Dykes, Sills, Laccoliths, and Inclined Sheets in Iceland

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Abstract

Dykes and inclined sheets are extremely common in the volcanic systems of Iceland, both the fossil ones as well as the active systems. Until recently, comparatively few sills and laccoliths were known, but recent studies show that many laccoliths occur in the lava pile and that sills are also very common. Many, perhaps most, shallow magma chambers in Iceland (including laccoliths) develop from sills, so that understanding the conditions for sill formation is of great volcanotectonic importance. Some of the laccoliths described here are felsic, others are mafic, and reach a maximum thickness of several hundred metres. They were emplaced at shallow depths (several hundred metres below the surface) and presumably acted as short-lived shallow magma chambers. Most sills in Iceland are mafic. The largest sills reach at least 120 m in thickness and presumably many kilometres in diameter. Inclined sheets and vertical dykes supply magma to essentially all eruptions in Iceland. Sheet swarms are confined to central volcanoes (stratovolcanoes, calderas), whereas regional dykes occur outside central volcanoes. Most inclined sheet are injected from shallow magma chambers. Individual swarms of inclined sheets are circular to slightly elliptical in plan view (with a maximum diameter of about 18 km), contain up to tens of thousands of sheets, generating a crustal dilation of as much as 80 % (measured in a profile roughly perpendicular to the average sheet attitude), the sheets being

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mostly <1 m thick and dipping 30°–60° towards the shallow magma source chamber. By contrast, the regional dyke swarms are highly elongated (elliptical) in plan view (with common maximum lengths of 50 km and widths of 5–10 km), contain hundreds of dykes at the level of exposure, mostly subvertical and 2–6 m thick. Recent studies suggest that many regional dykes were emplaced through inclined or vertical magma flow. We conclude that, while much progress has been made, we still do not have reliable models for forecasting the likely paths of sheet-like intrusions during volcanic unrest periods with magma-chamber rupture.

1 Introduction

There are numerous dykes in Iceland; tens of thousands have been studied for more than a century and their characteristics are well known. Inclined sheets were discovered later, primarily through the work of Walker (1974, 1975), and are now known to be very common in central volcanoes (stratovolcanoes and calderas). Few laccoliths and sills, however, were known in Iceland until comparatively recently, whereby studies have shown these intrusions to be much more common than they were thought to be.

Dykes occur mainly in elongated swarms outside the central volcanoes, whereas the inclined sheets are mostly confined to the central volcanoes (Fig. 1). The dykes are mostly controlled by the regional stress field associated with the divergent and propagating plate boundaries, whereas the inclined sheets are primarily controlled by the local stress field associated with the shallow crustal magma chambers that supply magma to the

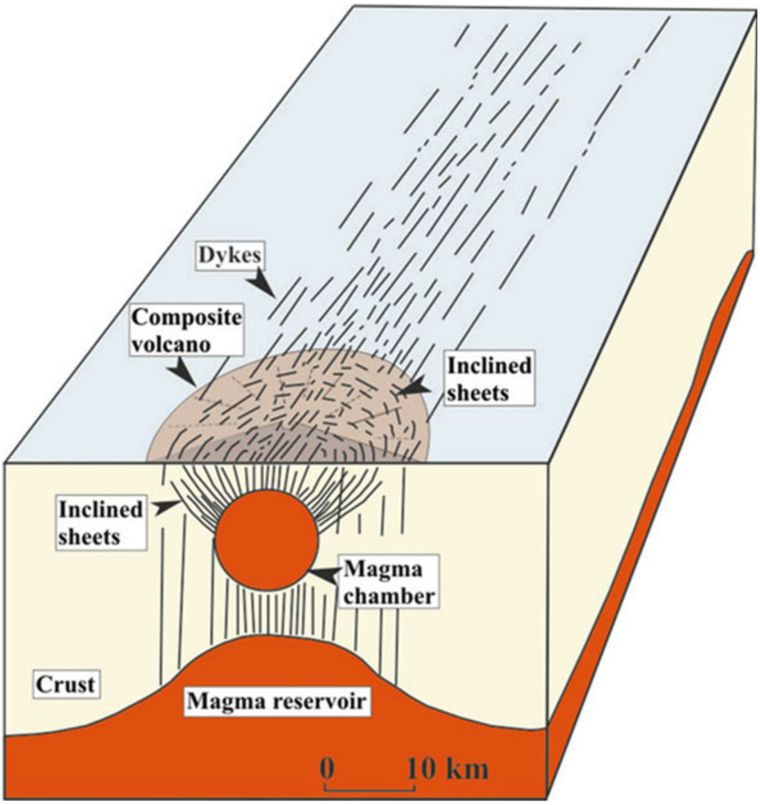

Fig. 1 Schematic overview of the internal structure of volcanic systems in Iceland. Associated with the central volcano (here a composite volcano) is a shallow magma chamber which, in turn, is supplied with magma from a deep-seated magma reservoir. It is likely the many, perhaps most, of the regional dykes are fed by deep-seated reservoirs, whereas most or all the inclined sheets are supplied with magma from shallow magma chambers

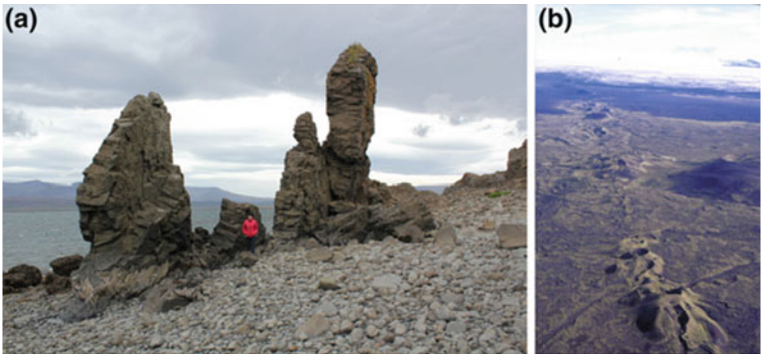

Fig. 2 Regional dykes. **a** A dyke on the coast in Southwest Iceland, view northeast, the dyke strike is N30ºE, the dip 82ºW, and the thickness 3 m. **b** View northeast, part of the 27-km-long (but segmented) volcanic fissure/crater row formed during the AD 1783 Laki eruption in southern Iceland. The feeder dyke must have been at least 27 km long

sheets and to the eruptions of the central volcanoes. Sills and laccoliths occur both inside and outside central volcanoes. Sills and laccoliths are potential shallow magma chambers, and many function as such. Many, and presumably most, shallow magma chambers (including laccoliths) initiate from sills (Gudmundsson 2012a).Traditionally, the dyke and sheet swarms are, depending on age, referred to as Tertiary, Pleistocene, and Holocene swarms. The oldest rocks in Iceland are about 15 Ma, so that Tertiary swarms in Iceland were formed in Miocene and Pliocene.

The main aim of this paper is to discuss and describe briefly all these four types of intrusions, their structure and mechanism of emplacement. Dykes in Iceland have been treated very extensively in the literature (e.g., Walker 1960, 1974; Gudmundsson 1995; Paquet et al. 2007; Galindo and Gudmundsson 2012) and so have inclined sheets, although to a lesser degree (Walker 1975; Gudmundsson 1995; Klausen 2004, 2006; Siler and Karson 2009; Tibaldi et al. 2011). By contrast, laccoliths and sills in Iceland have received comparatively little attention (Pasquarè and Tibaldi 2007; Gudmundsson and Lotveit 2012).

2 Dykes

The regional dykes occur in elongated swarms, commonly around 50 km long and 5–10 km wide, outside the central volcanoes (Fig. 1). The regional dykes are mostly close to vertical (Fig. 2a) and have generally similar strike (are subparallel) within each swarm. In the southern half of Iceland, the dyke trend is mostly northeast, whereas in the northern half of the country, the dyke trend is mostly north-northeast—similar to the general trends of the active volcanic systems (Fig. 3; Gudmundsson et al. 2014). The change in tectonic orientation from north to south across Iceland reflects the change in the trend of the ocean ridges north and south of the island; the Reykjanes Ridge, to the south, strikes northeast whereas the Kolbeinsey Ridge, to the north, strikes north-northeast (Fig. 3).

The dykes vary in thickness from a few centimetres to about 60 m. The thick dykes are mostly formed in multiple magma injections; the individual injections can often be recognised as ‘columnar rows’ (Gudmundsson 1995). The most common (mode) thickness of dykes in a given swarm is normally 1–2 m. The Tertiary (Miocene-Pliocene) and Pleistocene swarms, however, have different mean thicknesses; the Tertiary swarms have a mean dyke thickness of 4–6 m whereas the Pleistocene swarms have mean thickness of 1–2 m. Thus, generally, the mean thickness of regional dykes in Iceland is 2–6 m. Some Tertiary dykes have been traced along their lengths or strike dimensions to distances exceeding 20 km, but the total lengths are unknown since one or both lateral ends are normally uncertain.

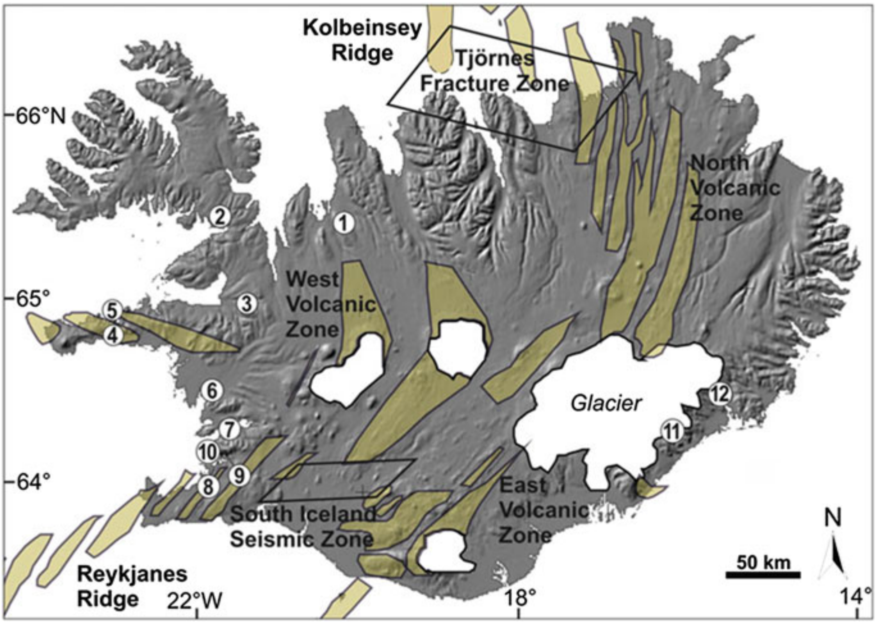

Fig. 3 Volcanic zones and systems as well as the associated transform zones (the Tjornes Fracture Zone and the South Iceland Seismic Zone) in Iceland. The strike of volcanic systems in the northern part of the country reflects that of the Kolbeinsey Ridge, whereas that in the southern part of the country reflects that of the Reykjanes Ridge. Numbers are locations of the centrally-inclined sheet swarms described in the present paper and of the gabbro plutons: *1* Vatnsdalur, *2* Kroksfjordur, *3* Reykjadalur, *4* Midhyrna-Lysuskard, *5* Kolgrafarmùli, *6* Thverfell, *7* Stardalur, *8* Kjalarnes, *9* Hvalfjordur, *10* Hafnarfjall, *11* Thverartindur, *12* Geitafell

Volcanic fissures are the surface expressions of feeder dykes (Fig. 2b). The longest (segmented) Holocene volcanic fissure in Iceland is about 65 km long, and there are several that reach tens of kilometres (Gudmundsson 1995). The associated feeder dykes must reach at least the same lengths. Comparatively few feeder dykes have been reported as being directly connected to their eruptive materials—this applies not only to Iceland but worldwide (Galindo and Gudmundsson 2012). One reason for the rarity of reported connections of this kind is lack of systematic research. For example, when the exposures are exceptionally good in active volcanoes, such as in Miyakejima in Japan, careful studies reveal many feeder dykes connected to their eruptive materials (Geshi et al. 2010).

The propagation direction of dykes have received considerable attention (Gudmundsson et al. 2014). There is considerable evidence that many dykes propagate essentially laterally from shallow magma chambers or conduits in many large volcanic edifices such as Etna and Stromboli (Acocella and Neri 2003; Acocella and Tibaldi 2005). In fact, simple analytical models (Gudmundsson 2011a, b) suggest that lateral dyke propagation may, under certain conditions, be favoured (over vertical propagation) out to distances of many kilometres from the centre of the source conduit or a magma chamber. But such dykes are normally thin, of rather evolved composition, and form a part of the general sheet swarm of the volcano. In Iceland swarms of inclined sheets are up to 18 km in diameter. And even if many dykes may propagate to a degree laterally within the sheet swarm, all the feeders must reach the surface and thus propagate at least partly vertically. In fact, fractures in solids normally propagate in various directions (Pook 2002; Sun and Jin 2012), and the same must apply to dykes and other rock fractures. Detailed studies of sheet swarms also show that many sheets can be traced to the fossil magma chambers (plutons), so that there is generally no doubt about their source and the direction of propagation (e.g., Gudmundsson 2002: Klausen 2004; Burchardt and Gudmundsson 2009).

While the sources and propagation directions of local dykes and inclined sheets are thus well known, the same does not apply to the thick and long and subvertical regional dykes. For these, two basic ideas have been discussed: (1) the dykes are primarily injected vertically from reservoirs in the lower crust or at the crust-mantle boundary; (2) the dykes are primarily injected laterally from shallow magma chambers at the depth of a few kilometres (e.g., Sigurdsson and Sparks 1978; Paquet et al. 2007). The lateral propagation is here supposed to apply to dykes that, in Iceland, reach tens of kilometres in length, and in other areas (such as Canada) hundreds of kilometres (e.g., Ernst et al. 2001).

As for Iceland, the common differences in chemistry and volume between typical eruptive materials associated with feeder dykes inside and outside central volcanoes (the erupted materials outside the volcanoes tend to be much more primitive in composition and of larger volumes) is often taken as an indication that the regional feeder dykes do not form through lateral propagation from shallow magma chambers (which normally hold rather evolved magmas) but rather in primarily vertical flow from deep-seated reservoirs (Gudmundsson 1990; Hartley and Thordarson 2012, 2013). Recently, there have been many magnetic anisotropy studies in Iceland focusing on the direction of magma flow in regional dykes. All kinematic indicators for dykes are subject to somewhat different interpretations, and it should also be noted that the direction of magma flow does not necessarily reflect the main direction of fracture propagation. This latter is well known from volcanic-fissure formation. Thus, close to the surface the magma flow is necessarily primarily vertical. This follows because the flow must reach the commonly flat surface and form volcanic fissures, crater cones, and other structures. At the same time the volcanic-fissure propagation is necessarily primarily lateral at the surface. Thus, commonly, a laterally propagating volcanic fissure channels vertically flowing magma to the surface. However, these recent magnetic anisotropy results indicate primarily inclined, at 30°–60° (Eriksson et al. 2011), or vertical magma flow (Kissel et al. 2010). So far as these results go, they tend to support inclined or vertical magma flow rather than lateral for the regional dykes of Iceland.

3 Sills

Until recently, sills were rarely reported from Iceland. Studies by the present authors in the past decade, however, show that sills are common in Iceland. They occur in the Tertiary and Pleistocene lava piles, as well as in the active volcanic zones (Fig. 4). Sills are particularly common in Pleistocene rocks, partly because of the common abrupt changes in mechanical properties between layers —changes that encourage dyke deflection into sills (Gudmundsson 2011a, b; Gudmundsson and Lotveit 2012). Abrupt changes of this type occur, for example, where lava flows or earlier sills alternate with basaltic breccias, hyaloclastites.

Since the active volcanic systems and central volcanoes contain numerous lava flows and hyaloclastite layers, sill formation is very common in many active volcanoes. Examples include many sills in the Eyjafjallajökull Volcano in South Iceland (Fig. 4a). The emplacement of similar sills is thought to have taken place prior to the 2010 eruptions in Eyjafjallajökull (Sigmundsson et al. 2010; Gudmundsson et al. 2012; Tarasewicz et al. 2012). In some of these interpretations, there were many sill injections in Eyjafjallajökull in the decade before the 2010 eruptions, and some of the sills, it is suggested, reached lateral dimensions (diameters) of as much as 17 km (Sigmundsson et al. 2010).

Sill emplacement and propagation direction are reasonably well understood in general terms. The sills tend to form when dykes or inclined sheets become deflected along discontinuities such as contacts between dissimilar rock layers (Gudmundsson 1990, 2011a, b; Kavanagh et al. 2006). The details of sill formation and propagation are, however, poorly understood. In particular, the conditions that allow dykes to become deflected into sills are still a matter of intense

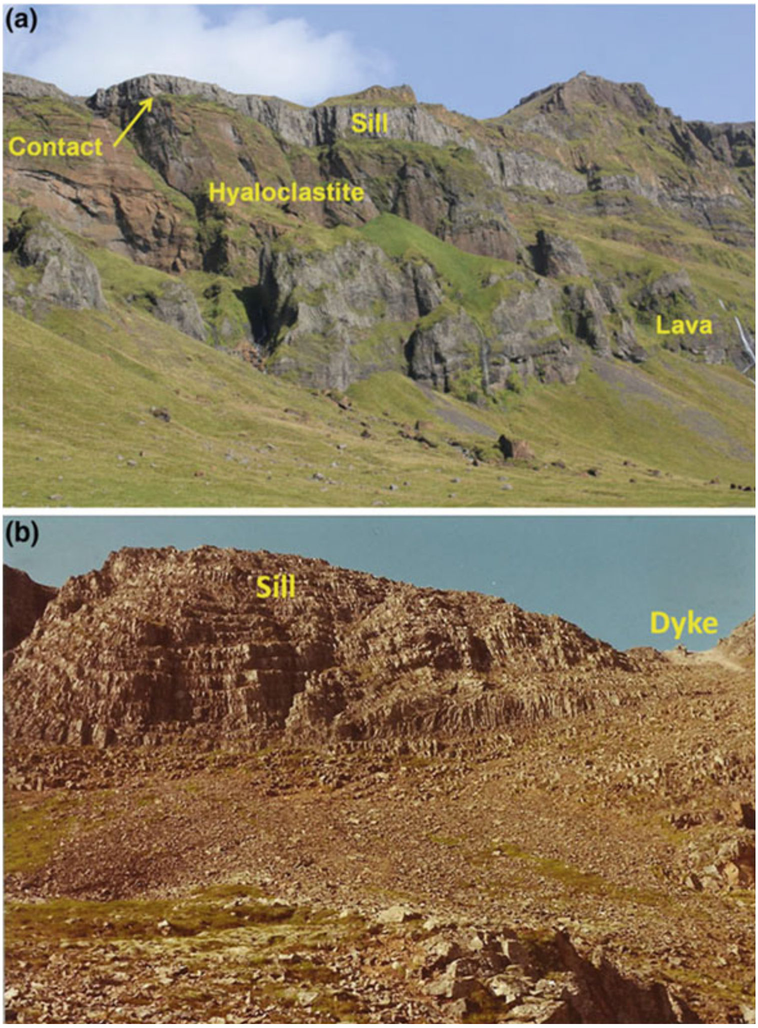

Fig. 4 Sills. **a** Basaltic sills, lava flows, hyaloclastite layers, and contacts in the southern slopes of the Eyjafjallajökull Volcano. **b** View north, part of a 120-m-thick basaltic sill in East Iceland. The sill was formed through multiple injections

research. Also, some dykes become doubly deflected along contacts to form sills, while other dykes are singly deflected; the reasons for these propagation differences are not well understood. Also, sills show many different geometric shapes (Gudmundsson and Lotveit 2012) whose origin are still being studied and analysed.

Observed sills in Iceland range in thickness from centimetres to at least 120 m (Fig. 4b). Little systematic work has been made to trace the sills laterally. Some extend for several kilometres (Gudmundsson and Lotveit 2012), but the ends are often eroded so that the true dimensions are poorly known. Common aspect ratios (lateral dimension/thickness) of sills in the Faeroe Islands are between about 167 and 500 (Hansen et al. 2011), which agrees well with predictions based on simple analytical fracture-mechanics models (Gudmundsson and Lotveit 2012). Based on these ratios, which are likely to be similar for Iceland, many of the thicker sills in Iceland could be many kilometres in diameter.

Sills are important in their own right as one of the three main types of sheet-like intrusions. But they are also widely regarded as the primary structures from which shallow magma chambers in central volcanoes develop (Gudmundsson 1990, 2012a). Some chambers develop from single sill injections, whereas others form gradually through many injections. Many magma chambers maintain their sill-like geometry during the lifetimes of the associated central volcano. Sill-like chambers may generate stress fields that encourage the formation of collapse calderas. Other magma chambers change their shapes as they expand and evolve from the initial sill. Such magma chambers include laccoliths.

4 Laccoliths

There are many laccoliths in Iceland, most of which are composed of acid (felsic) rocks. The best known laccolith is Sandfell in East Iceland. This laccolith is exceptionally well preserved, with part of the roof—a basaltic lava pile—still maintained (Fig. 5a). Sandfell peaks at 743 m a.s.l. and at the time of emplacement the roof of the laccolith was within about 500 m of the surface of the volcanic system within which it formed (Hawkes and Hawkes 1933). It is likely to have acted as a shallow magma chamber for a while, as most shallow intrusions in Iceland apparently do.

Another felsic laccolith is Baula in West Iceland (Fig. 5b). Baula peaks at about 934 m a.s.l. and has an estimated age of 3.5 Ma (Johannesson 1974). The lava pile next to the laccolith shows evidence of upbending, but the roof is not nearly as well preserved as in the Sandfell laccolith. Baula and Sandfell are both several hundred metres thick and composed of felsic rocks.

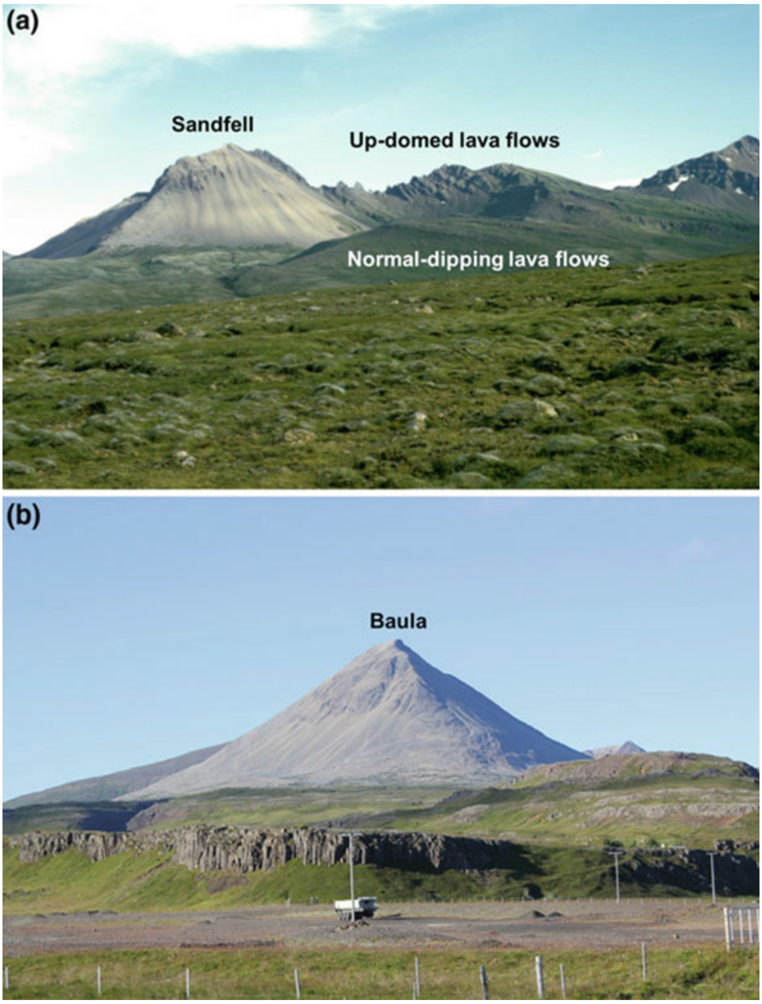

Fig. 5 Felsic laccoliths in the Tertiary lava pile. **a** The laccolith Sandfell in East Iceland. **b** The laccolith Baula in West Iceland

There are also some mafic (basaltic) laccoliths in Iceland. Perhaps the best studied is the mafic laccolith at Stardalur in Southwest Iceland. This laccolith was generated through multiple sheet intrusion, reaches a total thickness of about 200 m, and is located in the middle of a swarm of inclined sheets associated with the 1.8 Ma Stardalur Volcano (Pasquarè and Tibaldi 2007). This laccolith is thus generated in a somewhat similar way as thick, multiple sills (Fig. 4b).

The basic conceptual model of laccolith formation was proposed long ago, and analysed mechanically by Pollard and Johnson (1973). Subsequently, many similar analyses have been made (e.g., McCaffrey and Petford 1997; Rocchi et al. 2002; Bunger and Cruden 2011; Michaut 2011). The basic model, however, remains the same; bending of an elastic crustal plate, the overburden, as a result of magmatic overpressure. The general idea is that laccoliths, like many other plutons (and magma chambers), develop from sills, namely once the sills start to deflect their overburden. While this general model is still used as a basis for understanding laccolith formation, it is clear that elastic bending alone cannot account for the shape of many laccoliths, including those in Iceland (Fig. 5). The bending and uplift is simply too great for elastic deformation to be plausible. Fracturing and plastic deformation are likely to have played a major role in the formation of the laccoliths in Iceland.

5 Inclined Sheets

Most inclined sheets in Iceland are arranged into centrally-dipping swarms departing from a focus area (e.g. Pasquarè and Tibaldi 2007; Tibaldi et al. 2008). The central-dipping sheet geometry and symmetrical arrangement suggest the location and depth of the source magma chamber (e.g. Tibaldi et al. 2011), although uncertainties remain regarding the possibility of reconstructing the exact shape and size of the shallow magma chamber (Figs. 1 and 6).

Outcrops of centrally-inclined sheet swarms below eroded volcanoes are usually limited in lateral/vertical extent, with different geometries of inclined sheets being found, as well as different models proposed to explain them. These models comprise: (i) Concave-downward (trumpet-shaped) sheets with increasing dip closer to the

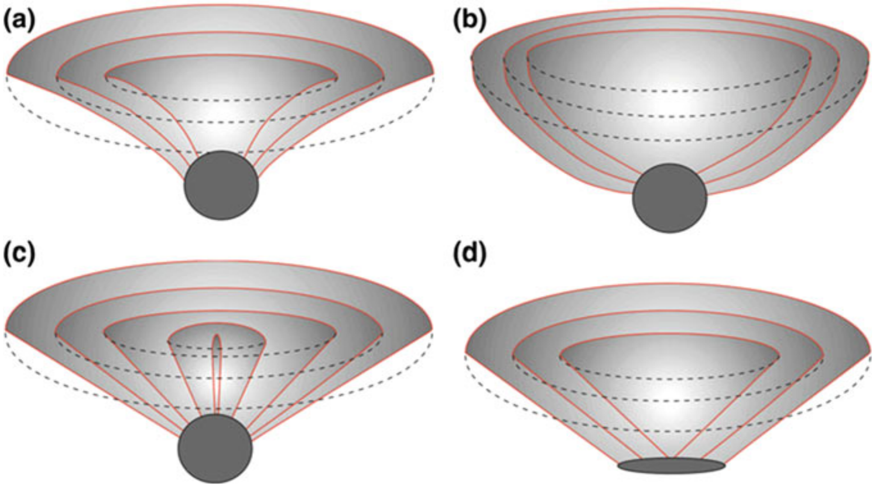

Fig. 6 Possible geometries of centrally-inclined sheet swarms resulting from internal excess magma pressure: **a** radial planar sheets from a spherical magma chamber (after Chadwick and Dieterich 1995; Gudmundsson 1998); **b** concave-upward (bowl-shaped) sheets from a spherical magma chamber (after Chadwick and Dieterich 1995; Gudmundsson 1998); **c** concave-downward (trumpet-shaped) sheets from a sill-shaped magma chamber (after Phillips 1974; Chadwick and Dieterich 1995); **d** planar parallel sheets from a laccolith-like chamber (after Bistacchi et al. 2012)

magmatic source (Fig. 6a) (Phillips 1974); sheets are missing in the central part. (ii) Concave-upward (bowl-shaped) sheets with decreasing sheet dip with depth from a pressurised magma chamber (Fig. 6b) (Phillips 1974); sheets are missing in the central part. (iii) Radial planar sheets from a spherical magma chamber (Fig. 6c) (Chadwick and Dieterich 1995; Gudmundsson 1998). (iv) Planar parallel to sub-parallel sheets originated from a lobate (sill-like) magma chamber (Fig. 6d) (Gudmundsson 1998; Tibaldi et al. 2011; Bistacchi et al. 2012). Here we will review the inclined sheet data collected all over Iceland (Fig. 3) by various authors in order to highlight the common features and possible factors controlling their emplacement.

5.1 West Iceland

In northwest Iceland, inclined sheet swarms are present in three locations in the Vatnsdalur area (Fig. 3) (Siler and Karson 2009). These swarms consist of mafic sheets generally <1.0 m thick that dip radially inward, with dips between 20° and 60°. The largest sheet swarm is 16 km in diameter. Sheets have a planar geometry and 3D reconstructions at the best site (Vididalsfjall) indicate here two cone sheets swarms focusing at 1.0 and 5.0 km bsl respectively. "Hot slickenlines" created during intrusion exclusively plunge down-dip in the planes of the sheets, indicating they were fed from below. These centrally-inclined sheets are associated with major gabbroid intrusions and to eroded volcanoes.

To the southwest, in the area of Kroksfjordur, there is a complex of centrally-inclined sheets associated with a depression (Hald et al. 1971) (Fig. 3). These sheets intrude basal lava flows, breccia and a series of basaltic plugs. Above the centre of the complex, which is about 10 km in diameter, cone sheets are almost lacking. The individual sheets have thickness usually <3 m with most common thickness of 0.5–1.0 m. The sheet complex shows a weak tendency to decrease in dip away from the centre. In the area, a gabbro body crops out over an area of about 1 km^2 but it is not cut by the inclined sheets.

Further to the south, in the Tertiary Reykjadalur Volcano, there is a swarm of centrally-inclined sheets with a total diameter of about 18 km (Gautneb and Gudmundsson 1992) (Fig. 3). The sheets have an average dip of 45° and thickness of 1.0 m. Locally, the sheets make up nearly 90 % of the rock, but in 1–1.5-km-long profiles they are 5.8–7.9 %. One-third of the sheets are porphyritic, containing as much as 50 % of plagioclase phenocrysts. The local magmatic stress field associated with the shallow magma chamber controlled the geometry and, partly, thickness of the sheets to a distance of 9 km from the centre of the volcano.

In westernmost Iceland, in the Snaefellsnes Peninsula that is essentially made up of Tertiary-Quaternary basalts, there are three major intrusions, each one surrounded by a centrally-inclined sheet swarm (Fig. 3). Along the southern side there are the Midhyrna gabbroid and Lysuskard granophiric intrusions (Upton and Wright 1961), whereas on the northern coast there is the Kolgrafarmùli gabbro. All of them intrude the Tertiary basaltic lava flows. The Midhyrna and Lysuskard intrusions are surrounded and intruded by two centrally dipping sheet swarms (Fig. 7) (Tibaldi et al. 2013); these sheets show no gradual variation in dip with distance from the focus area, are rectilinear in section view, and intrude with the same geometry the main intrusive bodies as well as the layered Tertiary lavas. The diameter of both sheet swarms is about 12 km, the average sheet thickness is 0.63 m, and the average dip is 28° (Tibaldi et al. 2013), lower than for other sheet swarms in Iceland whose average dip is 34°. The Kolgrafarmùli gabbro is located near a centrally-inclined sheet swarm (Fig. 3) that corresponds to the Setberg volcanic centre (Sigurdsson 1966). These sheets are inclined 25°–40° towards a focus at about 3 km depth underneath a caldera, filled with silicic breccia and the gabbro intrusion. Based on the Sigurdsson's (1966) map, the sheets cut also the gabbro body. The diameter of the sheet swarm is 11 km.

To the south, the mountain Esja has three centrally-inclined sheet swarms that were emplaced mostly within almost isotropic hyaloclastite deposits (Pasquarè and Tibaldi 2007;

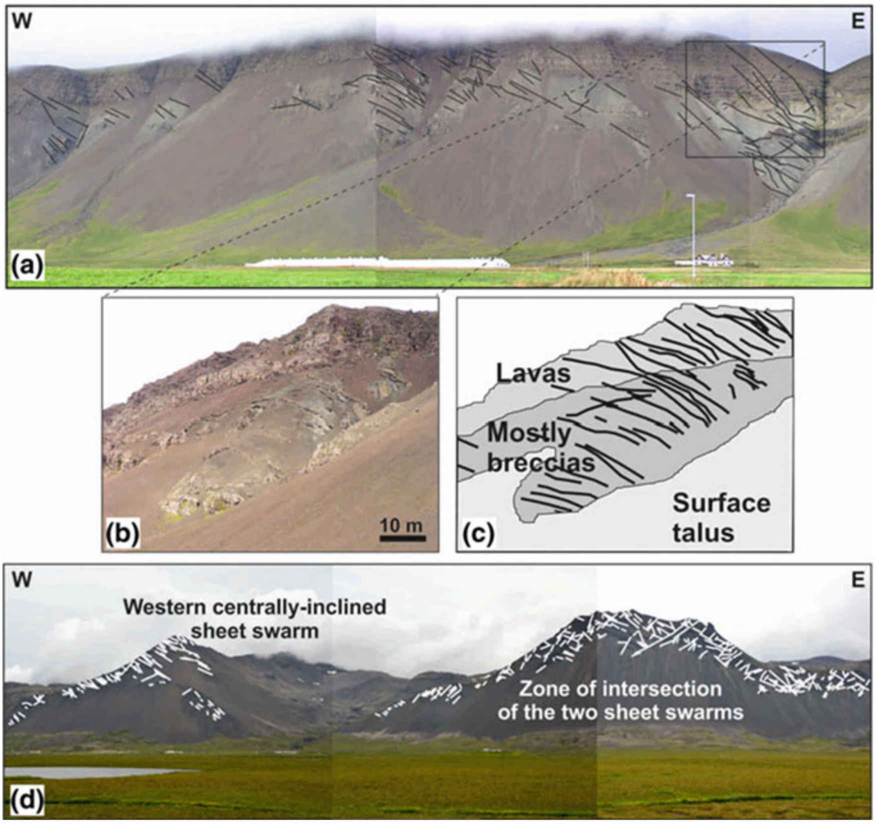

Fig. 7 Examples of centrally-inclined sheet swarms at two different locations in Western Iceland. **a** At Thverfell, SW Iceland, sheets are dipping toward the centrally-located focus area. **b** Detailed image of the sheets intruding the earlier, effusive sequence. **c** Interpretation of the previous image, showing lavas and breccias intruded by inclined sheets. **d** At the Snaefellsnes Peninsula, two different swarms converge toward two different focus areas. The eastward-dipping swarm and the area where the two swarms cross-cut are clearly visible

Tibaldi et al. 2008) (Fig. 3). These sheet swarms were emplaced during a transcurrent fault phase, in plan view have an E-W elongation and alignment parallel to the strike-slip faults, and show a slight but systematic gradual dip decrease outwards. All of them are associated with dioritic laccoliths (Tibaldi and Pasquarè 2008). At the Thverfell swarm, 8 km in diameter, the average sheet thickness is 1.1 m and the dip is 32°. At Stardalur swarm, 12 km in diameter, sheets are associated with a caldera, have average thickness of 1.7 m and dip of 35°. At Kjalarnes the sheet swarm diameter is 5 km.

At the extinct Hvalfjordur Volcano, of Tertiary age, in southwest Iceland (Fig. 3) sheet strike is spread over the whole circle, with a slight peak in the northeastern sector, parallel with the trend of the rift zone in southwest Iceland within which the swarm formed (Gudmundsson 1995). The dip of the sheets ranges 5°–90°. The dip-frequency distribution has two peaks at 70°–90° and at 10°–40°. The sheets range in thickness from several centimeters to 14 m, the most common thickness being <0.5 m.

In southwest Iceland, the 4–6 Ma old Hafnarfjall Volcano was studied by Gautneb et al. (1989) who documented a centrally-inclined sheet swarm that deviates from a circular distribution more than other swarms in Iceland: in particular, the sheets are preferentially NE-striking, that is, parallel to the NE-trending West Volcanic Zone and partly controlled by the associated regional stress field.

5.2 East Iceland

The exposed interior of the Thverartindur igneous centre (Fig. 3; Klausen 2004) is characterised by a dense circular swarm of centrally inclined sheets. The study of the orientation and thickness of 745 mafic sheets suggest a bowl- and slightly fan-shaped swarm geometry, located above a 4-km-thick, ~140-km^3-large, slightly flattened magma source. The sharp decrease in sheet density along the inner and outer margins of the swarm suggest that most sheets were injected from a narrower source area than the swarm's estimated 2–3 km width at the surface. The sheet swarm is marked by a significant (17°/km) outward decrease away from the source, as noted also at several other eroded central volcanoes in Iceland, such as Reykjadalur (Gautneb and Gudmundsson 1992) and Stardalur (Pasquarè and Tibaldi 2007). The 0.1 m/km decrease in the average sheet thickness through the swarm reflects the upward narrowing of sheets, while the relatively low number of <0.5-m-thick sheets in the uppermost part of the swarm is interpreted to reflect the subsurface arrest of more than a third of all sheets injected from the source.

The 5–6 Ma old Geitafell Volcano in Southeast Iceland (Fig. 3) is located in an area marked by the deepest glacial erosion in Iceland (2 km). Glacial valleys cut the centre of the volcano and expose sections that reach down to the roofs of several gabbro plutons, which in turn are surrounded by dense swarms of inclined sheets and remnants of a high-temperature geothermal system (Fridleifsson 1983, 1984). Inclined sheets, exposed along several deep canyons in the vicinity of the gabbros, comprise about 10,000, mainly basaltic, sheet intrusions. Burchardt and Gudmundsson (2009) suggest that the Geitafell sheet swarm is most likely bowl-shaped (i.e., concave upward), and field studies support that most of the sheets are related to the gabbros in the area, presumably the uppermost part of the shallow magma chamber of the Geitafell Volcano. A second swarm of younger and steeper-dipping inclined sheets may represent a later and deeper magma source located a few hundred meters to the east that may indicate an independent pulse of activity.

6 Discussion

Field studies of dykes, sills, laccoliths and inclined sheets improve our understanding of their mechanics of emplacement and general transport of magma in the crust. In particular, since almost all eruptions are fed by dykes or inclined sheets, understanding how they propagate to the surface or, alternatively, become arrested in some crustal layers at depth is of fundamental importance for interpreting volcanic unrest periods and hazards in active volcanoes and, in particular, the geophysical and geochemical data obtained through volcano monitoring.

As indicated above, the details of the mechanics of propagation and path formation for sheet-like intrusions are still poorly understood and subject to intensive research. For the Icelandic intrusions, it is reasonably clear that most of the inclined sheets (including the associated local dykes) can be traced to shallow magma chambers, located at 1–5 km depth below the surface of the volcano at the time of sheet formation. From these shallow magma chambers, the sheets propagate in all directions—but those that are located above the magma chambers must to a large degree propagate upwards and dip-parallel, particularly the feeders for eruptions. For the regional dykes, the results are not so clear; some data may suggest primarily lateral flow of magma from shallow magma chambers, whereas other data indicate primarily inclined or vertical flow of magma from deep-seated reservoirs.

The details of the propagation path itself, whether generated through lateral flow, vertical flow, or a mixture of both, is of fundamental importance for hazard assessment. When a magma chamber ruptures and injects a sheet-like intrusion during an unrest period, the propagation path and final geometry of that intrusion depends on various factors. These include the elastic energy available to produce the fracture (the surface energy) and propagate the intrusion, the local stresses in the host rock, and the rheological properties of the magma (e.g., Gudmundsson 2012b; Tait and Taisne 2013; Gonnermann and Manga 2013). When the host rock is modelled as a homogeneous, isotropic elastic half space, as is common in some deformation studies, the primary constraint on the rate of intrusion propagation is the viscosity of the magma (Spence and Turcotte 1985; Lister and Kerr 1991).

Volcanic zones and, in particular, central volcanoes (stratovolcanoes, calderas) are characterised by layers that commonly have widely different properties (Fig. 4; Apuani et al. 2005; Geshi et al. 2010). They are thus analogous to composite materials whose mechanical properties commonly vary abruptly between layers. A primary control on fracture propagation and arrest in composite materials is the variation in their mechanical properties, particularly abrupt changes in Young's modulus between layers as well as the properties of the layer contacts or interfaces in relation to those of the adjacent layers (He and Hutchinson 1989; Pook 2002; Sun and Jin 2012). In fact, composite materials are made strong—that is, resistant to fracture propagation—through alternating layers and contacts of widely different mechanical properties.

Most arrested dykes become arrested at contacts between layers (Gudmundsson 2002). Similarly, most deflected dykes become deflected (commonly into sills) at contacts (Gudmundsson 2011a). It is thus clear that layering in volcanoes has great effects on sheet-intrusion propagation paths. This is well known from field studies (Geshi et al. 2010), and is also implied in the interpretation of geodetic and seismic studies during unrest periods in volcanoes. For example, there appear to have been several episodes of dyke injections in the Eyjafjallajökull Volcano in the 1990s and again in 2009 before the dyke-fed eruptions of 2010 occurred (Jakobsdottir 2008; Sigmundsson et al. 2010). The earlier dykes apparently became arrested, presumably at contacts between mechanically dissimilar rocks (Fig. 4a), and some dykes are thought to have been deflected into sills (Sigmundsson et al. 2010; Gudmundsson et al. 2012; Tarasewicz et al. 2012).

While Eyjafjallajökull was very well monitored prior to the 2010 eruptions, the details of the paths of the dykes and sills and inclined sheets that eventually resulted in the eruptions are poorly known and understood. Mechanical layering is a major factor that largely controls the sheet-intrusion paths, including their attitudes (and thus whether they propagate as dykes, inclined sheets, or sills) and arrest (and thus whether they become feeders to eruptions). Another factor is the elastic energy available to drive the sheet-fracture propagation (Gudmundsson 2012b). While both these aspects of sheet-intrusion propagation and magma movement have received considerable attention in recent years, the mechanical complexity of many volcanic zones and central volcanoes means that much research is needed before reasonably accurate models will be available for forecasting the likely sheet-intrusion propagation paths during unrest periods.

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