Alkaline sill intrusions in sedimentary basins: emplacement of the Mussentuchit Wash Sill in San Rafael Swell, Utah.

Martin Kjenes[1], Christian Haug Eide[1], Nick Schofield[2], Lauren Chedburn[2].

[1]Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway.

[2]Geology and Petroleum Geology, School of Geosciences, University of Aberdeen, Aberdeen, UK.

ORCID ID: MK, 0000-0001-7728-4265; CHE, 0000-0003-4949-9917; NS, 0000-0002-3083-735X;
LC, 0000-0002-6613-9684

Correspondence: martin.kjenes@uib.no

Abstract

Sills are important components of magmatic plumbing systems due to their role as storage features of magma. Previous studies have indirectly investigated sill propagation and architecture by using laboratory experiments, remote sensing, modelling and theory. These studies, however, often struggle to include the complexity of natural systems, which often includes strong interplay between host and intruder. To elevate the importance of host rock and magma interaction, we present the results from a study of combined UAV- and outcrop datasets from world-class 1.3 km long, 30 m high 3D exposure of a 12 m thick alkaline trachybasalt sill in Mussentuchit Wash, San Rafael Swell, Utah. The sill intruded into Jurassic, dominantly sandy, sedimentary rocks. Results of this study shows that the propagation of the Mussentuchit Wash Sill features both fracture-driven- and complex non-brittle fluid interaction emplacement, which are strongly influenced by local sedimentology and presence of porewater. Segregated melt emplaced progressively within the sill during emplacement is used to document the evolution of sill inflation. The fracture-driven propagation is initiated along sedimentary discontinuities through hydrofracturing, while the non-brittle fluid interaction is caused by the presence of local porewater within the sedimentary host rocks. This suggests that local lithology may exert strong control on the architecture and morphology of sills in sedimentary basins.

Supplementary material:

The 3D model of the Mussentuchit Wash Sill (e.g. Figure 4) will be published on V3Geo.com (currently open-access database for 3D models) when the manuscript is published. Uninterpreted images of the sill will be published on figshare and are included as DR1.

Igneous intrusions, such as dykes, sills, and laccoliths, are key components of volcanic plumbing systems and are common in many sedimentary basins worldwide. Mafic intrusions are particularly common in rifted basins and passive margins and generally associated with flood basalt emplacement and large igneous provinces (Hutton, 2009; Jerram and Bryan, 2015; Magee et al., 2016; 2019; Spacapan et al., 2017). Layer parallel sill-intrusions play a major role in magma transport within the crust and are volumetrically a major component of magmatic systems (Cartwright and Hansen, 2006; Richardson et al., 2015; Schofield et al., 2017; Eide et al., 2021). Because of their great importance, sills and dykes have been the subject of large amounts studies using remote sensing (e.g. Ni et al. 2019), laboratory experiments (e.g. Kavanagh et al. 2006), modelling (e.g. Galland et al. 2009), theory (e.g. Dragoni et al. 1997) and field (e.g. Spacapan et al. 2017). Such indirect studies of the evolution of mafic sill intrusions, especially field studies, often lack the element of high-resolution time perspective. To counter this issue, it is important to combine various studies to develop high-qualitative and accurate models for sill emplacement- and evolution, which can be challenging due to the complexity of igneous intrusions. This study is focusing on the qualitative aspect of internal sill architecture and to reflect the various processes that are active during emplacement and evolution of sills.

Sills are typically layer parallel, tabular bodies of magma that may show a range of different architectures, geometries and features based on conditions during emplacement (e.g. Hutton et al. 2009; Eide et al. 2016; Magee et al. 2016). However, sills may also appear with architectures that are saucer-shaped or transgressive, which is mainly based on depth and host-rock conditions at time of emplacement (Pollard, 1973; Gill and Walker, 2020). These conditions include the depth-dependent increase in Youngs Modulus (e.g. Hansen, 2015) or shear failure of the overburden (e.g. Haug et al., 2018). Propagating sills may show different features depending on different host rock- and magma properties (e.g. Hutton et al. 2009; Eide et al. 2016; Stephens et al. 2020). Host rocks with brittle behavior is associated with features such as *steps, broken bridges* and *splays* (Schofield et al 2012); emplacement within host rocks featuring non-brittle behavior is associated with lobate morphologies termed fingers (Schofield et al 2012; Galland et al. 2019), and *viscous indenter-geometries* are likely associated with viscous magma and weak host-rocks bedding planes (e.g. Spacapan et al 2017). Finger can also, however, coalesce to form intrusive broken bridges or steps between segments (Galland et al., 2019; Magee et al., 2019). Sill margins may also show evidence for other physical processes, such as *peperites* common when magma is intruding into wet, unconsolidated sediments (e.g. Skilling et al. 2002), and *sharp margins* which are common when sills are propagating as simple fractures in front of inflating sills (Schofield et al. 2010). Different emplacement mechanisms and post-emplacement features may be important to include for certain types of studies, but the diversity and controls on such sill features are not currently well known.

This paper presents observations from the exceptionally well-exposed Mussentuchit Wash Sill in San Rafael Swell, Utah (Figure 1). The section is c. 1.3 km long and 30 m high and shows a detailed view of an alkaline trachybasalt sill emplaced into a variable but sandstone-dominated package of Jurassic host-rock (e.g. Gilluly, 1927; Delaney and Gartner; 1997). The emplacement of the Mussentuchit Wash Sill occurred at an approximate depth of 0.8-1 km, related to intraplate volcanism along the transition zone of the Colorado Plateau and the Basin and Range province (Smith & Luedke, 1984; Delaney and Gartner, 1997). Here, a wide variety of sill features and architectures show that many different emplacement mechanisms occurred together, and that sill and host-rock interactions varied strongly from place to place within the same sill. These results show that sills are not only emplaced in *"one fashion"* but rather that there is a complex interaction between a propagating and inflating sill, a varied host-rock, and a geochemically evolving melt. This study shows why different sill features occur in certain places and at certain times during emplacement, how they can be used to infer sill evolution in other places and show which emplacement models could be expected in different settings.

The aims of this contribution are: (1) to present detailed observations from the Mussentuchit Wash at various scales, with focus on the sill margins and their lateral variation; (2) to document and explain complex internal sill layering and groundwater interaction features; (3) to present a holistic model for the emplacement of the Mussentuchit Wash Sill; and (4) to compare and discuss the implications of the observed architecture in light of the existing models of propagation, emplacement and magma transport.

Geological framework

Igneous and sedimentary setting

The San Rafael Volcanic Field is in the San Rafael Swell, southeast Utah, on the northwestern margin of the Colorado Plateau (Figure 1). The San Rafael Swell consists of a ~40 km-thick crust, made of 3-5 km thick Phanerozoic sedimentary rocks (mainly Jurassic age) overlying a Precambrian igneous and metamorphic basement (Thompson & Zoback, 1979; Reid et al., 2012). The magmatism in the San Rafael Volcanic Field is related to the subduction of oceanic lithosphere during the Late Cretaceous through the early Cenozoic but erupted long after the end of subduction (Tingey et al., 1991; Humphreys, 1995). Slab rollback and lithospheric delamination during the Neogene caused crustal extension along the margins of the Colorado Plateau, and voluminous intraplate volcanism occurred along the transition zone between the Colorado Plateau and the Basin and Range Province (Smith & Luedke, 1984; Gonzales & Lake, 2017). The San Rafael Volcanic Field features a deeply eroded subvolcanic complex of mafic alkaline sills and dykes. K-Ar dating of the intrusions by Delaney and Gartner (1997) yielded ages of 3.4-4.7 Ma, which corresponds with the regional intraplate volcanism. The stratigraphic position of the subvolcanic complex and the presence of vesicles in the intrusions suggests an emplacement depth of <1 km (Diez et al., 2009; Richardson et al., 2015; Germa et al., 2020). Estimations of late Cenozoic erosion rates, and the age of magmatism, have concluded that approx. 800 m – 1 km of overlying material (i.e., sedimentary strata) have been eroded following emplacement of the intrusions (Pederson et al. 2002; Richardson et al., 2015), yielding the exposures visible today.

The San Rafael Volcanic Field and corresponding igneous rocks have previously been described in several studies and is comprised of approximately 200 dykes and sills (e.g., Delaney & Gartner, 1997; Diez et al., 2009; Kiyosugi et al., 2012; Richardson et al., 2015). Most dykes crosscuts sills and shows weakly chilled margins. The intrusions consist of two different types of magmatic rocks: (1) fine-to-medium-grained alkali trachybasalt that make up the bulk of the sills, and (2) medium-to-coarse-grained leucocratic syenite which occurs almost exclusively within sills (Carman et al., 1994; Germa et al., 2020). Trachybasalt is the dominant rock type across the field and occurs in both dykes, sills, and conduits. The trachybasalt is *melanocratic* and *porphyritic*, with up to 60 vol. % crystals scattered in an *aphanitic* to *microcrystalline* groundmass (Germa et al. 2020). The syenite appears *leucocratic holocrystalline* with *phaneritic* textures and crystals from 0.5 mm to 2 cm. A recent study by Germa et al. (2020) shows that the syenite segregated from the basaltic crystal mush during cooling and accumulated into larger bodies within the sills. This is evident by the absence of chilled margins between the syenite and the trachybasalt, as well as the coarse-grained texture of the syenite.

The intruded sedimentary host rocks in the San Rafael Volcanic Field are comprised of the Middle Jurassic strata of the San Rafael Group (Figure 1). This sedimentary group consists of the Carmel Formation (limestones, siltstones, and mudstones), Entrada Sandstone, Curtis Formation (both sandstone, siltstones, and sparse conglomerates) and Summerville Formation (siltstones, mudstone, and fine-grained sandstones). These formations originated in shallow-marine to nearshore, paralic, and eolian environments (Gilluly, 1927; Delaney and Gartner, 1997). The Mussentuchit Wash outcrop features the Curtis Fm. Sandstone only, which formed as an intertidal platform, which features a range of local discontinuities such as tidal cross bedding with mudstone-draped foresets (Wilcox, 2008).

Sill emplacement structures

Emplacement structures of both sills and dykes have been a topic of interest for the past decades (e.g. Rickwood 1990; Nicholson & Pollard,1985; Hutton 2009; Schofield et al. 2012; Magee et al. 2016; Spacapan et al. 2017; Ghodke et al. 2018; Stephens et al. 2021). Sills and dykes share similar processes even though the orientation is quite different (e.g. Hutton et al., 2009). However, these studies have concluded that host-rock lithology and related properties exhibit critical influence on the emplacement and subsequent development of sills, resulting in an inherent link between emplacement mechanisms and resultant sill morphology (e.g. Schofield et al. 2012; Eide et al., 2016; Magee et al., 2016; 2018). Some examples of relating processes include emplacement depth (e.g. Gill and Walker 2020), layer boundaries (e.g. Kavanagh et al. 2006), cohesion (e.g. Schmiedel et al. 2017), and elastic moduli (such as Young's modulus, E; Poisson's ratio, v; and shear modulus μ) (e.g. Haug et al. 2018). Although these factors are of great importance, a dominant factor is the mechanical strength of the host rock at the time of intrusion, and the host rock's ability to act with either brittle or a non-brittle behavior. In clastic rocks, this is mostly controlled by the degree of consolidation and cementation within the host rock at the time of magma emplacement (e.g. Pollard et al., 1975; Duffield et al., 1986; Schofield et al. 2012). Brittle and non-brittle emplacement structures reflect the cohesion of the host rock, which can further be used to understand magma flow directions (Schofield et al. 2012).

Intrusive bridge and step structures formed by brittle fracturing

Bridges occur when separate intruding sills occur on slightly offset but overlapping horizons (Figure 2A-stage 1) (Rickwood, 1990; Hutton 2009). Subsequent inflation of each segment causes bending of the sedimentary strata, resulting in longitudinal extension along the convex surfaces and contraction along the concave surface of the bridge (Figure 2A-stage 2). As a result of the bending, a series of open tensile fractures open perpendicular to the bridge axis in the zones of maximum flexure (Schofield et al., 2012). The fractures extend away from segment tips, which results in a gradual change of orientation. These fractures may further grow and unite into larger inclined sheets, which may coalesce with the main sheet and transgress from a lower segment to an overlying, adjacent sheet (Figure 2A-stage 3). This process resembles linking of fault segments in relay ramps (e.g., Rotevatn et al., 2007; Schofield et al. 2012b; Magee et al., 2019; Stephens et al., 2020). The open tensile fractures become filled by magma as the intrusion starts to inflate.

Steps form either by the exploitation horizons with slightly offset and no overlap, or by the formation of stepped fractures (i.e. en echelon fractures), which later coalesce into a single sheet often through magma inflation (Figure 2B) (Pollard 1973; Schofield et al. 2012). This is often represented by two end-member processes. If the steps form due to preferential exploitation of horizons, they appear to have no preferential trend and exhibit an inconsistent stepping direction, e.g. up-and-down (Schofield et al. 2012; Magee et al. 2019) (Figure 2B – inconsistent stepping direction). However, sills may also exhibit a step-stair morphology (Figure 2B – consistent stepping direction) if the step formation is attributed from stepped fractures ahead of the sill (Magee et al. 2019). These en echelon fractures show a similarity in their form to hackle marks on joint planes, which are thought to result from the rapid propagation of a fracture through host rock under high stress intensity at a critical velocity (Frid et al. 2005; Schofield et al. 2012). The offset fractures are preserved as the steps on sill margins and therefore oriented perpendicular to the direction of magma flow (Rickwood 1990; Schofield et al. 2012).

Magma finger emplacement through non-brittle processes

Host rocks with low cohesiveness and mechanical strength, such as uncemented sediments, will often exhibit ductile, or non-brittle, behavior during magma emplacement. In these host rocks, ductile deformation occurs at the propagating front of the intrusion, which induces a viscous-viscous interface between the host rock and intruding magma (Schofield et al. 2012) (Figure 2C). This process eventually becomes unstable and creates elliptical propagating lobes of magma (termed *magma fingers,* Figure 2C-stage 1 and 2) (Pollard 1973; Schofield et al 2010), in which the rock particles will be displaced around the intruding front (Duffield et al. 1986). Intrusion into unconsolidated or poorly lithified sediments may additionally cause a dynamic interaction between the magma and sediments. This process forms a zone of incoherent, ragged, or clast-like mixture of host sediment and igneous rock known as *'peperite'* (Skilling et al. 2002). Such zones are often, if not exclusively, related to boiling of pore-fluid or volatiles. These fluids may originate through heating and dewatering of host rock. This results in a rapid drop in pore-fluid pressure, thus triggering of fluidization- and brecciation processes (Kokelaar, 1982). Peperites and complex breccias commonly form where the unconsolidated sediment is wet (Skilling et al. 2002) but can also form in dry sediments (e.g. Jerram & Stollhofen 2002).

Methods and datasets

The study area comprises the north (Figure 3A) and south (Figure 3B) side of an ephemeral, meandering river channel called Mussentuchit Wash in San Rafael Swell, Utah. This river cuts through the Curtis Formation and reveals a 12-meter-thick sill. The dataset consists of sedimentary logs and igneous rocks and multiple photorealistic virtual outcrop models of both sides of the Mussentuchit Wash. The outcrop models use data acquired from a 'DJI Mavic 2 Pro' UAV with a 28 mm lens, which gathered data and images at multiple resolutions by flying at constant distance (c. 15 meters) from the cliffs in San Rafael Swell. The camera was pointed perpendicular to the cliffs of Mussentuchit Wash. Preplanned mapping was not used, due to the nature of the meandering river channel, and all images were collected by manually flying the drone. Approximately 2 271 images containing full GPS- and altitude metadata was collected with c. 60-70% overlap. These images were further processed with *Agisoft Metashape* to create the high-quality 3D models. Processing steps include alignment of images, point-cloud editing and decimation, triangulation of the points to create the mesh for the topographic model, and texturing of the model with selected images (e.g. Rittersbacher et al., 2014). Errors were accounted for by using *Agisofts gradual selection tool* for reprojection error, reconstruction uncertainty, and projection accuracy. This resulted in multiple models with ground pixel resolution ranging from 1.06-1.67 cm/pixel, and a reprojection error of 0.36-1.67 pix. The models with the highest amount of reprojection error (> 1.00 pix) were not used for measuring points of interests along the cliffs, but only for visualization of the valley.

The sedimentary and igneous logs collected at Mussentuchit Wash record grain size, sedimentary structures, nature of bed contacts, weathering surfaces, internal igneous layering, and vesicles. Lateral variability is relatively low for the sedimentary rocks, while it is relatively high for the igneous intrusion. The log presented in Figure 3C represents the most complete and well-exposed section logged in the study area, as it includes all the recognized igneous layering within the sill. Certain apparent layers within the sill are local and does not occur out along the entire outcrop.

The outcrop is sinuous along strike due to the local morphology, and limited 3D control is constrained by the gullies of the relict river channel. Studies of the magmatism in the San Rafael Volcanic Field conducted by Delaney and Gartner (1997) estimated the regional magma flow to be along NNW-SSE (indicated in Figure 3), by mapping the orientation of the opening of feeder dykes (Figure 14, Delaney and Gartner 1997). This correlates well with the emplacement structures (e.g. steps and bridges) observed within the Mussentuchit Wash, which can be used as paleocurrent indicators for primary magma flow. There are no faults present in the study area of this paper, and the dip of the intrusions is on average 7°SW, which is parallel to the sedimentary bedding.

Results

The Mussentuchit Wash Sill

In the North side of the valley (Figure 3A), the Mussentuchit Wash Sill is continuous and shows no significant transgressive behavior. In the south side of the valley, the sills display clear transgressive behavior through a series of steps and bridges where it steps upward approx. 16 m through the stratigraphy. Each step and bridge have an offset of c. 1-5 m and are spaced 50-100 m apart. No dykes are observed in the Mussentuchit Wash (see also Figure 1). However, two dykes are located 1.2km NNW of the sill which could be related to the magmatism.

Investigation of the two valley sections through magmatic logging and investigations of virtual outcrop data revealed that the sill consists of four different textures (Figure 4), three distinguishable layers (Figure 5), and syenite veins (Figure 6). The layers found in the sill are termed the Lower-, Middle-, and Upper- Layers herein. The Middle Layer consists of massive trachybasalt with occasional chaotic, 1-360 cm thick syenite sheets, while the Upper and Lower Layers contain thin (0.5-2cm), closely spaced (20-30 cm), layer-parallel syenite veins. The Upper layers also contain abundant vesicles. The 12-m-thick sill appears to have a somewhat constant thickness despite of its local changes in geometry, as illustrated in Figure 5. The sill follows sedimentary discontinuities of the Curtis Formation (Figure 7), which includes primary sedimentary structures such as cross bedding.

The following subchapters will present distinctive textures found within the intrusion, internal layers and their unique and classifiable features, and lastly the interplay between host rock and intruder.

Textures

Different textures are found within the 12-meter-thick sill, which provides evidence of different processes during emplacement, such as massive trachybasalt (Figures 4A-D), chilled margins (Figures 4B), fine-grained zones (Figure 4A and 4C), and peperitic zones (Figure 4D). The fine-grained zones resemble chilled margins due to their appearance with respect to both grain size and color. The textures are easy to distinguish due to their distinct appearance. However, weathering creates some ambiguity with regards to textural difference in some places. The massive trachybasalt is the most common type and exhibits little-to-no features but may include prominent vertical fractures.

Chilled margins (e.g. Figure 4B) appear somewhat scarcely along the lower and upper sill margins but occur more consistent at the bottom of the sill rather than the top. It is recognized based on its finer grain size, and darker color compared to the massive trachybasalt. Smaller vertical fractures limited to the chilled margins appear commonly.

Fine-grained zones (e.g. Figures 4A; 4C) appears to enclose and dominate broken bridges. This texture might resemble breccia due to its fractured appearance but feature rounded magmatic material rather than angular. Fine-grained zones are commonly weathered, but some areas feature more pristine dark grey appearance (Figure 4C). The unaltered fine-grained zones do resemble the chilled margins. Individual mineral grains are recognized in the field, such as olivine and pyroxenes. The fine-grained do not exhibit a constant width (or height) but varies greatly across the sill- and host-rock contact (e.g. Figure 4A). The size does, however, seem to be influenced by the size of the emplacement structure. In general, broken bridges with larger offsets have larger enclosing zones of fine-grained zones, but a lot of variation is seen with regards to the size of the zone. Locally, fine-grained zones may contain small chimney-structures (e.g Figure 4A), expressed by sub-vertical patches of fractures enclosed in fine-grained zones stretching from the broken bridges into the more massive parts of the sill. Some vesicles close to broken bridges are observed with the diameter ranging from 1-3 mm. The fine-grained zones also exhibit higher frequencies of fractures compared to the massive trachybasalt (5-8 fractures pr 30 cm).

Peperitic zones (e.g. Figure 4D) occur scarcely in the outcrop but appears to occur at localities with broken bridges, and exclusively within the fine-grained zones. This texture is distinguished from fine-grained zones due to the inclusion within of sand from the host rock. The zone contains a mixture of sand and magma (c.15% sand and 85% magma), which could suggest magma-sediment mingling. The fluidized zones appear to originate from sedimentary xenoliths within broken bridges, as indicated in Figure 4D. Such zones may be related to boiling of pore-fluid or volatiles, through heating and dewatering of host rock. Notably, peperitic zones may occur extending from broken bridges inside fine-grained zones.

Internal sill layering

Lower Layer

The Lower Layer of the Mussentuchit Wash Sill is approximately 5-6 m thick (Figure 5A). The otherwise yellowish Curtis sandstone host-rock is usually bleached around 3 m away from the intrusion and exhibits a much lighter color. The layer contact between the host rock and the sill occurs most often along flat discontinuities in the host rock but may locally appear more undulating due to primary sedimentary structures (e.g. cross bedding).

The first 5-10 cm from the base of the sill exhibits a very fine-grained trachybasalt, with a somewhat glassy appearance (Figure 5B). This section represents the chilled margin of the bottom contact of the sill. In addition, the chilled margin features a higher frequency of vertical fractures. The remaining section appear phaneritic.

Syenite veins occurs frequently in the Lower Layer of the sill (Figure 5C). They are easily distinguished as they crop out with a light color which contrasts the otherwise dark grey trachybasalt (Figure 5A; 5C). The veins exhibit a thickness commonly ranging from 0.5 mm to 2 cm. The spacing between each vein differs, ranging from 20-30 cm. The thickness-spacing of each vein exhibit a linear relationship. Thicker syenite veins (e.g. > 2 cm) are exclusively followed by greater spacing (30 cm). Syenite veins may either appear as continuous- or as small individual inclined veins with *en echelon* arrangement which shows top towards the SSE direction (Figure 5C).

Middle Layer

The Middle Layer of the Mussentuchit Wash Sill is approximately 7-8 m thick. It includes locally occurring syenite segments, but for the most part (in c. 85% of the exposure) it consists entirely of massive trachybasalt and does not feature any other complex magmatic textures. The massive trachybasalt features less- to no visible textures and crop out with a medium- to dark-gray color with visible mineral grains, such as pyroxene and amphibole. It exhibits thin, open vertical fracture sets with secondary mineral precipitation of either zeolite or calcite.

The syenite in the Middle Layer differs greatly from the syenite veins in the Lower Layer. The syenite occurs with several different geometries, such as tear-drop shaped sheets (> 50 cm thickness), blobs (elliptical with long axes greater than 50 cm) and ocelli (circular with a diameter of a few cms), but tear-drop shaped shaped sheets are the most common shape (Figure. 5D). These different shapes of syenite appear locally and not parallel to each other, compared to the veins from the Lower Layer, or the sill margins (Figure 6A). The phenocrysts appear with more developed crystal faces, which range in size from 0.5 mm to 4 cm. Notably, the mafic minerals show either no apparent arrangement, radial growth or, in some rare cases, imbrication (Figure 6B). The long, developed crystals are limited to grow within the syenite, as they stop propagating at the border between the vein and the trachybasalt (Figure 6C), indicating that they formed at a later stage than the trachybasalt. The thickness of the syenite sheets vary greatly but may reach up to 3.6 meters thick. Locally, network of thin sheets (1-2 cm thick) of syenite appear to amalgamate into thicker sheets (Figure 5D). Within 80 cm from the transition between the Middle- and Upper Layer, some syenite veins are parallel to the sill-host rock margin, and starts resembling the pattern in the Lower Layer, but with a more undulating morphology. The thickness of these syenite veins resembles the thicknesses found within the Lower Layer, and varies from 1 to 3 cm.

Upper Layer

The uppermost layer of the Mussentuchit Wash Sill is approximately 2-3 thick. This layer, like the Lower Layer, is in direct contact with the Curtis Sandstone. The sandstone appears generally less bleached at the top of the Upper Layer, compared to the contact at the Lower Layer (Figure 5A). It is difficult to quantify the amount of bleaching, as the stratigraphy above the sill is often eroded in the exposure. Bleaching does occur to some extent at the uppermost host rock boundary, but it is less prominent and is patchier. However, the Curtis Sandstone above the sill features more intensive fractures, which are both vertical and horizontal (Figure 5A).

There is an abundance of vesicles towards the upper 2 meters of the Upper Layer, but these are absent within the uppermost 30-50 cm. The vesicles appear circular and show no apparent trend distribution or geometry (Figure 5E). They are filled by precipitated zeolite and in some cases calcite (Figure 5F). Syenite veins occur in the lower part of the Upper Layer, but they do not appear as frequent as in the Lower Layer and are thus classified as locally occurring. Syenite veins in the Upper Layer show an undulating geometry, like the syenite occurring in the Middle Layer. This could be connected to the presence of gas bubbles at the top of the sill.

These syenite veins share the same thickness as the syenite veins in the Lower Layer (0.5-2 mm) and spacing (20-30 cm), but not morphology (undulating versus sill-parallel, respectively).

Features at sill margins

Host rock interplay

The Mussentuchit Wash Sill is emplaced within host rocks of the Jurassic Curtis Formation. The contact between the sill and the host rock shows two main geometries: planar to bedding and cross bedding (Figure 7A-E), and irregular (Figure 7F-G). In general, the Mussentuchit Wash Sill appears to follow local sedimentary discontinuities, which includes sedimentary structures, such as cross bedding, and bed boundaries (Figure 7D-E). The cross bed foresets contain mud drapes. This results in undulating geometry, which is illustrated in Figure 7E. The sill appears to generally follow larger horizontal or inclined discontinuities, and show sharp contact geometries, which indicates that the sill created and exploited fractures along these discontinuities. However, in some places, the contact between intrusion and host rock is undulating on a cm-scale, as shown in Figure 7F-G. No fractures are observed at these types of contacts. The boundary between the host rock and intruder is still sharp but does not show any indication primary sedimentary structures. The irregular bedding contacts does not extend for greater distances (e.g. > 30 cm) but rather on smaller (<30 cm) and local scales.

Bridges

The Mussentuchit Wash Sill features many different brittle emplacement structures at the interface between trachybasalt and the Curtis Formation host rock. This is evident by the abundance of magmatic bridges, which all occur as broken bridges (e.g. Figures 8A-C). There is no apparent evidence of unbroken bridges, however, but they may have been eroded. The broken bridges display vertical jogs of various sizes, ranging from 0.8 (Figure 8A) to 7 meters (Figure 8C).

The broken bridge structures occur in homogenous sandstone of the Curtis Formation, where the primary sill splays have intruded along local discontinuities. The degree of alteration is strongest at the sill contact, especially the broken bridge xenolith (e.g. Figure 8A-C). In some cases, the broken bridges show remnants of the sedimentary bridge expressed as xenoliths bended/folded at the base of the sill.

At the base of the sill, syenite veins are tabular and parallel to the lower sill margin. Near broken bridges, however, syenite veins are tilted upwards within a few meters of the broken bridges (e.g. Figure 8A-B), and this tilt decreases upwards through the Lower Layer until the veins are planar to the sill margin. Furthermore, at the tips of the upturned flaps of the broken bridges, the sill shows a fine-grained zones texture extending away from the flap.

Broken bridges with a vertical jog off less than 1 m show one clear cross cutting fracture (Figure 8A-B). Broken bridges that have an offset larger than 1 m show a much greater number of magma-filled fractures (Figure 8C), which could either have formed during bending of the sedimentary bridge, or during inflation and coalescence of the two sill segments. The broken bridge in Figure 8C exceptionally displays sill segmentation parallel to the emplacement direction towards the NNW-SSE. It moves from the lower discontinuity to the next strong discontinuity that occurs approximately seven meters above. Remnants of the initial lower intrusion continues along the lower discontinuity and becomes gradually thinner. It appears that the original splay is following the initial horizon, but it becomes arrested as the sill prefers to inflate and connect to the overlying sill segment.

Fractures are abundant close to bridges and are most commonly vertical, which occurs below and above the magmatic body. However, horizontal fracturing is very abundant parallel and perpendicular to sedimentary discontinuities above the intrusion, showing clear evidence of local uplift caused by inflation.

Discussion

Controls on sill propagation

Emplacement models of sills in the shallow crust suggest that sills emplace either under a brittle or non-brittle regime (e.g. Schofield et al. 2010; Schofield et al. 2012a). These regimes are often assumed to be mutually exclusive, as they are heavily influenced by the properties of the host rock, such as shear cohesion and tensile strength (Baer, 1991). In general, cemented sediments promote brittle processes, such as fracturing (e.g. Pollard, 1973; Malthe-

Sørensen et al. 2004; Kavanagh et al. 2006), while unconsolidated and poorly cemented sediments favor non-brittle emplacement (e.g. Schofield et al. 2010; Schofield 2012; Spacapan et al. 2017). However, consolidated coal and salt may promote non-brittle processes during emplacement due to their plastic behavior during heating (Pollard et al. 1975; Gerjarusak et al. 1991; Schofield et al. 2014). The Mussentuchit Wash Sill features both fracture-driven- (e.g. Figure 7B) and complex non-brittle fluid interaction emplacement (e.g. Figure 7F). This is reflected by neighboring planar bedding contacts and irregular contacts, thus suggesting that different emplacement mechanisms may occur locally. Observations from the Mussentuchit Wash suggests that the host rock lithology and its coupled rheological response to intrusion of magma heavily influences the morphology and architecture of sheet intrusions.

Planar bedding contacts

Most sill-host rock contacts in Mussentuchit Wash are strata-concordant and follows layer boundaries within the sedimentary host rock. In general, this suggests that the host rock was cemented at the time of magma emplacement and exhibits high shear cohesion. For instance, single fractures are more likely to develop in lithologies with high shear cohesion, while host rocks with low cohesion are not able to handle elevated shear stress and will therefore fail (Baer, 1991). However, studies have shown that the mechanical properties of the bedding their discontinuities are likely to influence the magnitude of pressure changes experienced by intruding magmas (e.g. Kavanagh et al. 2017). Thus, mechanical layering and local heterogeneities in the host rock may be exploited by the magmatic intrusion. This is evident as both local sedimentary bedding (e.g. Figure 7A-B) and cross bedding (e.g. Figure 7A; 7D), are used as pathways for the intrusion. The planar bedding contacts appear to exhibit single propagation point, which exploits either through pre-existing fractures or by hydraulic fracturing involving dilation parallel along layer boundaries. In the sense of evolution, the sill starts propagating along local bedding, at a planar bedding contact (Figure 10A-stage 1). This part of the Curtis Formation exhibits both high cohesion and tensile strength. However, observations from Mussentuchit Wash suggests that this also occurs within local cross bedding. In those areas, sill splays start propagating along local cross bedding which does feature poorly cemented cross bedding containing mud drapes (Figure 10B-stage 1). However, there is no evidence that the sill prefers mud drapes. These cross bedding exhibits low cohesive strength due to poor cementation. Further, the sill preserves the original geometry given by the primary sedimentary structures both for planar bedding contacts (Figure 10A – Stage 2; Figure 8B) and cross bedding contacts (Figure 10B – stage 2; Figure 7E). This is evident by the presence of either completely flat- (e.g. Figure 7C-D) or undulating host rock contacts (e.g. Figure 7E).

In terms of texture of the intrusive rocks, the zones exhibiting planar- and cross bedding contacts usually features chilled margins and to some extent fine-grained zones. Chilled margins appear most common, while fine-grained zones occur adjacent to zones with transgressive sill behavior, such as steps and broken bridges. All bridges occurring in the Mussentuchit Wash appear broken.

Irregular contacts

On the contrary to the fracture driven bedding propagation, the Mussentuchit Wash Sill does also feature irregular bedding contacts. This irregular bedding is almost exclusively related to complex igneous textures, such as fine-grained zones and peperitic zones (e.g. Figure 4A; 4C). We propose that these textures are the result of fluidization and heat induced boiling of pore fluids within the host rocks (Figure 11). Fluidization is often related to host rocks with low cohesion (e.g. Schofield et al. 2010) and occurs as the host rocks are not able to handle elevated shear stress and will therefore fail through distributed fracture networks along grain boundaries (Baer, 1991). Such shear stress can be initiated through the heating of either wet sediments or pore water within the host rocks by the intrusion. Consequently, fluidization can either occur as thermal fluidization or triggered fluidization. Thermal fluidization occurs as a continuous process with flash boiling of pore-fluids along the magma-host rock contact (Schofield et al. 2012). Triggered fluidization, however, initiate through rapid unconfinement of fluids (i.e. triggered fluidization) due to opening of tensile fractures ahead of a propagating sill tip (Schofield et al., 2010). The opening of fractures causes a rapid and momentary expansion of the pore-fluids, which leads to localized fluidization and clastic injections, or the rapid failure of the overburden in response to doming created by vertical inflation of the magmatic body (Schofield et al. 2012).

Fluidization may occur with or without the opening of tensile fractures (Figure 10A-C) that are sufficient to cause a large temporary drop in pore-fluid pressure if there are fluids present in the host rock. The Mussentuchit Wash sill features mainly triggered fluidization as most of the contacts involves fracturing along discontinuities. The sudden drop in fluid pressure causes an explosive expansion of water vapor that destroys the anisotropy of host rock, which forces the intrusion to preferentially follow the bedding and propagate (Figure 10D-E) (Kokelaar, 1982; Schofield et al. 2010). Further transgression is directed upward as the tensional crack is in the roof of the sill splay e.g. Kokelaar, 1982; Schofield et al., 2010). This process is shown multiple times in Mussentuchit Wash and where it is almost exclusively related to transgressive behavior, such as broken bridges (e.g. Figure 4A; 4C; 8B-C). Most broken bridges in the Mussentuchit Wash Sill exhibits both fine-grained zones and peperitic zones, where the fine-grained zones typically encircle fluidized host rock in larger sections (e.g. Figure 8A-B).

Fluidization may, however, occur without decreasing the pressure, through both heating and volatilization (i.e. thermal fluidization) of pore fluids by the magma (Schofield et al., 2010). This specific process is not completely evident by observations from the Mussentuchit Wash Sill, as the fluidized texture is directed inwards into the sill from host rock but could explain the irregular bedding contacts that occur locally where there is no broken bridges.

Syenite

Syenite appears within the studied Mussentuchit sill either as cm-thick veins or as meter-thick sheets, whereas the largest sheets are in the center of the sill. The syenite formed at the solidification front, which migrated from the bedding boundary towards the center of the partially solidified basalt (crystal mush) during cooling (Germa et al. 2020 – Figure 12B; Figure 11A-F). This is evident by the lack of chilled margins between the syenite and the basalt, in addition to the coarse-grained texture of the syenite. The solidification front moved progressively toward the interior of the magma body, away from the sill margins, as the sill cooled (Germa et al. 2020). It is believed (e.g. Germa et al. 2020) that density differences between the syenite melt and the basaltic host led to segregation of syenite towards the center of the sill. Our study demonstrate that the sill cooled as it was being emplaced, with a record of inflation and bridging preserved in the syenite veins. These syenite veins are potentially preserved because the sill margins cooled so rapidly at the margins that during initial emplacement of magma, the newly segregated syenite could not migrate out of the basaltic host before it solidified. During emplacement of the Middle Layer, cooling along the solidification front occurred more slowly because the material on the outside of the solidification front was very warm, and the syenite had more time to segregate, migrate and accumulate into larger tear-drop shaped syenite sheets (e.g. Germa et al. 2020). The complex en echelon arrangement of syenite veins suggests that these magmatic bodies were influenced by the structural domain, in addition to mineral segregation and buoyancy differences.

Syenite veins occur in the Lower Layer of the entire sill, also near broken bridges. Relationships between the syenite veins in the Lower Layer and the broken bridges (e.g. Figure 8) reveal the time-relationship between formation between the veins and the broken bridges as it does not cross-cut intrusive breccia or fluidized texture. The syenite veins demonstrates fluidity and alters its sub-parallel geometry to avoid percolating/emplacing within fine-grained zones and trachybasalt (e.g. Figure 8A-C). This suggests that the syenite veins were emplaced during initial emplacement and inflation of the Mussentuchit Wash Sill, since fine-grained zones and peperitic zones develop either through initial propagation or inflation of the sill. Therefore, we suggest the following development model of the syenite within the Mussentuchit Wash sill:

Initial sill propagation occurs (Figure 11A-B), during which solidification fronts propagate inward from the sill boundaries to the center of the sill (e.g. Germa et al. 2020). Both inflation of the main sill body and segregation of trachybasalt and syenite occurs (Figure 11C-D). Because the sill is inflating, and growing in thickness, small ocellis/droplets of syenite is segregated continuously as the sill inflates (Figure 11E-F) (e.g. Germa et al. 2020). These syenite droplets are transported/sheared parallel with the magma driving pressure. This motion causes coalescence of the droplets parallel to the sill, thus creating the syenite veins.

Studies carried out by Germa et al. (2020), however, suggests that the alkaline intrusions in San Rafael Volcanic Field were 30% crystalized at the time of emplacement. This implies that the propagating basaltic magma would flow as a Bingham plastic, rather than a fluid with Newtonian behavior (Magee, 2013, 2016; Kokandakar et al., 2018). This could potentially infer brittle behavior, which is acting on the boundary between the syenite veins and the “mushy” trachybasalt. This is evident by the presence of en echelon geometries of the syenite veins in the Lower Layer (e.g. Figure 5A).

Degassing and fluidization imply rapid cooling and crystallization of the sill. Thus, the flowing mushy trachybasalt and syenite will flow around these zones of intrusive breccia and fluidized breccia. The syenite veins are consequently a frozen image of how the internal magma flow moved around the solidified broken bridges (e.g. Figure 8). Further, either arrestment of sill tips or focused flow towards the center of the sill causes the Mussentuchit Wash Sill to rapidly inflate. More syenite is percolating in the Middle Layer, which eventually coalesce into greater syenite sheets (e.g. Figure 12 – Germa et al. 2020).

Emplacement model

Based on our observations of the sill and host rock interplay, complex melt interaction between the syenite and trachybasalt, associated host rock deformation, and previous propagation models, the following evolutionary model of the alkaline Mussentuchit Wash Sill intrusion is proposed:

Stage 1: Initial sheet propagation

Emplacement of trachybasalt occur along pre-existing weakness planes, either along planar bedding (e.g. Figure 7B) or along cross bedding (e.g. Figure 7E) in the Curtis Formation (Figure 11A). The initial sill propagation is mainly influenced by periodical driving pressure from its source. The origin of melt is still unknown but stems most likely from an undiscovered feeder-dyke related to the Colorado Plateau boundary magmatism (Delaney and Gartner, 1997). At this stage of emplacement, chilled margins will form at the host rock contact, which will gradually increase flow resistance of the intrusion (e.g., Pollard et al., 1975). These initial splays will continue to propagate until the driving pressure is unable to facilitate the next increment of growth, either due to local competition of available mechanical energy, or due to a drop-in driving pressure due to increasing segment length (Pollard et al., 1982). Notably, alkaline magmas exhibit high velocities due to their low viscous nature and richness in volatiles (Spera, 1984; Ghodke et al., 2018), which could imply that the initial sheet propagation occurred rather rapidly. Gas bubbles float to the Upper Layer as the sill propagates.

Stage 2: Sill segment coalescence

As time goes by, the magma flow is gradually localized towards the center of the Mussentuchit Wash Sill causing inflation due to cooling from the bedding contacts and inwards (Figure 11B). Overlapping sill segments that initially intruded at different levels in the host rocks starts to coalescence due to this inflation. This is evident by the presence of broken bridges in Mussentuchit Wash. Overlapping sill segments bends the enclosed sedimentary bridges and consequently develops open tensile fractures (e.g. Figure 8C). These fractures often occur in an en echelon arrangement. The fractures are influenced by magma pressure (e.g. Hutton et al., 2009), elastic strength of the host rocks (e.g. Schofield et al., 2010) and interstitial fluid pore-pressure (e.g. Rogers and Bird, 1987). In addition, the host rocks rheological response of sill segmentation is governed by its mechanical strength, lithology, porosity, cementation, and volume of pore fluid (Schofield et al., 2009). The fracturing causes a local drop in fluid pressure, which promotes further coalescence between the two sill segments (Kokelaar et al., 1982; Schofield et al., 2010). This is evident in Mussentuchit Wash, we can clearly see the presence of zones of intrusive- and fluidized breccia around the broken bridges. This infers the presence of a strong interaction between pore-fluid from the host rock and the hot magma through triggered fluidization.

Stage 3: Further inflation and melt evolution

Further inflation of the Mussentuchit Wash Sill continues, and the sill becomes gradually thicker and thicker (Figure 11C-F). Simultaneously, the sill is cooling inward from both host rock boundaries towards the middle. While this is happening, syenite is segregated from the trachybasaltic melt. This process is initiated due to segregation of tephrophonolitic residual liquid from the basaltic crystal mush after crystallization reaches 30-45 % (Germa et al., 2020). The syenite percolated into small droplets, which further coalescence into thin veins of syenite. These experience shear and propagation parallel to the magma driving pressure. Eventually the sill reached its final thickness of approx. 12 meters (Figure 11F). The final parts of the syenite were segregated in the Middle Layer of the sill, which was also the last section of the sill to completely cool. Studies by Germa et al., 2020 suggests that the sills in the San Rafael Volcanic Field would have solidified in 1 to 30 years. Further, cooling and crystallization model by Germa et al. 2020 estimates that it would take less than a year for a 10 m thick sill to solidify in the San Rafael Volcanic Field. By applying the same principle, we can estimate that it would take less than 3 years to solidify the Mussentuchit Wash Sill.

During magma emplacement, dynamic changes may modify the properties of the magma, which may be inferred by post-emplacement textures in relict plumbing systems. Chilled margins, fine-grained zones, peperitic zones, and massive trachybasalt are all evidence of a gradual change within the intrusion. Chilled margins are created initially as hot magma intrudes cold sandstones, while fine-grained zones and peperitic zones are evidence of fluid interaction. The fluids generate vapor that flow laterally into the viscous magma, which is evident by the presence of vesicles in the top of the intrusion (e.g. Figure 6G). However, the vesicles may alternatively be the result of degassing, as the vesicles is not only present at the top layer over bridges.

Applications for modelling

This study has, in detail, shown the complex interactions between sedimentary host rocks and intrusive sills. Local sedimentary variations within the Curtis Formation alter the initial path of the sill, and consequently its morphology and architecture. Thus, small variations in host-rock properties, such as pore-water contact, may have an impact on how sills behave in sedimentary basins. Numerical and other types of models are an important technique to investigate how igneous intrusions behave at the time of the emplacement, but these often lack the complexity of real intrusions (e.g. Galland et al., 2009 Barnett et al., 2014). For simplicity, intrusion is often kept as purely tabular mediums, but as this study suggests that this is not always the case. Often, the sill responds to small alterations in the host rocks (e.g. Spacapan et al. 2017; Eide et al., 2021), which may control where the future path of the sill is. Understandably, the number of details that should be included in a particular study depends on the study objectives, but here we provide some key observations that could potentially be included in future models:

(I) Sill stepping. Observations from this study clearly shows that the sill does not intrude as a planar, flat, magmatic body manner. The morphology and architecture of the intrusion is influenced by the presence of multiple sedimentary layers, which is evident by the presence of multiple bridges and steps (e.g. Figure 8).

(II) Multiple textures. The presence of textures shows that multiple processes occur during emplacement of sills. Clear examples of this are the presence of planar and irregular bedding contacts. Planar bedding contacts develop due to fracturing along discontinuities or local heterogeneity (e.g. Kavanagh et al. 2017), such as planar- and cross bedding (e.g. Figure 7). Irregular contacts, on the other hand, most likely develop due to the presence of porewater in the sedimentary host rocks (e.g. Schofield et al. 2012; Figure 7F-G). The presence of porewater initiates triggered fluidization, which is reflected by the presence of fine-grained zones and peperitic zones (e.g. Figure 4).

Conclusions

This study has presented a world class 3D-exposure-model spanning 1.3 km long and 30 m thick section. The sill itself is c. 12 m thick, which provides a highly detailed model for studying the intrusion. This dataset has allowed for a thorough investigation and interpretation of the relationship between host rock and intruder, with the following main findings:

1. The Mussentuchit Wash Sill suggests that current emplacement models for sills are often too simplified, which may paint a wrong picture on the actual events of emplacement. Local behavior and properties of host rock may alter the emplacement processes vastly. This is shown by the appearance of both brittle and non-brittle processes for the same intrusive splay.
2. Initial propagation occurs either (I) parallel to local sedimentary bedding, e.g. planar- and cross bedding through hydraulic fracturing processes, or (II) irregular through triggered fluidization caused by presence of porewater within host rocks.
3. Geochemical and groundwater-related effects may lead to different internal geometries within igneous sill intrusion.
4. The trachybasaltic melt may segregate a secondary syenetic melt. The syenites does not appear to percolate through the sill, but rather emplace within the intrusion itself close to where it fractionated.
5. These syenites reveal internal melt flow indicators which constrain the timing of development of features at the margin of the sill relative to sill inflation. Such features include steps, broken bridges, and chimneys related to intrusive- and fluidized breccia.

In sum, this implies that sills not only tend to emplace differently, but they may also emplace by different processes locally due to the textural variability. This highlights the importance of a thorough understanding of the state of the host rocks. Local changes may significantly alter the path of splay propagation and consequently the architecture and morphology of the sill post-inflation. This is critical knowledge for the understanding of poorly imaged, deep sill intrusions, and active shallow intrusions in sedimentary basins.

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Figure captions

Figure 1: Geological map of the San Rafael Swell and corresponding cross section. The map is modified from USGS Interim geological map of the East half of the Salina 30’ x 60’ quadrangle by Doeling (2004). This is only a section of the USGS map, focusing on the area surrounding the studied Mussentuchit Wash Sill. The San Rafael Swell is mainly comprised of Jurassic Sandstones (various shades of green), Quaternary deposits (yellow) and igneous intrusions, such as dykes and sills (red). Cross section of selected line from the map. This transect shows the main lithologies of San Rafael Swell, various unconformities, and relative thickness of the sedimentary strata. The upper cross section shows todays topography, while the lower cross section shows a simple reconstruction of how the basin was during emplacement of the magmatic intrusions.

Figure 2: Overview of sill emplacement structures in consolidated (**a**, **b**) and unconsolidated (**c**) host rocks. Modified from Schofield et al 2012. **A**: Schematic illustration showing development and relationship of broken bridges. **B**: Schematic showing development of en echelon steps within a sill, highlighting the increase in offset in a downflow direction. **C**: Schematic drawing showing the evolution of magma fingers.

Figure 3: Overview of the Mussentuchit Wash Sill dataset. Map-view of the meandering river valley cutting through the Mussentuchit Wash Sill. The north- and south-valley of the river channel is separated (**a**,**b**). A generalised magmatic log was also collected from the dataset (**c**). **A**: Picture and schematic illustration showing the main morphology of the North valley side. The black line indicates

the simplified sill geometry trend. **B**: Picture and schematic illustration of the main geometry of south valley, which is much longer than the North valley. The black line indicates the simplified sill geometry trend. **C**: Generalized log of the Mussentuchit Wash Sill, showing the layers and main features. Future figures are referenced in the log.

Figure 4: Figure and images showing the various textures found within the Mussentuchit Wash Sill. **A:** Image of a broken bridge. Schematic illustration highlighting the different textures enclosing the bridge. Syenite veins deviate and become transgressive parallel with the sill. This photo is acquired parallel to the magma driving pressure. **B:** Image of a chilled margin. **C:** Image highlighting the visual difference between the trachybasalt and the fine-grained zone. **D**: Image of a broken bridge. Schematic illustration highlighting peperitic zone enclosing the broken bridge.

Figure 5: Overview of the Mussentuchit Wash Sill igneous layers. **A**: UAV image and schematic showing the entire sill. The sill has a slightly undulating morphology. **B**: Picture showing chilled margin and contact between sill and host rock. **C**: Picture showing syenite veins of the Lower Layer. These syenite veins appear parallel to the sedimentary bedding. **D**: Picture showing a thick syenite sheet situated within the Middle Layer **E**: Picture of the Upper Layer, close to the upper sedimentary bedding contact, which exhibits small vesicles. **F:** Image showing filled vesicles from the Upper Layer.

Figure 6: Generalized overview of the syenites of Mussentuchit Wash Sill. The syenites occur in different thicknesses, ranging from a few milimeters to multiple meters. Syenites are easily distinguished based on their light-grey color (**a**,**b**) and easily distinguishable minerals (**c**,**d**). **A:** General arrangement of syenite veins within the Lower Layer. Image is taken perpendicular to primary propagation direction of the sill. **B:** Minerals within syenites might appear either with a radial growth structure or imbricated. **C:** Mineral growth stops at syenite boundaries.

Figure 2: Images and schematic illustrations highlighting intrusion and host rock interplay. Along the sill-host rock boundary we can observe planar- (**a, b, c, d, e**) and irregular bedding (**f, g**). The sill appears to follow mud-draped cross bedding, and follow these layers as lesser splays (**d, e**). **A:** Field photo with accompanying schematic illustration, demonstrating the uneven layer boundary morphology. **B:** Close up photo of a planar, brittle sill contact. **C:** Close up photo of a planar, brittle sill contact. **D:** Image

showing a tiny splay that followed a weak discontinuity in the host rock. **E:** Image showing contact between the sill and a cross bedding. **F:** Ductile, irregular, boundary between sill and sedimentary rock. **G:** Ductile, irregular, boundary between sill and sedimentary rock.

Figure 3: Schematic illustration images gathered from opposite valley-sides in Mussentuchit Wash (**a**). These images provides a 3D outcrop of a broken bridge (**b,c,d,e**). Schematic illustration to provide sense of direction of the following photos. Image B/C is taken from the south valley side of Mussentuchit Wash, while D/E is from the North side of the valley. The red line represents where the bridge was originally connected, which is completely eroded today. All images are taken perpendicular to primary propagation direction of the sill. **A**) Image of the north valley bridge and schematic illustration of image B, showing syenite veins and the broken bridge. **B**: Image of the South valley bridge featuring fine-grained zone. Also, schematic illustration of the image. This valley side features more syenite veins, which deviates away from the broken bridge xenolith. The broken bridge is also enclosed in a fine-grained-zone. C: UAV image of a large broken bridge. The bridge also features a lot of magmatic splays, which may give an indication of how the broken bridge was formed. Syenite veins deviate and become transgressive parallel with the sill. This photo is acquired parallel to the magma driving pressure.

Figure 9: Schematic diagram showing the emplacement of sills within the Curtis Formation, with focus on planar bedding- (**a**) and cross bedding geometry (**b**). **A**: Stage 0, no intrusions. Stage 1, magma propagates as a series of offsets along planar bedding of the host rock. Stage 3, the magmatic bodies begin to inflate and develops a broken bridge. **B**: Stage 0, no intrusions. Stage 1, magma propagates along cross bedding within the host rock. Single splays follow mud drapes, as it is easier for the sill to follow these continuities. Stage 2, the magmatic body starts to inflate, and the sill grows vertically.

Figure 40: Schematic diagram showing the emplacement of sills along irregular boundaries, with a accompanying image. This process involves processes like fluidization, which is affected by pore fluid (**a**) and pore fluid pressure generated by heating water within the host rock (**b**). Once sill-induced fracturing reaches the heated pore water (**c**), an explosive vapor is released which fluidize surrounding country rock (**d**). Thus, creating peperitic zone (**e**). **A**: Stage 0, no intrusions. **B:** Stage 1, propagating magma heats the rocks and present pore fluids. **C**: Stage 2, the pore fluids reach high temperatures. When sill-induced fracturing reaches the pore fluids, there is a sudden drop in pressure, causing an

explosive expansion of water vapor. **D**: Triggered fluidization caused by drop in pressure associated with tensile failure, which causes flash boiling of pore fluids. **E**: Stage 4, further inflation of the sill due to continued propagation.

Figure 11: Schematic illustration showing the emplacement of the Mussentuchit Wash Sill. **A**: Stage 1, magma propagates as a series of offsets along bedding of the host rock. **B**: Stage 2, further propagation of individual magma splays, and we get overlapping bodies. **C**: Stage 3, the magmatic bodies begin to inflate and develops a broken bridge. This process is influenced by fluidization. **D**: Stage 4, the sill continues to inflate, and starts segregating syenite as small en echelon steps within the sill itself. **E**: Stage 5, the sill continues to inflate, and the syenite en echelon steps starts to coalescence to create veins. The sill is quite thick as this point, and thus segregation and crystallization take longer time. **F**: The sill inflates and segregates syenite to today's morphology and architecture.

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