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Abstract: Sills are concordant sheet-like bodies of magma. Their mechanics of emplacement is an important but still not fully understood topic. The well-exposed basaltic Njardvik Sill in the extinct Tertiary Dyrfjöll Volcano in Northeast Iceland offers exceptionally clear insights into the mechanism of sill emplacement. The sill is multiple and consists of at least 7 units (sills) all of which were emplaced along a sharp contact between a rhyolitic intrusion and adjacent basaltic lava flows. Each sill unit was supplied with magma from an inclined sheet. The contacts between the sheets and the sill units are very clear and show that the sill units are much thicker than their feeder sheets. Since the Njardvik Sill consists of separate units, it obviously did not evolve into a homogeneous magma body. Nevertheless, the abrupt change in dip and thickness from inclined sheets to horizontal sills at this particular locality indicates that the earlier sills were influencing the stress field in their vicinity during the subsequent sheet injections. The local stresses around the newly formed sill units forced each of the subsequently injected sheets to change into sills. The Njardvik Sill can be followed laterally in a coastal section for 140 m until it ends abruptly at a fault that cuts the sill. Using these field observations as a basis, a numerical model shows how an inclined sheet opens up the contact between the felsic intrusion and the basaltic lava pile, along which the sill emplacement takes place. The results suggest that sill emplacement is primarily the result of stress rotation at contacts between layers of contrasting mechanical properties. There, the orientation of the maximum principal compressive stress σ_1 is

horizontal. Hence, such contacts can represent interfaces along which sill emplacement is encouraged. Once a sill has been emplaced, it extends the stress field with a horizontal orientation of σ_1 . Consequently, inclined sheets and dykes injected near the sill will be deflected into sills. The injection frequency of further sill units controls if the sill can grow into a larger magma body by mixing of the newly supplied with the initially injected magma. In case of the Njardvik Sill, the injection frequency was low, so subsequently emplaced sill units can be distinguished.

New insights into the mechanics of sill emplacement provided by field observations of the Njardvik Sill, Northeast Iceland

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Abstract

Sills are concordant sheet-like bodies of magma. Their mechanics of emplacement is an important but still not fully understood topic. The well-exposed basaltic Njardvik Sill in the extinct Tertiary Dyrfjöll Volcano in Northeast Iceland offers exceptionally clear insights into the mechanism of sill emplacement. The sill is multiple and consists of at least 7 units (sills) all of which were emplaced along a sharp contact between a rhyolitic intrusion and adjacent basaltic lava flows. Each sill unit was supplied with magma from an inclined sheet. The contacts between the sheets and the sill units are very clear and show that the sill units are much thicker than their feeder sheets. Since the Njardvik Sill consists of separate units, it obviously did not evolve into a homogeneous magma body. Nevertheless, the abrupt change in dip and thickness from inclined sheets to horizontal sills at this particular locality indicates that the earlier sills were influencing the stress field in their vicinity during the subsequent sheet injections. The local stresses around the newly formed sill units forced each of the subsequently injected sheets to change into sills. The Njardvik Sill can be followed laterally in a coastal section for 140 m until it ends abruptly at a fault that cuts the sill. Using these field observations as a basis, a numerical model shows how an inclined sheet opens up the contact between the felsic intrusion and the basaltic lava pile, along which the sill emplacement takes place. The results suggest that sill emplacement is primarily the result of

stress rotation at contacts between layers of contrasting mechanical properties. There, the orientation of the maximum principal compressive stress σ_1 is horizontal. Hence, such contacts can represent interfaces along which sill emplacement is encouraged. Once a sill has been emplaced, it extends the stress field with a horizontal orientation of σ_1 . Consequently, inclined sheets and dykes injected near the sill will be deflected into sills. The injection frequency of further sill units controls if the sill can grow into a larger magma body by mixing of the newly supplied with the initially injected magma. In case of the Njardvik Sill, the injection frequency was low, so subsequently emplaced sill units can be distinguished.

Key words: sill geometry, sill emplacement, mechanical layering, stress field modelling

1. Introduction

Sills are sheet-like bodies of intrusive igneous rocks that conformably intrude into layers in the hosting crustal segment. Most sills are supplied with magma through dykes and form when magma gets trapped along its way to shallower depths in the crust. The mechanism of sill emplacement is still a matter of research because sills are recognised to enhance the petroleum prospectivity inside sedimentary basins (e.g. Jones et al., 2007). In addition, a general understanding of sill emplacement is part of the analysis of the formation of plutons in general and magma chambers in active volcanic regions in particular.

Sills have been studied in the field at many locations. Examples include the Traigh Bhan na Sgurra Sill on the Isle of Mull (Holness and Humphreys, 2003) and the Great Whin and the Midland Valley Sills, Great Britain (Francis, 1982; Goult, 2005), and sills in Greenland, such as the Jameson Land Basin (Hald and Tegner, 2000) and Zig-Zag Dal (Upton et al., 2005). Other examples include sills in the Henry Mountains, Utah (Johnson and Pollard, 1973; Pollard and Johnson, 1973; Horsman et al., 2005; de Saint-Blanquat et al., 2006), the Palisades Sill, New Jersey (Shirley, 1987), and sills in Lajitas, Texas (Barker,

2000) as well as in Karoo, South Africa (Chevalier and Woodford, 1999). Geophysical methods have also been used to study sills in the Northern Rockall Trough (Thomson and Hutton, 2004) and the Møre Basin, North Atlantic (Hansen and Cartwright, 2006) and, as fluid magma chambers below active volcanoes (Auger et al., 2001) and mid-ocean ridges (Sinton and Detrick, 1992; Mutter et al., 1995; Singh et al., 2006).

In addition to geological and geophysical field studies, there have been many theoretical studies on the mechanisms of sill emplacement. These latter include the analysis of conceptual models (Bradley, 1965; Roberts, 1970; Spence and Turcotte, 1985; Chevalier and Woodford, 1999), analogue experiments (Kavanagh et al., 2006), numerical (Malthe-Sorensen et al., 2004), and analytical models (Anderson, 1938, 1942; Pollard and Johnson, 1973; Kerr and Pollard, 1998; Goulet, 2005).

Sill emplacement is commonly explained by magma storage at the so-called level of neutral buoyancy (Bradley, 1965; Williams and McBirney, 1979; Barker, 2000) where the magma has the same density as the surrounding rock. Recently however, layers with mechanically different properties, and weak interfaces in between, have been recognised to greatly influence the emplacement of magma and to be able to enforce sill emplacement (e.g. Johnson and Pollard, 1973; Hyndman and Alt, 1987; Holness and Humphreys, 2003; Kavanagh et al., 2006). However, the emplacement mechanism of sills is still not completely understood. A combination of field observations and modelling could therefore provide more insights into this topic.

This study is based on field observations of a small multiple basaltic sill in the extinct Tertiary Dyrhöföll Volcano in Northeast Iceland (Fig. 1). The sill was fed from several inclined sheets that intruded a contact between basaltic lavas and a felsic intrusion. It represents an exceptionally well-exposed example of the geometry and the mode of emplacement of a sill. The first aim of this paper is, thus, to give a detailed description of the geometry of the Njardvik sill, its structure, and the inferred mode of emplacement. The second aim of the

paper is to explain the field observations in terms of a simple numerical model. The purpose of this model is to provide a better understanding of the stress conditions that favour sill emplacement.

2. Geological setting

The Dyrfjöll Volcano is one of the extinct Tertiary central volcanoes (stratovolcanoes) exposed in Eastern Iceland (Fig. 1). It was active around 12 Ma (Gustafsson, 1992; L. E. Gustafsson, pers. comm., 2006). During its lifetime it produced large volumes of silicic rocks that are now a part of the second largest rhyolitic area in Northeast Iceland. The only comprehensive study on the Dyrfjöll Volcano so far was done by Gustafsson (1992) and was used as a basis for the author's field work.

As a result of glacial erosion, a vertical section of some 1100 metres through the Dyrfjöll Volcano is exposed in the cove of Njardvik. In its lowest part, at sea level, the section comprises acid intrusive rocks of the Njardvik Silicic Complex (Gustafsson, 1992). These shallow acid intrusions were emplaced into a succession of basaltic lava flows from the earlier eruptive history of the Dyrfjöll Volcano). In addition, they are associated with a considerable volume of acid extrusive rocks exposed on the flanks of the volcano. The highest part of the volcano, as presently exposed, is overlain by regional basalt lavas that buried the volcano after it became extinct.

The entire interior of the Dyrfjöll Volcano is dissected by numerous, mostly basaltic, inclined sheets and dykes. The inclined sheets form a swarm around a common centre (the crustal magma chamber that fed the sheets) located in the Njardvik bay, whereas most dykes belong to a N-striking swarm of regional dykes associated with the Dyrfjöll Volcano (Gustafsson, 1992; and own unpublished data). The multiple basaltic sill described in the next section (from now on referred to as the Njardvik Sill) is exposed on the northern shore of Njardvik (Fig. 1) and is fed by inclined sheets.

104

105 **3. The Njardvik Sill**

106 The Njardvik Sill is a basaltic sill with an exposed length (strike dimension) of approximately
 107 140 m and thickness of around 20 m (Fig. 2). The sill was clearly initiated when an inclined
 108 sheet dipping 46° met and entered the horizontal contact between a flat-roofed rhyolitic
 109 intrusion belonging to the Njardvik Silicic Complex and the overlying basaltic lava flows. On
 110 reaching the contact plane between the rhyolitic intrusion and the basalt, the inclined basaltic
 111 sheet changed its dip and propagated further along the horizontal interface. Contact
 112 metamorphism of the rhyolitic intrusion and its development of sill-parallel jointing indicate
 113 that the rhyolitic intrusion had cooled down before emplacement of the Njardvik Sill. Where
 114 the inclined basaltic sheet changes into a horizontal sill, the thickness of the intrusion
 115 increases from 0.85 m to more than 2 m (Fig. 3).

116 At least eight sheet injections can be traced into the sill. These injections resulted in
 117 gradual thickening and growth of the sill. However, the Njardvik Sill did not evolve into a
 118 homogeneous magma body since at least seven units can be distinguished where the sill
 119 reaches its maximum thickness (Fig. 4). This indicates that the time between subsequent
 120 emplacements of the parts (units) that constitute the sill was at least so long that a partial or
 121 complete cooling of a unit (fed by an inclined sheet) occurred before the emplacement of the
 122 next unit. Furthermore, a step-and-stair geometry of individual units occurs in the upper part
 123 of the sill (Fig. 2).

124 The Njardvik Sill terminates at the contact with a dip-slip fault striking 135° and
 125 dipping 70°E (Fig. 2). Apparently, the sill is cut by the fault. The outcrop, however, is too
 126 limited to allow a determination of the type of displacement along the fault plane.

127 Dyke emplacement in the vicinity was clearly influenced by the Njardvik Sill for
 128 example a regional dyke generally striking 175° and dipping 87°W changes its attitude so as
 129 to become parallel to the sill at a distance of less than one metre below the sill. Several

inclined sheets dissected the Njardvik Sill at a time when it was probably mostly or completely solidified. These inclined sheets cut the sill but while their paths are inside the sill they change from their normal attitude to a sill-parallel attitude in some units (Fig. 5). Once the inclined sheet paths have passed through these units, their paths change back to their original attitude.

Field observations indicate the following schematic evolution of the Njardvik Sill (Fig. 6). From the stratified crustal magma chamber of the Dyrfjöll Volcano (Fig. 6A), rhyolitic magma was injected forming a shallow intrusion at a few hundred metres depth. This acid intrusion is a part of the Njardvik Silicic Complex (Fig. 6B; Gustafsson, 1992). The Njardvik Silicic Complex has mechanical properties contrasting with those of the adjacent basaltic lava flows. Consequently, in our conceptual model, when the inclined basaltic sheets subsequently injected from the shallow chamber met the upper contact between the rhyolitic intrusion and the basaltic lava above, the sheets changed into sills (Fig. 6C). These sill intrusions resulted in the formation of a sill consisting of several units, that is, the Nardvik Sill (Fig. 6D). After solidification and cooling down of the entire Njardvik Sill, the later-formed inclined sheets and dykes were able to cut through it (Fig. 6E).

4. Numerical modelling of sill formation

Using the field observations as a basis, a numerical model was constructed to test the mechanical aspects of the conceptual model presented in Fig. 6 focussing on the emplacement of the first sill unit. For this purpose, the Finite Element modelling software COMSOL Multiphysics 3.3 was used. This program is based on Finite Element Methods (FEM). There, the geometry of a model is first discretised into a set of volumetric or planar elements and then the differential equations that govern the problem are solved numerically to obtain displacements, magnitude, and orientation of stresses and strains (Zienkiewicz, 1977; Logan, 2002).

The geometry of the FE model presented here is derived from generalised field observations of the Njardvik Sill and illustrated in Fig. 7. An inclined sheet with zero initial thickness and a dip of 45° meets the interface between the rhyolite intrusion and a basaltic lava flow. Unfortunately, the properties of the interface between both layers are unknown and cannot be reconstructed. In the model, the contact zone is described by a Coulomb friction model that is based on the Navier-Coloumb criterion for rock failure (e.g. Hoek, 1968). This fracture criterion defines the onset of rupture when the intrinsic shear resistance is overcome by an applied shear stress. Fracture propagation is possible when the shear stress is high enough to sustain movement as described by the product of the normal stress and the coefficient of internal friction. According to Pollard and Johnson (1973), in nature, there is always some friction between layers, but a shear stress created by this friction is probably negligible in many cases compared to the stresses created in the layer as a result of the intrusion of magma. However, the influence of cohesion along the interface between basalt and rhyolite has been tested in the model by applying different values for the cohesion but no differences in opening width or length along the contact zone occur. This might probably be a problem of the software. Normally, a high value of cohesion could prevent the contact from opening. In contrast, there is no cohesion or friction between the sides of the fracture representing the inclined sheet. The Poisson's ratio of the host rock types is assumed to be 0.25, a typical value for most solid crustal rocks (Bell, 2004). Using available data on Icelandic rocks, Young's modulus of the basaltic lava flow is taken as 30 GPa whereas that of the rhyolite intrusion as 10 GPa (Oddson, 1984; Carmichael, 1989; Egilsson et al., 1989). The model was fastened along its lateral margins (Fig. 7), using the condition of no displacement. This represents the small aerial extent of deformation around the intrusion (cf. Pollard and Johnson, 1973). The excess pressure used for the inclined sheet is defined as 3 MPa, which is in the range of the tensile strength of crustal rocks (Jaeger and Cook, 1979).

The model results as to the magnitude of the maximum principal tensile (minimum principal compressive) stress σ_3 is shown by the contours in Fig. 8, the contours of the von Mises shear stress are shown in Fig. 9. The distribution of tensile stress in the model (Fig. 8) is characterised by a maximum below the lateral end of the opened contact to the right of the inclined sheet. In addition, tensile stress concentrations occur at the tips of the contact zone on both sides. The von Mises shear stress (Jaeger and Cook, 1979; Benham et al., 1996) concentrates mainly below the tip region of the opened contact that is subsequently used for the sill (Fig. 9). This stress distribution is in agreement with photoelastic gelatine experiments and analytical solutions by Pollard and Johnson (1973). According to Anderson (1938), sheet-like intrusions propagate as a result of high tensile stress concentrations near the tip that enable the intrusion to “wedge open” the host rock.

The deformation of the model shows opening of the contact zone to the right of the sheet but not to the left. This is in agreement with the field observation of the Njardvik Sill (cf. Figs. 2, 8, 9). The maximum opening width along the contact zone is 0.12 m whereas the opening of the fracture representing the inclined sheet is 0.2 m. In the field, the inclined sheet feeding the first unit of the Njardvik Sill has a thickness of 0.55 m. This might indicate that the overpressure of 3 MPa applied in the model is lower than the overpressure of the sheet in Njardvik. In this context, the very small opening width of the contact zone is a result of the too low value of the overpressure. However, the actual geometry and opening width of the sill in the model is not comparable to the field observations since it is not possible to model influx of magma with an overpressure into the newly formed sill in a static model. It is, however, not the purpose of the model to make quantitative predictions but to provide insight into the mechanisms acting during sill emplacement in case of the Njardvik Sill.

For the given boundary conditions, the trajectories of σ_1 are perpendicular to the opened contact zone on the right side of the inclined sheet (Fig. 10). The trajectories of the maximum principal compressive stress σ_1 reflect the direction in which extension-fracture

propagation is most likely whereas shear fractures make a certain angle (commonly $<45^\circ$) to the direction of σ_1 (Jaeger and Cook, 1979). The vertical orientation of σ_1 below the newly opened contact zone might explain the observed thickening of the first sill unit by fracturing of the area below the sill. Below this area, σ_1 trajectories are horizontal favouring the diversion of subsequently injected sheet into further sill units.

The limitations of our model include the purely elastic behaviour of the material and its instantaneous deformation. As mentioned above, the problem of sill emplacement and propagation is not an entirely static one. In addition, thermal effects, which clearly played a role as indicated by contact metamorphism of the rhyolitic host rock, have not been regarded in the models.

5. Emplacement of the Njardvik Sill

A mechanical model for the emplacement of the Njardvik Sill should be able to explain the field observations (Section 3) based on the results of the numerical model in Section 4. Like other sheet intrusions, the Njardvik Sill formed as a magma-driven fracture. It follows that its emplacement was primarily controlled by the internal magmatic overpressure, the local orientation of the principal stresses in the host rock, and the mechanical properties of the host rock and the interface between the rhyolite intrusion and the adjacent basaltic lava flows.

In an extensional stress regime, such as it is typical for rift zone volcanoes as the one in which the Dyrfjöll Volcano was situated, the maximum principal compressive stress, σ_1 , is commonly vertical, whereas σ_3 is horizontal. Such a regional stress field controlled the emplacement of the $\pm$ N-striking regional dykes in the Dyrfjöll area. Within the volcano itself, there was an additional local stress field around the crustal magma chamber that fed the swarm of inclined sheets. Initial sill formation requires the development of a local stress field must have within the volcano with a horizontal orientation of σ_1 . This local stress field was

probably primarily the result of rotation of σ_1 from its normal vertical orientation to a horizontal one at the contact between the rhyolitic intrusion and the adjacent basaltic lava flow above.

Such a local re-orientation of the principal stress directions can be achieved by the presence of layers with different mechanical properties (see Section 6.1). Within the Tertiary lava pile of Iceland, contrasting mechanical properties between layers are most commonly found within central volcanoes, because there the rocks (intrusive and extrusive) show the greatest variety in mechanical properties (acid, intermediate, basaltic; igneous as well as sedimentary, mainly volcanoclastic). Rocks of such a variety are, indeed, abundant within in the Dyrfjöll Volcano. For the Njardvik Sill in particular, the contrast between the rhyolitic Njardvik Silicic Complex (Gustafsson, 1992) and the overlying basaltic lava flows might have caused a local stress rotation from a σ_1 parallel to the inclined sheets (following the σ_1 stress trajectories around the magma chamber that fed the sheet dipping with around 45° towards the chamber) towards a horizontal orientation. In addition, the mechanical properties of the interface between rhyolite and basalt might have enhanced stress rotation and, hence, the intrusion of the first sill unit of the Njardvik Sill. Unfortunately, this interface is not exposed so one can only speculate about its properties. In the numerical model in Section 4, it is modelled as a contact defined by a Coloumb friction model because it is not possible to model fracturing with COMSOL Multiphysics 3.3 in any other way.

The injection of the first sill unit definitely altered the stress field in its vicinity. This can be seen from subsequently injected sheets being diverted from their original paths and deflected into sills. Therefore, the first sill installed a local stress field that was enhancing further sill emplacement by following sheets. The local stress field around the first sill may have had a very small extend; however, it was able to divert at least 7 other inclined sheets and force them to join the first sill as subsequent units of the Njardvik Sill. In addition, the

small regional dyke that changes its dip from 87° to being subparallel to the Njardvik Sill less than 1 m below the sill is an example for the reach of the local stress field around it.

The injection frequency of new sheets, that is, how frequently the first sill received new magma through inclined sheets, controlled whether the first sill developed into a larger, homogeneous magma body, and thus eventually into a shallow magma chamber. The field observations of the Njardvik Sill show clearly that the first injected sill had at least partly solidified before the next inclined sheet near the sill was injected (Figs. 2, 4). Similarly, during subsequent sill injections in this place, all the previous sills had solidified. As a consequence, the first sill (and the subsequent ones) had no chance to develop into a shallow magma chamber. Consequently, the multiple Njardvik Sill is a complex consisting of at least 7 individual sills or units (Fig. 4). However, it should be noted that initially solidified sills could later on become partially melted and thus potentially form homogeneous magma bodies when enough heat can be accumulated through repeated injection of later sills (Annen and Sparks, 2002). Even though the individual sills in the Njardvik Sill had partly solidified, it is obvious that their influence on the local stress field was still existent during subsequent sheet emplacement. Even when the Njardvik Sill was probably entirely solidified, its local stress field was – at least within some of the sill units – able to locally divert inclined sheets that cut the Njardvik Sill (Fig. 5).

The thickening of the first sill unit from 0.85 m in the inclined sheet to more than 2 m in the sill (Fig. 3) is probably a result of continuing magma supply through the inclined sheet in connection with the mechanical response of the rhyolite below. Pollard and Johnson (1973) explain an increase in thickness observed in the Maiden Creek Sill, Henry Mountains, by a mechanism called “ductile blunting”. It has been deduced from observations of the severe deformation of the host rock around the termination of the sill. During sill propagation the formation of closely-spaced cataclastic shear planes caused a blunting of the sill termination and an increase in sill thickness. However, since this mechanism is only partly applicable to

brittle rocks and the host rock of the Njardvik Sill was most likely completely solidified when the sill was emplaced (see Section 3), ductile blunting cannot have had a great influence. In addition, since the termination of the Njardvik Sill is not exposed because it is cut by a fault (Fig. 2), the radius of curvature of the sill termination that is an indication for the brittle or ductile behaviour of the host rock (Pollard and Johnson, 1973) cannot be measured and the deformation around the termination cannot be analysed, it is not possible to test the influence of ductile blunting.

Thus, the mechanism of emplacement of the Njardvik Sill was strongly controlled by rotation of the principal stresses as a result of the contrasting mechanical properties of the host rock layers (basalt and rhyolite) and probably the interface between these layers. At the time when the first inclined sheet was deflected into a sill a local stress field existed along this interface with a horizontal orientation of σ_1 that enforced sill emplacement. After its emplacement the first sill created its own local stress field by extending the area of a horizontal σ_1 . As a consequence, the emplacement of subsequent sill units was enhanced.

6. Discussion

6.1 Mechanisms of sill emplacement

Sill emplacement is commonly explained by magma storage at the so-called “level of neutral buoyancy” (LNB; Glazner and Ussler, 1988; Walker, 1989; Ryan, 1993) where the density of the magma equals the density of the surrounding crust. Such density or buoyancy-controlled sill-emplacement models have been discussed, for example, by Bradley (1965), Williams and McBirney (1979), Barker (2000), and Kavanagh et al. (2006), and developed into a general model for magma storage or shallow magma-chamber formation by Glazner and Ussler (1988), Ryan (1993), Lister and Kerr (1991), and Dahm (2000). However, the concept of a LNB is not consistent with geological and geophysical observations, e.g. felsic

intrusions could not occur inside a denser basaltic crust as it is the case inside the Dyrfjöll Volcano (cf. Fig. 6).

According to Vigneresse et al. (1999), the intrusion of (granitic) magma into an isotropic and homogeneous brittle crust locally alters the stress field. In a tensional stress regime such as the rift zone in Iceland, the vertical intrusion plane becomes horizontal when the horizontal stress components (σ_2 and σ_3) overcome the lithostatic load (vertical stress, σ_1). This is possible because the magma pressure in a vertical conduit or dyke is added to the horizontal σ_3 . During the ascent of the magma the vertical σ_1 decreases. As soon as σ_1 is less than the combined magma pressure and σ_3 , the intrusion plane becomes horizontal, i.e., the dyke changes into a sill (Anderson, 1942).

Only during the last decades has it been recognised that the presence of layers with contrasting rock mechanical properties greatly influences the emplacement of magma especially in the upper crust. Heterogeneities and anisotropies can be regarded as pre-existing stress guides that facilitate stress re-orientation because layers of weaker material lower the stress level at which stress rotation occurs by lowering the stress differential (Vigneresse et al., 1999). Many field observations of sills underline the importance of crustal layering during the emplacement of a sill (e.g. Johnson and Pollard, 1973; Holness and Humphreys, 2003). Good examples of sills emplaced between layers of different mechanical properties include e.g. the Sonju Lake Intrusion, Minnesota (Maes et al., 2007), sills in the Paiute Ridge area, Nevada (Valentine and Krogh, 2006), the Papoose Flat Pluton, California (de Saint-Blanquat et al., 2001), and the Black Mesa Pluton and other intrusions in the Henry Mountains, Utah (Pollard and Johnson, 1973; de Saint-Blanquat et al., 2006). These observations are also supported by results of analogue experiments (Hyndman and Alt, 1987).

Some authors suggest that, in addition to the existence of rock mechanical layering, the properties of the interface between individual layers control the emplacement of sills. E.g., Mudge (1968) suggest that well-defined parting surfaces, i.e., weak or open contacts

such as bedding planes or unconformities, are prerequisites for sill emplacement. Similar results have also been obtained in analogue modelling. For example, Kavanagh et al. (2006) observed sill formation in gelatine experiments at a weak interface between two mechanically different layers. According to Kavanagh et al. (2006), the presence of an interface is necessary since in a homogeneous medium without an interface sill emplacement could not be observed. In contrast, sill emplacement was especially encouraged by a layered system with an upper more rigid layer and a weak interface between the layers. This is a striking analogue for the Njardvik Sill that was emplaced between relatively rigid basaltic lava flows overlying a less rigid rhyolitic intrusion (e.g. Fig. 6).;

Hence, the primary controls of sill formation are abrupt stress rotations whereby the principal compressive stress σ_1 becomes horizontal and the minimum principal compressive stress σ_3 vertical. Such stress rotations occur preferentially in a layered crust with considerable contrasts between the mechanical properties of individual layers. When in addition this local stress field coincides with a weak or open horizontal contact between layers, sill emplacement can be encouraged.

6.2 Dykes as feeders for sills

The feeders to most sills are thought to be inclined sheets or dykes. In some cases dykes are seen to change into sills, but the feeders for sills are often poorly exposed in the field so that a clear connection between the feeder and the sill is commonly lacking (Johnson and Dunham, 2001). In this respect, the Njardvik Sill offers an exceptionally clear example for the feeding relationships between inclined sheets and the sills they acted as feeders for. As is shown in Figs. 2, 3 and 4, and illustrated schematically in Fig. 6, all the units of the Njardvik Sill are fed from the side by inclined sheets.

While there are few as clear examples of the connection between the feeders and the sills as the Njardvik Sill, several other field examples with direct connection between feeders

and sills are known. These include the sills of Great Whin and the Midland Valley (Francis, 1982; Goulty, 2005), a sill in Lajitas, Texas (Barker, 2000), sills in the Jameson Land Basin, East Greenland (Hald and Tegner, 2000), and in the North Rockall Trough (Thomson and Hutton, 2004) and the Møre Basin (Hansen and Cartwright, 2006), North Atlantic. Even though the feeder dykes of most sills are not exposed or directly linked to the sill in outcrops, feeding relationships and the geometry of the feeder can sometimes be inferred from magmatic foliations or the preferred orientation of the magnetic susceptibility (e.g. de Saint-Blanquat et al., 2006; Maes et al., 2007; Palmer et al., 2007).

The geometry of a sill may depend on how it is fed. In plan view, the geometries of sills are of two main types: radially symmetrical and bilaterally symmetrical. Radially symmetrical sills are thought to be fed from the centre (e.g. Thomson and Hutton, 2004; Hansen and Cartwright, 2006), whereas bilaterally symmetrical sills are fed from one side of the sill. While radially symmetrical sills do occur, some of which develop into laccoliths (Pollard and Johnson, 1973), many and perhaps most sills are actually bilaterally symmetrical. For example, there is evidence that the Great Whin and Midland Valley Sills (Francis, 1982, Goulty, 2005) have a bilateral symmetry. Similarly, Anderson's (1942) conceptual model, partly based on field observations, suggests sill emplacement through one of the walls of a vertical feeder dyke. And, of course, the Njardvik Sill is clearly bilaterally symmetrical (Figs. 2, 4, 6).

6.3 Sills as potential magma chambers

Although the Njardvik Sill did not develop into a homogeneous magma body that could act as a magma chamber, there is abundant evidence that sills commonly develop into shallow magma chambers. E.g. magma chambers along fast-spreading mid-ocean ridges are known to be sill-like (Sinton and Detrick, 1992; Mutter et al., 1995; Singh et al. 2006). Larsen and Marcussen (1992) also propose that sills acted as open crustal reservoirs feeding flood

basalt volcanism. Additionally, Németh and Martin (2006) outline a genetic relationship between a complex of sills and dykes and a diatreme in western Hungary. There is also geochemical and field evidence for the supply of magma for eruptions from sill-like chambers in different tectonic environments (e.g., Upton et al., 2005).

Furthermore, according to Pollard and Johnson (1973), sills are the preliminary stage of the development of laccoliths and other bigger intrusive bodies. This is in agreement with Glazner et al. (2004) who suggest that large plutons can form through the incremental accumulation of many small igneous bodies. Sheeted emplacement, which can be interpreted as the stacking of sills or sill units, has been observed in many large plutons in different tectonic settings (Hutton, 1992). Examples for plutons that evolved from the coalescence of several sills or sheet-like intrusions include several laccoliths on the Isle of Elba, Italy (Rocchi et al, 2002), the Birch Creek pluton (Barton et al., 1995), and the Papoose Flat pluton, California (de Saint-Blanquat et al., 2001).

A similar observation of a sill that consists of more than one unit is the Maiden Creek Sill in the Henry Mountains, Utah (Horsman et al., 2005). There, the initially emplaced sill was followed by a subsequent second sill that intruded immediately adjacent to the first sill. In agreement with the mechanical model proposed for the Njardvik Sill (see Section 5), Horsman et al. (2005) suggest that the intrusion of the first sill mechanically controlled the emplacement of the second sill through a thermal and/or strength anisotropy imparted by the emplacement of the first sill. This observation from both the Maiden Creek and the Njardvik Sill indicates that sill emplacement mechanically enhances the intrusion of further sills by intensifying the area of a local stress field with σ_1 horizontal that is, thus, favourable for sill emplacement.

The development of a sill into a magma chamber depends then on the magma supply rate into the sill. If the injection frequency is high enough, the magma inside the sill remains liquid and can mix with newly injected magma. In case of the Njardvik Sill, the injection

frequency was relatively low. This resulted in the – at least partial – solidification of individual units before the next unit was emplaced. As a consequence, mixing among the layers by convection was prevented. Hence, the Njardvik Sill did not have the chance to evolve into a magma chamber.

7. Conclusions

Based on field studies of the multiple Njardvik Sill in Northeast Iceland, as well as numerical modelling, the following conclusions regarding its mechanics of emplacement and sill emplacement in general may be drawn.

The Njardvik Sill was initiated when an inclined sheet met the contact between subvolcanic rhyolite of the Njardvik Silicic Complex and the overlying basaltic lava flows inside the Dyrfjöll Volcano. The local stress field that existed at the interface between these mechanically contrasting layers was characterised by a horizontal orientation of the maximum principal compressive stress σ_1 that differed significantly from the stress field in which the inclined sheet was propagating. As a result, the inclined sheet was forced to intrude along the interface as a sill. Therefore, stress rotation as a consequence of mechanical layering and the presence of weak interfaced between layers can be regarded as a condition for sill emplacement in the upper crust.

The emplacement of the first sill increased the sphere of influence of the local stress field with σ_1 being horizontal. Consequently, subsequently injected inclined sheets near the sill were deflected into sills forming additional units of the Njardvik Sill. Hence, the emplacement of a sill enhances the emplacement of further sills that can add to its magma volume.

The time between successive sill emplacements in the Njardvik Sill was sufficient for the (at least partial) solidification of the previously formed sill unit. This prevented mixing of the individual units and, thus, the homogenisation of the Njardvik Sill. Hence, at least 7 units can

be distinguished inside the sill (Fig. 4). Therefore, the injection frequency is a controlling parameter deciding if a sill can develop into a larger magma body that is eventually able to act as a magma reservoir for dyke emplacement. For this, the injection frequency into a sill must be high enough to avoid the solidification of previous magma batches or to provide enough heat to re-melt the already solidified parts of the sill.

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Figure captions

Fig. 1. Location of the Dyrfjöll Volcano in Northeast Iceland. The site of the Njardvik Sill is indicated by a star.

Fig. 2. View of the Njardvik Sill on the shore of the cove of Njardvik. The sill is emplaced between the light-coloured rocks of the Njardvik Silicic Complex (Gustafsson, 1992) and the overlying dark-coloured basaltic lavas of the Dyrfjöll Volcano. The multiple Njardvik sill is fed from eight inclined sheets. A step-and-stair geometry can be inferred in some places. View north, the sill terminates at a fault visible in the right side of the picture.

Fig. 3. Western margin of the Njardvik Sill. Where the inclined sheets start to propagate horizontally they thicken considerably after a constriction. View northeast, the person provides a scale.

Fig. 4. In the centre of the Njardvik Sill, at least seven individual units constitute the multiple sill. They can be distinguished by different jointing and a slightly different colour. View north.

Fig. 5. Two inclined sheets that cut the Njardvik Sill change their attitude while within some of the sill units but change back to their original attitude once they have propagated through them. View northeast, the upper inclined sheet has a thickness of 0.85 m.

Fig. 6. Schematic illustration of the evolution of the Njardvik Sill. A) The Dyrfjöll Volcano consists of a succession of acid and basaltic lava flows and pyroclastic rocks. Inclined sheets fed from the crustal magma chamber and regional dykes cut the interior of the volcano. B)

The Njardvik Silicic Complex includes intrusive acid rocks that are exposed in the cove of Njardvik. C) The Njardvik Sill was emplaced at the contact between the Njardvik Silicic Complex and the overlying basalts. D) A low intrusion frequency prevented the sill from becoming a homogeneous magma body, a magma chamber. Instead, at least seven individual units can be recognised. E) After solidification of the Njardvik Sill it was cut by new inclined sheets and dykes.

Fig. 7. Geometry of the numerical model presented in Figures 8 to 10. The geometry and boundary conditions are based on field observations of the Njardvik Sill.

Fig. 8. Contours of the minimum principal compressive (maximum principal tensile) stress σ_3 . The geometry of the model is illustrated in Figure 7.

Fig. 9. Contours of the von Mises shear stress. The geometry of the model is illustrated in Figure 7.

Fig. 10. Trajectories of the maximum principal compressive stress σ_1 representing pathways for ideal fracture propagation. The geometry of the model is illustrated in Figure 7.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

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To the editors of
Journal of Volcanology and Geothermal Research

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Dear Sir or Madam,

together with this letter, I submit a manuscript entitled „New insights into the mechanics of sill emplacement provided by field observations of the Njardvik Sill, Northeast Iceland“ which I wish to submit for consideration for publication in *Journal of Volcanology and Geothermal Research*. The manuscript deals with field observations of an exceptionally well exposed sill in the Dyrfjöll Volcano in Northeast Iceland and a Finite Element model that has been developed based on these observations. The main aim of the paper is a better understanding of the mechanics of sill emplacement.

The manuscript had already been submitted in an earlier version with a co-author in February. The revision process was managed by editors Herman Engelen and Joan Martí. Two reviews were sent to me by Arnau Folch and Thierry Menand. The manuscript has therefore been revised in larger detail and accepted both by the editor and the editor in chief. However, my co-author did not agree on the changes and insisted on a withdrawal. I have therefore re-written the manuscript leaving out all parts written by the co-author and at the same time considering the comments by the reviewers.

Editor Herman Engelen encouraged me to submit the manuscript again since reviewers and editors have put much effort into the reviewing process.

Yours sincerely,

Steffi Burchardt

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