Field Data and Numerical Models on the Emplacement of Sill Complexes

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Introduction

Most shallow magma chambers have been suggested to develop from sills , more specifically sill complexes (or clusters). Sill complexes can commonly be found in both active volcanic areas e.g. Tenerife, Canary Islands and also in sedimentary basins e.g. Vøring margin, offshore Norway. Overall, the most favourable condition for sill formation is when there is an abrupt change from soft rock (e.g. pyroclastic rock) to a stiff rock (e.g. lava flow), commonly seen in stratovolcanoes [1,2] (Fig.1).

Here we present geophysical and field data of sill complexes from active volcanic areas (Fig. 2). These observations have been combined with numerical models (FEM; COMSOL Multiphysics) on the emplacement of individual sills and sill complexes.

Numerous numerical models were made to understand the emplacement of sills and in particular sill complexes to gain more knowledge on their mechanical interactions.

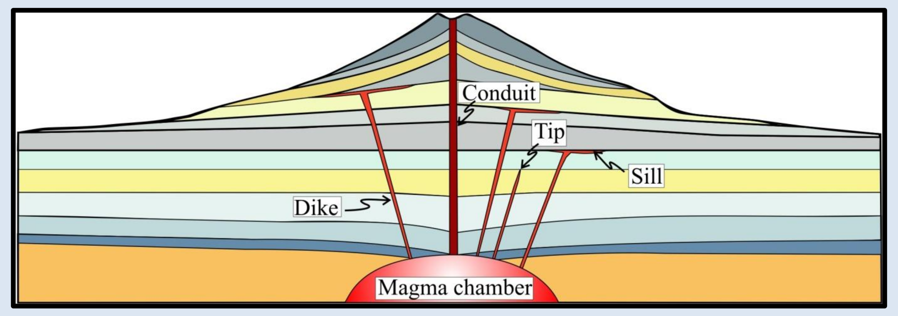

Figure 1: Sill emplacement is common in a layered host rock where a dyke is arrested as it meets unfavourable mechanical properties advancing into a sill.

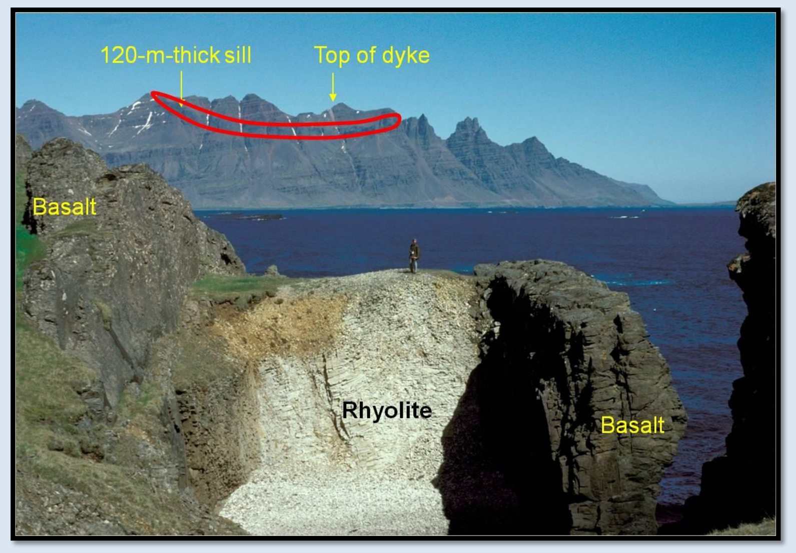

Figure 2: A rhyolitic dyke, East Iceland, in the foreground is cut by a sill highlighted in red. This sill demonstrates a characteristic concave geometry .

Individual sills

Sills emplaced into layered country rock, generate stresses in stiffer layers i.e. those with a high Young's modulus (E). Such stiff layers would stop the propagation of the dyke causing it to deflect into a sill, either single (asymmetric) or double deflection (symmetric, Fig.3). Figure 4A shows that when the dyke meets a weak contact (low E) with unfavourable mechanical properties the dyke is arrested. However, this is favourable for sill formation and propagation along the contact, due to the contact opening up and the stress field becoming rotated 90°, so that σ_3 (minimum stress) becomes vertical[1]. Observations and models also show that when the weak contact is inclined, it is more probable that a single deflected sill will form upwards following buoyancy (Fig.4B).

When modelling three different sill geometries, the most important differential was the depth below the Earth's free surface. Figure 5 demonstrates that there may be very strong surface stresses if the depth below the surface is less than that of the aperture of the sill.

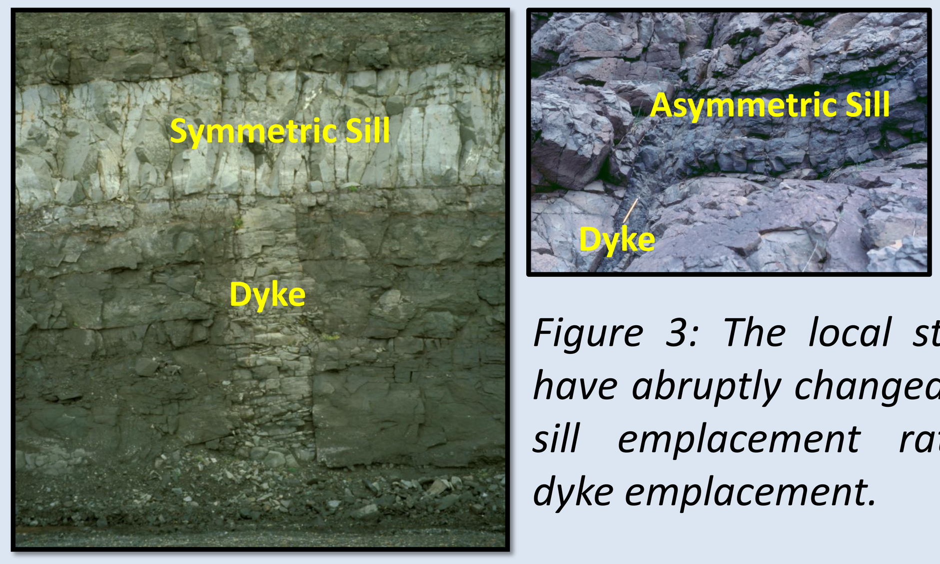

Figure 3: The local stress fields have abruptly changed favouring sill emplacement rather than dyke emplacement.

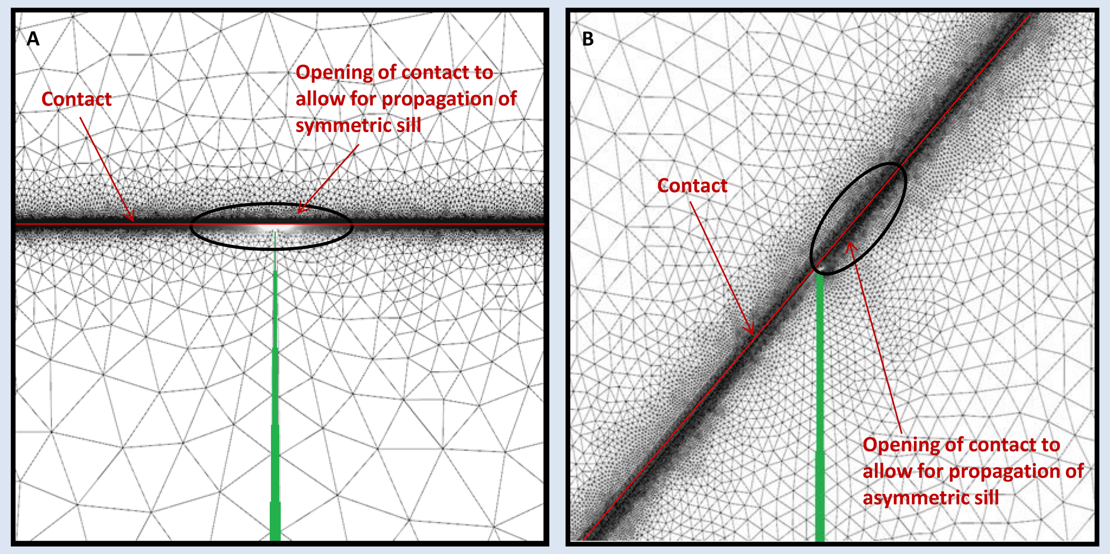

Figure 4: FEM of a dyke being deflected into a sill along a weak contact, E=0.01GPa. A) shows a horizontal weak contact where the dyke becomes doubly deflected along the contact B) shows an inclined weak contact where the dyke become singly deflected up along the contact.

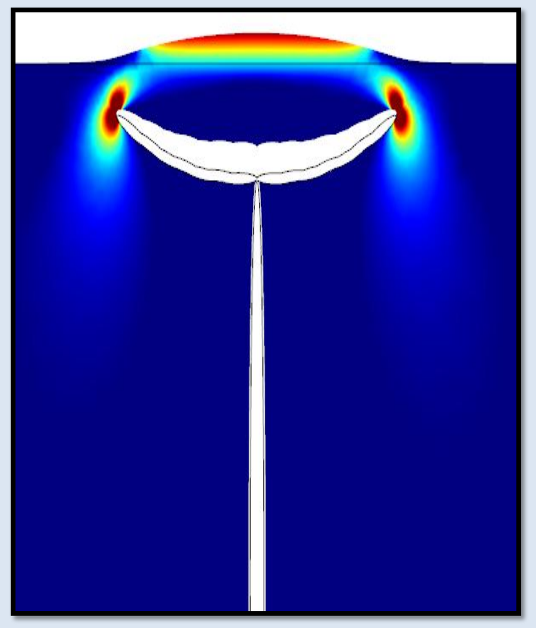

Figure 5: FEM of a sill, where the sill diameter <depth below Earth's free surface inducing a surface effect as well as the stresses generated at the sill tips. Also, the large tensile stresses induced at the surface has lead to deformation/doming at the surface.

Sill complexes

A sill complex (Fig. 6) is emplaced over a relatively short period of geological time. The upper sill tends to be the oldest as it is more difficult for latter sills to propagate the initial sill because it could potentially still be partially molten. A sill complex shows that the surface has a large effect on the local stress field along with the sill tips.

In summary of the numerical models presented in figure 7 it can be said that the stress concentrations at the lower boundary of the sill causing rupturing, depends on several factors. These include the overall geometry of the sill, the distance between the sills, the overpressure (driving force) of the underlying sill, the Young's modulus of the overlying sill, which has been solidified and finally general loading conditions. Sill rupturing can lead the sill to potentially act as a fractured reservoir for different crustal fluids.

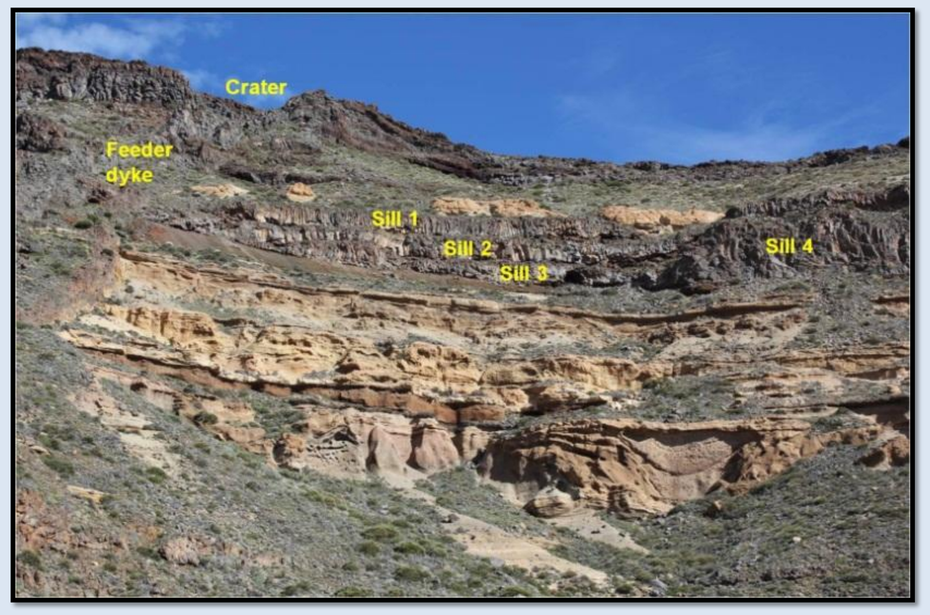

Figure 6: A sill complex (sills 1-4) in the caldera wall of Las Cañadas, Tenerife. This complex is ~100m below the surface extending >100m within an igneous province of lighter pyroclastic rocks and darker lava flows.

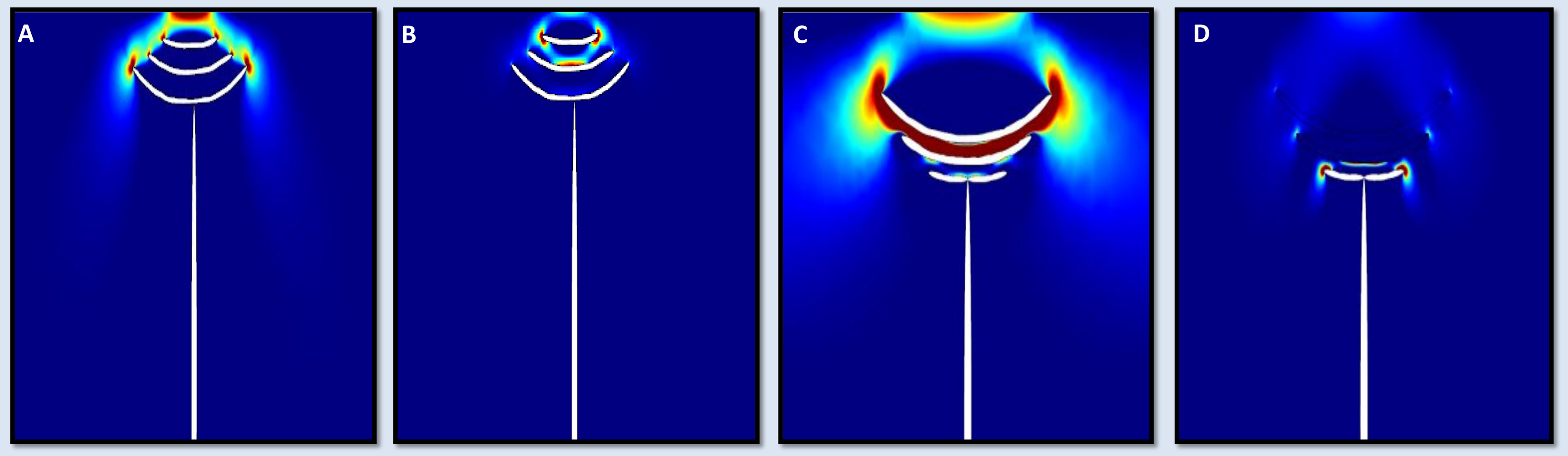

Figure 7: FEM A) with the overpressures being the same, the largest sill dominates the stress field, inducing stresses at the surface. B) the smallest sill with the largest overpressure dominates the local stresses that are generated resulting in the upper boundary of the middle sill being ruptured. C) largest sill induces large surface effects not only because of its length, but also because of its large overpressure, causing the upper margin of the middle sill and the lower margin of the top sill to rupture. D) upper 2 sills solidified are dominated by stresses generated by the lower active sill, rupturing the lower margin of the middle sill.

Conclusions

1. Field observations and numerical models show that the most favourable condition for sill emplacement is where there in an abrupt change from a soft rock to a stiff rock as seen in stratovolcanoes, rift zones and sedimentary basins.
2. Sills tend to form when a dyke becomes arrested at a weak contact and is deflected along the contact either symmetrically or asymmetrically following buoyancy.
3. Surface stresses and deformation are induced by the large tensile stresses generated by the sill tips. This often is the case at relatively shallow depths below the surface.
4. Sill complexes are generally emplaced over a short period of time i.e. thousands of years where the oldest sill tends to be the topmost sill.
5. The sill with the largest lateral dimension or the largest overpressure in a complex tends to dominate the local stress field around the complex and is not dependent on where the particular sill is located within the complex.

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References:

[1]Gudmundsson, A., 2011. Deflection of dykes into sills at discontinuities and magma-chamber formation. *Tectonophysics*, **500**, 50-64.

[2]Gudmundsson, A., Løtveit, I.F., 2012. Sills as fractured hydrocarbon reservoirs: examples and models. *Geological Society of London Special issue on fractured reservoirs* (in review).