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

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Abstract: Mafic sills/dolerites, commonly occurring 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, cropping out in the Faroe-Islands, offer new insight of sill evolvement in layered crystalline host-rocks. This study strongly suggests that the slightly upward-curving geometries of these sills stem from radial propagation/intrusion of thin magma fronts. Their melts likely propagated as lobes or thin magma-fingers in a mole-like fashion, 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 measurements for the latter versions. Widespread sill networks can be highly visible in seismic images from offshore sedimentary basins[7,8], but direct investigation of sill networks

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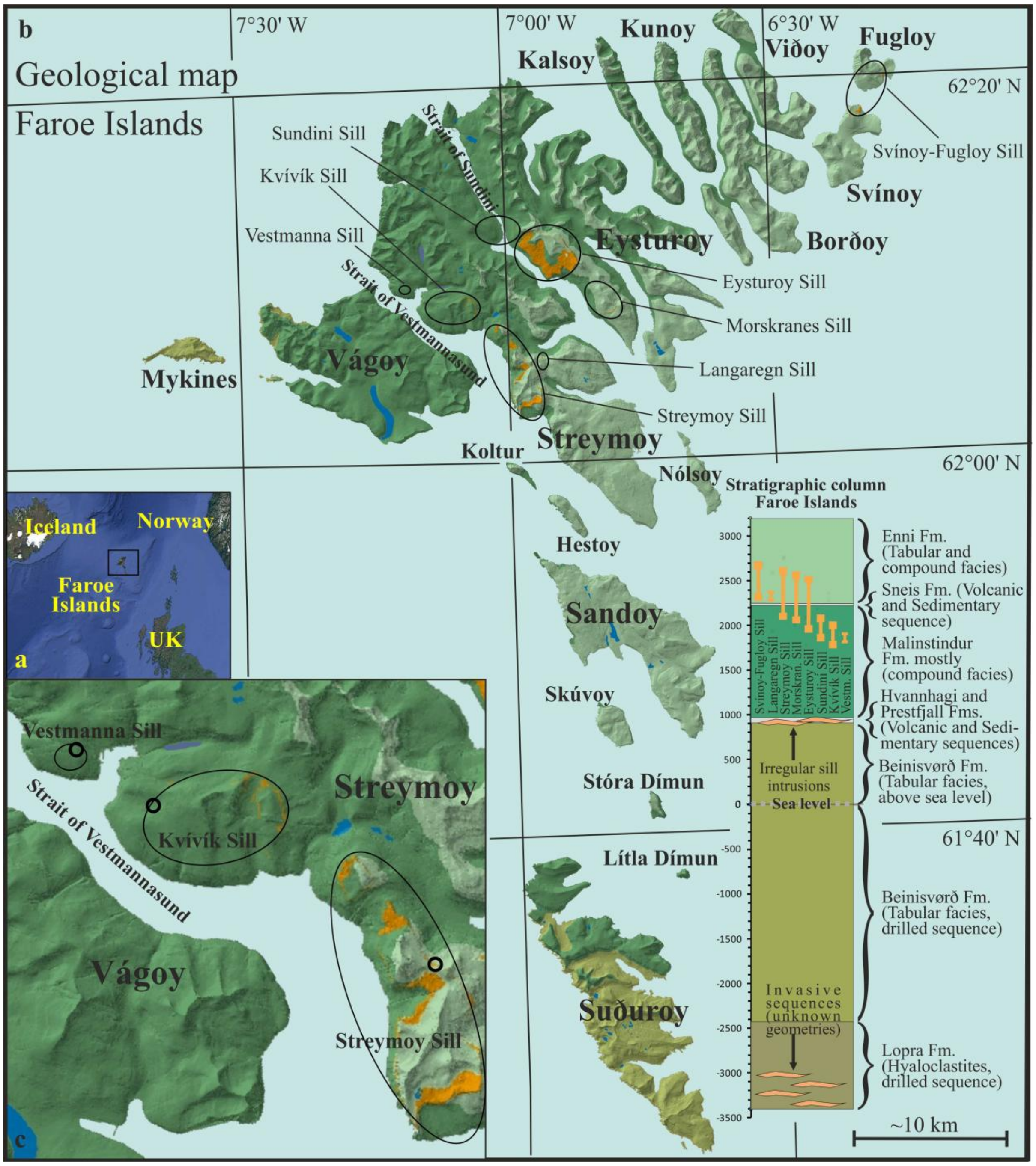

Fig.1 | Brief description of the general area and locations utilised in this study (Modified from: Hansen and Ganerød, 2023). a, Geographical location of the Faroe Islands, based on Google Earth. **b**, Geology of the Faroe Islands, with map-based on topographic data from Munin fo, displaying local geological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

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, is frequently 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 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 (I.e. basaltic lava flows of various thicknesses, occasionally separated by thinner sedimentary/volcaniclastic sequences.), suggests propagation of thin magma fronts, where displacement of strata above and below advancing sill tips determine their angles of gradual and continuous transgression/climbing[1,4,10], which in turn would be in accordance with estimated depth dependent values of Young's Modulus in the Earth's crust[11]. These authors did not envisage any noticeable interaction between the advancing melts and overlying free surfaces prior to the main inflation phases.

The basaltic lava pile, making up 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 focused on well-exposed margins of a few Faroese sills of various thicknesses. Field evidences suggest that their initial magmas progressed in a radial fashion in part as lobes or as broad fingers, 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 less 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 increasing stratigraphical intrusive 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 Kvivik sill, ~1.5 to 2 metres for the Vestmanna Sill and > 10 metres for the Streymoy Sill.

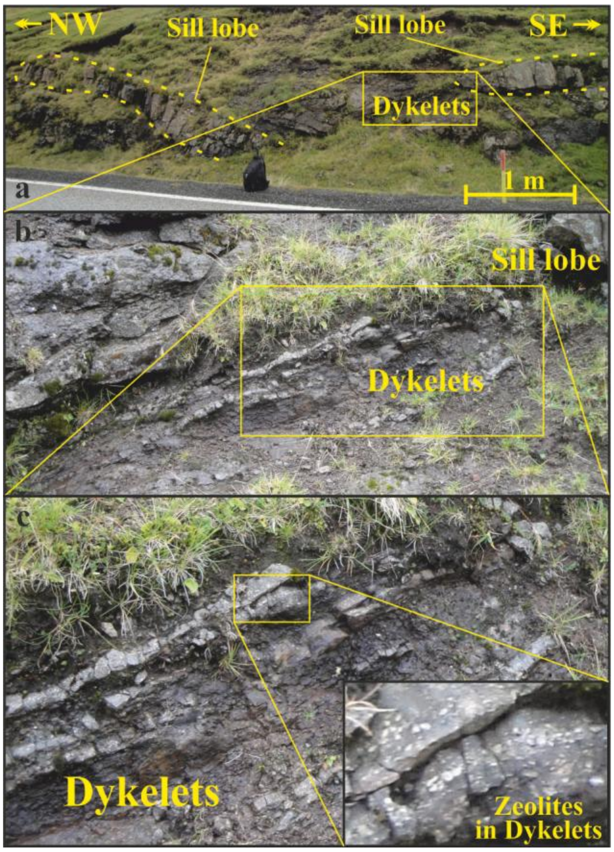

Fig.2 | Images of a thin margin of the Kvívík Sill in the valley of Gassádal. a, Slightly inclined thin sill lobes (≤ 3-4° dip towards ESE), being ≤ 0.5 m thick, arranged in a sort of en-echelon fashion, which are more or less connected by a steeply-dipping 'dykelet swarm'. Yellow dashed lines indicate outlines of sill lobes. **b**, Thin 'dykelets', as seen diagonal from right to left, become thinner with decreasing depths. **c**, Closer view of **b**, where the magnified inset show zeolites in centres of dykelets.

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, 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 thin margins of the Kvívík and Vestmanna sills crystallised at 400 to 500 metres greater stratigraphical depths than that of the much thicker Streymoy Sill. The characteristics displayed by these three sill margins can be described as follows:

The studied locality of the Kvívík Sill is characterised by discontinuous slightly inclined thin sill margins/sections arranged in a sort of an en-echelon fashion (Fig. 2a). Here, the front of one 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', which dip at moderate angles (Fig. 2b). It can be noted that thicknesses and density of the 'dykelets' decrease slightly downwards from the SE towards the NW (Fig. 2c).

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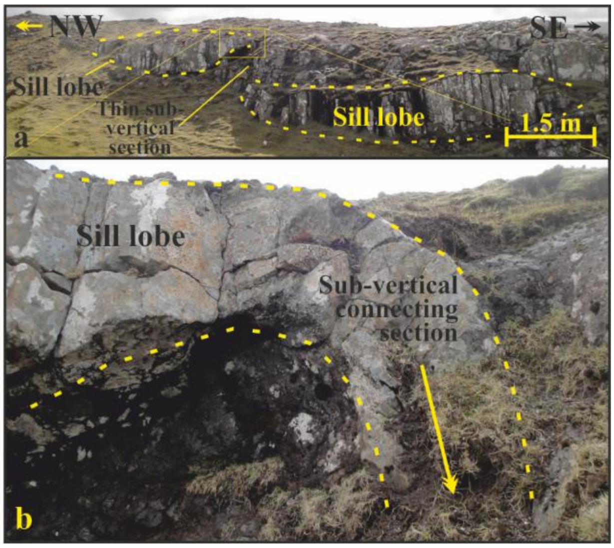

Fig.3 | Images of a thin margin of the Vestmanna Sill on the mountain of Hægstafjall. a, Cross-section of thin (≤ 1.5 m thick) roughly sub-horizontal sill lobes arranged at slightly different altitudes. Yellow dashed lines indicate lobe outlines. **b**, The sill lobes are connected by an even thinner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

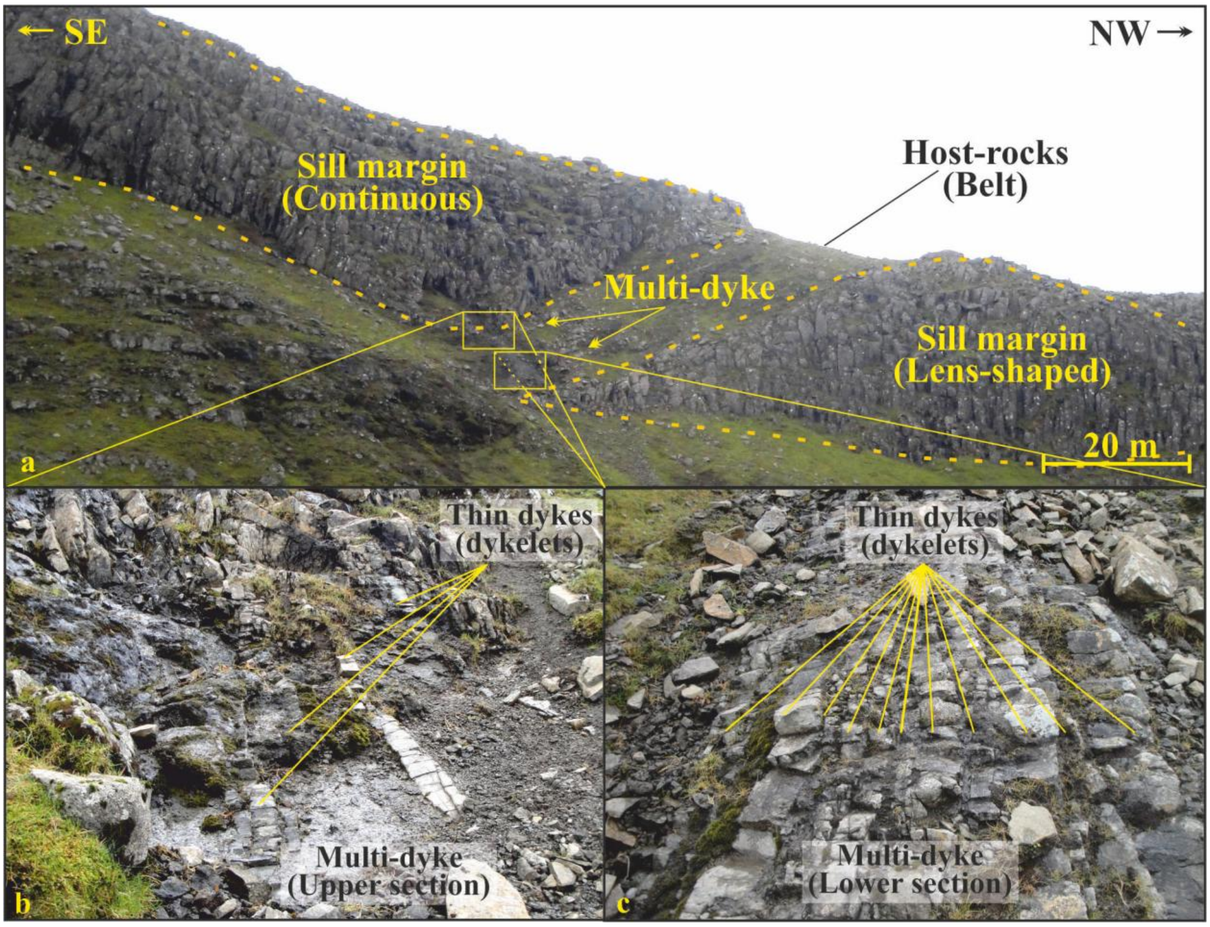

Fig.4 | Images of the thick margin of the Streymoy Sill in the valley of Hundsarabotn. a, Cross-section of a more than ~20 m thick sill margin, moderately inclined (≥ ~5° dip.) towards the SW arranged as a lens-shaped body to the left and a continuous section to the right and separated by a belt of host-rocks.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

The actual cross section of the margin of the Vestmanna Sill is characterised by two relatively thin sub-horizontal magmatic lobes (orthogonal view of cross-section) 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 cross section 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), where these are separated by around 15 to 20 metres of host-rocks (Fig. 4a). These two part-margins are more or less connected by a multi-dike, emanating sub-vertically upwards from the SE tip of the lens-shaped lower margin and 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 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 combined maximum width of between 1.6 to 1.8 metres, extend upwards for ~3/4 of the distance from the lower margin (Fig. 4b,c).

Modes of sill intrusion

Some of the most noticeable characteristics displayed by the investigated margins of this contribution include the facts that the actual margin of the Streymoy Sill is thick, very probably fully developed and intruded at relatively high stratigraphic levels, while the actual margins of the Vestmanna and Kvívík sills are thin and were quite clearly only in their infancy during their crystallisation, when intruded at relatively deeper stratigraphic levels. Here, the actual margin of the Vestmanna Sill very probably represents a slight development from the stage, which is shown for the Kvívík Sill (Fig. 2; Fig. 3).

The multi-dykes/’dykelets’, associated with the other two sill margins of this study indicate details on initial principal stress axes at/around their advancing tips. During sill intrusion prior to any breach of overlaying free surfaces two sets of principal stress axes are in existence, namely the regional stress axes and intrusion-induced stress axes next to the advancing melts[4] (Fig. 5). Fracture strengths within actual host-rocks play a crucial role too, when it comes to modes of sill propagation, where breaching of overlaying free surfaces during sill intrusion/inflation can have a profound effect on ultimate sill geometries[1-4,10]. The two lobes and associated thin ‘dykelets’, shown for the Kvívík Sill margin (Fig. 2), provide a

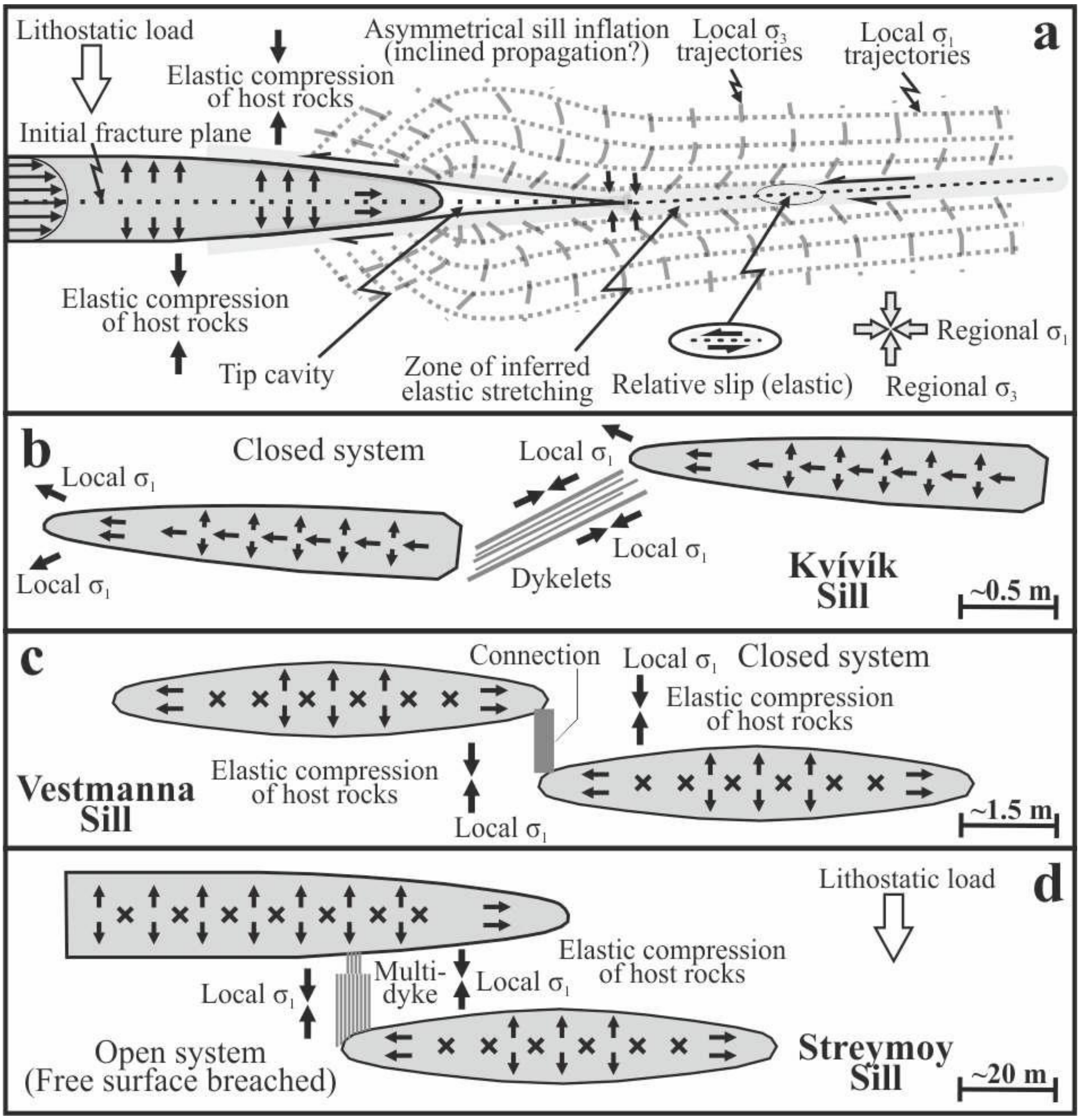

Fig.5 | Brief description of mechanics/processes associated with sub-horizontal sill intrusion (**a** is modified from: Hansen, 2015). **a**, Asymmetrical small-scale inflation of advancing thin magma fronts will result in asymmetrical local stress trajectories in host-rocks around the tips of these and generate slightly inclined propagation. One-sided arrows indicate local shear stresses, while full black arrows indicate magma flow and 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 from right to left. **c**, Simplified sketch illustrating relevant stress fields during formation of thin connecting section, as shown for the Vestmanna Sill in Fig. 3. Magma propagation towards the reader. **d**, Simplified sketch illustrating relevant stress fields during formation of multi-dyke, as shown for the Streymoy Sill in Fig. 4. Magma propagation towards the reader.

'classic example' of propagation of thin magma fronts with semi-elastic displacement of their host-rocks, where orientations of 'dykelets' coincide perfectly with inferred orientations of the local principal stress axis σ_1 trajectories at advancing sill tips (Fig. 5a,b). Moreover, the fact that the 'dykelets' emanate diagonally downwards at moderate angles from the front of one of the actual lobes is an ample proof for 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 and their relatively great stratigraphic depths strongly suggest that their initial melts advanced and climbed as slightly inclined lobes or fingers in a mole-like fashion without interacting with the Earth's free surface. Any suggested/theoretical interactions of such thin magma fingers and lobes with the overlaying free surfaces would be in accordance with a "Princess and the Pea" mechanism only[14], which would of course not make much sense. Instead, depth-dependent variations in Young's Modulus, where host-rocks atop thin advancing magma fronts are displaced slightly more than those below these, most probably caused the magma lobes/fingers to advance and climb at gentle angles, as envisaged in previous studies[1,4,10] (Fig. 5).

When it comes to the actual margin of the Vestmanna Sill (Fig. 3), it probably represents a slight evolution from its counterpart in the Kvivik Sill, where the thin connecting section either represents a single 'dykelet' that has inflated or it may represent several 'dykelets' that ultimately coalesced into one following displacement of the host-rocks in between.

It is overwhelmingly probable that the actual margin of the Streymoy Sill, situated at a relatively high stratigraphic level, displaced its overburden all the way to the Earth's free surface and breached it during inflation. This scenario most likely caused a reorganisation of local principal stress axes, which is reflected by the orientation and asymmetrical nature of the actual multi-dyke (Fig. 4). 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. Here, the probable breaching of the overlaying free surface likely interfered with the local largest principal stress axis σ_1 between the two inflating sill section, so as to reduce compression below both of the two sill sections. Accordingly, host-rocks above the advancing/inflating sill margins were more affected by sill propagation/inflation than those below it, as demonstrated by the differences in 'dykelet' densities and lengths in the multi-dyke below and atop the actual sill margins.

The conclusion of this study is that when thin magma fronts in developing sills advance at relatively deep stratigraphic levels, without interacting with overlaying free surfaces, general depth-dependent values of Young's Modulus govern intrusion styles. Once free surfaces atop advancing/inflating sill margins are breached, reorganisations of principal stress axes follow, which in turn may affect subsequent local intrusion styles.

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