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Tectonics and magma dynamics coupling in a dyke swarm of Iceland

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Abstract

To study the dynamics of dyke and fissure swarms in Iceland, we analyse the distribution of the dykes across the Tertiary Alftafjördur dyke swarm and that of open fissures and faults across the active Krafla fissure swarm. Within these narrow (5 to 10 km wide) and long (length/width ratio >10) swarms, deformation is accommodated both by tectonics and magmatism. The dyke swarm built during the westward regional tilting of the host-rock lava pile. The populations of dykes suggest that a characteristic thickness at about 3 m is involved during dyking. Dykes show a quasi-periodic distribution across the swarm and form clusters spaced by about 2.5 km. The analysis of the fissure distribution in the Krafla volcanic system reveals a cluster spacing of about half of that of the dyke clusters. We discuss the potential origins of these features as a result of magma dynamics, host-rock properties and tectonics. Clustering possibly reflects the intrinsic mechanical response to stretching of the upper levels of the brittle crust. We propose a three-dimensional model of dyke swarms in which magma likely migrates laterally within the upper crust from igneous centres where high magmatic supply rates locally perturb the regional stress field.

Keywords: Dyke swarm; Fissure swarm; Magma dynamics; Extensional tectonics; Iceland

1. Introduction

Magmatism and tectonics occur contemporaneously in many geodynamic contexts. The interactions between magmatism and tectonics are complex and the processes which govern magma ascent are strongly dependent on the context (e.g. Galland et al., 2003, 2006). In extensional domains such as mid-ocean rifts, volcanic passive margins and some continental rifts (Dauteuil and Bergerat, 2005), magma supply varies drastically both laterally and through time. Dykes or other sheet-like intrusions resulting from the magmatic supply largely contribute to crustal deformation by increasing the volume of the stretched zone. Such dyking may accommodate partly or totally the stretching induced by regional extension. Dykes often propagate away from an eruptive centre. The propagation is either radial or strikes within a limited range of directions depending on the stress field (Nakamura, 1977). In both cases, the dykes are gathered into swarms within rift zones (Walker, 1999). Close to shield volcanoes such as in Hawaii or in Japan islands, the rift zones are narrow and follow discrete radial orientations (2 to 4 directions). Complete annular distribution of dykes is rare and dyke swarms are sometimes difficult to define such as it is in Fernandino Island (Galapagos). Often dyke propagation is confined in a single limited direction. Such an oriented propagation is common in extensional domain such as those of the Azores, Afar or Iceland.

Iceland constitutes an ideal target to study the interactions between extensional tectonics and magmatism since it is located both on a hot spot and on an oceanic ridge. The combined effects of the oceanic ridge and of the mantle plume generate a large and thick basaltic plateau that spreads at a rate of about 1.9 cm per year, since at least 25 Ma. Magmatic and tectonic activities are nowadays mainly focused inside fissure swarms (Fig. 1). Fissure swarms often include a central volcano where the eruptive supply is maximal. Therefore, they are the locus where interactions between tectonics and magmatism are expected to vary with the distance from the eruptive centre. Fissure swarms may be as long as 100 km for widths ranging from 5 to 10 km: their length/width ratio

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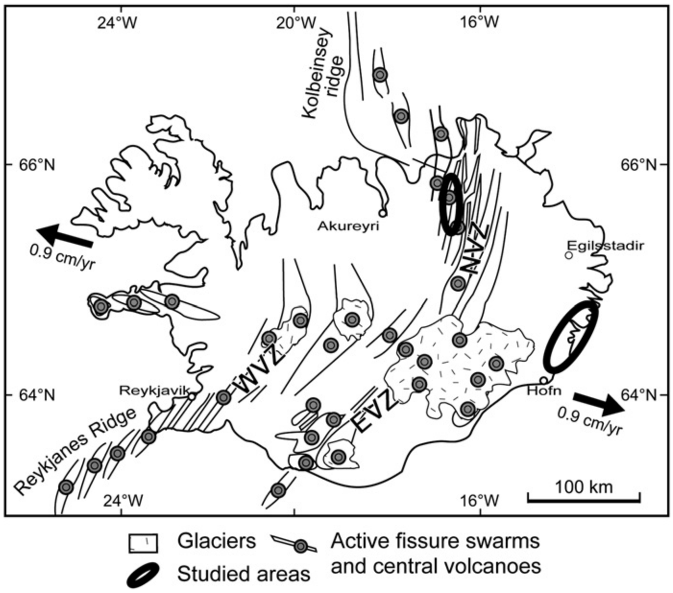

Fig. 1. General tectonic map of Iceland modified from Johannesson and Saemundsson (1998b) and Bourgeois et al. (2005 and references therein). The active rift zone is divided into four branches (EVZ, East Volcanic Zone; NVZ, North Volcanic Zone; WVZ, West Volcanic Zone; and the Reykanes segment just NE of the Reykanes ridge) and is formed by narrow fissure swarms almost systematically including a central volcano. The fissure swarms display an en-echelon pattern consecutive to an oblique rifting. The thick ellipses locate the Alftafjördur dyke swarm to the east and the Krafla fissure swarm in the NVZ.

is greater than 10. Faulting generating imbricated grabens may affect the fissure swarms (Angelier et al., 1997). Such fissure swarms result from successive rifting events. At surface some fissures guide the magma towards the surface while others remain dry. At depth fissure swarms prolong into dyke swarms (Helgason and Zentilli, 1985; Forslund and Gudmundsson, 1991; Gudmundsson, 1995a; Dauteuil et al., 2001; Tentler, 2005) where most of the dykes are arrested on their way to the surface due to mechanical heterogeneities within the crust (Gudmundsson and Brenner, 2001; Gudmundsson, 2002, 2006).

In the swarms, the spreading is accommodated (i) at surface by eruptive fissures, dry fissures and faults, (ii) at depth by dykes and faults (Dauteuil et al., 2001). Some studies (Gudmundsson, 2002) point out that the density of surface fissures could differ from that of deep dykes. As this implies some volume differences from depth to surface, how are such differences in strain accommodated? For example, it is not straightforward to demonstrate that the fissures result from regional tectonics or from dyking at depth. Also unclear is how the magma migrates within a swarm. Is the flow mainly vertical through the crust all along the swarms (Gudmundsson, 1990, 1995b, 1998, 2000, 2002; Mège and Korme, 2004)? Or can the flow be mainly lateral from shallow magma chambers located within the upper crust beneath volcanic centres (Sigurdsson and Sparks, 1978; Helgason and Zentilli, 1985; Gudmundsson, 1984; Callot et al., 2001)?

In order to address these questions and to discuss the processes leading to the construction of regional swarms we have studied in detail distributions of dykes and fissures across Icelandic swarms. From our results, we propose (i) to interpret the observed distributions as a result of magma dynamics, host-rock properties and tectonics, (ii) to describe the geometry of a dyke swarm to end up with a three-dimensional (3D) model discussed in its extensional setting, and (iii) to discuss the relationships between surface and deep structures. We focused our analysis on the Tertiary Alftafjördur dyke swarm that outcrops along the eastern coast, and then compare the results to the active Krafla fissure swarm.

2. Geological settings

2.1. Geodynamic context

Iceland plateau is located on the northern segment of the Mid-Atlantic ridge, above a hot spot. It is 1000 km long and 800 km wide, and emerges at least 1500 m above the seafloor. It was generated during the opening of the northern Atlantic ocean which started 53 Ma ago (Lawer and Muller, 1994). The formation of the plateau itself started 25 Ma ago. The spreading rate between the North American and the European plates is about 1.9 cm/year, trending at N104°E (DeMets et al., 1994). Today, the mantle plume reaches the lithosphere below the Vatnajökull ice cap. It generates an excess magma supply that is responsible for the Iceland emergence and a crustal thickness of 39 km (Brandsdottir et al., 1997). Since 20 Ma, the rift zone has migrated eastward relative to the Kolbeinsey ridge in north and the Reykjanes ridge in southwest (Hegalson, 1984; Garcia et al., 2003). The rift jump generated two transform zones: the Tjörnes fracture in north and the South Icelandic Seismic Zone in south. The presence of the hot spot drastically influences the rift zone which exhibits a peculiar tectonic pattern (Angelier et al., 1997; Searle et al., 1998; Bourgeois et al., 2005; Dauteuil and Bergerat, 2005): (i) a wide deformed zone (from 50 to 120 km), (ii) volcanic roll-overs with listric faults, (iii) lack of rift shoulder, and (iv) the occurrence of open fractures.

2.2. Active rift

Present day activity is mainly located within four segments connected to the Kolbeinsey ridge in north and to the Mid-Atlantic ridge in south: the North Volcanic Zone (NVZ), the East Volcanic Zone (EVZ), the West Volcanic Zone (WVZ) and the Reykjanes segment whose widths range from 50 to 120 km (Fig. 1). Within the volcanic zones, spreading which results both from tectonics and magmatism is focused into narrow fissure swarms, generally including at least a central volcano. These swarms are distributed en-échelon indicating oblique rifting (Dauteuil and Bergerat, 2005; Clifton and Kattenhorn, 2006; Fig. 1). They are 2 to 10 km wide and are separated by undeformed zones 10–15 km wide. Normal faults limit the swarms but also affect their inner parts. Usually the fault along the western border has a vertical throw larger than the other ones. This is well documented in the Thingvellir fissure swarm in the WVZ.

Such a pattern is compatible with a model of volcanic roll-over (Palmason, 1973; Bourgeois et al., 2005). The most studied example of such systems is the Krafla fissure swarm in the NVZ. It is a 80 km long graben wide of 3 to 8 km, bordered by normal faults that strike perpendicular to the spreading direction (Torge, 1981; Tryggvason, 1984; Opheim and Gudmundsson, 1989; Fjäder et al., 1994; Angelier et al., 1997; Dauteuil et al., 2001; Henriot et al., 2001; Sturkell et al., 2006). At the surface, fissures and faults strike slightly oblique to the swarm trend by approximately 10° (Dauteuil et al., 2001). During the 1975–1984 rifting episode, not much magma reached the surface through aligned fissures. Most open fissures and faults were created in the swarm without lava eruption. The earthquake's distribution and characteristics reveal that magma migrated laterally at shallow depth in the crust (Einarsson and Bransdottir, 1980). The shallow depth and shape of the magma reservoir are also estimated from long-term ground deflation (Henriot et al., 2001).

2.3. Ancient systems of the eastern coast

In Iceland, several regional dyke swarms are well exposed in fjords, especially on the eastern and western coasts where the oldest basaltic flows crop out thanks to high cliffs. Along the eastern coast, a thick Miocene lava pile is cross-cut by the dyke swarms and extinct volcanic centres (Moorbath et al., 1968; McDougall et al., 1976; Musset et al., 1980). They correspond to extinct volcanic zones that were possibly active during several igneous episodes (as shown in Scotland by Speight et al., 1982). Walker (1959, 1960, 1963, 1974), Gudmundsson (1983, 1990, 1995a,b, 1998, 2002), Helgason and Zentilli (1985) have described the dyke swarms of eastern Iceland. There, the flow succession is tilted toward WSW and presents angular unconformities (Fig. 2). Bourgeois et al. (2005) suggested that such a tilt results in a large roll-over driven by an eastward dipping, normal listric fault located to the west. Dips of the lava flows increase from 3° to 15° W

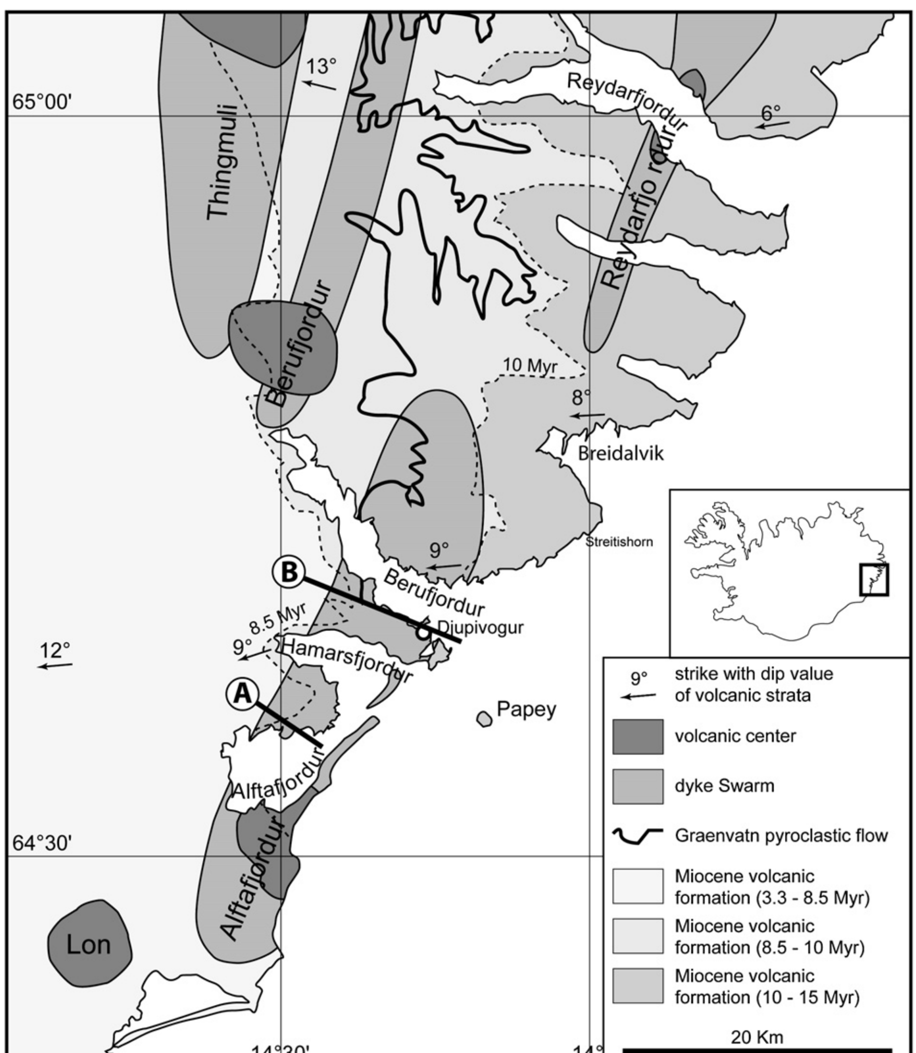

Fig. 2. Simplified geological map of the eastern coast of Iceland (from Walker, 1959, 1963, 1966, 1974; Johannesson and Saemundsson, 1998a,b) showing the different dyke swarms and their related igneous centres. The lava flows are older than 3.3 Ma. Sections A and B are drawn with thick black lines. The arrows indicate the lava tilt.

downward in the pile (Walker, 1959, 1963, 1974; Bourgeois et al., 2005). Eruptive rocks are mainly basaltic lava flows with interbedded intermediate to felsic flows close to the volcanic centres (Walker, 1966). The deep parts of the volcanic centres are composed by mafic to felsic plutonic rocks forming intrusions of various shapes and sizes: stock-like intrusions including laccoliths, sills, cone-sheets and dykes (Walker, 1966; Gudmundsson, 1995a; Johannesson and Seamundsson, 1998a; Klausen, 2006). The mafic and felsic stock-like intrusions were interpreted as magma reservoirs, feeders of the eruptive flows and of the other sheet-like intrusions. Walker (1966) demonstrates that the eastern volcanic systems were active simultaneously by studying the lava flow sequences. The exhumation of the dyke swarms and host-rocks results both from recent uplift and glacial erosion. In SE Iceland the depth of erosion reaches 2 km (Walker 1960, 1974; Neuhoff et al., 1999; Klausen, 2006).

3. Data analysis

The Alftafjördur dyke swarm roughly trends NNE–SSW and N–S to the north of Berufjörfur (Fig. 2). Several fjords cross the swarm and show almost continuous outcrops broadly normal to the swarm trend, but we have selected two traverses offering long and continuous sections at different distances from the igneous centre (Fig. 3). The Alftafjördur section (section A) is located along the northern shore of Alftafjördur fjord, at about 10 km north from the igneous centre. It is the longest continuous section (6.1 km long) outcropping as close as possible to the igneous centre. The Berufjördur section (section B) is 16 km long and follows the southern shore of Berufjördur fjord at about 20 km north from the igneous centre.

Systematic observations and measurements allowed us to develop a statistical database along each traverse across the swarm. Location, strike, dip and thickness measured normal to the dyke wall, as well as geometrical relationships with the host-rocks, structural and petrological features, were recorded for each dyke. Only representative values of strike, dip and/or thickness were retained where dyke shape varied at the outcrop scale. Where a fault was observed, location and geometrical features were also recorded. Data are given with an accuracy of about 2° on strikes and dips. The thickness accuracy is about one order of magnitude smaller than the measured value, but the thickness variations along the dykes which are thicker than 3 m were never observed to exceed 0.5 m. Despite rare exposure gaps due to little creeks, field observations were performed nearly continuously along WNW–ESE to W–E segments. We restricted our observations at elevations from 0 to 200 m above the sea level to avoid variations with elevation (Walker, 1974; Gudmundsson, 1983). Due to the shore shape and the outcrop locations, a same dyke could have been crossed twice, or more, at different places. However, such a dyke was only taken into account once in our database and located at its lowest altitude.

The dykes were mapped using a GIS. Strike values were corrected from magnetic declination (~13°). Dykes were plotted on a 1/100,000 topographic map (Valsson, 2002). On the map of Fig. 3, the segment centres locate the outcrops. Stereograms of dyke geometries were realised for each section. Histograms of strikes, dips and thicknesses were processed for analysis and comparison with former studies (Fig. 4). Averages of strikes and dips were calculated following the method described by Gumiaux et al. (2003). The average of strikes along a section was used to define the swarm trend. The statistical distribution of thicknesses was analysed using cumulative frequency plots (Fig. 5).

To study the spatial distribution of the dykes across a section, each outcrop was projected along the individual dyke strike to intercept a reference line normal to the swarm trend. The line was located as close as possible to a maximum of outcrops to avoid, in the distribution, large distortions due to dyke relocation. As most dykes make a small angle to the swarm trend, most of them were relocated onto the projection line at relative positions similar to those on the field. Inevitably, dykes striking at high angle from the swarm trend were relocated to relative positions significantly different from those on the field. Along each projection line, dyke density, given as the number of dykes per 100-m-long interval, and cumulative thicknesses were plotted against location (Fig. 3, upper left, and Fig. 6). We have then extracted a wavelength from the periodical signal shown by such plots using a classical Fast Fourier Transform analysis (FFT).

Finally, the spatial distribution of the dykes in the Alftafjördur swarm is compared to that of the fissures in the active Krafla swarm. The latter was chosen because it has been largely studied and belongs to the same volcanic zone than the former. Using a map provided by Ferber and Villemin (1995), we have extracted the number of fissures and faults per 100-m-long interval along a cross-section. Unfortunately, no information is available about the apertures of the fissures and the open fractures.

With dykes, faults also accommodate deformation in a dyke swarm. Previous studies (Gudmundsson, 1992) have described dykes injecting open faults. Although systematically searched for along the sections, no significant offset of the lava pile (>0.5 m) was observed from the margins of the dykes to the others, except in a single example. An important difficulty comes from the irregularity of the flow surfaces that makes difficult the observation of offsets smaller than half a metre. It is still possible that some dykes record small offsets of the lava pile between their margins. They are therefore neglected in this study. Striated planes within the dykes were not systematically analysed because this late post-intrusive deformation was previously studied (Bergerat et al., 1990) and beyond the scope of this paper.

4. Field observations and results

4.1. Dyke types and rock textures

Different types of dykes can be observed in the area: simple, multiple and composite (Guppy and Hawkes, 1925; Walker, 1966; Gudmundsson, 1983). Most of the dykes are simple and monogenetic (Fig. 7a). Perpendicular to the dyke margins, they display a single network of uniformly spaced columnar

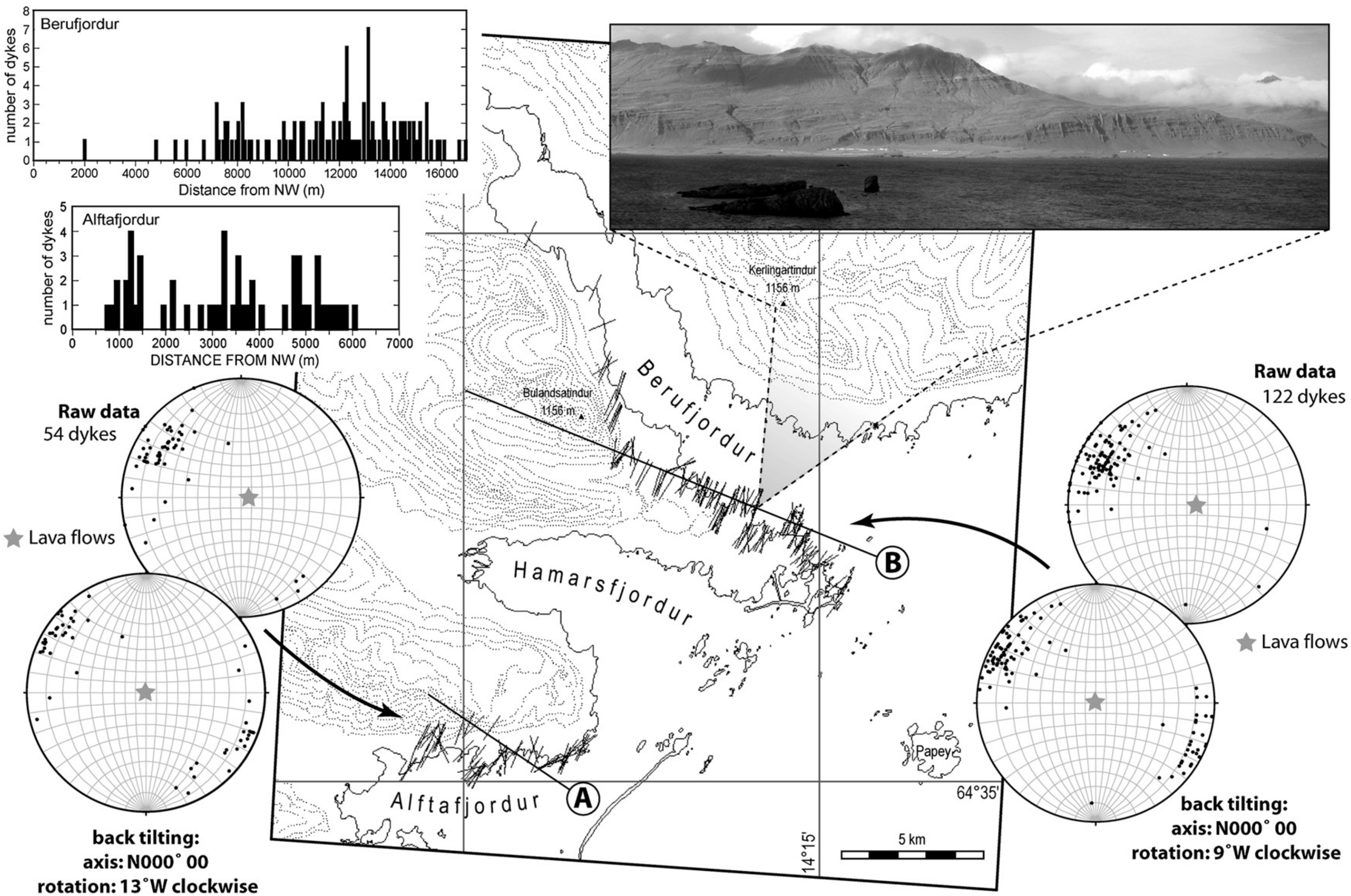

Fig. 3. Detailed map of the studied area locating the dykes and the projection lines A and B. Dykes are represented by short lines striking in directions measured at the centre of the segments. For each section the plane poles of the dykes were plotted on two stereograms showing raw and backtilted data (see text). Stipple lines represent relief contours separated by 100 m vertical intervals. The photograph shows the northern shore of Berufjördur from the southern shore as indicated on the map. Note that several dykes appear in the foothills to the right. The two diagrams in the upper left display the number of dykes by 100 m intervals (dyke density) along the projection lines.

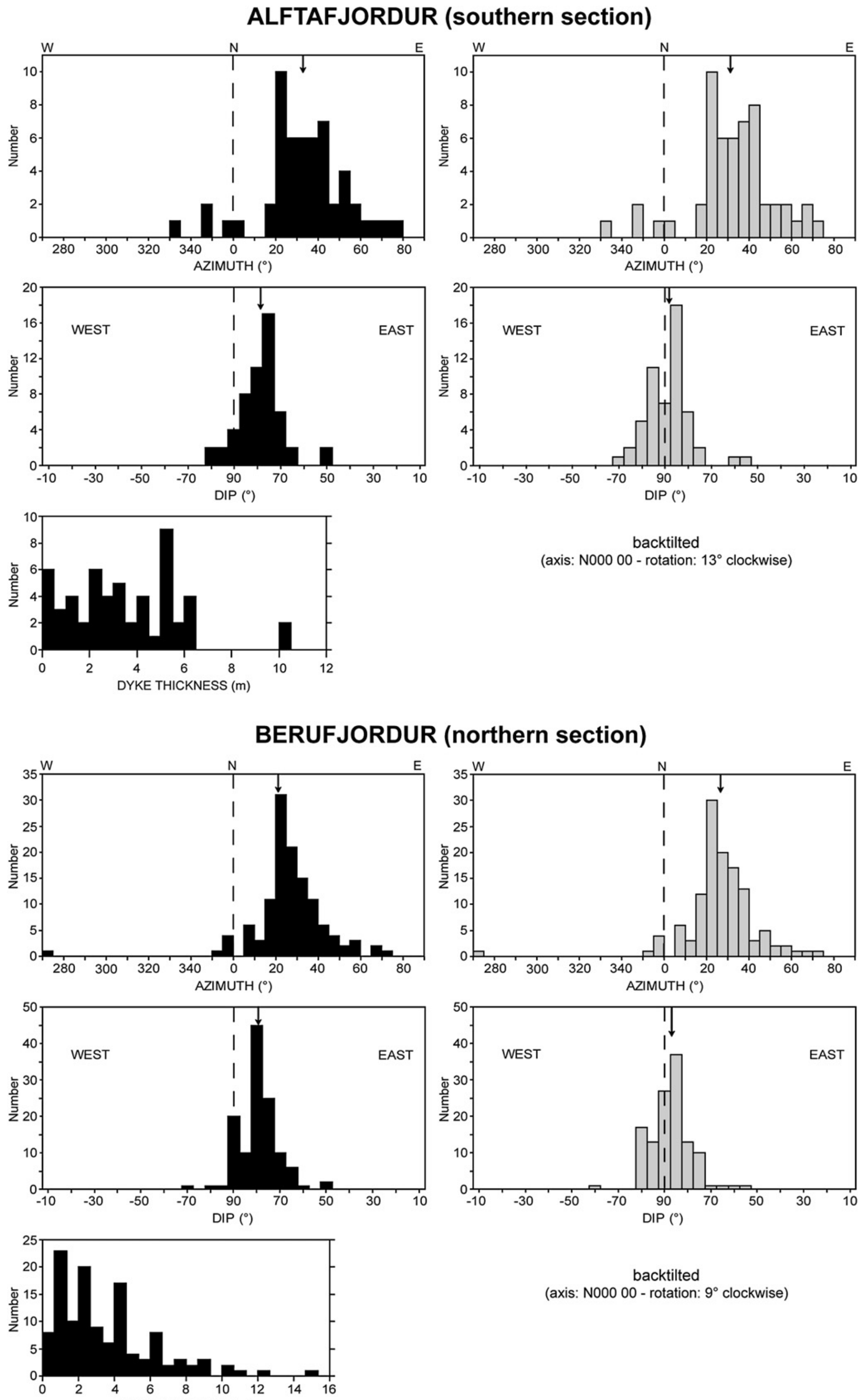

Fig. 4. Histograms of strikes, dips and thicknesses of dykes of the southern Alftafjördur section (A, $n = 54$) and of the northern Berufjördur section (B, $n = 122$). The strike and the dip histograms show raw data (black) and backtilted data (grey). The arrows point the average values of the populations.

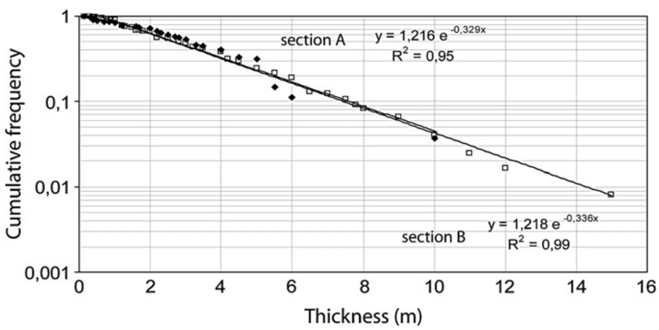

Fig. 5. Cumulative frequency plot of thicknesses of sections A (black diamonds) and B (open squares) showing that negatives exponential curves reasonably fit the whole data of each sections.

joints resulting from shrinkage during cooling. The spacing between the joints, which enlarges progressively toward the dyke centre, suggests that such dykes formed during a single magmatic injection and subsequent cooling stage. Other dykes display several networks of columnar joints, which are often separated by internal chilled margins (Gudmundsson, 1984). They correspond to multiple dykes formed by successive episodic injections and cooling stages of similar magma compositions (Fig. 7b). Among the 176 observed dykes, only 12 are multiple. No composite dyke, i.e. a dyke filled with different rock types, was ever observed along the two sections. However, such dykes are known in the area: a composite dyke up to 25 m thick can be observed at about 10 km east of the eastern margin of the Alftafjördur swarm between Berufjördur and Breiddalvik (Figs. 2 and 7c; Guppy and Hawkes, 1925; Walker, 1966). The centre of the dyke is filled by a felsic rock in between margins of more mafic rocks. Along the contacts between the main rock types, mafic to intermediate enclaves crop out within the more felsic rocks, suggesting that two main magma types were able to mingle and/or mix while they were flowing subcontemporaneously within the composite dyke.

The dykes are classically filled with mafic, aphyric and microcrystalline rocks exhibiting a doleritic texture which grain size is about 1 mm and usually decreases towards chilled margins. In thin sections, the mineralogy is typical of a basaltic magma composition. Subeuhedral randomly oriented plagioclase laths often form a network in between more equant, sometimes subophitic clinopyroxene grains, and opaque minerals. Sometimes olivine is also present. Some dykes display vesicles, which are sometimes filled up by low temperature hydrothermal phases such as zeolites. Dykes may also contain plagioclase phenocrysts, usually in a small amount (few vol%). However, few dykes are also strongly porphyritic and the phenocrysts are often more abundant within the dykes of section A than in those of section B. The maximum phenocryst content decreases from about 30 vol% to about 20 vol% in sections A and B, respectively. A few dykes also contain xenoliths of the host rocks. No fabric was observed to obviously indicate any magmatic flow direction.

Most of the dykes were observed to be continuous and straight. However, some of them (less than 10%) display wavy shapes, bends, or almond-shaped internal structures (Fig. 7d). Dykes with wavy shape have strike variations up to 15°. The inner almond structures affect the dyke both in horizontal and vertical planes and correspond to the juxtaposition of almond-shaped segments having plurimetric length. In vertical sections, segments show small variations in dip but are often by few degrees steeper than the mean dip of the dyke to which they belong. In scarce examples such dykes are multiple and the segments result from distinct incremental injection that cross cut and are chilled against former segments. However, in most segmented dykes such a relationship could not be established. We were neither able to clearly link the inner segmentation with a faulting nor, with a significant offset of the host-rocks from a margin of a dyke to the other.

4.2. *Alftafjördur section*

Along section A, the projection line strikes at N124 and crosses 54 dykes over a distance of 5878 m. Dyke density is null at the western end of the section and abruptly increases to the east marking the beginning of the swarm at about 700 m (Fig. 3, Fig. 6). The eastern boundary of the swarm cannot be observed because the section ends at sea. Walker (1963) estimated that the swarm extends 4 km eastward within small islands located offshore.

In this section, the dyke strikes range from N330° to N080°, i.e. over 110°, with an average at N034.1° (Figs. 3 and 4). The histogram of azimuths shows a wide peak exhibiting a slightly bimodal distribution with maxima at about N025° and N040°. Sixty-five percent of the dykes strike between N020° and N045° and 78% differ from the swarm trend by less than ±20°. The dyke dips vary from 80° W to 50° E with a maximum (83%) in the range 90°–70°E centred on the average at 79° E. Eighty-five percent of the dykes dip eastward.

The dykes intrude lava flows broadly striking N–S that are tilted up to 13° W. The tilt decreases upward in the lava pile down to 3–4° W. This vertical decrease is interpreted as resulting from tilting synchronous with the construction of the lava pile (Palmason, 1973; Bourgeois et al., 2005). Strike and dip data of the lava flows and dykes were back tilted by 13° relative to a N–S horizontal axis rotated clockwise, looking north. The new azimuth distribution is almost unchanged from N330° to N075° with a wide bimodal peak from N020° to N045° (average N033°). The new dip distribution is slightly wider from 72° W to 54° E and a maximum at 85° E (average 88° E). 79% of the dykes become vertical or differ from the vertical by less than 10°.

The dyke thickness varies from 0.1 m to 7.0 m, except two dykes that are 10 m wide. Mean and median thicknesses of the population are 3.3 m and 3.0 m, respectively. The number of dykes appears broadly constant up to 7 m in the histogram of thicknesses (Fig. 4). However, a plot of the cumulative frequency of thicknesses shows that a negative exponential curve reasonably fits the whole data (Fig. 5) with an expression of the shape:

$$F(w) = c \exp(-w/w_0) \tag{1}$$

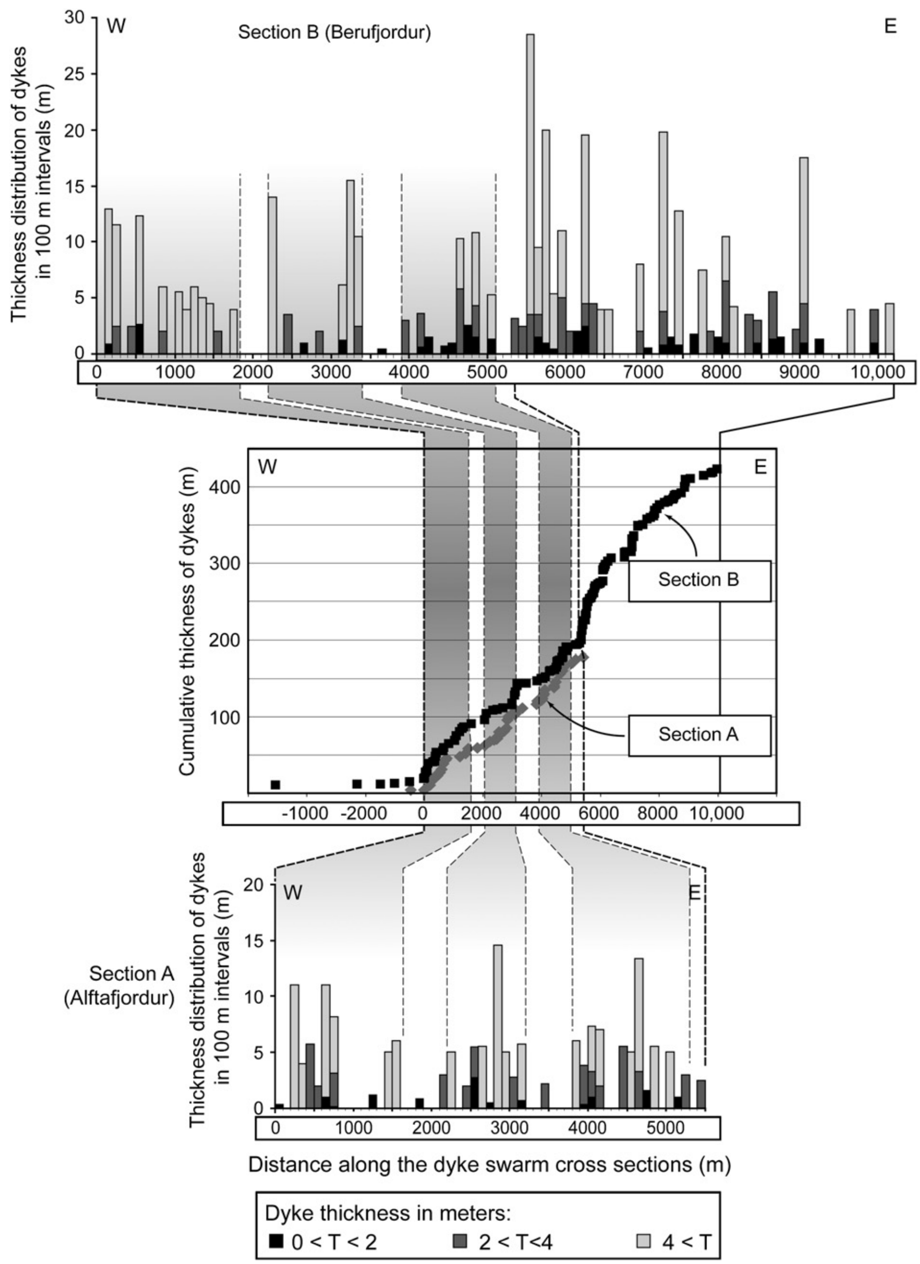

Fig. 6. Spatial distribution of dykes along the two projection lines showing that within the swarm the dykes are gathered into clusters. The upper and lower graphs display the thickness distribution per 100-m interval along section B and A, respectively. The grey levels in the bars represent thickness ranges as indicated at the bottom. The middle graph shows the cumulative thicknesses as a function of the location of the dykes along the sections. The curves display a step-by-step pattern. Note that the clusters of dykes can be traced from one section to the other as underlined by the grey bands across the graphs.

F is the percentage of dykes with thickness greater or equal to w, w_0 is a characteristic thickness and c is a constant approaching 1. The characteristic thickness is 3.0 m.

Fig. 3 (upper left) and Fig. 6 show that along section A, the dykes are gathered into groups separated by bands of a few hundred metres wide without any dyke. The peaks of the groups of dykes are visually spaced by 1.5 to 2.5 km. A wavelength of about 2.5 km was extracted from the FFT analysis. Plot of the cumulative thickness against the distance along the section (Fig. 6, middle) shows a sudden occurrence of dykes that reveal the western margin of the swarm. The plot displays a step-by-step pattern correlative to the grouping of the dykes within the swarm. It does not end easterly by a plateau as the margin of the swarm is not reached. Within the swarm, the thicknesses are rather uniformly distributed among the groups of dykes (Fig. 6, bottom).

4.3. Berufjördur section

Section B data were projected along a line striking at N112°. One hundred and twenty-two dykes cross this section over a distance of 15039 m. Dyke density increases significantly at 7000 m from the NW extremity of the section marking the western margin of the swarm (Fig. 3). From 0 to

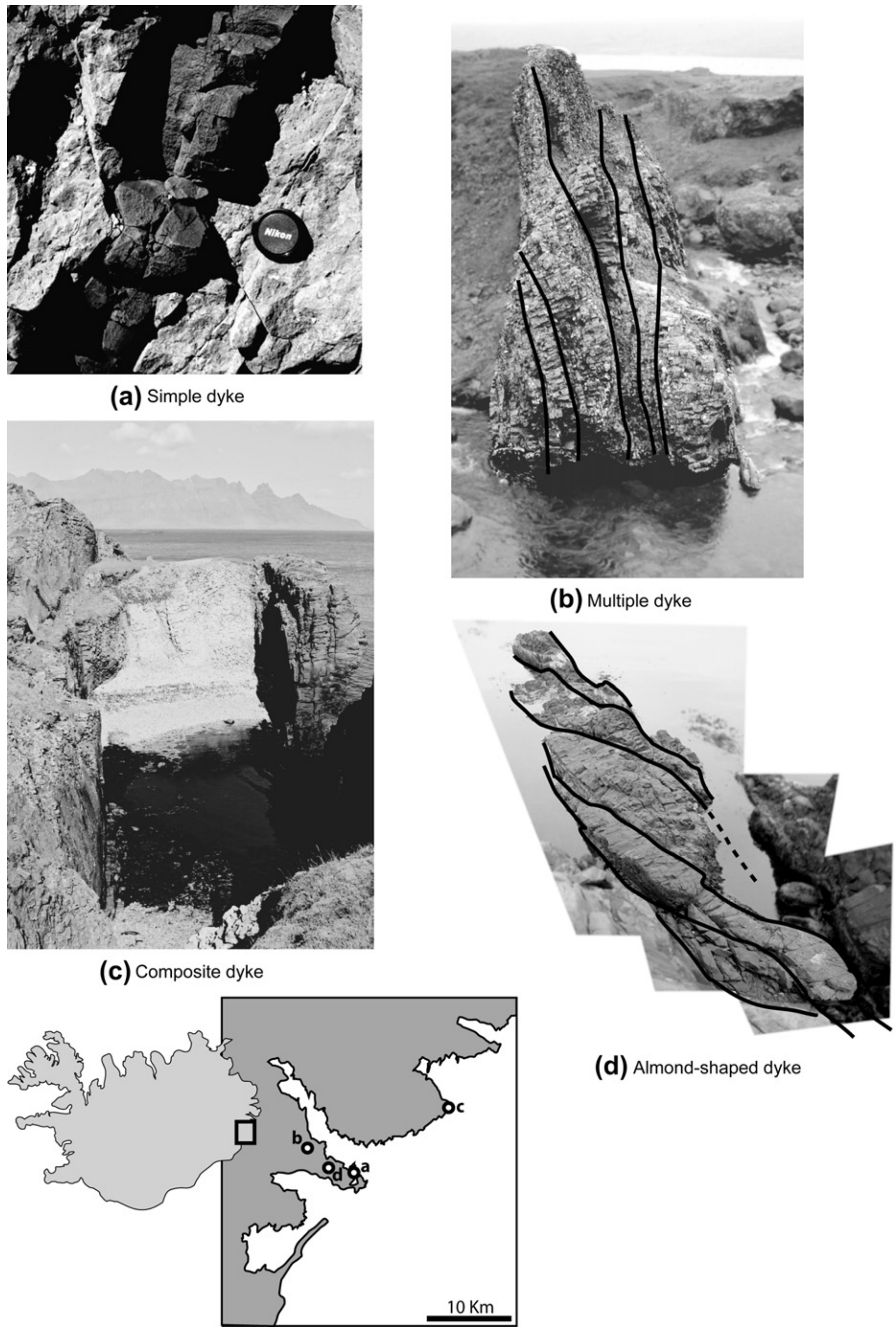

Fig. 7. Dyke typology: (a) 10 cm thick classic dyke; (b) 10 m thick multiple dyke in the Bulandsa valley; (c) 25 m thick composite dyke at Streitishorn, with dark mafic margins and leucocratic felsic centre; (d) 3 m thick almond-shaped dyke near Djupivogur; Dykes are located on the map of the inset.

7000 m, five scattered dykes were observed. Within the swarm, the highest density is reached at 12,000 m. At the SE extremity of the section, density decreases but remains significant so that the swarm possibly prolongs under the sea.

Most of the dykes strike from N350° to N075° with a maximum at N020°-N025° centred on the mean at N021.6° (Figs. 3 and 4). Only 16% of the data differ from the swarm trend by more than 20°. The dips vary from 70° W to 50° E with a main peak at 80° E corresponding to the average at 79° E. Note that only three dykes dip westward or northward. The host lava flows strike at about N–S and dip 9° W in section B. Data were back tilted relative to a N–S horizontal axis rotated clockwise, looking north, by 9°. After back tilting, most dykes strike from N330° to N070°, with a maximum at N015–035° (average N027°). The new dips range from 60° W to 55° E. The dip distribution is roughly centred at 85° E (average 87° E). 81% of the dykes become vertical or differ from the vertical by less than 10°.

Along section B, the dyke thickness reaches 15 m. Most of the dykes have a thickness at about 2 m, and then the thickness distribution decreases toward larger values (Fig. 4). Mean and median thicknesses are 3.5 m and 2.8 m, respectively. A negative exponential curve (eq. 1) best fits the whole data on a plot of the cumulative frequency of thicknesses (Fig. 5) with a characteristic thickness of 3.0 m.

Inside the swarm, the dykes are not uniformly distributed: they are gathered into groups roughly periodically spaced each 1.5 to 2.0 km, except in the eastern third of the section where a group is apparently wider (Fig. 3, upper left and Fig. 6, top). A wavelength of 2.5 km was extracted from the FFT analysis performed on the whole section. The thickness distribution inside the groups does not follow any organisation (Fig. 6, top): the widest dykes (>4 m) seem uniformly distributed while the thinnest are preferentially located to the centre and to the eastern part of the section. From west to east, Fig. 6 (middle) shows a sudden increase of the cumulative thickness that defines the beginning of the swarm. The curve displays a step by step pattern where each step corresponds to a dyke group. Each plateau points out zones without dyke or with a low dyke density. To the east, we interpret the plateau as indicating the beginning of the eastern margin of the swarm. Therefore we assume that section B is almost complete across the entire width of the swarm.

Along section B, a single normal faulted zone was observed. It trends at N170 with a dip of 65° E. The fault plane contains magma over a width of 1.5 m. This fault offsets a dyke 4 m wide. From field observation, it was not possible to argue that intrusion and faulting were coeval.

5. Interpretations and discussion

5.1. Dyke swarm characteristics

The outcropping conditions along the Alftafjördur dyke swarm make possible an analysis at different distances from the eruptive centre but the width of the swarm cannot be directly compared from section A to B. The cumulative thickness curve of section B provides a way to fix the width of the swarm at about 9 km (Fig. 6). This suggests that section A displays about the half of the entire swarm width, assuming that it remains constant from one section to the other. This is consistent with the shape previously defined by Walker (1963).

The strike population of section A, close to the igneous centre, significantly differs from that of section B, located further north (Fig. 4). It displays a slightly bimodal pattern with peaks at N025° and N040°, while section B shows a single peak at N025°. N025° is thus a common peak and N040° only appears close to the igneous centre. In addition, the peak at N025° of section A is slightly larger than the other one. Therefore, we interpret this peak as resulting from regional extension which trends N104° (DeMets et al., 1994). The peak at N040° possibly results from more local effects related to the proximity of the extinct volcanic centre. It contributes to the change of swarm direction trend by 12° from N to S. Fissure and dyke swarms usually have different trends in the NVZ marking N–S changes: they are oriented N00°–015° at north and N035°–040° at south, just north of the Vatnajokull. The occurrence of two dyke populations in section A together with dykes with intermediate azimuths may indicate that these changes are partially progressive. Without dating it is impossible to know if the two dyke populations correspond to different generations or if they were intruding at the same time.

The eastward dipping of the dykes is compatible with the westward tilt of the host flows. The dip distribution seems independent of the distance from the igneous centre (Fig. 4). By back-tilting the dykes to take into account the lava tilt, the dip distribution of the two sections remains similar except that section A exhibits a bimodal distribution which may reflect some effects of the relative proximity of the igneous centre. However, this also indicates that back-tilting rotation is incorrect for some of the dykes: the dykes dipping to the west being over-rotated compared to those that are still eastward dipping. This suggests that, if not all, a part of the tilting is contemporaneous with dyke intrusions. This is compatible with the roll-over structural pattern described by Palmason (1973) and Bourgeois et al. (2005). Indeed, bending of poorly deformed zones is expected in a regional deformation pattern involving roll-over anticlines in the hanging walls of growth faults. Therefore, we assume that dyke intrusions started before the regional tilting and ended after this tilting.

The dyke thickness distributions are very similar in the two sections (Fig. 5). The distributions fit exponential decreases of the cumulative frequency versus thickness with characteristic thicknesses at 3 m. The differences in the histogram shapes (Fig. 4) may result from an undersampling in section A which corresponds to about the half of the swarm width. As no significant offset of the lava pile was observed from one margin of most dykes to the other, the dyke emplacement mechanism mainly corresponded to the opening of a mode I crack normal to the dyke walls (orthogonal dilation). If any, the shearing component along the intrusion plane was very weak. The stretching ratio of each profile was estimated using the section lengths and the sum of the dyke thicknesses. Similar values were obtained: 1.046 for section B and 1.036 for section A.

One of the main outcomes of this study is to demonstrate the clustering of the dykes within a swarm. The cumulative curves (Fig. 6, middle) display the same step-like pattern. The steps of each cumulative curve are correlated from one section to the other suggesting that the groups of dykes can be followed over long distances (at least 10 km). The spacing between the peaks of the clusters is about 2.5 km in both sections (Figs. 3 and 6).

The thickness distributions of dykes in Iceland have often been described as power laws (Gudmundsson, 1995a,b, 1998). However, our data do not fit such laws, which are independent of a length scale. Our study reveals that many thin and/or thick dykes are missing in our populations to fit power laws. It is still possible that we missed a few of the thinnest dykes (<0.2 m) on the field. However, it is unrealistic to infer that we missed either some of the thickest dykes or as many dykes as required in the thickness range 0.2–2.0 m. The relative scarcity of thin dykes is thus a real feature of our distributions (see also Jolly and Sanderson, 1995 and references therein; Klausen, 2004). Cut off within dyke populations can also be introduced to improve fits of data over restricted thickness ranges (e.g. Le Gall et al., 2005). However, such ranges become so restricted that their significance and reliability to any specific mechanism remains difficult to interpret.

5.2. Dyke distribution

As length distributions of fractures and faults in rocks (Bonnet et al., 2001), length distributions of dykes follow power laws (Mège and Korme, 2004). In addition, 2D distributions are often biased when compared to 3D ones. It follows that distributions of dyke thicknesses observed along 2D sections are to be cautiously analysed when involving a characteristic length scale as it is apparently the case here. However, other studies suggest that a characteristic thickness could be a real feature of dyke and/or sheet intrusion populations in different parts of the world including Iceland (Jolly and Sanderson, 1995 and references therein; Walker and Eyre, 1995; Klausen, 2004, 2006). Not all these studies describe negative exponential distributions. Some also show log-normal distributions (e.g. Walker and Eyre, 1995). Both involve a characteristic thickness which often corresponds to the average thickness of the dyke population (Klausen, 2004, 2006). Our results indicate that the characteristic thickness better matches the median thickness.

Dyke emplacement occurs by hydraulic fracturing of host rocks under pressure provided by the magma. The final shape and geometry of an individual dyke depend on the characteristics of the magmatic supply (mainly pressure and single or multiple injection), those of the host-rocks (mainly elastic properties and regional/local stress fields), and the thermal conditions during injection (e.g. Gudmundsson, 1983; Lister and Kerr, 1991; Rubin, 1995; Walker et al., 1995). For a given shape, dyke thickness depends on the other dyke dimensions along strike and dip: the longer the dyke, the thicker it is. A dyke thickens if it results from multiple injections. It is thinner if a same amount of available magma separates into several intrusions during a single event. Large magmatic pressures and extensional tectonic stresses favour dyke thickening. If compressive, tectonic stresses act against magmatic pressure. When intruding elastic host-rocks, dykes are thicker than when injecting rigid ones. If compressible or allowing some lateral compaction in porous layers and/or previously damaged zones, the host-rocks also favour dyke thickening. Thermal erosion of the host-rocks under high magmatic flow rates, or rapid cooling of the magma also affects dyke thicknesses.

All these effects potentially account for dyke thickness distributions. If real, the characteristic thickness of a dyke population must however relate to mechanisms which have also to explain why length distributions follow power laws. We assume first that magmatic conditions were possibly comparable or within a limited range of variation from one intrusive event to the other, so that dykes form with relatively similar shapes around a median case during each individual intrusive event. Second, we postulate that the characteristic thickness reflects, on average, the ability of the crust to accommodate magmatic dilation during a single injection. For given mechanical properties and stress field, dilation cannot be infinite but can reach values, given by the thickest dykes, larger than that of the characteristic thickness. For given magmatic conditions within a dyke which cannot thicken anymore, the magma is expected to propagate perpendicularly to the least principle stress farther than it would have done if the crust had allowed further dyke thickening, thus modifying the shapes of the median case. Such a control by magmas, host-rocks and tectonics may result in dyke populations, which are scale-independent with respect to lengths but scale-dependent relative to thicknesses. Although plausible such a qualitative model needs to be tested and refined. Additional mechanisms, which accounts for the relative scarcity of thin dykes have to be incorporated: rapid cooling explains why thin dykes cannot be sampled at long distances from their sources (Jolly and Sanderson, 1995); multiple dykes constitute ‘‘abnormally’’ thick intrusions within a population.

5.3. Dyke clustering

The dyke swarm itself and the periodic distribution of the dykes observed across the swarm are also controlled by magma dynamics, host-rock properties and tectonics. Dyke clustering shows that deformation is partitioned at different scales within the crust. Such partitioning potentially reflects (1) the locations, sizes and shapes of the magma sources from which the magmas are expelled, (2) the presence of heterogeneities within the crust and (3) a mechanical response of the crust to stretching. Although these effects are not exclusive, the first effect more likely accounts for the swarm location than the others, which potentially better explain dyke clustering within the swarm. Reviewing how the local stress field is modified in volcanoes, Gudmundsson (2006) shows that source geometries affect dyke locations (effect 1) but that simple magma chamber shapes hardly explain clustering within a swarm.

Regardless of the nature of the host-rocks within the lava pile which is laterally equivalent across the swarm, processes such as faulting, fissuring, jointing and hydrothermal alteration can produce heterogeneities focusing the location of intrusions (effect 2). Because faults are rare and fissures only occur in the shallowest part of the crust, they were probably not efficient in localising the dykes in sections A and B. Jointing and hydrothermal alteration subsequent to the lava pile construction may also control dyke locations, but they unlikely result in a periodical distribution. It follows that if heterogeneities are to trigger dyke clustering they must relate to dyking. Hydrothermal alteration by fluids immediately preceding magma injection could control subsequent dyke location. It is also plausible that the earliest dykes, which have damaged the host rocks, influence the location of later ones. Clustering suggests that a mechanical linkage exists between the dykes, earlier ones and/or associated fluids, making the crust heterogeneous. Such a linkage which also likely results from very short time lapse between successive intrusions (e.g. Mège and Korme, 2004) is consistent with the occurrence of multiple dykes tough they remain rare. Nevertheless, again this does

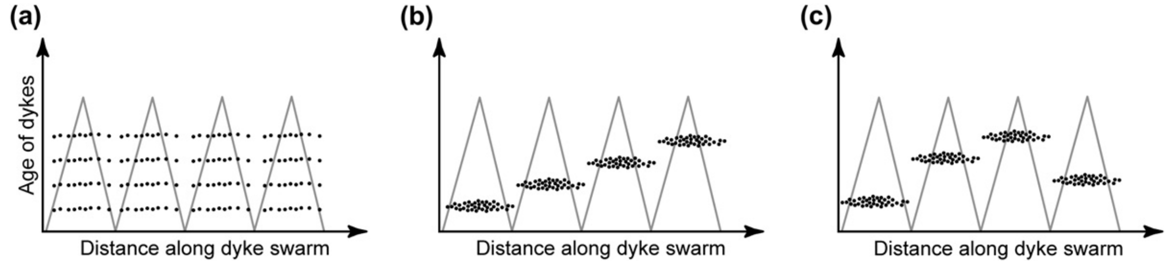

Fig. 8. Three possible cases of swarm dynamics. Each dot represents an intrusion event located in time and space. The grey curves schematise the distribution of dykes forming clusters across the swarm. Case A assumes that deformation controls dyke locations, clusters being contemporaneous. Cases B and C consider that each cluster formed during a short time lapse and that subsequent magmatic activity migrates with time randomly or not, respectively.

not explain why the earliest intrusions should be periodically spaced.

Assuming that the dyke clusters form contemporaneously, such a periodicity indicates that the stretching of the crust has to occur periodically at wavelengths controlled by physical properties (thickness of the dilating layer, rheological layering, effect 3). This phenomenon is known at larger scale as boudinage. The observed periodicity is about half of the thickness of the upper brittle crust in Iceland where present day brittle-ductile transition reaches about 5 km (Bourgeois et al., 2005). So it directly reflects the stretching of the whole brittle crust above a low viscosity ductile layer, but it is interesting to note that it better matches the thickness of the brittle crust above shallow level magmatic reservoirs. Alternatively, assuming a rheologically layered crust, in which a thin zone of low strength separates two stronger brittle layers and acts as a decoupling zone, the observed periodicity could also correspond to a secondary spacing in the upper brittle layer induced by a larger spacing in the deeper one (Martinod and Davy, 1992).

Because we do not know if the dyke clusters are contemporaneous, Fig. 8 sums up three possible cases of swarm construction. Firstly, the clusters may form simultaneously and result from cyclic magmatic supplies (Fig. 8a). During early stages, clustering can be initiated by a mechanical response to stretching of the upper part of the brittle crust above a shallow level low viscosity magma chamber. During later ones, it may be reinforced by heterogeneities created by earlier dykes. The detailed and potentially complex shape of the magma chamber may also play a role in locating dyke clusters. Secondly, the clusters may be diachronous, each cluster resulting from a single short-lived magmatic cycle formed by several intrusion events. The difference between Fig. 8b and c is that deformation propagates with time randomly or not, respectively. Such dynamics could, for example, reflect local changes in shapes of the magma source with time. To discriminate between these cases and to discuss further the underlying mechanisms responsible for the dynamics of the swarm construction, high resolution dating would be necessary.

5.4. Magma properties and initial depth of dyke injection

The occurrence of both poorly porphyritic and aphyric basaltic rocks within most of the dykes indicates that magmas were mainly injected as melts at about liquidus temperatures. However, strongly porphyritic dykes (up to about 30 vol% of phenocrysts) attest that some basaltic magma was also injected at temperature significantly lower than liquidus. Microcrystalline groundmass, chilled margins, columnar joints and vesicles in some dykes are in agreement with a shallow level emplacement of the basaltic magmas which rapidly cooled against older host-rock lava flows beneath the surface (Walker, 1974; Gudmundsson, 1983). However, the original depth of our sections up to about 200 m above the present sea level remains difficult to estimate precisely.

As most of the dykes are vesicle-free, most magma probably emplaced deeper than the depth at which bubbles nucleate and were volatile-poor melts. Vesicular dykes suggest that some volatile-rich magma also intruded and cooled above the depth of bubble nucleation. Assuming a melt that contains up to 1% of dissolved water, as some water-rich Icelandic basaltic magma exhibits (Nichols et al., 2002), and a pressure for water solubility of about 15 MPa (Moore et al., 1998), vapour bubbles nucleate down to about 500 m in a pile of basaltic rocks which density is 3100 kg/m^3. Considering a carbon poor basaltic melt with 80 ppm of dissolved carbon (Aubaud et al., 2004; Macpherson et al., 2005), saturation (1.37 ppm C/MPa) reaches 1.8 km within the same lava pile. Such estimates provide a range of minimum depths of intrusion. Greater depths are expected if the melt contains more carbon (or water), if the host lava pile has a smaller density due to intense jointing and high porosity layers, and/or if open fissures occur above some dykes.

Walker (1974) provided maximum depths of intrusion from extrapolations of the elevation of the initial top of the crust. In the area, he estimated between 1.3 and 1.8 km of erosion down to the present sea level. Assuming 1.5 km, our sections should lay in a range of depths of 1.3–1.5 km below the original top of the crust (Tentler, 2005). Clearly such depths are compatible with CO_2-rich vesicles in the magmas rather than vapour-rich ones. Because of tilting, the original depths of our sections are not the same at both margins of the swarm. The western margin is expected to show a shallower part of the swarm than the eastern one. Assuming a tilt of 10° yields a difference of about 1.5 km between the initial depths of two margins spaced by about 9 km. To fit this observation with erosion estimations (Walker, 1960, 1974; Neuhoff et al., 1999; Klausen, 2006), we conclude that section B possibly images the crust

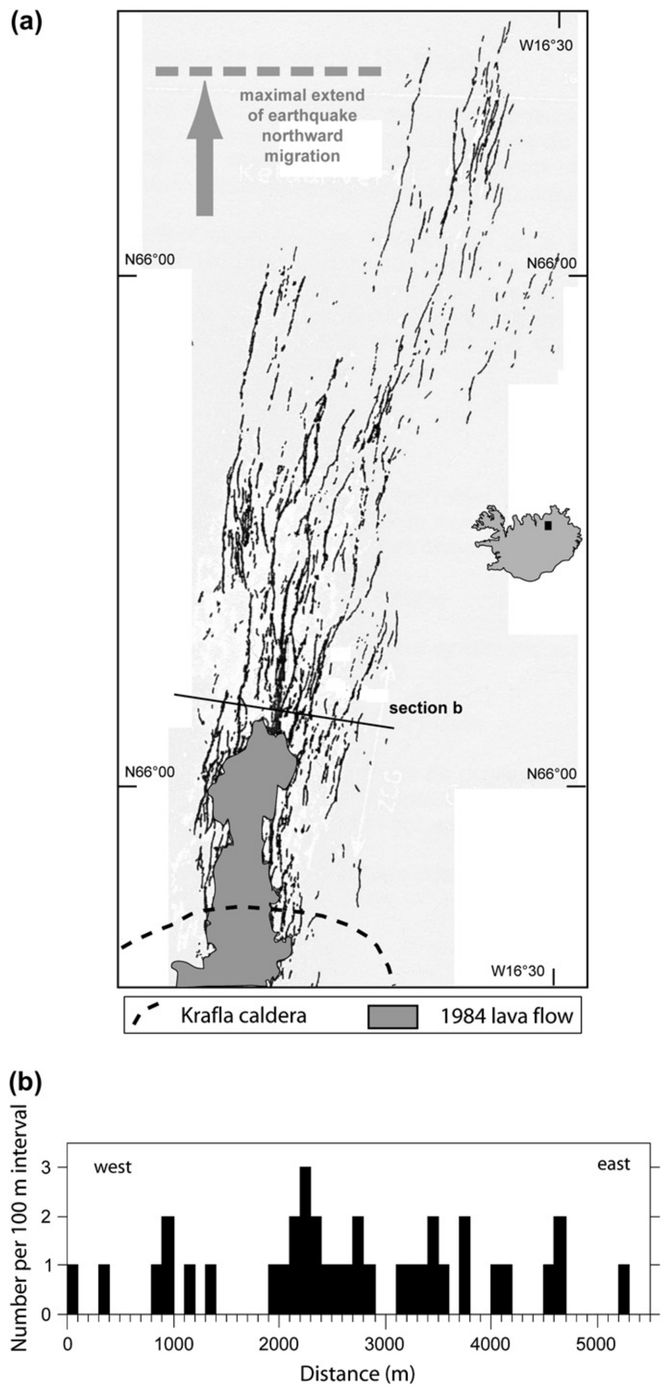

Fig. 9. Krafla fissure swarm. (a) Map of the Krafla fissure swarm showing fissures and faults (Ferber and Villemin, 1995; Dauteuil et al., 2001). (b) Histogram showing the number of fissures and faults per 100-m interval (density) along the section located on (a). Note that the open fissures are gathered into groups spaced by about 1200–1300 m.

at initial depths of about 0.7–1.0 km to the west down to about 2.2–2.5 km to the east. Such ranges are larger than those usually admitted in SE Iceland (Gudmundsson, 1983; Tentler, 2005), but the maximum depth is close to that proposed by Klausen (2006). Note that despite different initial depths of the swarm margins, the thicker dykes are not preferentially located in the original deeper part of section B (Fig. 6). The apparent widening of the dyke cluster in the eastern third of section B possibly documents an increase with depth of the wavelength between the clusters.

5.5. Dyke swarm versus fissure swarm

Many papers deal with comparisons between dyke and fissure swarms (Helgason and Zentilli, 1985; Forslund and Gudmundsson, 1991; Gudmundsson, 1995a; Tentler, 2005). They propose that fissure swarms at the surface of active zones are extensions of deep dyke swarms such as those in the Tertiary lava-pile of Iceland. No direct observation links a fissure swarm to a dyke swarm, neither in active zones where rare open fissures erupt lavas, nor in Tertiary zones where erosion removed the upper part of the crust.

A complete analysis of the Krafla fissure swarm was published in Angelier et al. (1997) and Dauteuil et al. (2001). The Krafla fissure swarm is a small asymmetric graben bounded by two main open fractures affecting lava flows (Fig. 9). Within the swarm, numerous fissures and normal faults outcrop. Some fissures are open and others are filled by lava and often masked by flows. The feeder fissures are mainly located close to the Krafla eruptive centre, while open fissures are more frequent northward. At the junction with the Tjornes fracture zone to the north, no eruptive feature is described (Garcia and Dhont, 2005). Some normal faults may grade laterally into open fissures. The Holocene basalt flows are localised close to the caldera centre (Fig. 9). We have performed the analysis of the fissure and fault distribution across the swarm just north of the 1984 lava flow, along the nearest profile from the eruptive centre where the fissures are not masked by recent lava flows. This area provides an image of the deformation accumulated since 10,000 years ago (Dauteuil et al., 2001). Forty-one fissures cross the profile (Fig. 9b). The width of open fissures reaches 30 m: the greatest values (>3 m) correspond to open fractures (Dauteuil et al., 2001). In the same area, these authors estimated a stretching ratio of 1.009. In the Krafla swarm, the FFT analysis performed on the quasi periodical signal shown by the distribution of fissures and faults per 100 m interval reveals groups spaced by 1200–1300 m (Fig. 9b).

Direct comparison between active fissure swarms and extinct dyke swarms have to take into account that the two kinds of swarms have accommodated different strain amount. The dyke swarm is wider and exhibits larger stretching ratios (1.036 to 1.046 over 9 km) than the fissure swarm (1.009 over 5 km). Such discrepancies may result from different durations of activities of the swarms: the dyke swarm images a deformation that lasted 1 Ma or more, while the Krafla swarm accumulates deformation only since 10,000 years ago. Also different are the apparent wavelengths of the periodicity of the clusters. Fissure clusters are spaced by about the half of the spacing of dyke clusters (Figs. 6 and 9). Such a discrepancy hardly results from different activity durations or thermal conditions within present and ancient crusts. It more likely reflects a mechanical response to stretching of the upper levels of the crust. It may indicate that a thin layer acting as a decoupling zone exists in between two layers of different thicknesses within the brittle upper crust, so that the crust stretches differently at different depth. However, our results do not demonstrate that dilation drastically varies with depth in a swarm, and layers with low strengths capable to accommodate dilation variations remain hypothetical and are not observed in the Icelandic crust.

5.6. Magma source location, vertical versus lateral flow

Two models discuss the location of the magma sources of the dykes. Historically the first one proposed that regional dykes mainly result from lateral flow of magma from shallow magma chambers located just beneath central volcanoes in the upper crust (Sigurdsson and Sparks, 1978; Einarsson and Brandsdottir, 1980; Helgason and Zentilli, 1985). In agreement with such a model, Gudmundsson (1984) suggested that some mixed flow occurs within sub-vertical dykes in which the main flow direction is horizontal below depths of about 0.5–1 km but becomes mainly vertical above it within segments of the dykes. More recently Gudmundsson (1990, 1995a, 1998, 2000, 2002) proposed another model that mainly involves vertical migration of magmas from elongated elliptical reservoirs as deep as 10–20 km at about the crust mantle boundary and spreading below the swarms. In the model a shallow magma chamber beneath a central volcano may result from magma trap within the upper part of the crust at depth of 1–3 km. The deep reservoir continues to feed vertically both the shallow chamber and the regional dyke swarms while the shallow chamber mainly supplies the sheet swarm and lava flows around the central volcano.

Beneath the Krafla swarm, seismic data indicate the presence of magma at about only 3 km beneath the surface (Brandsdottir et al., 1997). During the 1975–1984 Krafla volcanic events, hypocentres related to dyke propagations were located between 1 and 4 km at depth and indicate northward migration of magma as far as 30 km from the Krafla system (Einarsson and Brandsdottir, 1980). Henriot et al. (2001) studied the long-term deflation of the Krafla region following the 1975–1984 event. The subsidence is compatible with intrusions located in the first 3 km of the crust. Located beneath the Krafla, they are elongated over few kilometres along the swarm direction. These observations, which identify a shallow magmatic reservoir beneath an eruptive centre and lateral migration of magmas, suggest that lateral flow is common in the upper Icelandic crust.

Gudmundsson (1990) develops arguments against dominant lateral flow but our observations are in agreement with lateral migration of magmas from shallow reservoirs:

(i) The dyke population varies with the distance to the eruptive centre: variations in strikes (and to a lesser extent back-tilted dips) when approaching the volcanic centre indicates that it perturbs the swarm. Such variations which are probably progressive are compatible with dyke propagation away from an eruptive centre.

(ii) Some clusters of dykes form within the swarm with very similar characteristics over the 10 km that separate sections A and B. Such a lateral apparent continuity in the network is also in agreement with lateral propagation of magmas.

(iii) When present, phenocrysts indicate that some magma cooled below their liquidus temperatures and resided at depth before dyking. This argues against a direct extraction of magmas from the deepest reservoirs and is in better agreement with a residence into shallow level magmatic chambers.

(iv) Phenocrysts are more abundant near the central volcano (maximum at about 30% in section A and 20% in section B). During lateral magma migration, such longitudinal variations may result from the higher viscosity of phenocryst-rich magmas, which propagate over shorter distances than less viscous phenocryst-poor ones.

(v) Satellite dykes outcropping outside a swarm can also directly relate to the roots of a volcanic centre. Mafic and felsic associations of contemporaneous magmas usually occur within the igneous centres themselves. To observe similar associations within dykes strongly supports the idea of lateral transport of magma several tens of kilometres away from the igneous centre.

5.7. A 3D model of Icelandic swarm

Brought together with the results of previous studies (Walker, 1974; Gudmundsson, 1983), our interpretations result in a three-dimensional conceptual model of a swarm in Iceland taking into account (i) lateral magma migration, (ii) potential relationships between fissures and dykes, (iii) the shallow depth of the magma reservoir, and (iv) the relationships between regional and magmatic stresses (Fig. 10). Most regional dykes and fissures trend sub-parallel to the swarm direction and propagate preferentially in a direction, which is perpendicular to the minimum principal stress (σ_3). This is a robust criterion that regional tectonics mainly controls the rough shape of the swarm, even at a short distance from the eruptive centre. At the volcanic centre, this scheme is locally perturbed due to high magmatic supply rates and high magmatic pressures. Magmatic pressure modifies the regional stresses by increasing the relative value of the minimum stress σ_3 to a value close to σ_2. This generates a radial dyke pattern and cone sheet intrusions around the eruptive centre. In the model most of the dykes propagates laterally from the shallow reservoir beneath the eruptive centre within the upper part of the crust. As magmatic pressure decreases with the distance to the eruptive centre, tectonic effects dominate magmatic ones, so that the dyke trends become more regular. It is also assumed in the model that vertical magma flow is mainly focused below the eruptive centre and mainly concerns the feeding of the shallow reservoir from below. This assumption is supported by the fact that in Iceland swarms are very often associated to central volcanoes or extinct centres where magmatic supply rates are or were higher than elsewhere. Swarms without volcano and volcanoes outside swarms are relatively rare. In addition, historic fissure eruptions were located close to central volcanoes where the break up of the upper crust under magmatic pressure thus appears more efficient than

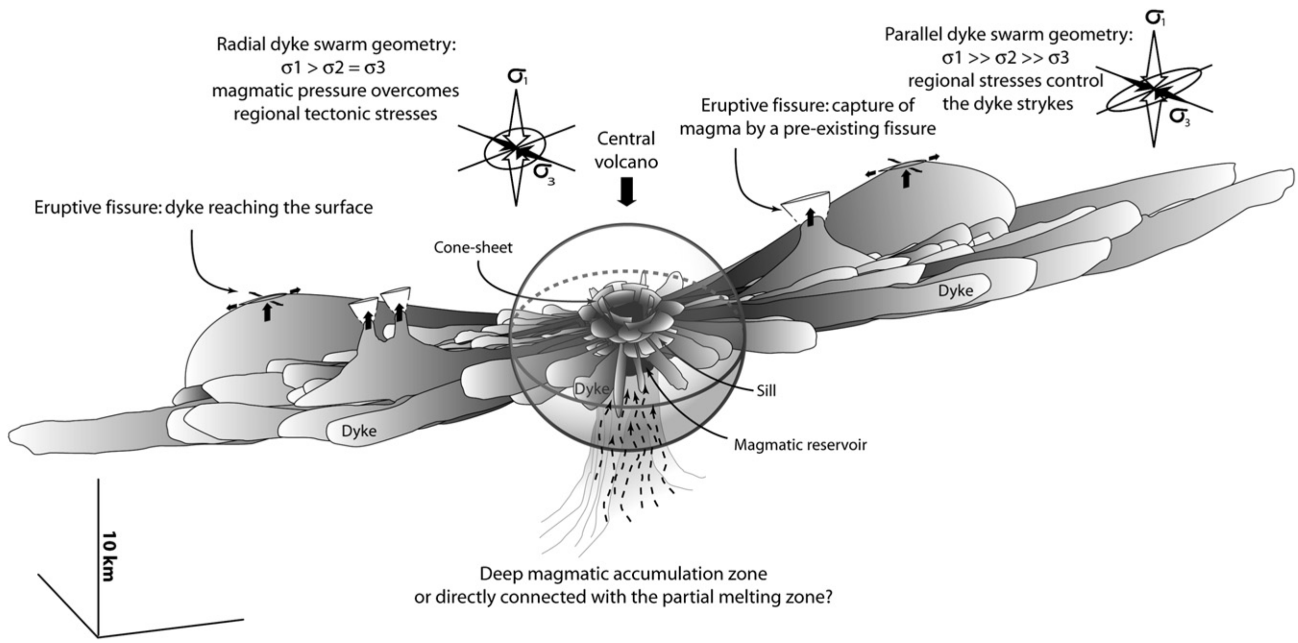

Fig. 10. Schematic 3D representation of a dyke swarm in Iceland cleared from the surroundings host rocks (lava pile). Connection between the partial melting zone and the magma chamber is drawn as an example. The model assumes an upward migration of magma from depth to the igneous reservoir beneath the eruptive centre. Within the crust the magma is expected to flow mainly laterally from the magma chamber beneath the eruptive centre. The strikes of the intrusions are assumed to be controlled by the variations of the stress distribution along the swarm. Near the eruptive centre where the magmatic supply is high, the stress field becomes almost isotropic leading to a radial distribution of dykes (and cone sheet intrusions). Away from the eruptive centre, the parallel distribution of dykes results from the regional extensional stress field.

farther away. Such eruptive fissures could correspond to dykes reaching the surface (Fig. 10). Several authors (Walker, 1965; Opheim and Gudmundsson, 1989; Tentler, 2005) proposed that open fissures and open fractures at the surface might be triggered by dyke emplacement at depth. Therefore several eruptions should occur far away from the volcanic centres. However, eruptive fissures usually occur within the first ten kilometres of the volcanic centre, while open fissures can form farther where they are rarely eruptive. This suggests that tectonics mainly control the formation of most of the open fissures and that fissures can form before the dykes. Such fissures might be subsequently closed by burial under more recent lava flows and/or filled by magmas. To become eruptive, a dyke might also intersect at depth a pre-existing open fissure (Fig. 10). Such a capture might cause magmatic pressure drops in the plumbing system preventing coeval intrusions from reaching the surface. With the assumption of lateral propagation, the shapes and sizes of the dykes (along strike dimension much larger than along dip dimension, Fig. 10) must result from tectonic effects. Our model emphasises a strong control of the regional stresses on both generation of the fissures and magma propagation, except close to the volcanic centre where magmatic pressures may obliterate regional stresses.

6. Conclusions

Iceland is an excellent laboratory to explore the interactions between magmatic dynamics and extensional tectonics because it is located above a hot-spot and on a divergent plate boundary. Uplift history and intense glacial erosion allow deep parts of the crust to crop out. Extension and magmatism are focused into narrow and very long fissure/dyke swarms, almost systematically crossed by an eruptive centre.

In eastern Iceland, the Alftafjördur dyke swarm built during the westward regional tilting of the lava pile resulting from the formation of a volcanic roll-over. The dykes strikes and, to a lesser extent, dips, vary with the distance to the igneous centre where high magmatic supply rates have locally perturbed the geometry of the swarm. Thin dykes are relatively scarce in the swarm so that the cumulative frequency versus thickness curves fit negative exponential distributions with characteristic thicknesses at about 3 m (almost the median thicknesses of the populations). Such a characteristic thickness is potentially triggered by (1) the ability of the crust to provide space for magmas which is controlled by regional tectonics and physical properties of the host-rocks and by (2) magmatic conditions, quite similar at each injection stage. Across the swarm, which is 9 km wide, the dykes are gathered into clusters with a quasi-periodical spacing which can be traced from a section to the other and of about 2.5 km. Assuming that the earliest dykes in different clusters were almost contemporaneous, such a periodicity may reflect the intrinsic response of the upper levels of the crust to stretching. However, high-resolution dating of the dykes is critical in order to discuss the underlying mechanisms of construction of the swarms. In fissure swarms, open fissures are also gathered into clusters periodically spaced by 1200–1300 m, a spacing about half that of dyke clusters. Clustering may result from a mechanical response to stretching of the crust but the origin of the difference in spacing between fissure and dyke swarms remains unknown.

A three-dimensional conceptual model of dyke swarms is proposed. In this model, most magma migrates laterally within the upper crust from the shallow reservoir beneath the extinct volcanic centre. Such a migration must be controlled by regional stresses. Large magmatic pressures near the volcanic centre modify the stress field, which becomes locally almost isotropic. Increasing with the distance from the extinct volcanic centre, the effects of regional tectonics trigger the swarm shape.

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