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Sill propagation and climbing in layered crystalline host-rocks: Examples from saucer-shaped sills of the Faroe Islands

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Mafic sills, which commonly occur in layered sedimentary and crystalline settings worldwide, may occur as sub-lateral sheets or as saucer-shaped bodies. Values and distributions of Young's Modulus within their ambient host-rocks determine their mode of emplacement. Current models on development of saucer-shaped sills depict either melt propagation from single sources along sub-lateral relatively weak layers, from which they abruptly climb/transgress through stronger layers at intervals, or they may evolve by radial melt propagation/intrusion from one or more sources, while gradually/continuously ascending/climbing through strong and weak layers alike. The first model invokes involvement of sill overburdens and overlying free surfaces, while the latter envisages closed igneous systems, where host-rocks both above and below the advancing magmas are affected without involvement of overlying free surfaces. Margins of saucer-shaped sills at various stages of developments, cropping out in the Faroe-Islands, offer some new insights into sill evolvement in layered crystalline host-rocks. This study suggests that the slightly upward-curving geometries of Faroese sills stem from initial radial propagations/intrusions of thin magma fronts, where systematic depth-dependent variations of Young's Modulus in the Earth's crust governed gradual and continuous climbing of these. Some of their melts likely propagated initially as lobes or thin magma-fingers in a mole-like fashion before coalescing, without noticeably affecting the overlying free surfaces prior to the main inflation phases.

Introduction

Basaltic sills, displaying a variety of geometries and sizes, have been reported in numerous extension/rifting related settings worldwide, the most common of which being sedimentary basins and basaltic lava piles[1,2]. Sills may occur individually, but do not un-commonly occur in droves, where individual intrusions can be interconnected and are thus often thought to have acted as reservoirs and conduits during magma transport to the Earth's surface[1-6]. As sill intrusions reside in both offshore and onshore environments, investigations of these are in general based on seismic images/profiles for the former and on direct visual observations and

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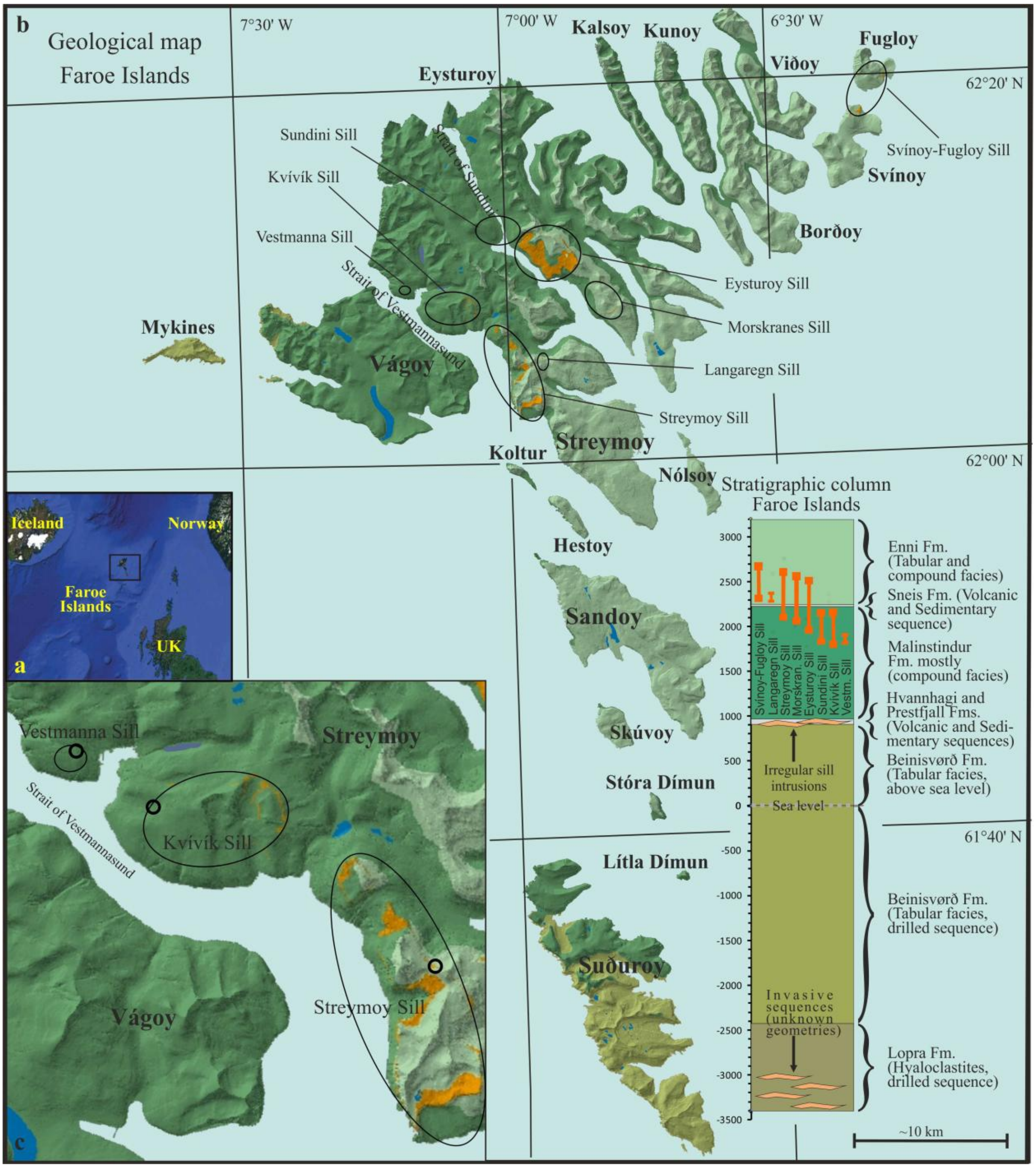

Figure 1. Brief description of the general area and locations utilised in this study (Modified from: Hansen and Ganerød, 2023). **a**, Geographical location of the Faroe Islands, based on Google Earth. **b**, Geological map of the Faroe Islands, based on topographic data from Munin fo, displays local geological formations and geo-locations of the local saucer-shaped sills of this study. **c**, Close-up view of the three sills included in this contribution, based on topographic data from Munin fo, where small black circles indicate exact localities.

measurements for the latter versions. Although widespread sill networks can be highly visible in seismic images from offshore sedimentary basins[7,8], direct investigation of sill networks and/or individual sills, cropping out onshore, may better disclose details in their developing history.

A mechanism with sub-lateral melt propagation along weak layers with intermittent transgressions/climbing through stronger stratum, i.e. melt advancement through layers with varying values of Young's Modulus, has frequently been invoked for development of saucer-shaped sills in stratified sedimentary media[9]. Interaction between advancing melts and overlying free surfaces during sill formation is commonly envisaged for sill emplacement in relatively shallow crustal environments, where certain sill lengths/diameters versus their depths of intrusion are thought to determine their angles of transgression/climbing and hence their ultimate sizes[6,9]. An alternative theory, applicable for sill intrusion into layered crystalline media, such as basaltic lava successions of various thicknesses, which are occasionally separated by thinner sedimentary/volcaniclastic sequences, proposes propagation of thin magma fronts, where uneven displacement of strata above and below advancing sill tips determine their angles of gradual and continuous transgression/climbing[1,4,10]. These authors did not envisage any noticeable interaction between the advancing melts and overlying free surfaces prior to any main inflation phases. This latter model relies on the fact that systematic depth dependent variations in values of Young's Modulus have been reported for the Earth's crust previously[11].

The basaltic lava pile, making up the archipelago of the Faroe Islands, which are situated at the NW European margin (Fig. 1), hosts a number of saucer-shaped sills of various sizes, which are 'frozen in time' in various stages of developments[1,4,10]. In general, most of the eight formations making up these basaltic successions are intruded by a host of sub-vertical dykes and numerous irregular intrusions, while the sills of this study crop out in the uppermost Malinstindur, Sneis and Enni formations (Fig. 1).

Sill occurrences in the Faroe Islands

In this study, we focus on well-exposed margins of a few Faroese sills of various thicknesses (Fig. 1). Field evidences suggest that at least some of their initial magmas progressed in a radial fashion in part as lobes or as broad fingers prior to ultimately coalescing, as demonstrated in this contribution.

The sills of the Faroe Islands were emplaced in an extensional/rifting related geological environment during a relatively wide time span from ~55.5 Ma to ~50.5 Ma[12]. These sills are typified in that they decreased in sizes and volumes with time, i.e. the largest sills are ~55.5 Ma old with younger ones decreasing in size until intrusion of the least voluminous at ~50.5 Ma[12]. The oldest Faroese sills and sill segments decrease in thicknesses from the SE towards the NW, which is also consistent with intrusion at increasingly greater stratigraphical depths from the SE towards the NW[1,4,10,12].

Field evidences and measurements

The sill margins being focused on in this study display thicknesses of 0.35 to 0.60 metres for the Kvívík Sill, ≤ 1.5 metres for the Vestmanna Sill and ≥ 15 metres for the Streymoy Sill. If it is assumed that the uppermost Faroese Enni Formation (Fig. 1) had an original average thickness of ~1 to ~1 ½ km[13], then the melts that gave rise to the fringes of the sills, which are utilised in this contribution, originally crystallised at stratigraphical depths of ~1 to ~1 ½ km as regards the ~55.5 Ma old Streymoy Sill and ~1.4 to ~1.9 km as regard the ~55.5 Ma Kvívík Sill and the ~50.5 Ma Vestmanna Sill. Hence, the studied thin margins of the Kvívík and Vestmanna sills crystallised at 400 to 500 metres greater stratigraphical depths when compared to the much thicker studied margin of the Streymoy Sill. The characteristics displayed by these three sill margins/fringes can briefly be described as:

The actual locality of the Kvívík Sill is characterised by discontinuous slightly inclined thin sill lobes, which are more or less arranged in en-echelon fashions (Fig. 2a). Here, the front of one exemplified section to the right (SE) is connected to the tail of the next one at slightly lower elevation to the left (NW) by a number of very thin dykes/'dykelets' (Fig. 2b). It is noteworthy that thicknesses and density of 'dykelets' decrease slightly downwards from the SE towards the NW (Fig. 2c).

The studied margin of the Vestmanna Sill represents a cross section of two relatively thin sub-horizontal magmatic lobes exposed at slightly different elevations, with the higher to the left (NW) and the lower to the right (SE) (Fig. 3a). These two lobes are connected 'end to end' by a much thinner sub-vertical 'connection' (Fig. 3b).

The studied margin of the Streymoy Sill is characterised by a thick and continuous margin to the left (SE), with a somewhat thinner and lower-lying lens-shaped margin/section to the right (NW). These are separated by a belt of host-rocks measuring around 15 to 20 metres (Fig. 4a). These two margin sections are more or less connected by a multi-dike, emanating sub-vertically upwards from the SE tip of the lens-shaped lower margin and sub-vertically downwards from the bottom of the upper margin. The uppermost parts of this multi-dyke, consisting of 4 to 5 thin individual dykes/'dykelets', extend downwards for ~1/4 of the total distance from the upper margin, while ~12 closely spaced individual thin dykes/'dykelets', with individual thicknesses from a few centimetres to a maximum of ~12 cm with a

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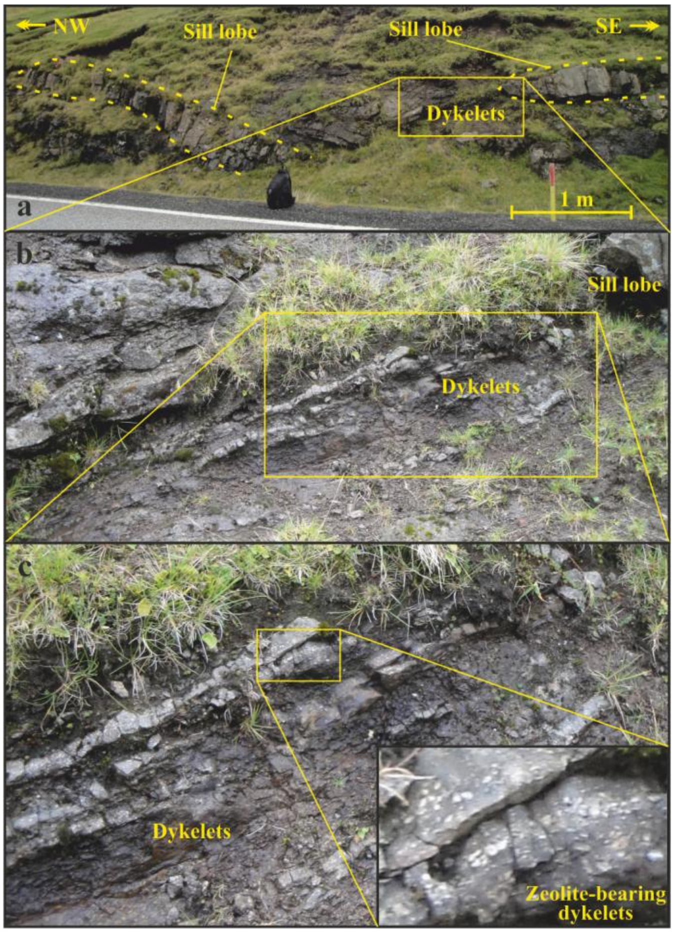

Figure 2. Images of a very thin margin of the Kvívík Sill in the valley of Gassádal. **a**, Slightly inclined thin sill lobes (≤ 3-4° dip towards ESE), being ≤ 0.5 m thick, arranged in en-echelon fashion, which are more or less connected by a moderately inclined 'dykelets'. Yellow dashed lines indicate sill outlines. **b**, 'Dykelets' become thinner with decreasing depths. **c**, Closer view of **b**, with inset showing close-up view of dykelets.

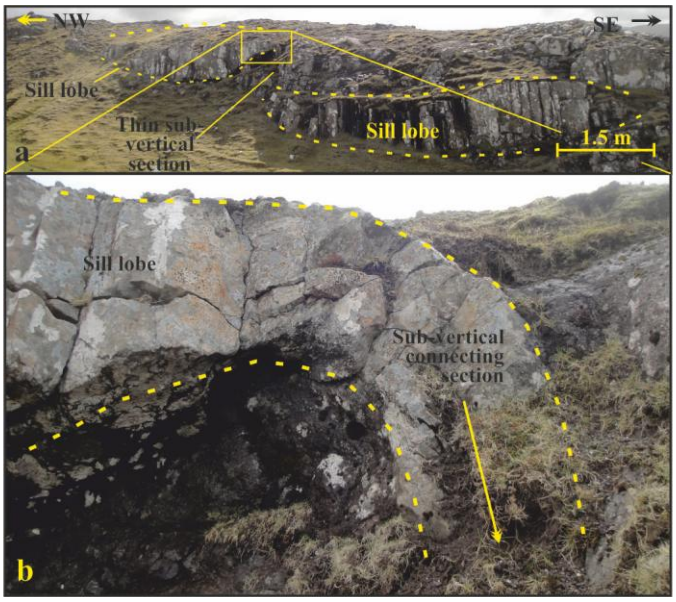

Figure 3. Images of a thin margin of the Vestmanna Sill on the mountain of Hægstafjall. **a**, Cross-section of thin (≤ 1.5 m thick) roughly sub-horizontal sill lobes arranged at slightly different altitudes. Yellow dashed lines indicate lobe outlines. **b**, The sill lobes are connected by an even thinner (≤ 0.35 m thick) short sub-vertical section.

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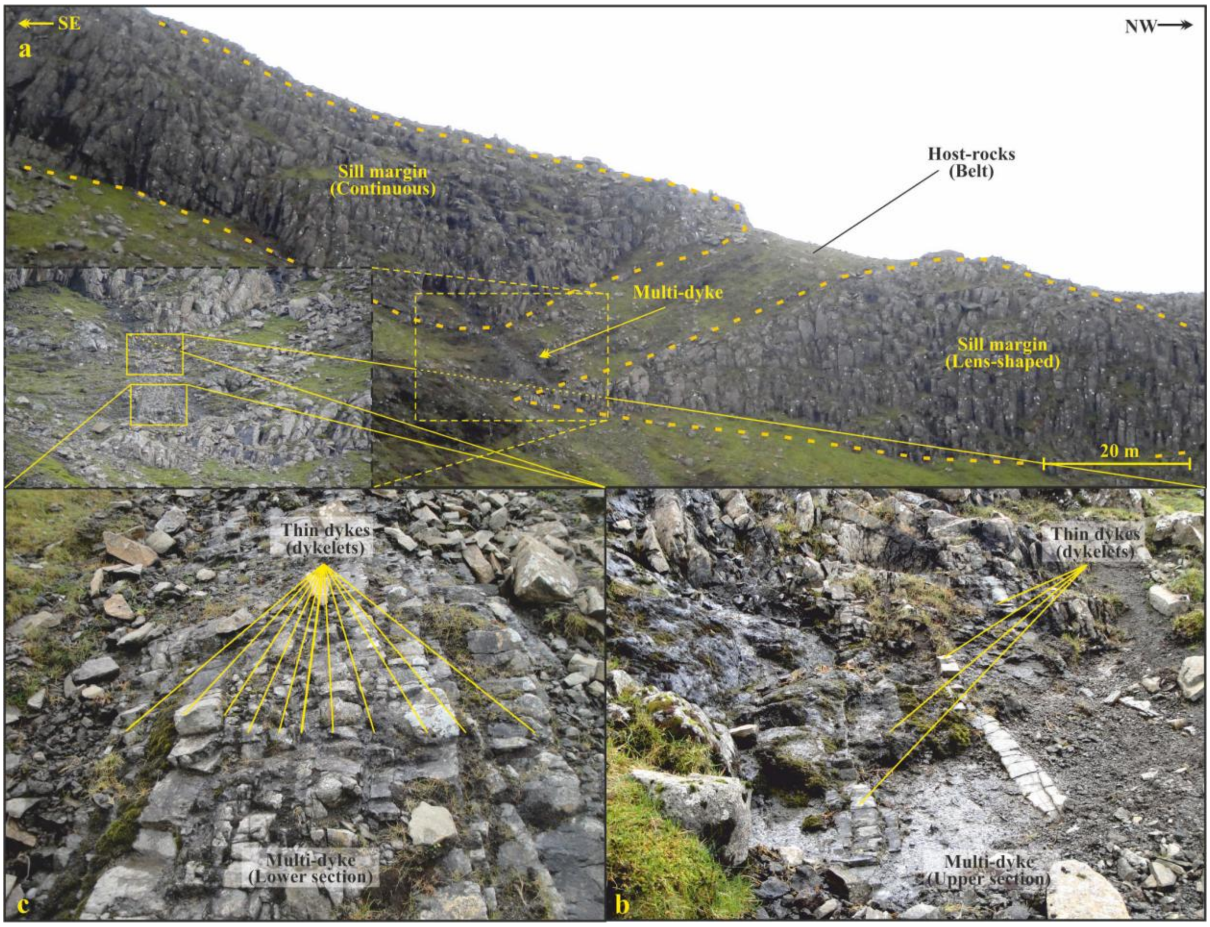

Figure 4. Images of the thick margin of the Streymoy Sill in the valley of Hundsarabotn. **a**, Cross-section of a more than ~20 m thick sill margin, moderately inclined (≥ ~5° dip.) towards the SW arranged as a lens-shaped body to the right and a continuous section to the left at slightly higher altitude being separated by a belt of host-rocks. The margin/sections are more or less connected by a sub-vertical multi-dyke. Yellow dashed lines indicate outlines of sill margin/sections. **b**. A few 'dykelets' of the upper1/4 of the multi-dyke. **c**, Numerous 'dykelets' of the lower 3/4 of the multi-dyke.

combined maximum width of between 1.6 to 1.8 metres for the entire multi-dyke, extend upwards for ~3/4 of the total distance from the lower margin (Fig. 4b,c).

Strike and dip measurements suggest that initial magma flows progressed more or less from right to left for the Kvívík Sill (Fig. 2), while initial melts broadly progressed towards the reader at slight upwards angles in the other two sill margins (Fig. 3; Fig. 4).

Modes of sill intrusion

Based on some of the noticeable characteristics displayed by the investigated sill margins/rims of this contribution, a few inferences can be put forward.

The actual margin of the Streymoy Sill is thick and this intrusion was probably fully developed, while the studied margins of the basal sections of the Vestmanna and Kvívík sills are thin and were quite likely only in their infancy once they crystallised at deeper stratigraphical levels. It is noticeable that the upper rims of e.g. the Kvívík Sill a few kilometres towards the ENE (Fig. 1, not shown) are much thicker (≤ 15 m), thus giving this sill an overall wedge shaped appearance, a feature also displayed by the Faroese Morskranes and Sundini sills[1,10] (Fig. 1b).

The multi-dykes/'dykelets', associated with the margins of the Kvívík and Streymoy sills of this study reveal details on initial principal stress axes in host-rocks around their advancing tips and on either side of the evolving intrusions. During sill intrusion prior to any breach of overlaying free surfaces two sets of principal stress axes are in existence within their immediate host-rocks, namely the regional principal stress axes and the intrusion-induced principal stress axes next to the advancing melts[4] (Fig. 5). Fracture/tensile strengths within actual host-rocks play a noticeable role too, when it comes to modes of sill propagation. Ultimate breaching of sill overburdens to overlaying free surfaces during sill intrusion/inflation can have a profound effect on sill geometries during the latter stages of their evolutions[1-4,10].

The two lobes and associated thin 'dykelets', shown for the Kvívík Sill margin (Fig. 2), display a 'classic example' of propagation of very thin magma fronts/lobes with semi-elastic displacement of their host-rocks, where orientations of 'dykelets' between these lobes coincide perfectly with orientations of local principal stress axis σ_1 trajectories inferred for advancing sill tips in semi-elastic media (Fig. 5a,b). Moreover, the fact that the 'dykelets' emanate diagonally downwards at moderate angles from the front of one of the actual lobes provide an ample proof of the compression of host-rocks below thin advancing sub-horizontal magma tips/fronts, and not only above them. The restricted thicknesses of the actual lobes of the Kvívík Sill in particular and their relatively great stratigraphical depths strongly suggest that their initial melts advanced and climbed as slightly inclined lobes or fingers in a mole-like fashion (prior to ultimately joining together) without interacting with the Earth's free surface. Here, general depth-dependent variations in Young's Modulus in the Earth's crust[11], where host-rocks atop thin advancing magma fronts are displaced slightly more than those below these due to uneven values of Young's Modulus, most probably caused the magma lobes/fingers to advance and climb at slight angles, as envisaged in previous studies[1,4,10] (Fig. 5a,b).

When it comes to the actual margin of the Vestmanna Sill, it could represent a slight evolution from its thinner counterpart in the Kvívík Sill, where the thin connecting section either represents a single 'dykelet' that has inflated to ~0.35 metres or it may represent

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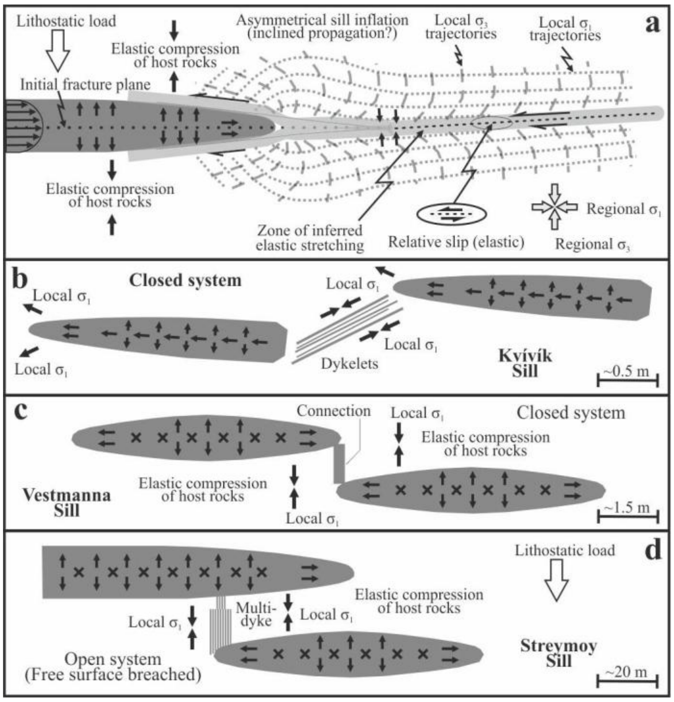

Figure 5. Brief description of mechanics/processes associated with sub-horizontal sill intrusion (**a** is modified from: Hansen, 2015). **a**, Asymmetrical small-scale inflation of advancing thin magma fronts will result in asymmetrical local stress trajectories in host-rocks around the tips of these and generate slightly inclined propagation. One-sided arrows indicate local shear stresses, while full black arrows inside sill indicate magma flow and those in surrounding host-rocks indicate stresses generated by the advancing magmas. σ_1 indicates largest principal stress axis while σ_3 point to the least principal stress axis. **b**, Simplified sketch illustrating relevant stress fields during formation of 'dykelets', as shown for the Kvivik Sill in Fig. 2. Slightly inclined magma propagation largely from right to left as indicated by black arrows. **c**, Simplified sketch illustrating relevant stress fields during formation of thin connecting section, as shown for the Vestmanna Sill in Fig. 3. Magma propagation largely towards the reader, as indicated by black crosses. **d**, Simplified sketch illustrating relevant stress fields during formation of multi-dyke, as shown for the Streymoy Sill in Fig. 4. Magma propagation largely towards the reader, as indicated by black crosses.

several 'dykelets' that ultimately coalesced into one following displacement of initial slivers of host-rocks in between (Fig. 3; Fig. 5c).

It is overwhelmingly likely that the actual margin of the Streymoy Sill, situated at a relatively high stratigraphic level, displaced and breached its overburden and the Earth's free surface during inflation. This scenario, where tensile strengths in host-rocks on top of the inflating sill no longer played a vital role, most likely caused a reorganisation of local principal stress axes, which is reflected by the orientation and overall asymmetrical nature of the actual sub-vertical multi-dyke (Fig. 4; Fig. 5d). Here, the greater density and lengths of 'dykelets' emanating upwards from the lower-laying lens-shaped sill margin, as compared to those stretching downwards from the higher sill margin, point to interaction with the overlaying free surface during sill inflation. Accordingly, the probable breaching of the overlaying free surface likely interfered with the local largest principal stress axis σ_1 between the two inflating sill sections, so as to reduce compression below both of these during the final

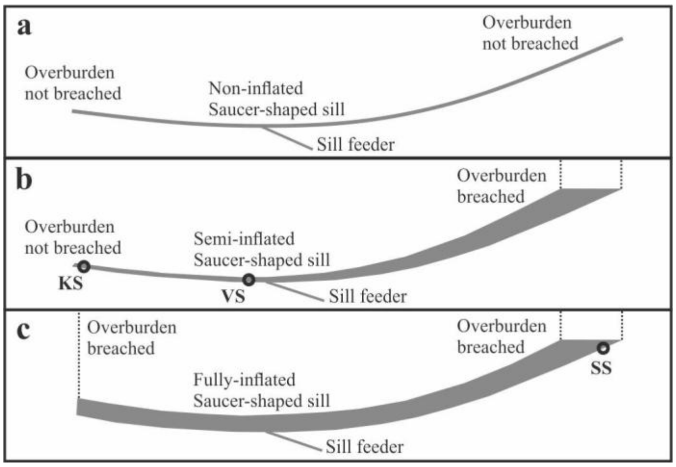

Figure 6. Simplified drawings depicting sill evolution in basaltic lava successions (Modified from: Hansen, 2011, Hansen et al., 2011). **a**, Fully developed sill geometry from propagation of thin magma fronts in a closed system. **b**, Sill overburden is breached atop its highest point and inflation has commenced. The Faroese Kvívík, Sundini and Morskranes sills display similar wedge-shaped geometries. Small open circle denoted **KS** points to studied margin of the Kvivik Sill while that being denoted **VS** points to studied margin of the Vestmanna Sill. **c**, Sill overburden is breached atop either ends and intrusion is fully inflated. The Faroese Streymoy, Eysturoy and Svínoy-Fugloy sills largely display similar geometries. Small open circle denoted **SS** points to the studied margin of the Streymoy Sill.

phases of their evolvement/inflation. Therefore, host-rocks above these margins were relatively more compressed by propagation/inflation compared to those below them (Fig. 4; Fig. 5d).

In conclusion, the sill margins of this study crystallised at various stratigraphical levels and at various stages of development. The characteristics displayed by these and associated multi-dykes may disclose general facts on evolution patterns of basaltic sills intruded into volcanic lava successions.

Here, the characteristics of the thinner sill margins point to development by slight climbing of thin magma fronts across strong and weaker layers alike in response to general depth-dependent variations in values of Young’s Modulus in the Earth’s crust. Accordingly, the greater parts of sill geometries in such settings may form prior to any involvement or breaching of overburdens and overlaying free surfaces. Once sill overburdens and overlaying free surfaces are indeed breached, general sill inflation will take place (Fig. 6a-c).

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