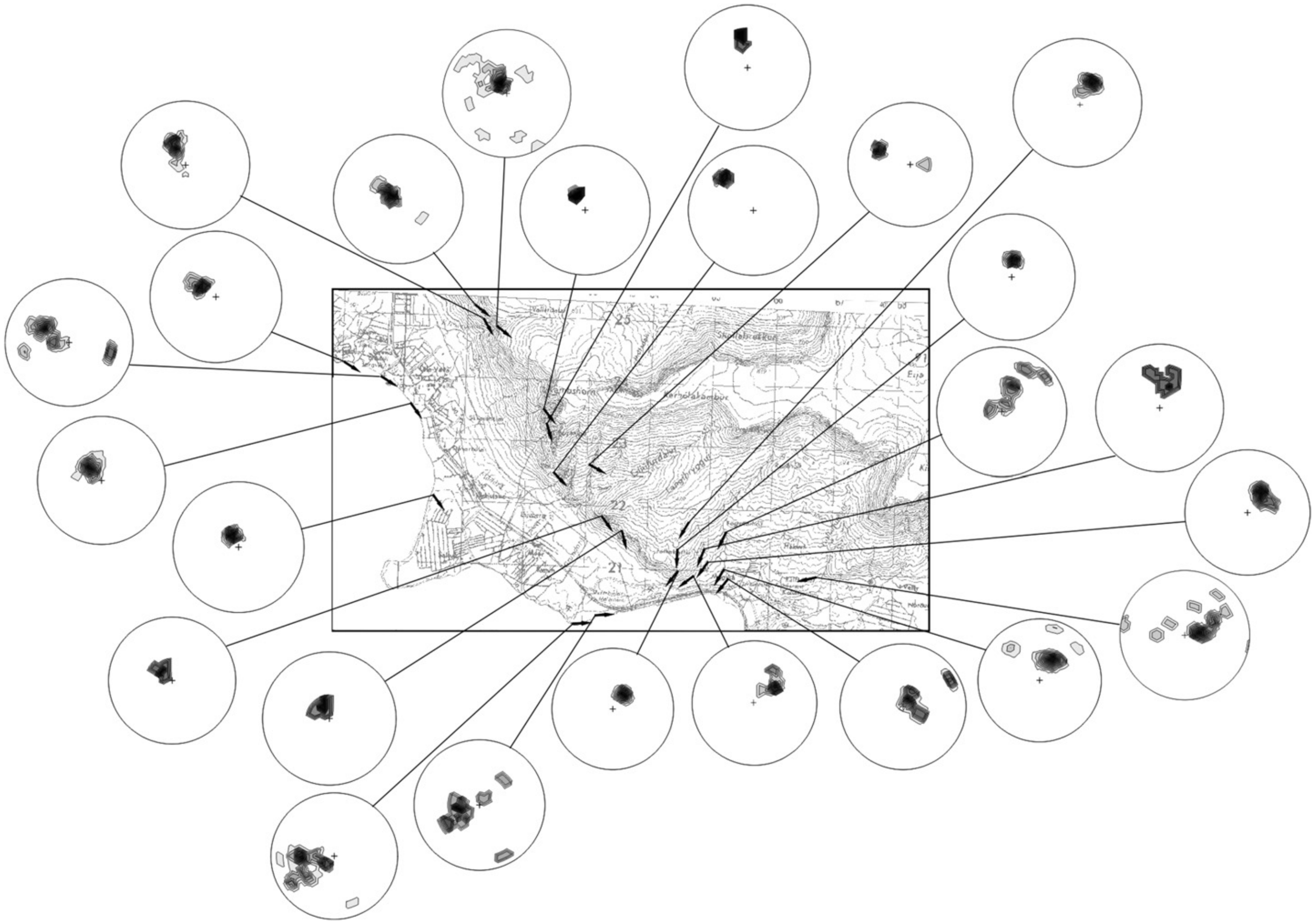

Fig. 8. Equal area, lower hemisphere contoured plots of poles to sheets at each station. Sheet trajectories (i.e. average dip direction) for each station, drawn as black arrows, point to the central portion of the study area, indicating a centrally-dipping sheet swarm geometry.

The sheets dipping eastwards in the eastern part of the studied area belong to the Stardalur centrally-dipping sheet swarm described by Pasquarè and Tibaldi (2007). The sheets belonging to the Thverfell sub-volcanic system extend about 12 km from west to east across the centre of the studied area.

6.2. Large intrusive bodies

There are three tabular large intrusive bodies in the Thverfell area (see Fig. 2). They crop out at progressively higher elevations and are separated from each other by hyaloclastite deposits. The lowermost body, which is about 10 m thick, is fed by a sub-vertical, 3-m-thick dike striking N30°. Its lower contact surface is convex downward, suggesting down-warping of the hyaloclastite host rock. The middle intrusive body, which has a thickness of about 20 m, is characterized by a well-exposed southern margin that is foliated, which is most likely a flow feature (Fig. 13). No feeder dikes were recognized, due to the lack of outcrops at lower elevations, but all its flow structures strike E–W. The uppermost, major intrusive body which crops out in the central portion of the Thverfell area, extends longitudinally about 4 km from SE to NW with an average thickness of about 150 m (Fig. 2).

In all the studied outcrops, the uppermost, major body is columnar jointed (Fig. 14). Columnar joints are widespread within the single emplacement units but do not cross the surfaces, where locally chilled margins have been recognized. These surfaces, thus, separate a discrete series of single emplacement units, each one a few metres to 30 m thick. Between the single intrusive units there is no interlayered host rock. In most of the central and eastern part of the studied area, the base of the stacked succession of units is represented by the intrusion contact with the hyaloclastite deposits, whereas in the western part the stack of units becomes thinner and its base lies within the lava sequence. The lower contact surface is mostly planar and horizontal.

The lateral contact between the major intrusion and the host rock (basaltic lavas) is clearly observed at the easternmost boundary of the intrusion, where the two lithologies are separated by a vertical contact outlined by stretched vesicles and sub-planar foliations in the intrusive body.

The upper boundary of the series of intrusive units is represented by the contact surface with the lava flow succession.

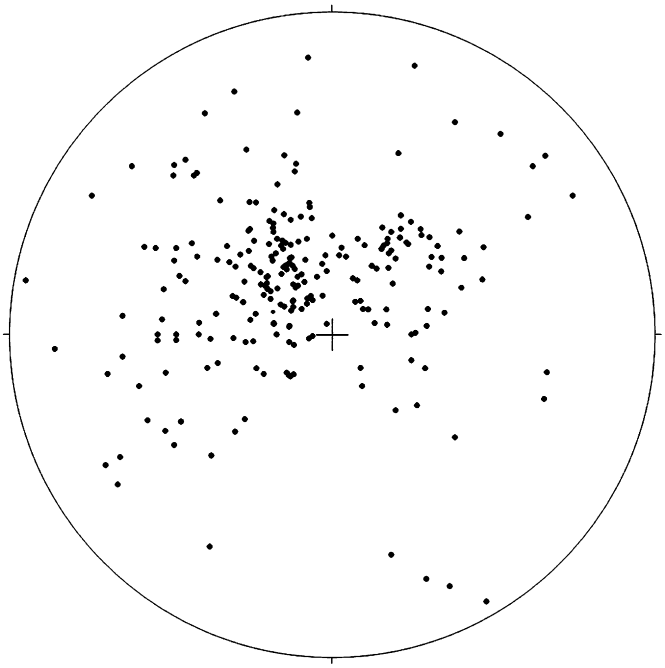

Fig. 9. Lower hemisphere equal area projection showing poles to all sheets measured in the study area. Almost all directions are well represented, as expected at swarms of centrally-dipping sheets.

Although it was difficult to track this surface in the field due to the presence of several vertical rock walls, systematic field measurements of the attitude of the overlying lava beds could be regarded as representative of the possible deformations induced in the overburden by the stack of intrusive units. The lava beds are mostly horizontal above the outermost sectors of the intrusion, whereas they systematically dip towards the NW (i.e. opposite to the regional attitude of strata) above the central and thicker part of the intrusion (Fig. 2). This suggests the occurrence of deformation induced by the intrusive process. Lava beds above the central portion of the intrusion dip towards the NW up to 35° whereas eastwards, in the area of lateral closure of the intrusion, lava deposits dip towards the SE. By applying the 8°-backtilting correction for strata to eliminate the regional tectonic tilt, we obtain a systematic NW dip of 15–43° in the area above the central portion of the intrusion and a SE dip of 5–6° in the eastern zone. Although this geometry cannot be constrained in a more satisfactory way, it can be taken as representative of the upward doming of the overburden.

The internal structure of superimposed sub-horizontal intrusive units and the geometry of the contact surfaces with the host rocks support the interpretation that the major Thverfell intrusive body was formed through the stacking of sills emplaced in a piecemeal fashion to form a laccolith.

6.3. Peripheral sills

Several sills were observed in the field projecting out of the westernmost sector of the major Thverfell intrusive body (Fig. 10A,B). Sill terminations mostly occur abruptly with a sudden decrease of their thickness. In some cases we observed a step-by-step decrease in sill thickness (Fig. 10C,F). With each step the sill transposes into a bulbous shape, similar to those observed at sills in Utah (Johnson and Pollard, 1973). Close observations of these step-like sheets in section did not reveal the presence of chilled margins. A possible interpretation is that this intrusion is composed of two or three main, partially amalgamated sills. If this interpretation is correct, the above-mentioned steps correspond to terminations of single sills. In other cases, however, from a thicker sill a thinner sill protrudes very clearly. Cross-cutting relations between the peripheral sills and the centrally dipping sheets indicate that the peripheral sills post-date the sheets.

6.4. Dikes

In the mapped area we observed and measured 79 (vertical) dikes (Fig. 7) that strike NNE-SSW, E–W and N–S, in order of decreasing frequency (Fig. 15). The N- and NNE-striking dikes cut all the rock succession; some of those striking E–W tend to rotate acquiring a sill-like attitude (Fig. 16). The 45 NNE-striking dikes are parallel to the NNE trend of the rift zone in SW Iceland (Gautneb and Gudmundsson, 1992) and can be regarded as regional dikes. The thickness of the whole dike population ranges from 0.2 to 10 m, with an average of 1.6 m. Cross-cutting relationships between vertical dikes and inclined sheets show that the N- and NNE-striking dikes are younger, as they crosscut the inclined sheets at all stations.

7. Discussion

7.1. Evolution of the regional tectonic regime

The Pliocene–Pleistocene rock succession cropping out in the Thverfell area, in the southwestern portion of the Esja peninsula, is characterized by the presence of sets of meso-scale and major fault planes, represented (apart from one case) by older strike-slip faults and younger normal dip-slip faults (Figs. 2, 3 and 17A–C). The two described sets of right-lateral and left-lateral strike-slip faults are kinematically compatible and might represent conjugate shear planes (Figs. 6 and 17B). Calculation of paleostress tensors for these faults (Fig. 4) yields a horizontal, NE- to E–W-trending $\sigma 1$, and a horizontal, NW- to N–S-trending $\sigma 3$. The average $\sigma 1$ trends N68°, whereas the average $\sigma 3$ trends N158°. Faults with similar orientation and kinematics have locally been found in SW Iceland by Bergerat et al. (1990) and Gudmundsson et al. (1992) who determined a horizontal N35°-trending $\sigma 1$ and a N125°-trending $\sigma 3$ on average. Since the $\sigma 3$ orientation calculated by these authors on transcurrent faults was coincident with the $\sigma 3$ from regional normal faults, they interpreted the state of stress as reflecting stress permutations $\sigma 2/\sigma 1$ related to variations in the ratio Φ between the principal stress differences. About 25 km north of the studied area, Passerini et al. (1997) also found transcurrent faults mainly striking parallel to sub-parallel to the NNE-trending rift axis. They interpreted these faults as the effects of two stress regimes: rift-parallel

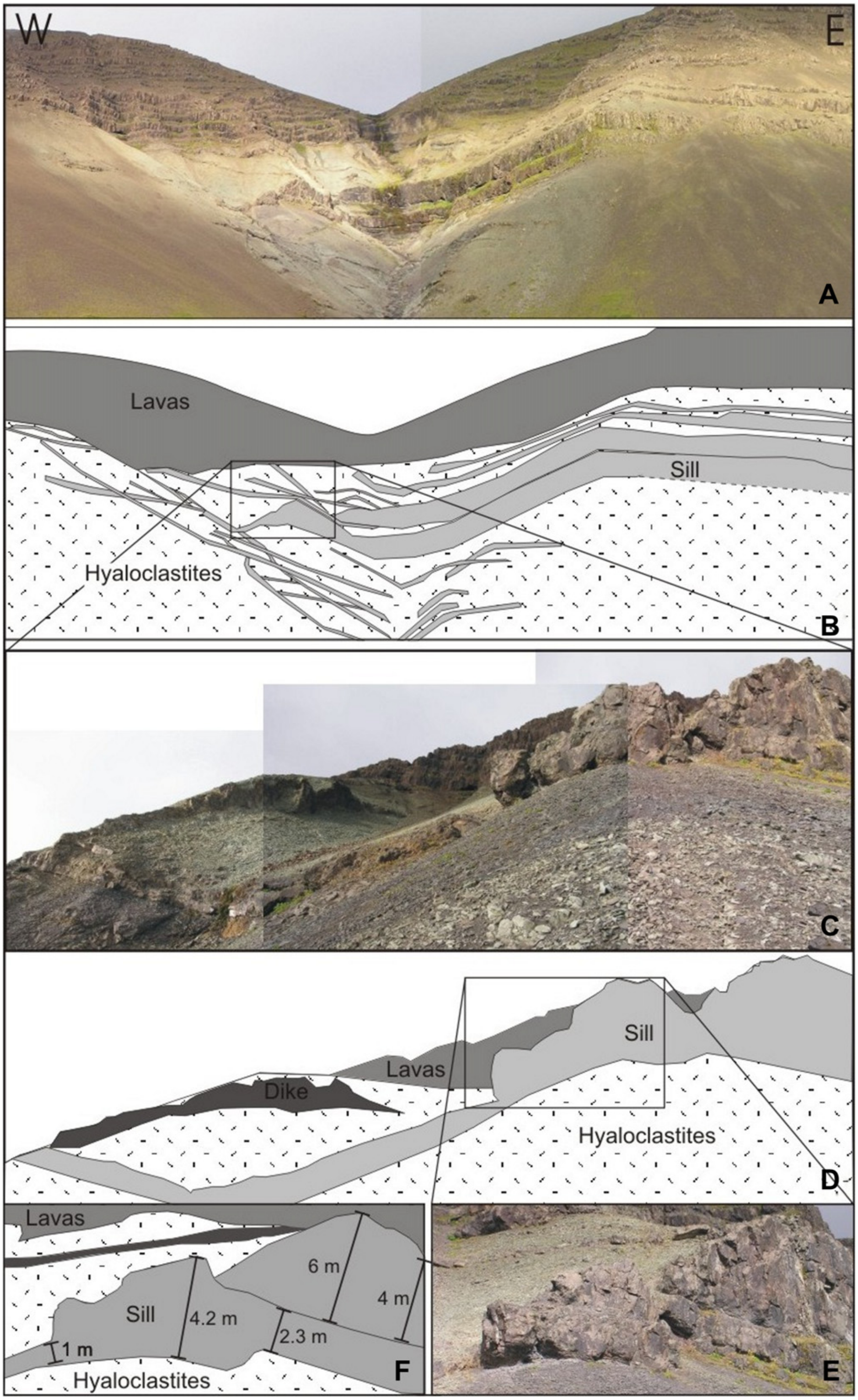

Fig. 10. (A) Example of concentration of inclined sheets in the hyaloclastite deposits and (B) relative interpretation. (C) Photograph and (D) interpretation showing the step-by-step decrease in thickness of a peripheral sill. (E) Close-up view and (F) interpretation.

compression and rift-parallel shear. These regimes are supposed to have episodically superseded the ongoing extension transverse to the rift. Both Gudmundsson et al. (1992) and Passerini et al. (1997) concluded that the available data are not sufficient to solve the problem of time succession between strike-slip and normal faulting regimes, although a few cross-cutting relations indicate that strike-slip and normal/oblique slip alternated in all the regions examined.

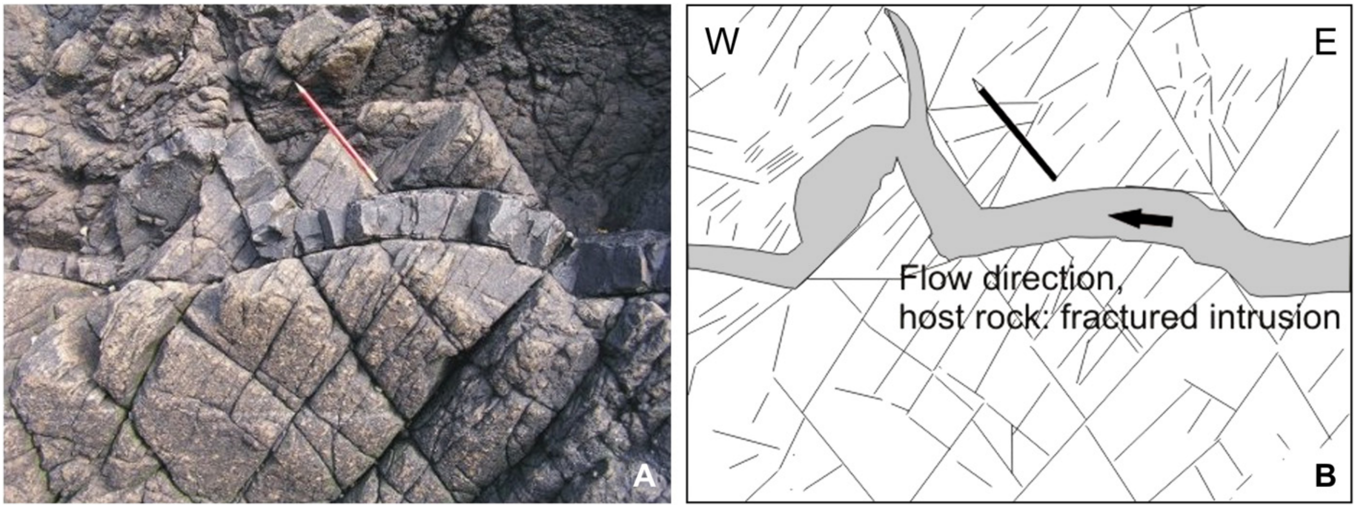

Fig. 11. (A) Photograph and (B) interpretation illustrating the sudden and multiple changes of dip and dip direction of a thin sheet, controlled by pre-existing fractures in the host rock.

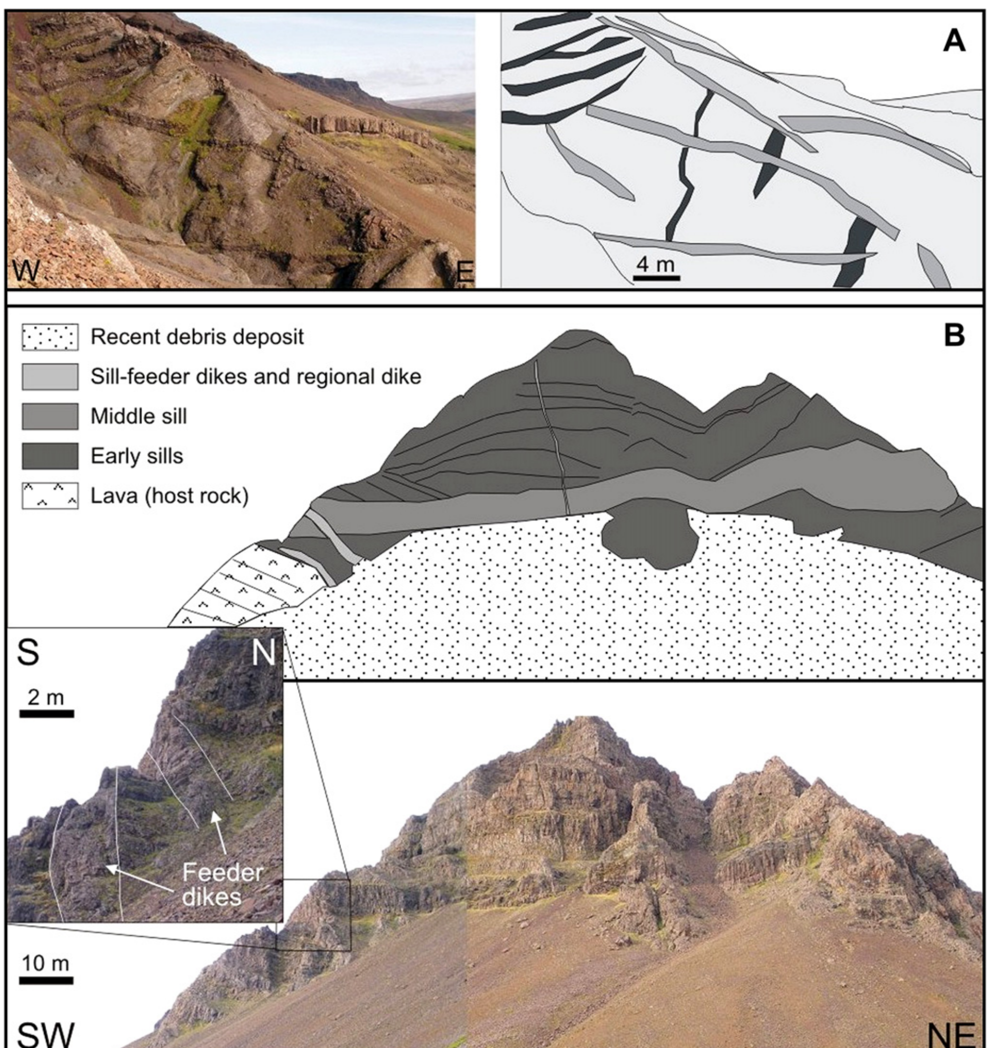

Fig. 12. (A) Photograph (left) and interpretation (right) of the sheets cropping out in the easternmost portion of the studied area. Here are two sets of sheets: One dipping to the east (pale grey) and the other in the opposite direction (dark grey). The same observation has been made in the westernmost portion of the studied area. (B) Interpretation (above) and photograph (below) of part of the sill-composed major intrusive body, with more examples of vertical to sub-vertical E–W striking feeder dikes.

Fig. 13. View of the outer margin of the middle intrusive body. The observable planes of foliation are interpreted as flow structures.

It has already been documented that most large-scale tectonic lineaments in SW Iceland strike either NNE or E–W (Gudmundsson et al., 1992; Villemin et al., 1994), but the latter trend has not been fully explained yet. The NNE trend can be mostly associated with dikes, normal faults or in a few cases, master joints (Forslund and Gudmundsson, 1991), structures clearly related to the prevailing regional stress field associated with the present rift. E–W-striking structures related to a N–S-trending extension have instead been found at the Snaefells peninsula, farther north, generally interpreted as the failed arm of a triple junction (Sigurdsson, 1970; Burke and Dewey, 1973; Einarsson, 1986). According to the latter hypothesis, the E–W-trending structures are related to normal faulting. Here we suggest an alternative explanation wherein the E–W-trending structures of the Esja Peninsula are older than those with a NNE trend. This interpretation is based on the morphological expression of E–W-striking structures, which appear either as erosion gullies and valleys (in the case of faults), or crests (in the case of dikes), depending on their resistance to erosion. These E–W-trending structures are less prevalent in the field than the NNE-trending structures and are offset and interrupted by the more continuous NNE-trending structures.

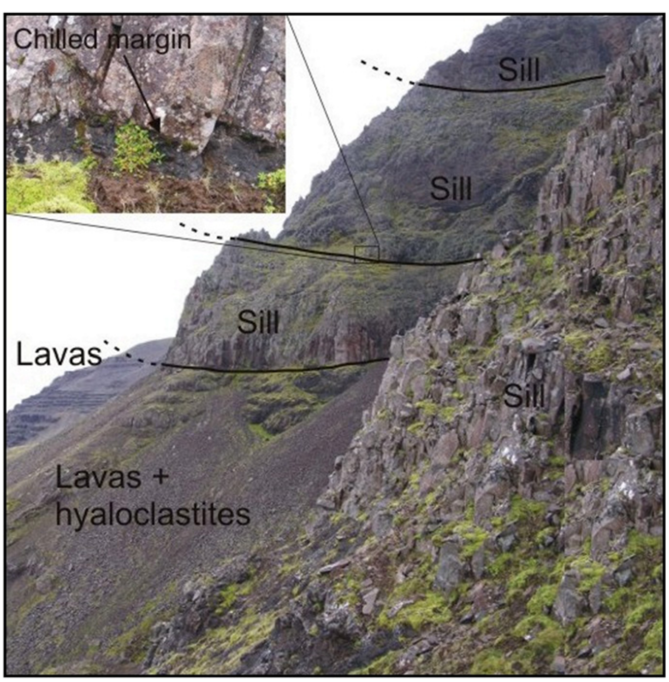

Fig. 14. Example of a series of stacked sills composing the major intrusive body. The sills are affected by columnar cooling joints, departing from well constrained planar, horizontal to sub-horizontal surfaces. Columnar joints are widespread within the single emplacement units but do not cross the surfaces, where locally chilled margins have been recognized (inset). In the background it is possible to observe the lava succession which has been deflected upward to provide room for sill emplacement.

Direct evidence from crosscutting relationships between transcurrent and normal faults also indicate that normal faulting always post-dated strike-slip faulting apart from one case. Furthermore, since normal faults in the studied area comprise the more continuous and persistent tectonic fabric, we conclude that the strike-slip tectonic regime is older than the extensional tectonic regime linked to the Icelandic rift (Fig. 17A–C). However, limited normal faulting is also recognized to have occurred before the strike-slip phase.

Another set of structures that strike between ENE–WSW and ESE–WNW is represented by veins. Similar to the variability of strike-slip faults, the orientations of these veins are found to be mostly parallel to the trend of the local $\sigma 1$ (Fig. 6). This range of orientations of strike-slip faults, veins and associated stresses could be interpreted as resulting from tilting of the rock succession both by the successive normal fault phase and/or by the intrusion of the various sub-volcanic bodies.

In synthesis, our data document an earlier transcurrent phase with an average horizontal, N68°-trending $\sigma 1$ and an average horizontal, N158°-trending $\sigma 3$, followed by a phase of normal faulting parallel to the present Icelandic rift system with a vertical $\sigma 1$ and a WNW-trending $\sigma 3$, the latter in agreement with Gudmundsson et al. (1992).

7.2. Tectonic and theological control on dike and sheet intrusion

The 79 vertical dikes in the Thverfell area were apparently injected along pre-existing faults at their shallowest level of emplacement. The 19 E–W-striking dikes are strictly related to the existence of E–W-trending structures, whereas the 45 NNE-striking dikes are parallel to the regional trend of the rift zone and are undoubtedly regional. This suggests that regional dikes occurred through opening of new fractures or already existing fractures on a plane normal to the $\sigma 3$ of the Iceland rift (Fig. 17E). The structural difference between the studied NNE-striking regional dike swarm and the centrally-inclined sheets reflects the possibility that the dikes were emplaced when the magmatic system of the centrally-dipping

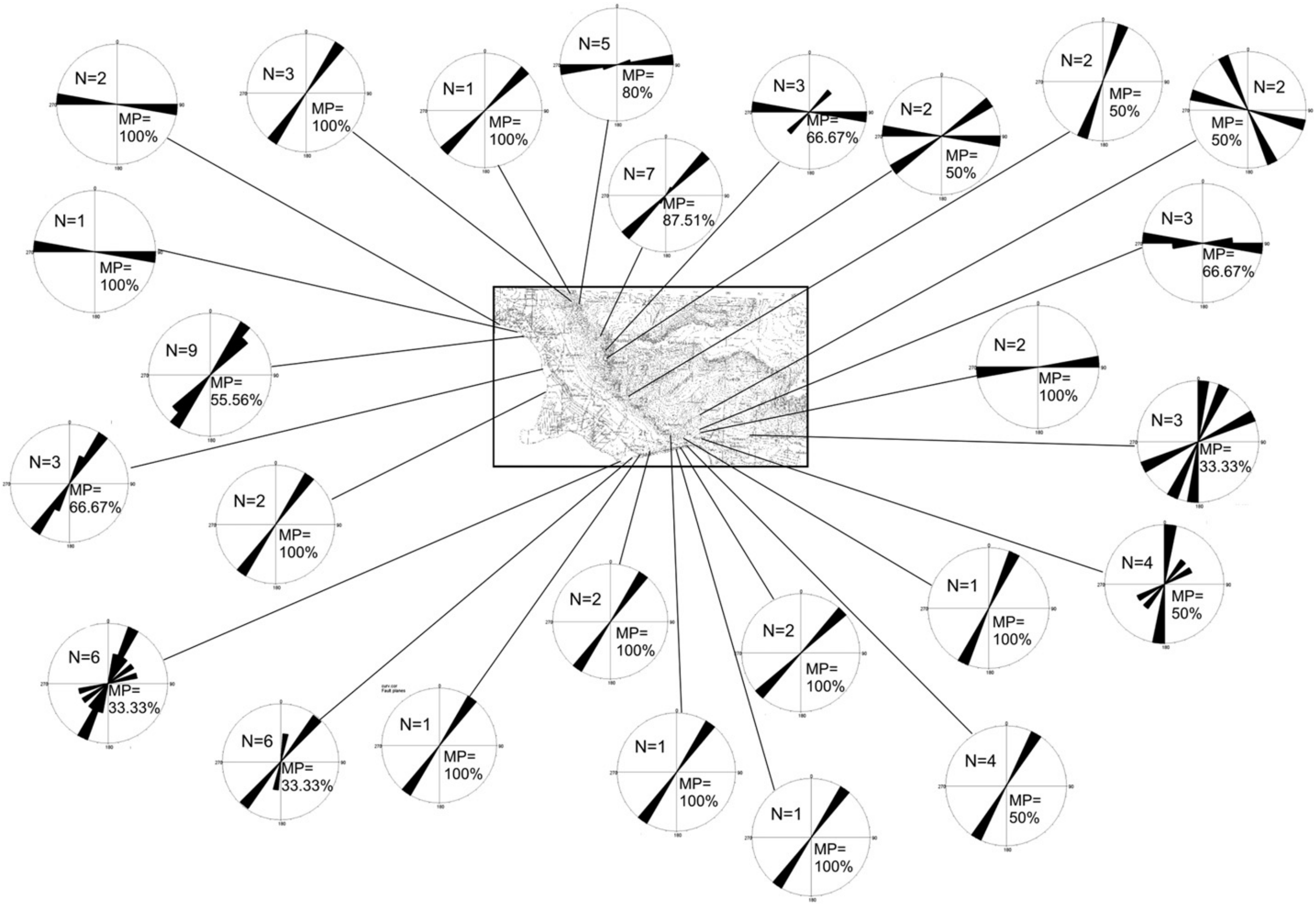

Fig. 15. Rose diagrams of all dikes at each station. Number of dikes (N) is indicated within each rose diagram, as is the maximum percentage (MP) making the perimeter. Sector size is 10°.

sheets and laccolith bodies was already inactive. This feature is best reflected in dikes that offset the major sheeted intrusion (Fig. 16). When magma excess pressure is weak or disappears as it freezes, the compressive stress field around the magma chamber also decreases. Under such conditions, the regional tectonic stress field becomes the dominant controlling factor in the development of dikes. Parallel dike swarms are formed if the $\sigma3$ is horizontal.

Cross-cutting relationships between the 251 centrally dipping sheets (Figs. 7 and 12) indicate three main systems. In the external parts of the studied area, the sheets dip outwards. Those dipping eastwards in the eastern part can be attributed to the Stardalur sub-volcanic system (Pasquarè and Tibaldi, 2007), whereas those dipping westwards in the western part might belong to the Kjalarnes complex located further west. All these data suggest that E-dipping sheets in the western part of the study area and those dipping to the W in the eastern part, belong to a unique system that can be classified as a centrally-dipping sheet swarm (Fig. 7) related to the Thverfell magmatic complex.

The origin of this centrally-dipping sheet system is not in good agreement with the classical Phillips (1974) ‘‘cone sheet’’ model. This is because the central zone still consists of inclined to sub-vertical sheets. Based on this and the lack of any evidence of a caldera development, our case study cannot be interpreted in terms of the model of Phillips (1974). We propose an alternative hypothesis wherein the intrusive system is a centrally-dipping sheet swarm linked to a shallow magma chamber. The condition for the magma flow from the chamber into the surrounding rocks is given by the lithostatic pressure plus the excess magmatic pressure which must be equal to the horizontal compressive stress in the roof of the chamber plus the tensile strength of the roof rock (Gudmundsson, 1995). This condition is largely reached when build-up of the tensile stress in the roof rock occurs as a consequence of regional extensional tectonics. Large overpressures, on the other hand, are needed where there is lack of extension. The excess pressure in the magma chamber creates a local compressive stress field around the reservoir where trajectories of $\sigma1$ depart radially. This scenario can favour the intrusion of concentric cone sheets (Gudmundsson, 1998).

A key factor in controlling the geometry of each single centrally-inclined sheet is also the presence of layers in the host rock with different Young’s moduli: If the host rock is heterogeneous and highly anisotropic, the orientation of sheets may

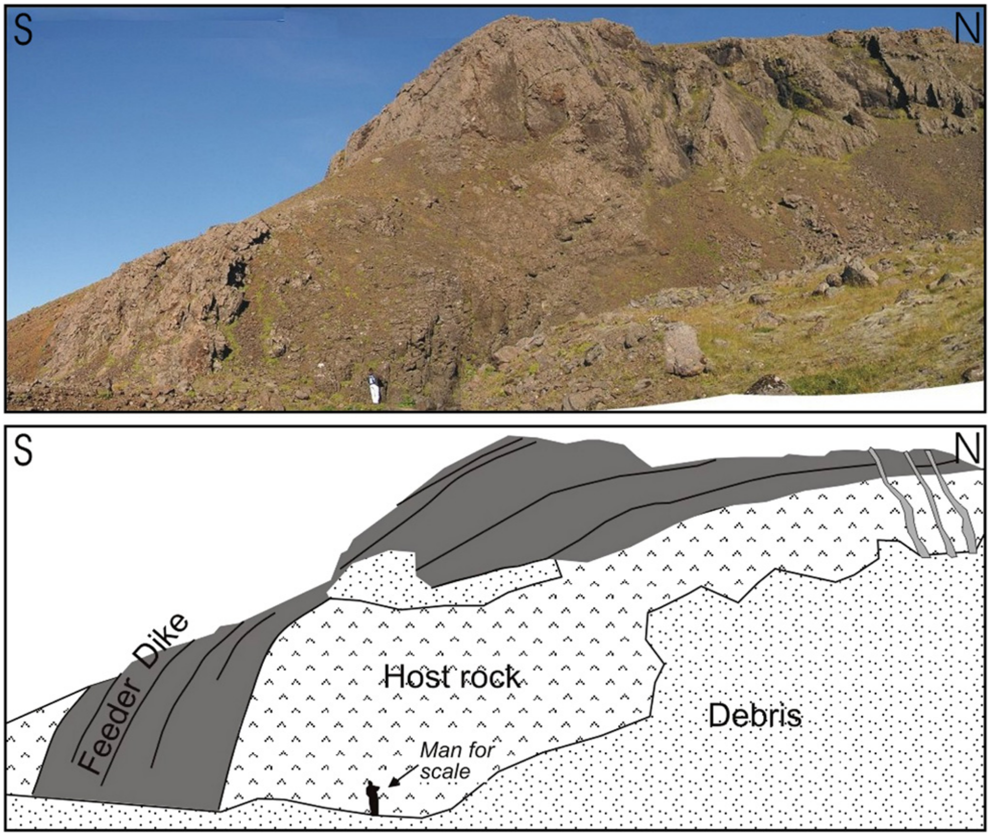

Fig. 16. Photograph (above) and interpretation (below) of the gradual bending of an E–W-striking dike that rotates to acquire a sill-like attitude. On the contrary, the later NNE-striking dikes observable to the upper right side of the photograph maintain a constant, vertical dip.

be strongly affected (Gudmundsson and Brenner, 2004, 2005). In the present case study, the hyaloclastite deposits (Fig. 2) which are highly fragmented with frequent occurrence of randomly oriented discontinuities, exert a low control on the intrusion geometry. For this reason, we surmise that the centrally-dipping sheets followed intrusion trajectories that were essentially guided by the magma chamber overpressure.

The possible tectonic influence on the emplacement of the Thverfell sheets is reflected in the geometry of the centrally-dipping sheet swarm, which shows an E–W-directed elongation in plan view (Fig. 7). This geometry suggests the presence of an originally elongated shallow magma chamber occupying a releasing bend that was formed along a transcurrent fault. This releasing bend has not yet been observed in the field, perhaps due to fragmentation of the original transcurrent fault. Other methods of mapping such as geophysical surveys may be used to locate this structural feature and test this hypothesis.

7.3. Tectonic control on the emplacement of the major intrusion

Our observations indicate that the Thverfell main central intrusive body, which in the previous geological maps and publications was presented as a single dolerite unit, is in fact made up of a series of mostly horizontal intrusions (Fig. 14). This central body, very similar to the one documented at Stardalur volcano by Pasquarè and Tibaldi (2007), might be regarded as a laccolith that is composed of sills. These sills are fed by E–W dikes that rotate as they ascend were they eventually acquire a horizontal attitude (Fig. 16). The sills are stacked atop one another mostly without any interleaved host rock and with low amalgamation indicating that emplacement occurred when previous intruded sills had already sufficiently cooled. This architecture is very similar to what has recently been observed in the Henry Mountains of Southern Utah by Horsman et al. (2005). Other detailed field observations indicate that these sills have abrupt terminations, sometimes with a bulbous shape.

The dominant E–W strike of the dikes feeding magma to the sill/laccolith can be explained by the control of the local E–W-trending $\sigma1$ and N–S-trending $\sigma3$ (computed at some of the stations where striated strike-slip faults have been found). However, since the data are not sufficient to provide a complete and detailed description of the $\sigma1$ trajectories at the time of the strike-slip faulting phase, an alternative hypothesis is formulated. It is also possible that the E–W feeder dikes were controlled by the E–W-elongated magma chamber. In fact, the feeder dikes are located in the centre of the centrally-inclined sheet swarm and hence above the likely position of the chamber's summit axis.

At the regional level, it is also necessary to highlight that the studied sheet swarm and the major, sill-made intrusive

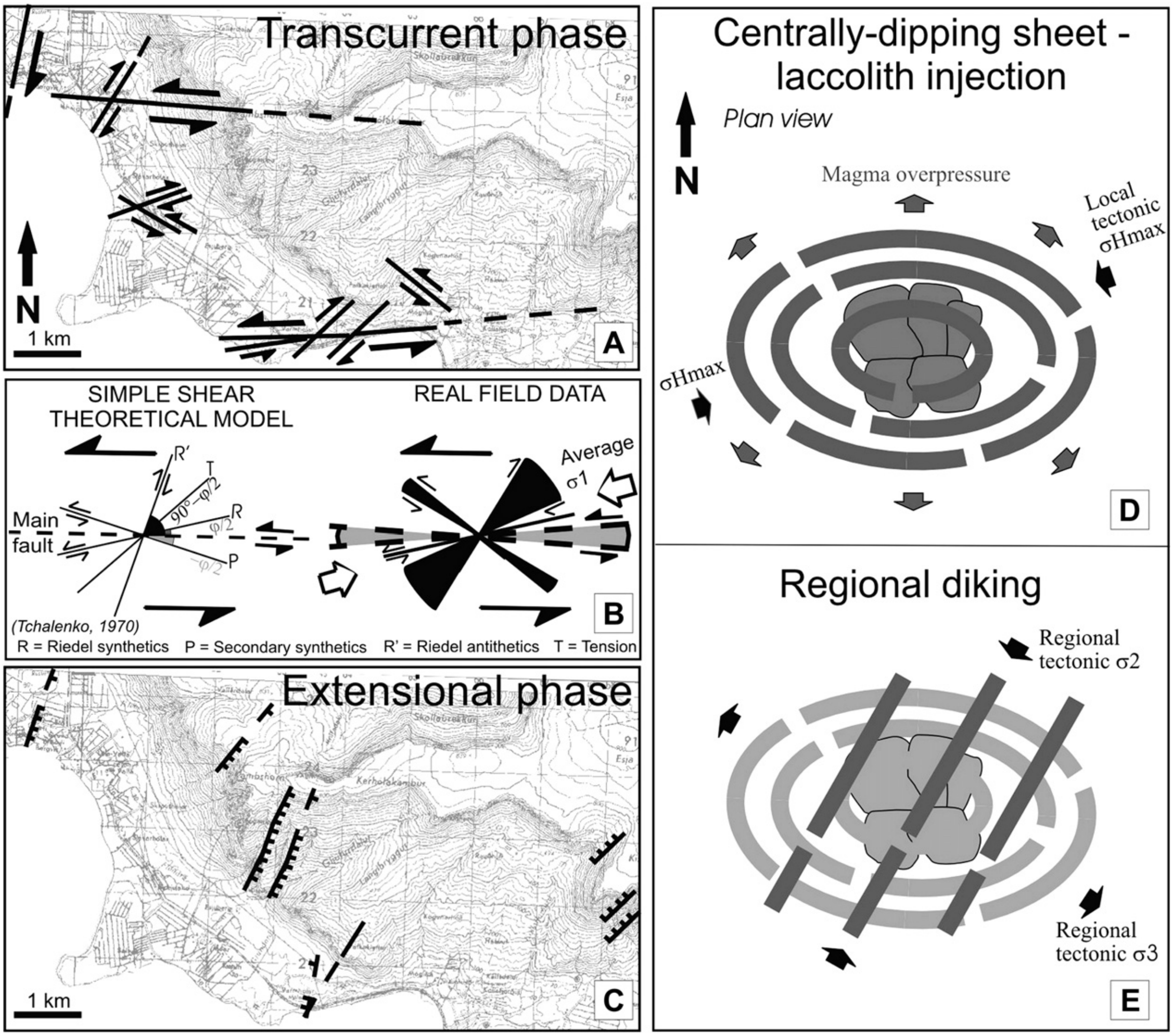

Fig. 17. Plan view sketch of the tectonic and intrusive evolution of the studied area. (A) A tectonic transcurrent phase took place following an average N68°-directed horizontal greatest principal stress ($\sigma1$) and a vertical intermediate principal stress ($\sigma2$), with the development of main left-lateral strike-slip faults. (B) Theoretical model of left-lateral simple shear (left side, from Tchalenko, 1970) compared with the orientation range of main left-lateral strike-slip and secondary left-lateral and right-lateral strike-slip faults found in the studied area (right side, from the present work). Their kinematics and strikes are consistent with the general model of simple shear along main E–W-striking left-lateral transcurrent faults. (C) A centrally-dipping sheet system was emplaced with an elliptical shape in plan view and an E–W-trending major axis, produced by a dominant excess magma pressure (white arrows). A major composite laccolith was emplaced mostly through an E–W directed fracture system. (D) NNE-striking normal faults are the youngest structures found in the area and resulted from an WNW-trending horizontal least principal stress ($\sigma3$) and a vertical $\sigma1$. (E) NNE-striking dykes emplaced at a later stage testify to the dominance of the regional tectonic forces linked to the NNE-trending rift zone in controlling their geometry.

body are aligned in an E–W direction along with another intrusive body located further west and with the Stardalur sheet–laccolith system (Fig. 1) documented by Pasquarè and Tibaldi (2007). Below the central sill-composed laccolith, there are two other main tabular bodies separated from each other by the hyaloclastites. The lowermost body has a downward-convex contact surface with the hyaloclastites, suggesting that room for the intrusion was provided both by upward deformation of the overburden and downward displacement of the rock succession.

Further evidence of the influence of regional tectonics on the emplacement of the studied intrusions is the effect of far-field stresses on the upward bending of the Thverfell E–W feeder dikes. The horizontal $\sigma1$ that acted on the hard lava overburden most likely induced a stress concentration that in turn might have generated stress barriers to dike propagation, as documented by Gudmundsson (1990). Moreover, the higher rigidity of the overlying lavas to the lower hyaloclastites probably acted as a rheological barrier (Kavanagh et al., 2006), hindering upward dike propagation. The stress concentration and the rheological contrast produced a greater resistance to fracture propagation and/or opening by the upwelling magma with respect to the underlying hyaloclastites. Moreover, the stress from the magma chamber overpressure was likely dissipated across the surrounding rocks, becoming weaker with distance from the magma chamber. This feature can be seen in most of the centrally-dipping sheets that become arrested due to the lava overburden. All these data suggest that the magma overpressure in the dikes was in sufficient to allow them to propagate through the overlying lava succession. Coupled with the above mentioned stress barriers and the effect induced by the high rigidity ratio of lavas to hyaloclastites, the observed transition (Fig. 16) from dikes to horizontal sills can be explained.

8. Conclusions

The interpretation of structural field data on faults, veins, inclined sheets, dikes and sills, enables us to illustrate (Fig. 17) the development of the studied sub-volcanic intrusive system emplaced in SW Iceland. We interpreted three magmato-tectonic stages, which demonstrate the sensitivity of magma feeding paths to changes in the relative magnitude between magma and tectonic stresses and their orientation:

(i) A centrally-dipping sheet swarm was emplaced, with an elongated shape and an E–W-trending major axis in plan view. The geometry of this intrusive system is interpreted as derived from the excess magma pressure within a shallow magma chamber, and the E–W elongation of this magma chamber that is probably controlled by a system of strike-slip faults.

(ii) The laccolith is made of stacked sills with little or no amalgamation. Sills were fed through E–W dikes, the geometry of which has been controlled by the magma chamber elongation and/or the locally E–W-directed $\sigma 1$ and N–S-trending $\sigma 3$ linked to the transcurrent phase. The rotation of dikes into sills is interpreted in terms of stress barriers, the high rigidity ratio of upper lavas to lower hyaloclastites, and the horizontal attitude of the $\sigma 1$.

(iii) The entire rock succession was offset by a system of NNE-striking normal faults and dikes. Fault striations indicate a horizontal WNW–ESE-trending $\sigma 3$. Regional tectonic forces are linked to the present rift system and completely controlled the geometry of this set of dike intrusions.

The data and interpretations provided above highlight the important role played by sheets in the growth of volcanoes, both through their inner expansion and eruptive build-up, when the intrusions intercept the cone slopes. It is therefore important to constrain sheet swarm geometries and their potential manner of emplacement based on field evidence. This type of study contributes to the understanding of magma paths and their relationships to magma stresses and local/regional tectonic stresses.

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