Lithological controls on architecture and development of igneous intrusions in sedimentary basins.

Martin Kjenes

Thesis for the degree of Philosophiae Doctor (PhD)
University of Bergen, Norway
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It is more fun to talk with someone who doesn’t use long,

difficult words but rather short, easy word like

“What about lunch?”

A.A. Milne.

Scientific environment

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Martin Kjenes, July, 2023

Abstract

Magma transport in the Earth's shallow crust is facilitated by interconnected igneous intrusions (i.e., sills and dykes), which are often referred to as magmatic plumbing systems. These networks of magma are found in most sedimentary basins worldwide, as they are associated with rifting, large igneous provinces, or shift of tectonic plates. For the past decades, three-dimensional seismic reflection data has been used extensively to map, characterize, and interpret intrusive complexes. However, such studies often face limitations due to the restricted resolution of seismic datasets, making it challenging to discern the processes influencing igneous intrusions, the lithology of host rocks, and emplacement features of sills. In some cases, entire sills may remain undetected by seismic visualization.

To counter this limitation, this study presents seismic scale (> 1 kilometer by > 100 meters) virtual outcrops that are based on field observations. These virtual outcrops have a high-detail resolution of a few centimeters, which makes it possible to map the architecture, morphology, and geometry of interconnected sills. The geometry of sills holds crucial insights into their initial emplacement, and often reflects the properties of the intruding magma and the host rocks. However, limited attention has been devoted to the importance of lithology. This thesis aims to contribute insights into the influence lithology may exert on sill emplacement and geometry. Understanding the dynamic relationship between sills and host rocks may enhance the general understanding of basin evolution, lead to better forecasting of volcanic eruptions, and better utilization of subsurface resources.

Internal sill architecture and marginal contacts with the host rocks are the theme of the first paper. This study was conducted as a case study of a 12-meter-thick alkaline sill in Mussentuchit Wash, San Rafael Volcanic Field, Utah. The results show that propagation of sills may feature both brittle and non-brittle emplacement, which is strongly influenced by local lithology and presence of pore-water. Initial propagation of sills in Mussentuchit Wash occurs through either linear elastic fracturing parallel to sedimentary bedding (e.g., planar bedding or cross-bedding), or irregularly through

triggered fluidization caused by the presence of pore water. The interaction between magma and pore-water is reflected by internal textures within the sills. This study also documented presence of segregated melt within the intrusion, in which the main sill consists of trachybasalt while the segregated melt is comprised of syenite. The syenites do not appear to percolate through the sill, but rather emplaced within the trachybasalts. In addition, the syenites include internal flow indicators, which constrain the timing of development of features at the margin of the sill relative to sill inflation. These emplacement features include broken bridges and chimneys related to intrusive and fluidized breccia.

The second paper focuses on sills and any distinctive geometry that are potentially related to lithology. This study presents both a quantitative and qualitative dataset which focuses on morphology and geometry of sills from the Cedar Mountains, San Rafael Volcanic Field, Utah. The virtual outcrops used in this study have a resolution of a few cm/pixels, which provide a strong, detailed control of the sills. This is visualized as geometric trends that occur within the three lithologies present in the outcrop. In mudstones, sills are typically strata-concordant with a few vertical jogs. In heteroliths, sills are commonly strata-concordant but also exhibits complex segmentation through multiple broken bridges. In sandstones, sills typically show strata-discordant geometry with multiple splays beneath the base of the sill. This study also shows that sills are more than 3.5 times more likely to intrude within mudstone intervals. In addition, this study used the virtual outcrops from Cedar Mountains to develop a synthetic seismic model to see how the aforementioned geometries were reflected in a seismic dataset. Interestingly, the different geometries observed in the different lithologies were detectable in the synthetic seismic, which provides a base of interpreting lithology in seismic datasets by using generalized sill geometries in datasets with little-to-no well control. The results from the second paper suggest that lithology plays a critical control on sill geometry.

Sills and resulting geometry in different lithologies are also the theme in the third paper, but this study aims to compare different sills from other outcrops around the world to test the hypothesis made in the second paper. The results suggest that sill geometries are consistent within similar lithologies, even if the emplacement depth and viscosity of the sills differ. The main conclusion from this study shows that the emplacement of sills in sedimentary basins are significantly influenced by the burial and evolutionary history of the host rocks, which is reflected by the consistent geometries observed across all the studied outcrops. Importantly, these geometries do not appear to be controlled by depth at the time of emplacement, but as a result of host rock properties such as consolidation and quartz cementation. This suggests that we need to consider the state of the host rocks at the time of magma emplacement.

In sum, this thesis provides a representation of why lithology should be considered an important factor that exerts control on the geometry of sills. Virtual outcrops provide great analogues that can be used for synthetic seismic models, which can further be compared to seismic datasets of intrusions in sedimentary basins. This provides a strong control on features that fall beneath seismic resolution, and potentially could help predict lithology based on visual interpretation of sill geometries in datasets with little-to-no well control.

Sammendrag

Magmatransport i jordskorpen forekommer igjennom magmatiske intrusjoner (siller og diker), som ofte omtales som et magmatisk rørsystem. Disse nettverkene av magma finnes i de fleste sedimentære bassenger over hele verden, ettersom de er assosiert med rifting, store magmatiske provinser eller forskyvning av tektoniske plater. I løpet av de siste tiårene har tredimensjonale seismiske refleksjonsdata blitt flittig brukt for å kartlegge, karakterisere og tolke komplekser av intrusjoner. Imidlertid møter slike studier ofte begrensninger på grunn av begrenset oppløsning i seismiske datasett, noe som gjør det utfordrende å skille prosessene som påvirker magmatiske intrusjoner, litologi til vertsbergarter og strukturer som dannes når siller intruderer. I noen tilfeller kan hele siller forbli uoppdaget av seismikk.

Denne doktorgradsavhandlingen presenterer feltobservasjoner samt tredimensjonale modeller av feltområder med seismisk skala (> 1 kilometer høyde, > 100 meter bredde) for å finne et motsvar til begrensningene ved seismiske studier. Høydetaljerte virtuelle feltområder gjør det mulig å kartlegge intern arkitektur for siller, samt morfologi og geometri. Geometrien til siller spiller en avgjørende rolle når intrusjoner propagerer i undergrunnen, og geometri gjenspeiler ofte egenskapene til både vertsbergarten og magmaen. Litologi er en egenskap som ikke har blitt mye studert tidligere. Denne avhandlingen har som mål å bidra med innsikt og observasjoner som kan hjelpe å definere hvilken innflytelse litologi har på geometrien til magmatiske intrusjoner i sedimentære basseng. Å forstå det dynamiske forholdet mellom siller og vertsbergarter kan forbedre den generelle forståelsen av bassengevolusjon, føre til bedre prognoser for vulkanutbrudd og bedre utnyttelse av ressurser fra undergrunnen.

Intern arkitektur og marginale kontakter mellom siller og vertsbergartene er temaet for den første artikkelen. Her ble det utført en «case» studie av en 12 meter tykk sill i Mussentuchit Wash, San Rafael Volcanic Field, Utah. Resultatene viser at propagering av siller kan både skje under både sprø og ikke-sprø forhold, noe som er sterkt påvirket av lokal litologi og tilstedeværelse av porevæsker. Innledende intrudering av sillen i Mussentuchit Wash skjer enten gjennom lineær elastisk oppsprekking parallelt med

sedimentære laggrenser (f.eks. planære lag eller kryssjikt), eller ved uregelmessige kontakter forårsaket av interaksjon mellom magma og porevæsker. Samspillet mellom magma og porevæsker reflekteres av indre teksturer i sillen. Denne studien dokumenterte også tilstedeværelse av segregert smelte i intrusjonen, der hovedsillen består av basalt mens den segregerte smelten består av syenitt. Syenittene ser tilsynelatende ut til å ha blitt avsatt i selve basalten. I tillegg inkluderer syenittene interne strømningsindikatorer, som videre kan tolkes som indikatorer av utviklingen til intrusjonen, ettersom de unnviker andre avsetningsstrukturer funnet langs marginen til sillen. Brutte broer, og skorsteinssoner, er eksempler på slike avsetningsstrukturer.

Den andre artikkelen setter søkelys på geometrien til siller og hvor disse geometriene oppstår i henhold til verstbergarten. Denne studien presenterer både et kvantitativt og kvalitativt datasett som fokuserer på morfologi og geometri til siller fra Cedar Mountains, San Rafael Volcanic Field, Utah. Studien inkluderer virtuelle feltmodeller med en oppløsning på noen få cm/piksler, som videre gir en sterk, detaljert kontroll av sillene. Denne kontrollen er reflektert i geometriske trender som man observerer innen hver enkelt litologi. I slamstein er sillene stort sett helt planære og parallell med vertsbergartene. I heterolittiske lag er sillene også planære og parallelle, men de viser også flere ulike segmenter av siller på ulike stratigrafiske nivåer. I sandstein er sillene en ikke-parallell med vertsbergartene, og oppstår vinkeldiskordant. Man kan også observere mange små siller parallell med hovedsillen. Studien viser også at det er 3,5 ganger mer sannsynlig at en sill vil intrudere langs et slamsteinslag enn i heterolitter og i sandstein. Denne studien har i tillegg brukt de virtuelle feltmodellene som base for å produsere syntetisk seismiske modeller. Dette ble gjort for å observere hvilke strukturer som ikke kan sees i seismiske datasett, samt for å undersøke hvordan vi kan tolke litologi i seismiske datasett ved å bruke intrusjonene med liten eller ingen brønnkontroll. Resultatene fra denne artikkelen antyder at litologi spiller en kritisk rolle for geometrien til siller.

Siller og resulterende geometri i forskjellige litologier er også temaet i den tredje artikkelen, men denne studien tar sikte på å sammenligne forskjellige siller fra andre feltområder rundt om i verden for å teste hypotesen satt i den andre artikkelen. Resultatene tyder på at geometrien til siller er konsistente innenfor lignende litologier, selv om plasseringsdybden og viskositeten til sillene er forskjellige. Hovedkonklusjonen fra denne studien viser at plassering av siller i sedimentære bassenger er betydelig påvirket av begravelsen og evolusjonshistorien til vertsbergartene, noe som gjenspeiles av de konsistente geometriene observert på tvers av lokaliteter. Studien antyder at disse geometriene ikke ser ut til å være kontrollert av dybden på tidspunktet for plassering, men som et resultat av egenskapene til vertsbergarten, som for eksempel og kvartssementering. Dette antyder at vi må vurdere tilstanden til vertsbergartene før magmaen har intrudert.

Denne avhandlingen kan betraktes som en representasjon av hvorfor litologi bør ansees som en viktig faktor som utøver kontroll på geometrien til siller. Virtuelle lokaliteter gir gode analoger som kan brukes til syntetiske seismiske modeller, som videre kan sammenlignes med seismiske datasett av intrusjoner i sedimentære bassenger. Dette gir en sterk kontroll på funksjoner som faller under seismisk oppløsning, og kan potensielt bidra til å forutsi litologi basert på visuell tolkning av geometrien til siller i datasett med liten eller ingen brønnkontroll.

List of Publications

PAPER I:

Kjenes, M., Eide, C. H., Schofield, N., & Chedburn, L. (2023). Alkaline sill intrusions in sedimentary basins: emplacement of the Mussentuchit Wash Sill in San Rafael Swell, Utah. *Journal of the Geological Society, 180(1)*.

PAPER II:

Kjenes, M., Eide, C. H., Scotti, A. A., Lecomte, I., Schofield, N., & Bøgh, A., (2023): Lithological controls on emplacement structures of sills in sedimentary basins: controls and recognition in reflection seismic data. *Basin Research, In review*.

PAPER III:

Kjenes, M., Eide, C. H., Senger, K., Rabbel, O., & Schofield, N. (2023): Geometry of Igneous Sills in Sedimentary Basins: a comparison of igneous systems. *Manuscript in preparation for submission to Journal of the Geological Society.*

Contents

Chapter 1

Introduction

Volcanoes and other forms of magmatic activity is found not only on Earth, but also throughout our Solar System. Such a violent natural phenomenon has had the tendency to spark a fascination for a lot of people, from the dramatic landscapes they create to their impact on civilizations and natural resources. While it is easy for the eyes to be directed to what occurs above the surface, most of the magma is moving beneath the surface during volcanic events and never actually erupts. Magma that is emplaced in the subsurface is traditionally referred to as igneous intrusions. These bodies of magma appear either as sub-horizontal, inclined, or vertical. Their emplacement within host rocks involves relict (or active) transport of magma from deeper sources, which is located either in the mantle or in the middle or deep crust (Rocchi and Breitkreuz, 2017). Interconnect magmatic intrusions often represents a volcanic plumbing system, in which their geometry can be generalized based on their dominant geometry, such as (1) broadly layer-parallel and transgressive sills, (2) saucer shaped intrusions, (3) layer-discordant sub-vertical dykes, or (4) localized volcanic centers (Planke et al., 2000; Senger et al., 2017; Jerram and Bryan, 2018). Although dykes have traditionally been considered as the dominant storage for magma in the subsurface, modern seismic reflection studies have shown that sill complexes not only act as a major part of the plumbing system but perhaps a leading role in the transport of magma in sedimentary basins (Cartwright and Hansen, 2006; Magee et al. 2016; Eide et al. 2022). Sedimentary basins are region-scale depressions that are filled with thick sequences of sediments, and often host natural resources such as groundwater, methane, and hydrocarbons. Igneous intrusion may influence such reservoirs through thermal convection (e.g., Gardiner et al. 2019), release gases that affect the climate (e.g., Svensen et al. 2004), and alter potential hydrocarbon reservoirs (e.g., Rateau et al., 2013; Senger et al. 2017). The fill of sedimentary basins varies greatly across the globe, which implies that the igneous intrusions are naturally emplaced through different types of sedimentary rocks.

This thesis focuses on the relationship between different types of sedimentary host rocks and their intruders, igneous intrusions.

Sills and their relationship with sedimentary host rocks has not only been studied in offshore seismic studies (e.g., Jackson et al. 2013), but also through hands-on field outcrop studies (e.g., Delaney and Gartner, 1997), analogue laboratory experiments (e.g., Kavanagh et al, 2006), and numerical modelling (e.g., Haug et al. 2017). The field outcrop studies provide a unique opportunity to document and analyze natural sills and to observe their contact with their respective host rocks in detail. Such observations are important and useful to improve seismic analyzes of natural sills, as sills often represents thin geological layers of elevated acoustic impedance compared to host rocks in seismic studies and may be too thin to be imaged in seismic datasets (e.g., Schofield et al. 2015). Seismic datasets are also used to monitor active systems of magma emplacement (e.g., Barsotti et al. 2023). In general, field studies provide information about important elements that fall beneath seismic resolution, e.g., contact metamorphic aureoles, sill splays, fracture patters, bridge structures, and magma flow indicators (e.g., Hutton, 2009; Agirrezabala et al., 2014; Schofield et al., 2016). However, field outcrop studies may only represent the final geometry of sills and not necessarily how the sill itself were emplaced, propagated, and developed over time. In addition, field outcrops also provide a limited representation of a full-scale igneous plumbing system, which may reach tens to hundreds of kilometers in length. Key observations that could suggest emplacement processes can be found in the geochemistry and geometry of the sill, but this does not necessarily tell the entire story of the sills in question. While seismic studies provide a full overview of igneous plumbing systems and 3D control over interconnected sills, analogue laboratory experiments and numerical modelling are key tools that enable us with the opportunity to find the missing pieces of the puzzle. Both laboratory and numerical modelling represent two ways of studying sills with the opportunity to test different scenarios with controllable variables and measurable outcomes (e.g., Kavanagh et al. 2018). In sum, all these areas of volcanic studies are important to fully understand the relationship between sills and host rocks.

Understanding the development of volcanic plumbing systems, and consequently their relationship with their host rocks, is related many areas of societal significance such as resource management (e.g., carbon capture and storage, geothermal energy), geohazard mitigation (e.g., earthquakes, volcanic eruptions), public health (air pollution, groundwater contamination), and economic applications (e.g., hydrocarbon reservoirs and ore deposits).

In general, the effect sills, and consequently volcanic plumbing systems, infer in the upper crust provides key information that can help us to build a more sustainable future. Safe and reliable storage for CO_2 and hydrogen is an essential step to help the energy transition, in which relict interconnected sills may be used as potential cap rocks and traps (e.g., Senger et al. 2017; Schmitt et al. 2023). Geothermal energy is an example of where active systems meet energy development, where shallowly emplaced sills drive convection of meteoric groundwater which results in boiling, high-enthalpy geothermal systems that be exploited for power production (Hayba and Ingebritsen, 1997; Scott et al., 2015). Geothermal systems, however, may also interact with potential groundwater reservoirs, as volcanic rocks are recognized as potential aquifers for groundwater (Lenhardt et al. 2011; La Felice et al., 2014). This interaction may cause diffusion of arsenic from the geothermal reservoirs into the groundwater reservoirs, or oxidation of sulfides causing the groundwater to become more acidic (La Felice et al., 2014; Bundschuh et al., 2015). Geohazards, such as earthquakes and ground deformation are also closely related to active volcanic regions, such as Iceland (e.g., Sigmundsson et al. 2022), and local movement of igneous intrusions in the subsurface. Earthquakes, or microearthquakes, are related to the propagation of intrusions while surface deformation is connected to the inflation of sills (Tarasewicz et al. 2012; Hudson et al. 2017; Sigmundsson et al. 2022). Sills have also been known to cause the release of methane through hydrothermal vent complexes, due to heating of organic-rich carbon in sedimentary rocks (e.g., Svensen et al. 2004). These hydrothermal vent complexes are formed by release of fluids and sediments forms from the contact aureoles around sill intrusions (Jamtveit et al., 2004; Svensen et al. 2004; Svensen et al. 2009).

Igneous rocks have also been recognized as potential commercial reservoirs for hydrocarbons (e.g., Liu et al., 2012), and it is vital to have a great understanding of how true sill geometries develop in certain lithological intervals due to subsurface imaging resolution (Jackson et al. 2013; Magee et al. 2015; Schofield et al. 2015; Eide et al. 2017). Studies have found that mechanical layering and heterogeneity of host rocks influences the geometry and emplacement of sills, but some open question regarding their role on geometry of sills remains. In addition, igneous intrusions have the potential to influence (positively and negatively) the charge, migration, reservoir, trap, and seal (Hansen and Cartwright, 2006; Witte et al., 2012; Rateau et al., 2013; Senger et al., 2013). However, the amount of influence is limited by timing of magmatism, with respect to source rock maturity (Senger et al., 2017).

Motivated by the above, the main objectives of this thesis are to enhance the understanding of the lithological controls affecting the architecture and development of igneous intrusions in sedimentary basins. This thesis combines field observations, large virtual outcrops, and seismic modelling. The four main objectives of this thesis are:

- To investigate and describe qualitatively internal sill architecture and marginal contacts between igneous sills and sedimentary host rocks.

  Addressed by Manuscripts 1 and 2.

- To identify geometries and quantify potential preferential pathways for igneous intrusions in heterogeneous sedimentary strata.

  Addressed by Manuscript 2.

- To compare synthetic seismic models created from virtual outcrops with real seismic data from natural sills in sedimentary basins and investigate if sill geometries can be used to predict lithology in seismic datasets with limited or no well information.

  Addressed by Manuscripts 2.

- To compare different igneous intrusions from sedimentary basins and use this to understand how host rock strata may influence magmatic expression of sills.

  Addressed by Manuscript 3.

Chapter 2

State of the art

Sill emplacement and propagation

Sills, and dykes, have traditionally been considered as Mode I hydrofractures, while their propagation mechanism have been simplified within a Linear Elastic Fracture Mechanical (LEFM) framework (Pollard et al. 1973; Stephens et al. 2021). In this type of framework, sills are often idealised as sheets with tapered (wedge-shaped) tips. However, this is not the case for all sills as they have been observed in various field studies with rounded or blunt tip geometries. This suggests a non-brittle propagation mode of sills since lobate or blunt tips do not form through linear elasticity (e,g, Pollard et al. 1975; Delaney and Pollard, 1981; Kavanagh and Sparks, 2011; Schofield et al. 2012; Spacapan et al. 2017; Healy et al. 2018). Consequently, sill propagation mechanisms are split into two main groups: (i) elastic brittle and (ii) non-brittle. Studies have found that there are several factors that influence the mode of propagation, and emplacement, of sills. These factors include host rock properties such as lithology (e.g., Schofield et al., 2012), compaction (e.g., Schofield et al. 2010), cohesion (e.g., Schmiedel et al. 2017), elastic- and shear moduli (e.g., Haug et al. 2017).

Elastic brittle emplacement models

Both sill and dyke propagation feature elastic-brittle deformation as mode of emplacement. This can further be subdivided into two groups: the elastic-splitting model and the Barenblatt-cohesive zone model (Pollard, 1973; Rubin, 1993).

The *elastic-splitting model* is linked to linear elastic fracture mechanics, in which the fracture ahead of the intrusion tip exhibit knife-like geometries with sharp wedge-shaped tips. In this model, the intrusion tip propagates by tensile opening of the host rock, in which the opening vector is perpendicular to contact margins of the magma (Pollard et al. 1973; Spacapan et al., 2017). The elastic-splitting model have been linked to intrusion emplacement in brittle host rock with low confining stress and temperature, or emplacement at high strain rates under high confining stress (Pollard et al. 1973). Hydrofractures, in terms of linear elastic fracture mechanics, initiates propagation when the stress intensity factor at the crack tip equals or exceeds the material fracture toughness (Rubin, 1995). The host rock bends elastically during emplacement to accommodate the fracture aperture, such that layer thicknesses remains above and below the intrusion (Stephens et al. 2021).

The *Barenblatt-cohesive zone* model is an extension of the elastic splitting model, which includes a cohesive process zone at the intrusion tip. Cohesive stresses act to resist dilation caused by the intrusion and are on the order of rock tensile strength (Pollard, 1973; Lister, 1990; Poppe et al. 2020; Stephens et al. 2021). During emplacement, the magma's average flow velocity catches up with the fracture tip velocity. Hence, the pressure gradient fluctuates which leads to a reduction in magma pressure within the narrow intrusion tip. This creates a gap between the viscous magma and the fracture tip (Barenblatt, 1962; Rubin, 1995; Stephens et al. 2021). This gap, or process zone, can be filled by exsolved volatiles either from the magma or the surrounding host rock (Pollard, 1973; Lister, 1990; Poppe et al. 2020). The influx of pore fluids may result in non-localised inelastic damage in the process zone, in which fractures require more energy to continue to propagate (Rubin, 1993; Gudmundsson, 2011). However, the pressure gradient caused by the low pressure in the process zone also drives the magma flow towards the tip, but not enough to further drive propagation of the fracture plane (Gill and Walker, 2020). This process cause inflation of the intrusion and rounding of the magma front, resulting in a blunted tip shape.

Non-brittle emplacment models

Non-brittle emplacement models occurs when host rocks behave as a ductile or viscous medium. This suggests that viscosity contrasts influence the style of host rock deformation. For instance, magma may behave as a viscous indenter if the viscosity of the magma exceeds that of the host rock. In this scenario a low viscosity magma intruding into a more viscous host rock may issue a Saffman-Taylor instability, which results in the magma front to break down into multiple fingers or segments (Saffman and Taylor, 1958). Multiple models have been proposed due to the rounded tips and ductile deformation, which can be divided into two main models: *(iii) viscous indentation models (i.e., brittle-* and *ductile faulting model)*, and *(iv) fluidisation model*.

The *brittle- and ductile faulting model* represents two end-member models of host rock deformation, but they are similar in that they both account for deformation induced by a propagating body of magma (Pollard, 1973; Spacapan et al., 2017). This process includes host rock deformation such as buckling, folding, faulting, and/or ductile flow (Stephens et al. 2021). In general, this deformation results in a thickening of the host rock ahead of a rounded intrusion tip. The intrusion tip is similar in thickness as the intrusion itself (Pollard, 1973; Merle and Donnadieu, 2000; Spacapan et al. 2017). The main difference between brittle and ductile faulting models is the angle of the shear planes to the intrusion plane, which is 30° for brittle faulting and 45° for ductile faulting (Spacapan et al. 2017). However, these two models mainly account for the deformation of host rocks but does not include magma dynamics, which plays a major mechanical role during emplacement (Pollard, 1973; Bunger and Cruden, 2011; Galland et al. 2014). In addition, host rock formations may contain complex brittle or ductile mechanical systems. This is accounted for in the conceptual *viscous indenter* model, which shows that viscous shear stresses near the intrusion tip are high enough to overcome the strength of the host rock (Donnadieu and Merle, 1998; Mathieu et al., 2008; Abdelmalak et al., 2012; Galland et al. 2014). This model concludes that in certain scenarios, the propagating magma pushes its host rock ahead like an indenter with a blunt or rectangular tip (Spacapan et al. 2017).

The *fluidisation model* represents the enhancement and failure caused by heating of pore-fluids, or organic matter, through emplacement of propagating intrusions. The local heating of the host rocks causes the pore-fluid-pressure to exceed the cohesion of the host rock, which may cause disaggregation and flow of the host rock (Kokelaar, 1982; Schofield et al. 2010; 2012). In general, the diffusing of heat leads to boiling of aqueous fluids, or cracking of organic matter, which further causes local pressure build-up in the host rock close to the intrusion. If these zones of heated fluids become fractured due to the propagation of the sill tip, the sudden drop in pressure will cause flash boiling which would disaggregate and locally fluidise the host rock ahead of the sill (Kokelaar, 1982; Schofield et al. 2010). Fluidisation destroys the mechanical the mechanical anisotropy of the host rock, which forces the intrusion transgress along the local bedding (Schofield et al. 2010). This process is often referred to as *triggered fluidisation*, in which the fluidisation is a direct result of an external process such as opening of a fracture (Kokelaar, 1982). The intrusions that propagate through this type of sill emplacement often exhibits a lobate and/or irregular tip geometries and are associated with peperites and brecciation of the host rock (Kokelaar, 1982; Skillling et al. 2002; Eide et al, 2017). Peperites are defined as a zone of coherent, clast-like mixture of host rock sediments and igneous rock (Skilling et al. 2002). Peperites and breccias are commonly associated with emplacement of intrusion within wet, unconsolidated sediments, but they are also observed around sills emplaced in dry sediments (Jerram and Stollhofen, 2002; Kjenes et al. 2023). Fluidisation, however, may also occur without a sudden drop in pressure, but through heating and volatization of pore-fluids by the magma until they reach their respective liquid-vapor stability line (Schofield et al. 2010). This process is referred to as *thermal fluidisation*. Unconfined fluids within the host rock will boil and transgress away from the intrusion as they expand. Fluidisation occurs when the pore-fluid-pressure exceeds the mechanical strength between grains through excessive heating, which releases the raised pressure and dropping the pore-fluids rapidly into vapor.

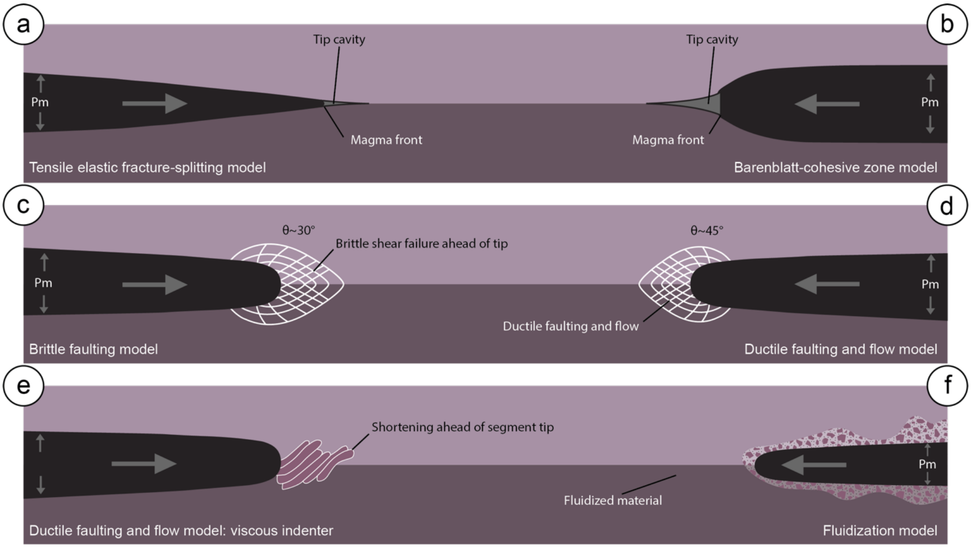


Figure 1: Schematic drawing of the different emplacement mechanisms of sills. From Paper 2, modified after Stephens et al. 2021. A: Shows tensile elastic fracture-splitting model. B: Shows Barenblatt-cohesive zone model. C: Shows Brittle faulting model. D: Ductile faulting and flow model. E: Viscous indenter model. F: Fluidization model.

Magma-sediment interaction

For the past decades, the properties of the host rocks surrounding igneous intrusions has increasingly received attention. A great range of multidisciplinary studies have suggested that it is crucial to comprehend how intrusions interact with their respective host rocks, as they mutually influence and limit one another. The host rocks and their properties (i.e., lithology) hold an influence on the emplacement and evolution of igneous intrusions.

In general, *lithology* describes physical characteristics (e.g., grain-size, minerals, sorting) of the host rock, and these characteristics exerts a critical influence on the emplacement and development of sills. There is an inherent link between emplacement mechanism of intrusions and the resulting geometry and morphology of the emplaced magma (Schofield et al. 2012; Magee et al. 2016). Sedimentary basins often exhibit complex sedimentary sequences, which provides multiple horizons, or layers, in which a sill may propagate. In general, sills tend to follow weaknesses in host rocks. Mechanical layering and heterogeneities, such as interface properties, provides potential propagation pathways for sills to exploit (Kavanagh et al. 2017). In general, host rock lithology can be subdivided into two types: brittle conditions or non-brittle/ductile conditions. In clastic sedimentary rocks, consolidation and cementation are generally developed due to increasing pressure and temperature with depth, primarily through quartz cementation (c. 1.5 to 2 kilometers) (e.g., Bjørlykke and Egeberg, 1993). The conditions of host rocks may therefore be reflected by either brittle or non-brittle emplacement structures, such as bridges or magma fingers. These structures also reflect the mode of emplacement and propagation, such as linear elastic fracture mechanic mode or non-brittle, respectively. Brittle host rocks represent well-consolidated, and mechanical strong, host rocks (Schofield et al. 2012). Sills emplaced in brittle host rocks often exhibit steps and bridges, which are emplacement structures that form when different sill segments connect. Bridges develop when separate intruding sills propagate on slightly offset, but overlapping horizons (Rickwood, 1990; Hutton, 2009). As two overlapping sills inflate, a series of open tensile fracture will open perpendicular to the bridge axis in the zones of maximum flexure (Schofield et al. 2012). These fractures may further grow and unite the two overlapping sill segments, causing the two sills to coalesce into a connected system of sills (Schofield et al. 2012). This process is similar to the linking of faults in relay ramps (c.f. Rotevatn et al. 2007; e.g., Magee et al. 2019). Steps form in a similar fashion, but this involves underlapping sill segments, rather than overlapping. Sills emplaced in non-brittle conditions, however, represents poorly consolidated and mechanically weak host rocks. In general, ductile deformation occurs at the propagating front of the intrusion, which induces a viscous-viscous interface between the host rock and the intruding magma (Schofield et al. 2012). This process eventually becomes unstable and develops elliptical propagating lobes (termed magma fingers), in which particles from the host rock are displaced around the intruding front (Duffield et al. 1986). Unconsolidated or poorly lithified sediments traditionally exhibits a dynamic interaction between magma and sediments (Duffield et al. 1986; Skilling et al. 2002). Overlapping and underlapping segments may coalesce in a similar fashion as bridges and steps, but they preserve their lobated structure (Schofield et al. 2012).

In general, the shape of sills is also strongly influenced by the elastic characteristics and shear strength (Schmiedel et al. 2017). Laboratory studies have also elevated the influence of *cohesion* of the host rocks, and how it may promote different sill geometries. For instance, saucer-shaped shills tend to form in high-cohesion host rocks, whereas low-cohesion host rocks may lead to the formation of punched laccoliths (Schmiedel et al. 2017). In general, the diameter of the intrusion tends to decrease as the cohesion and thickness of the overburden increases. Elastic bending and shear failure of the host rocks also contributes to the deformation of the overlying brittle crust surrounding sills.

Chapter 3

Study area

Field based observation and interpretation is the core of this thesis, where the focus was within the San Rafael Volcanic Field, Utah, US (Figure 2). This area is situated along the northwestern margin of the Colorado Plateau and is comprised of a Precambrian igneous and metamorphic basement overlain c. 3 to 5 kilometer of Phanerozoic sedimentary rocks and Pliocene magmatic rocks (Thompson & Zoback, 1979; Reid et al., 2012). Two field areas were chosen within San Rafael Volcanic Field for this study, namely the Mussentuchit Wash and the Cedar Mountains (Figure 3a), due to their world-class quality of both host rocks and intrusions. These areas both exhibits complex, and well-preserved, sills emplaced within different formations of the San Rafael Group: Mussentuchit Wash features the Curtis Formation, while Cedar Mountains consists mainly of the Entrada Formation and the Curtis Formation. This thesis presents data gathered from both field work and corresponding virtual outcrop models, collected over three field seasons.

Volcanic activity

The intrusions observed within the San Rafael Volcanic Field resemble Tertiary alkaline mafic rocks that are locally exposed along the transition zone between the Colorado Plateau and Basin and Range provinces (Thompson and Zoback, 1979; Kempton et al. 1991; Delaney and Gartner, 1997). The Colorado Plateau margin has been a center of magmatism since the Paleogene, which is evident by emplacement of large laccolith intrusions during the Eocene to Late Oligocene (Gartner, 1986; Delaney and Gartner, 1997). These intrusions are today known as Henry, Abajo, and La Sal Mountains (Figure X). The San Rafael Swell and the Waterpocket monoclines formed contemporaneously as a response the regional uplift caused by the laccoliths (Gartner, 1986). Younger eruptions related to the intrusions in this study occurred during the Late Miocene (c. 4.2 to 3.8 Ma) (Gartner, 1986). Stratigraphic position of the intrusions found within the Entrada Formation and Curtis Formation suggests an emplacement depth of <1 kilometer (Díez et al. 2009; Richardson et al. 2015; Germa et al. 2020). Mapping of the San Rafael Volcanic field has found at least 200 dykes and sills emplaced within the San Rafael Group strata (Delaney and Gartner, 1997). This thesis focuses on the sills emplaced within the Entrada Formation and the Curtis Formation.

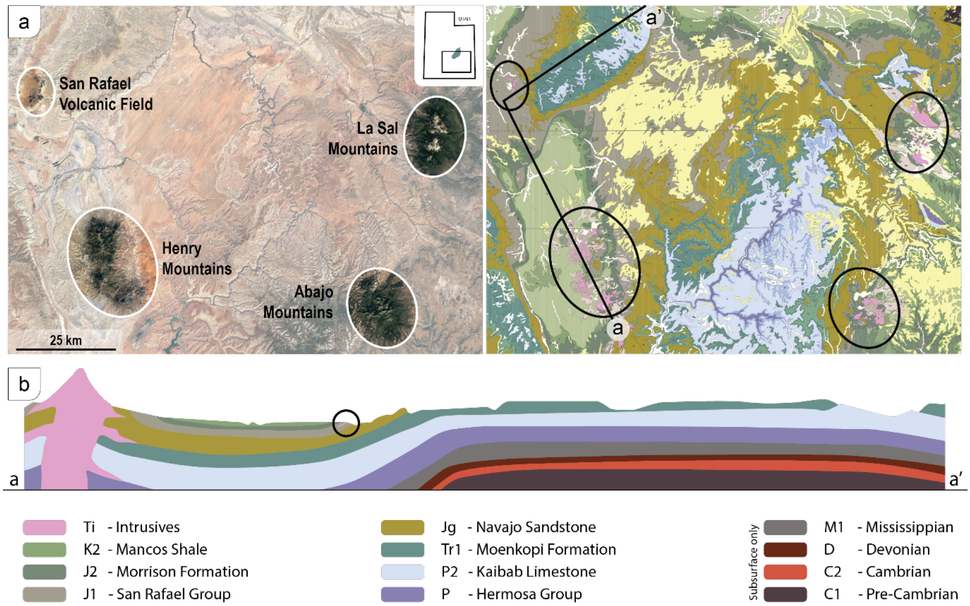


Figure 2: Map and cross-section of the area presented in this thesis. A: Satellite image derived from Google Earth, *23.07.2023*. B: Simplified geological map from Hintze et al. 2000. C: Simplified geological cross-section, modified after Hintze et al. 2000.

Sedimentary strata and depositional environment

Entrada Formation

The Entrada Formation is characterized by two stratigraphic units: (i) the eolian Slick Rock Member, consists of well-sorted and well-cemented, fine-grained sandstones, (ii) Earthy Facies, composed of poorly cemented, fine-grained silty and massive sandstone beds with locally interbedded sabkha siltstones, mudstones, gypsum, and thin trough-cross-bedded sandstone beds (Peterson, 1988; Crabaugh & Kocurek, 1993). Only the Earthy Facies Member was observed in this study area, and consequently in the Cedar Mountains outcrop. The Entrada Formation comprises four construction-destruction sequences bound by supersurfaces related to regional fluctuations of the paleo-water table and/or sea-level variations (Zuchuat et al. 2019a). The sediments from the Entrada Formation consist of recycled sediments from the Appalachian Mountains (Dickinson and Gehrels, 2009; 2010; Crabaugh and Kocurek, 1998; Mountey, 2012; Zuchuat et al. 2019a). The Entrada Formation mainly consists of mudstones (Figure 3a), sandstones (Figure 3b), and Heterolithic intervals of interbedded mudstones and sandstones (Figure 3c).

Curtis Formation

The Curtis Formation overlies the Entrada Formation and is typically characterized by an east and south-trending geometry (Zuchuat et al. 2019b). In general, this unit is separated into three informal units (*sensu* Zuchuat et al. 2019b): (i) Lower Curtis, comprised by laterally restricted upper shoreface to beach deposits, grading into thinly bedded heterolithic subtidal flat deposits (Figure 3d), (ii) Middle Curtis, characterized by better sorted sandstone (Figure 3e), (iii) Upper Curtis, represents thinly bedded, subtidal to intertidal deposits (Figure 3f), which grade into supratidal deposits of the Summerville Formation. All these subsections are observed within the Mussentuchit Wash and at the top of the Cedar Mountain localities. The Curtis Formation was deposited within a shallow- to marginal marine tide-dominated environment that responded to fluctuations in relative sea level. Tidal dominance is emphasized by mud-draped cross-beds within the sandstone units (Zuchuat et al. 2019a; Zuchuat et al. 2019b).

Magmatic intrusions

The San Rafael Volcanic Field and corresponding igneous rocks consists of c. 200 alkalic dykes and sills (Delaney and Gartner 1997). Most dykes are found around the Cedar Mountains, and few to non are observed close to the Mussentuchit Wash (Figure 3a). These intrusions mainly represent two types of magmatic rocks: (i) fine-to medium-grained alkali trachybasalt that make up the bulk of intrusions, (ii) medium- to coarse-grained syenite that are almost exclusively emplaced within the trachybasalts (Figure 3g) (Carman, 1994; Germa et al. 2020). Trachybasalt is the most dominant magmatic rock found within the San Rafael Volcanic Field and comprises the sills, dykes, and conduits. The trachybasalt is melanocratic and porphyritic, with aphanitic to microcrystalline groundmass (Figure 3h) (Germa et al. 2020). The syenite, however, is leucocratic holocrystalline with phaneritic textures and visible crystals (Figure 3i). Studies have suggested that syenite, which is emplaced within the trachybasalt, formed due to melt segregation during cooling of the intrusions (Germa et al. 2020).

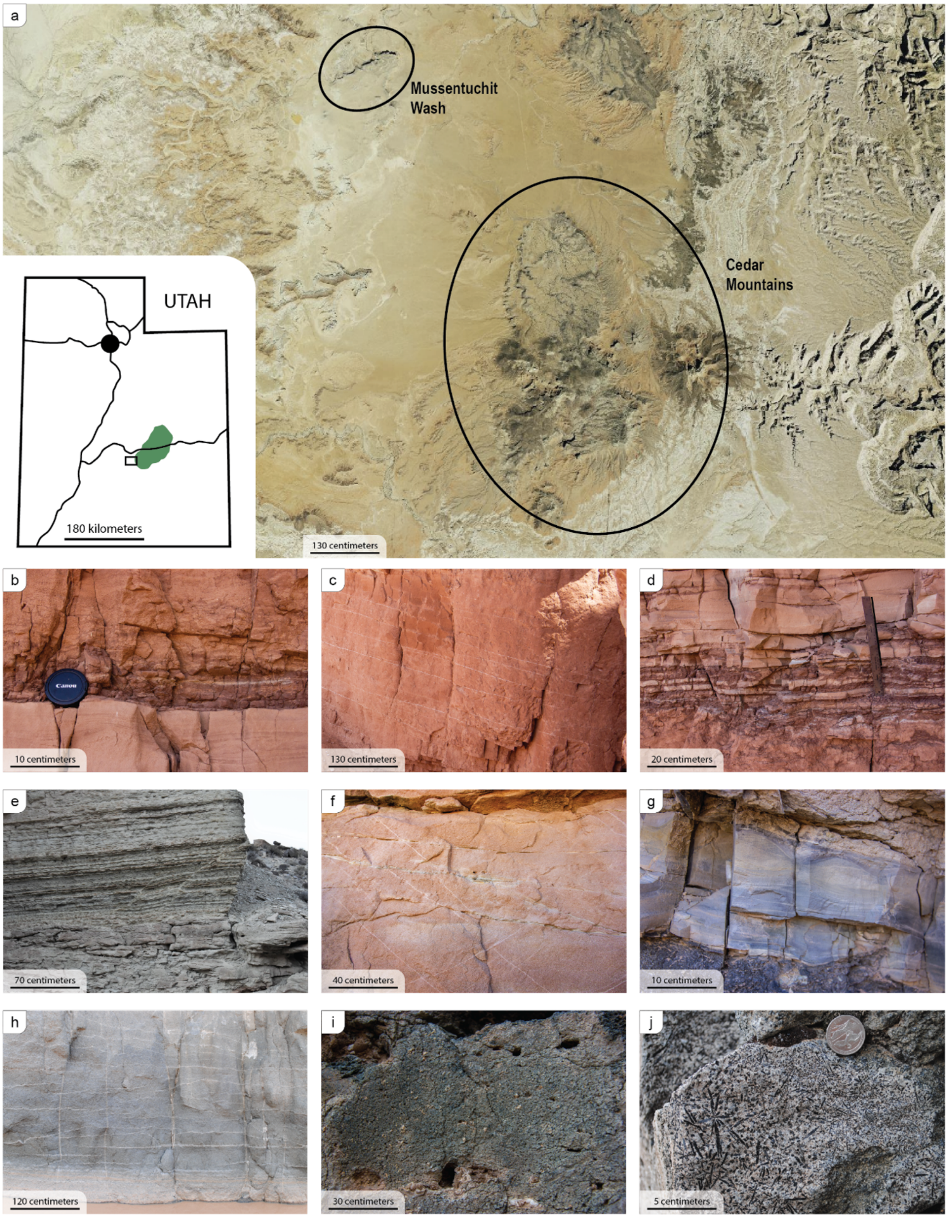


Figure 3: Map view of the study area and the rocks of interest. A: Satellite image derived from UGRC Raster Data Discovery, from 23.07.2023. B: Image of a mudstone layer. C: Image of sandstone with white anhydrite veins. D: Image of heterolithic intervals. E: Image of the Lower Curtis Formation. F: Image of the Middle Curtis Formation. G: Image of the Upper Curtis Formation. H: Image of trachybasalt with syenite veins. I: Image of trachybasalt. J: Image of syenite with visible mineral grains.

Chapter 4

Summary of papers

The overarching goal of this project, and consequently this thesis, is to enhance the understanding of the emplacement of igneous intrusions within sedimentary host rocks, and how to investigate if we can anticipate sill morphologies and geometry based on litholgy. The thesis applies a great variety of methods (sedimentary logging, 3D modelling, synthetic seismic modelling) and consist of three separate manuscripts, of which one is accepted for publication by a peer-review, international journal, one is submitted to a journal, and one is in the final preparation for submission. The following paragraphs will summarize the main findings of each individual manuscript, but also point out the connection between the articles.

- Manuscript 1:

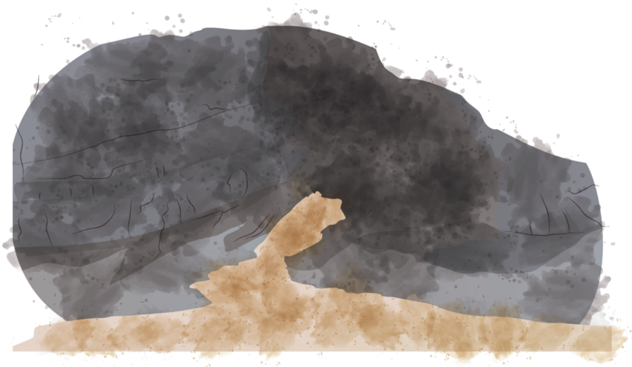
The first manuscript presents the complexity of sill emplacement within sedimentary basins, and how local lithology may cause the sill to exhibit both planar and irregular contacts with the host rocks. This study was conducted in Mussentuchit Wash, San Rafael Swell, Utah. Presence of multiple textures within the intrusion reveals a close relationship between the host rock and intruder. Results show that fracture-driven propagation is initiated along sedimentary discontinuities through hydrofracturing, while non-brittle fluid interaction is initiated by presence of local porewater within the sedimentary host rocks. Thus, providing key factors that should be implemented into modelling, laboratory experiments and theory, to broader the understanding of how sills emplace in sedimentary basin.

- Manuscript 2:

The second manuscript present a quantitative and qualitative study of sills, which illustrates the complexity of sill emplacement within sedimentary basins and how local lithology may be reflected by sill morphology. In addition, this study includes a seismic-scale sill analogue with a corresponding synthetic seismic model in order to show marginal sill features that often fall beneath seismic resolution. Results shows that sills are more than 3.5 times more likely to intrude in mudstone intervals than heterolotic and sandstone intevals. Furthermore, sills within heterolithic intervals tend to exhibit complex morphology with multiple smaller sill segments that would be difficult to see in seismic datasets. Sills emplaced in massive sandstone beds typically exhibit strata-discordant base contact to the host rock, while the sills within both heteroliths and mudstone display a strata-concordant base contact. These results could indicate how sill geometries can be used to predict lithology in seismic datasets from sedimentary basins with little to no well control.

- Manuscript 3:

The third manuscript broadens the study by comparing the outcrop from Cedar Mountain to similar sized virtual outcrops from other parts of the world. Thus, this study features a total of five virtual outcrops (> 1km by >100 meters) of complex sills emplaced in sedimentary basins. The outcrops were found through the v3Geo and Safari Database, or shared by collaborators. The results show that sill geometries are consistent within lithologies, although emplacement depth and viscosity of the sills differ. Thus, implying that the state of the host rocks and lithology exert influence on the geometry of sills in sedimentary basins. Also, the geometries observed from the second paper appear consistent with the new studied areas. The sills in Hurry Inlet also exhibits both brittle- and non-brittle emplacement behavior, similar to the sills found in Mussentuchit in paper 1, which suggests that sills exhibit a dynamic relationship with the host rocks in sedimentary basins. Thus, being able to emplace and propagate through both brittle- and non-brittle processes.



Paper 1: Alkaline sill intrusions in sedimentary basins: emplacement of the Mussentuchit Wash Sill in San Rafael Swell, Utah.

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

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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.

Introduction

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.

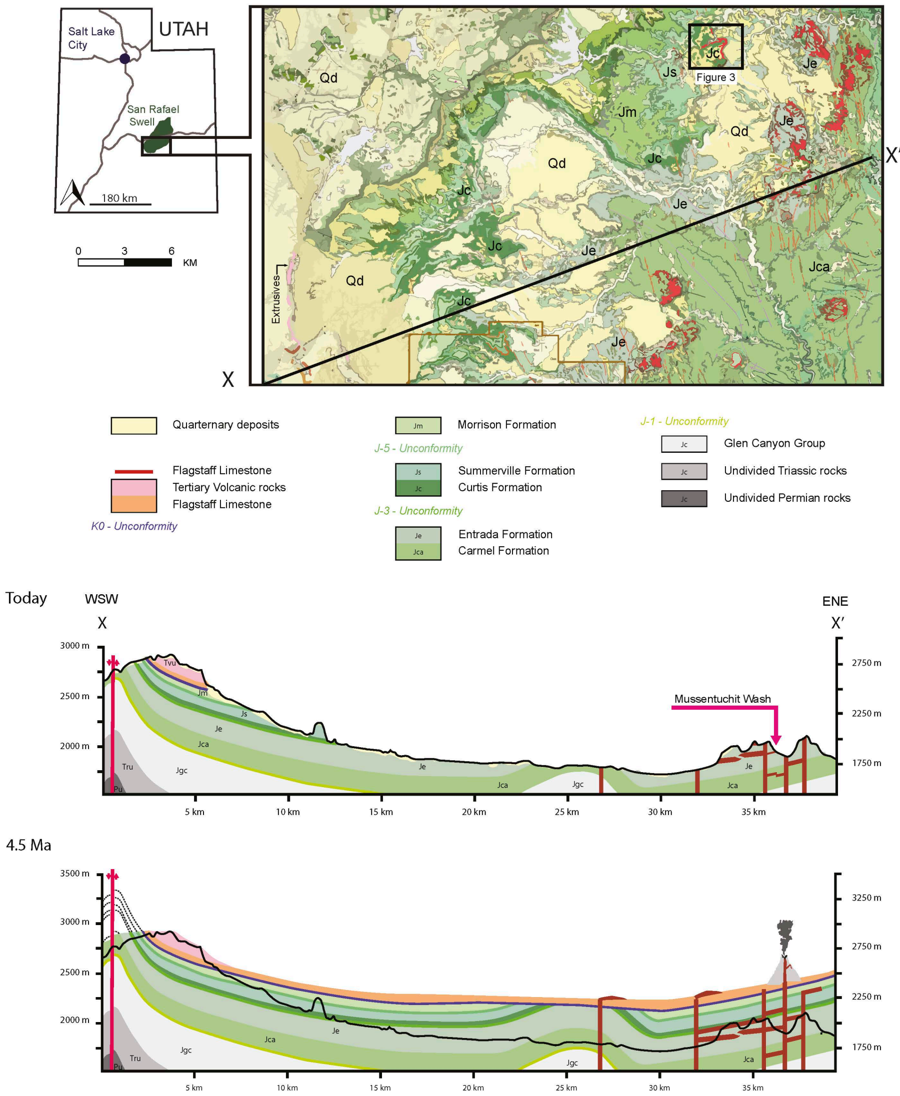

Figure 1: Geological map of the San Rafael Swell and corresponding cross section. The map is modified from USGS Interim geological map of the East half of the Salina 30’ x 60’ quadrangle by Doeling (2004). This is only a section of the USGS map, focusing on the area surrounding the studied Mussentuchit 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.

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).

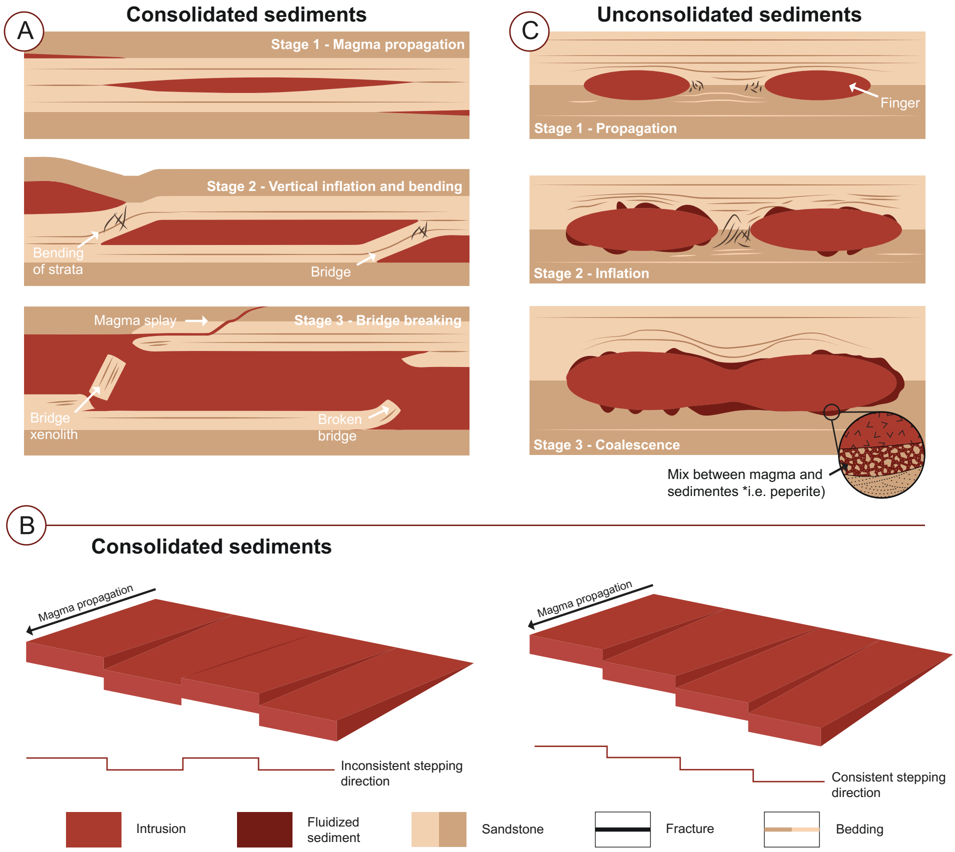

Figure 2: Overview of sill emplacement structures in consolidated (a, b) and unconsolidated (c) host rocks. Modified from Schofield et al 2012. A: Schematic illustration showing development and relationship of broken bridges. B: Schematic showing development of en echelon steps within a sill, highlighting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

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.

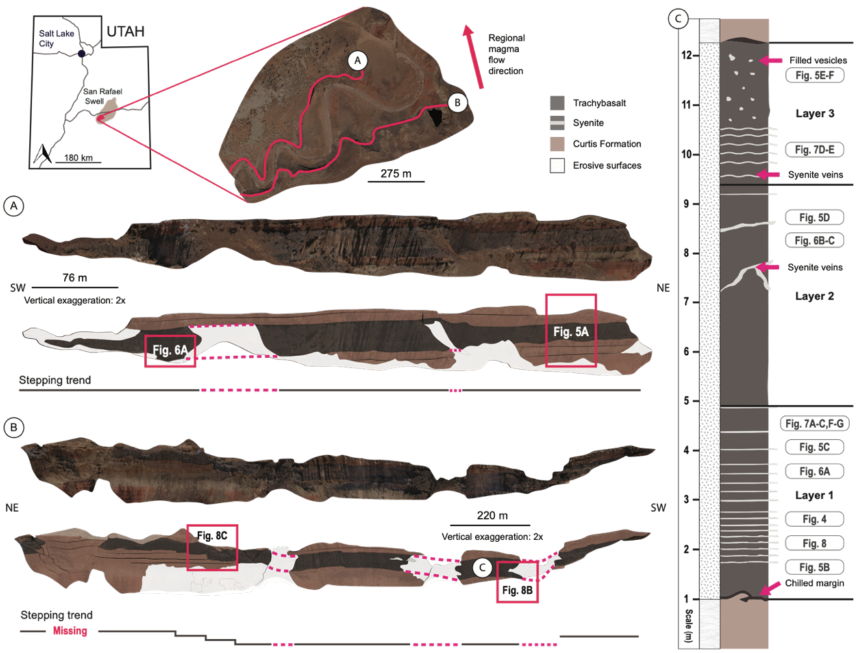

Figure 3: Overview of the Mussentuchit Wash Sill dataset. Map-view of the meandering river valley cutting through the Mussentuchit Wash Sill. The north- and south-valley of the river channel is separated (a,b). A generalized magmatic log was also collected from the dataset (c). A: Picture and schematic 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.

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.

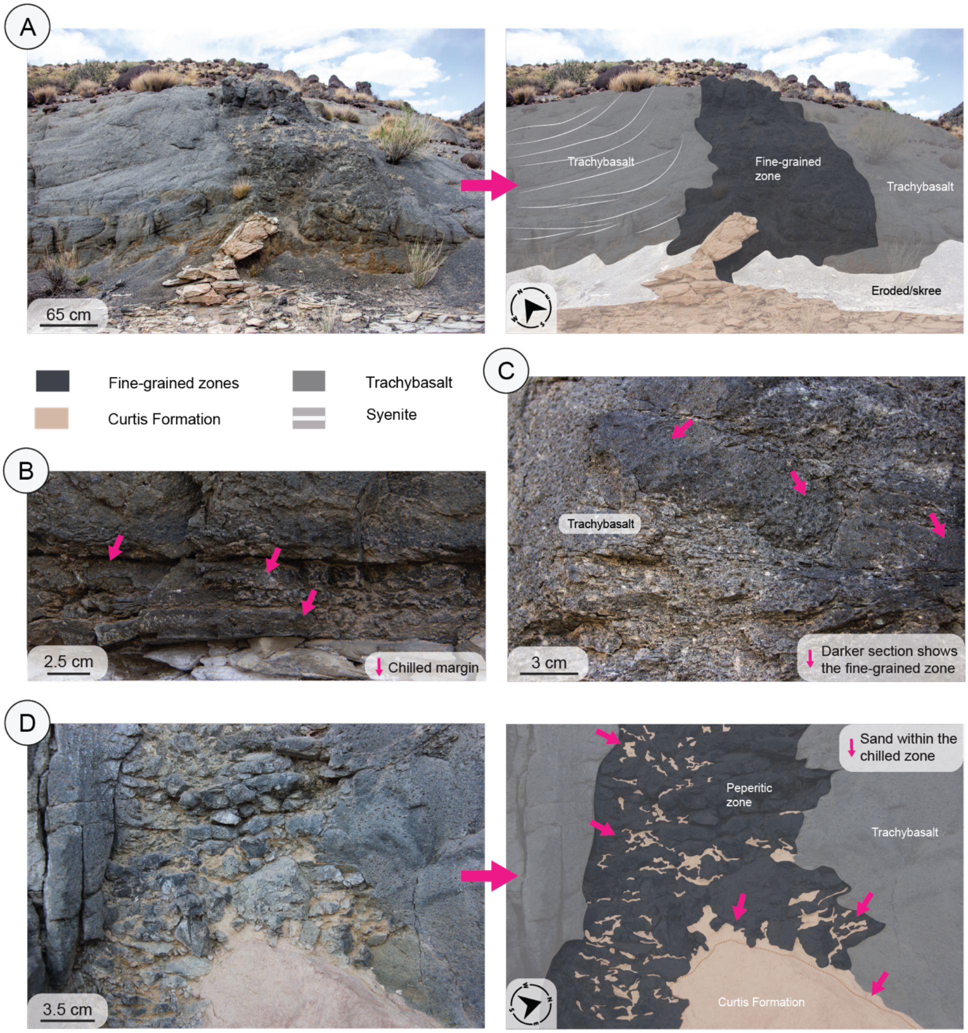

Figure 4: Figure and images showing the various textures found within the Mussentuchit Wash Sill. A: Image of a broken bridge. Schematic illustration highlighting the different textures enclosing the bridge. Syenite veins deviate and become transgressive parallel with the sill. This photo is acquired 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.

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).

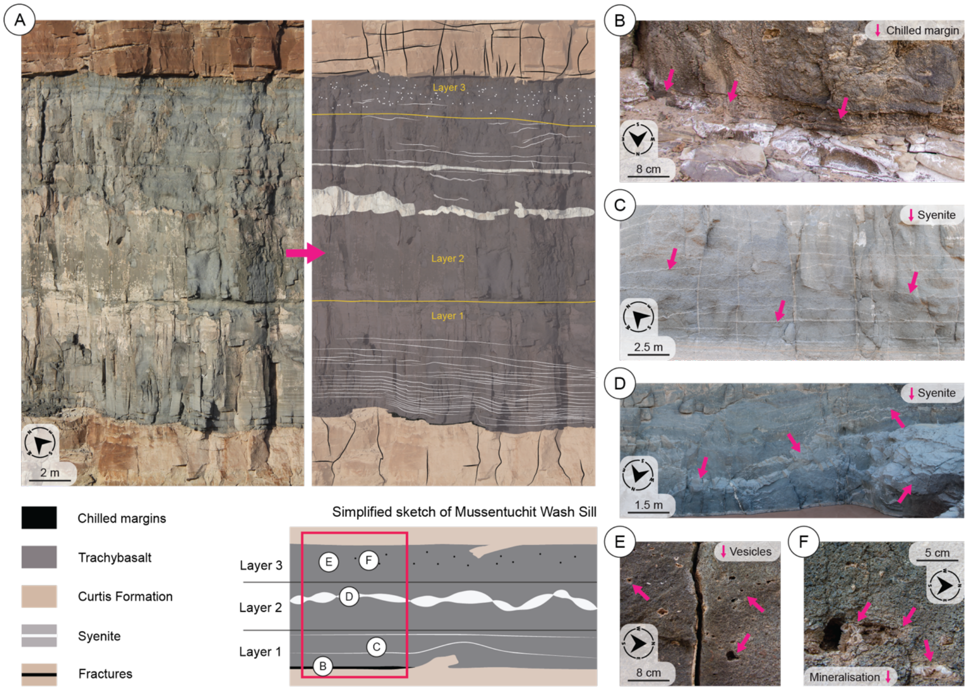

Figure 5: Figure 5: Overview of the Mussentuchit Wash Sill igneous layers. A: UAV image and schematic showing the entire sill. The sill has a slightly undulating morphology. B: Picture showing chilled margin and contact between sill and host rock. C: Picture showing syenite veins of the Lower Layer. 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.

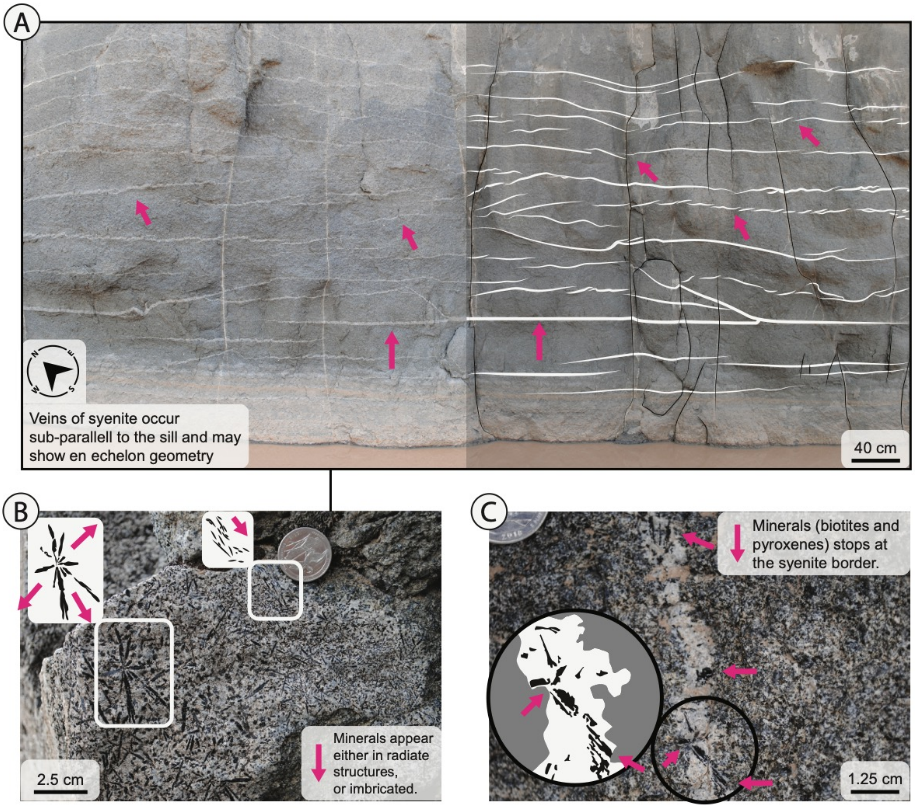

Figure 6: Generalized overview of the syenites of Mussentuchit Wash Sill. The syenites occur in different thicknesses, ranging from a few milimeters to multiple meters. Syenites are easily distinguished based on their light-grey color (a,b) and easily distinguishable minerals (c,d). A: General arrangement 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.

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.

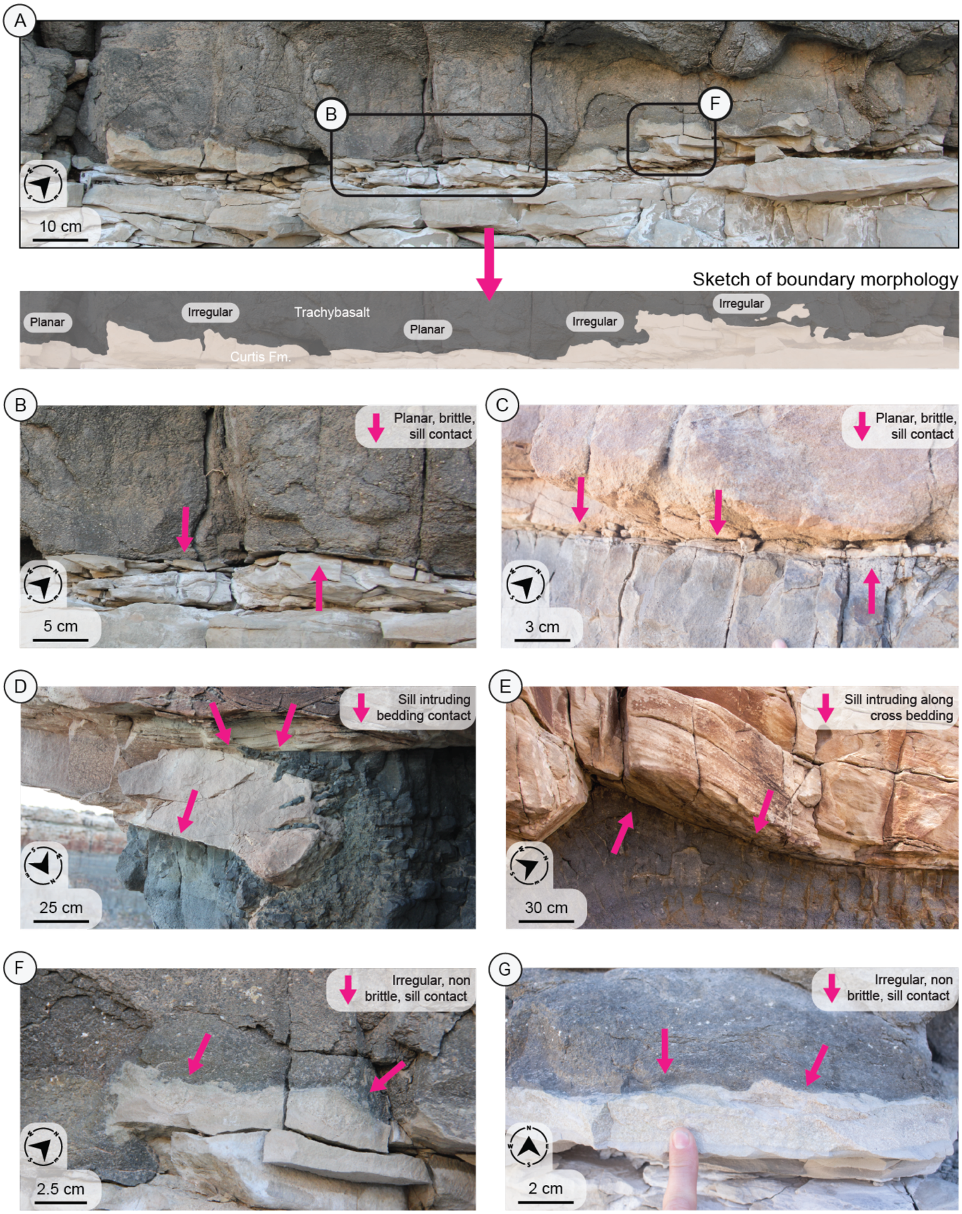

Figure 7: Images and schematic illustrations highlighting intrusion and host rock interplay. Along the sill-host rock boundary we can observe planar- (a, b, c, d, e) and irregular bedding (f, g). The sill appears to follow mud-draped cross bedding, and follow these layers as lesser splays (d, e). A: 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.

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.

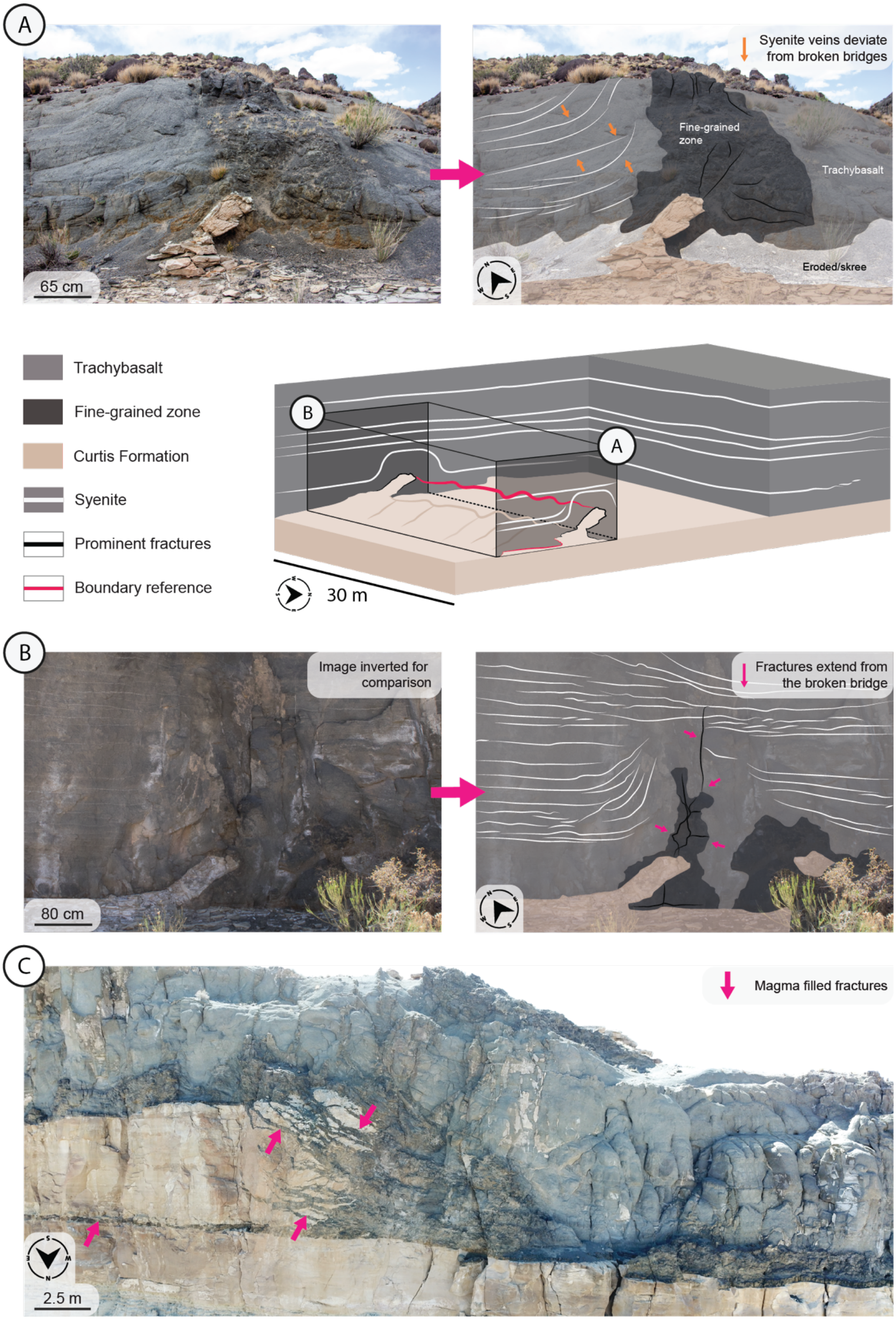
A
65 cm
Syenite veins deviate from broken bridges
Fine-grained zone
Trachybasalt
Eroded/skree
Trachybasalt
Fine-grained zone
Curtis Formation
Syenite
Prominent fractures
Boundary reference
B
A
30 m
B
Image inverted for comparison
80 cm
Fractures extend from the broken bridge
C
Magma filled fractures
2.5 m

Figure 8: 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.

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.

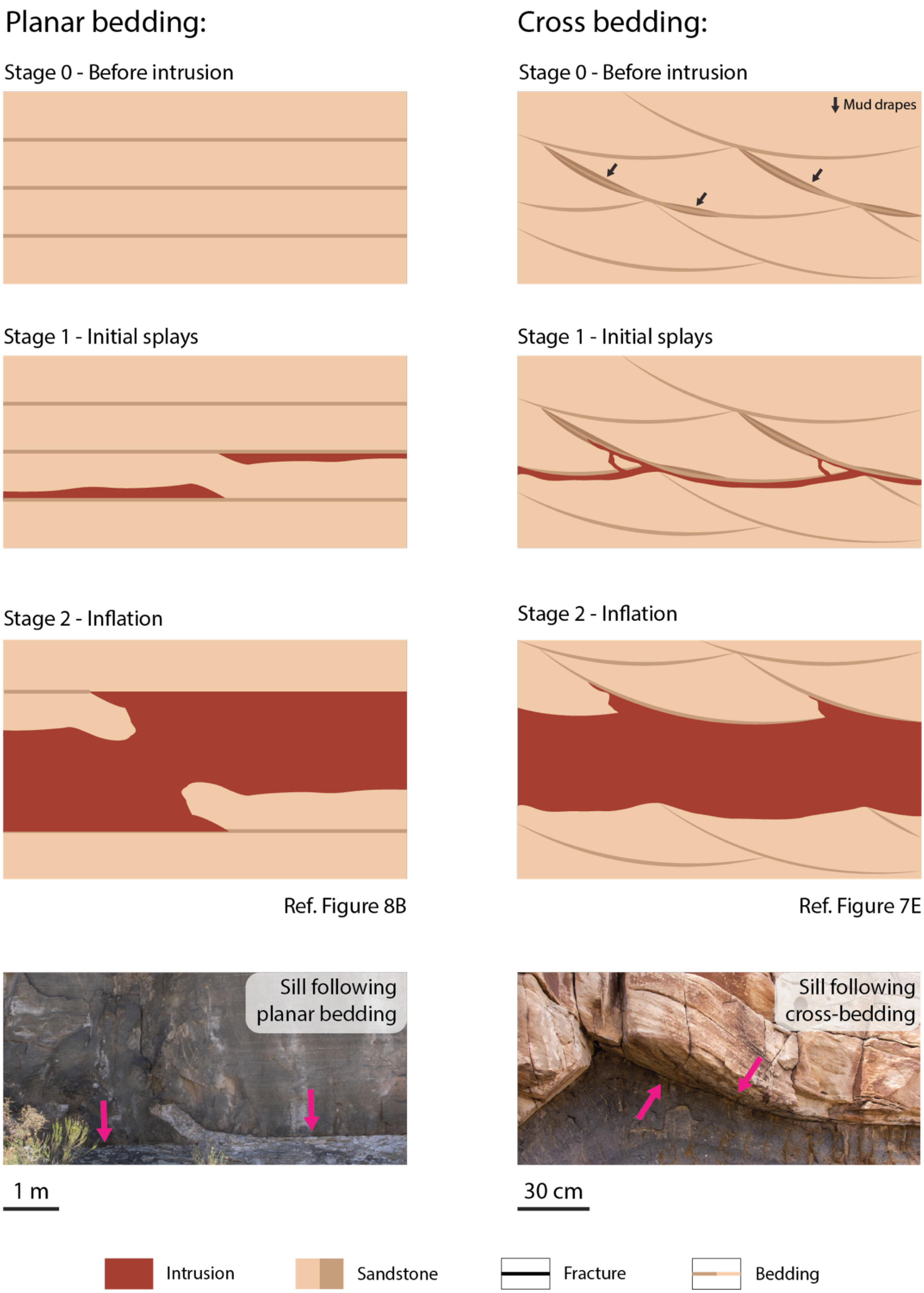

Figure 9: Schematic diagram showing the emplacement of sills within the Curtis Formation, with focus on planar bedding- (a) and cross bedding geometry (b). A: Stage 0, no intrusions. Stage 1, magma propagates as a series of offsets along planar bedding of the host rock. Stage 3, the magmatic bodies begin 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.

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 are no broken bridges.

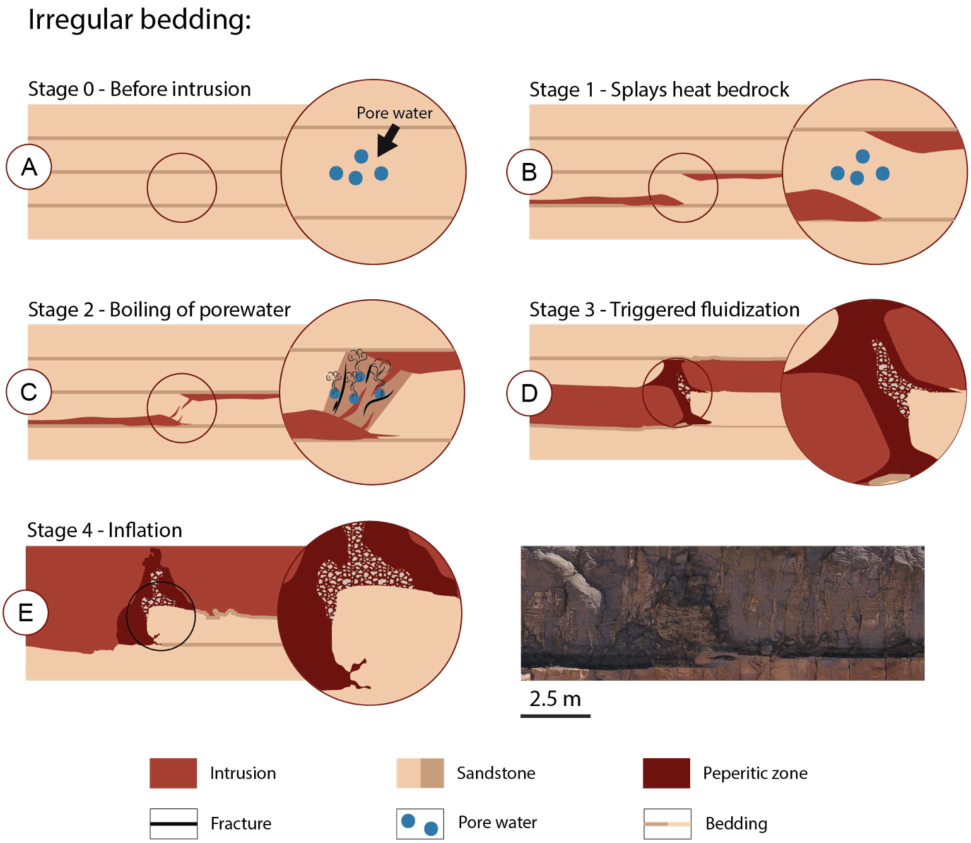

Figure 10: Schematic diagram showing the emplacement of sills along irregular boundaries, with an accompanying image. This process involves processes like fluidization, which is affected by pore fluid (a) and pore fluid pressure generated by heating water within the host rock (b). Once sill-induced fracturing 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.

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).

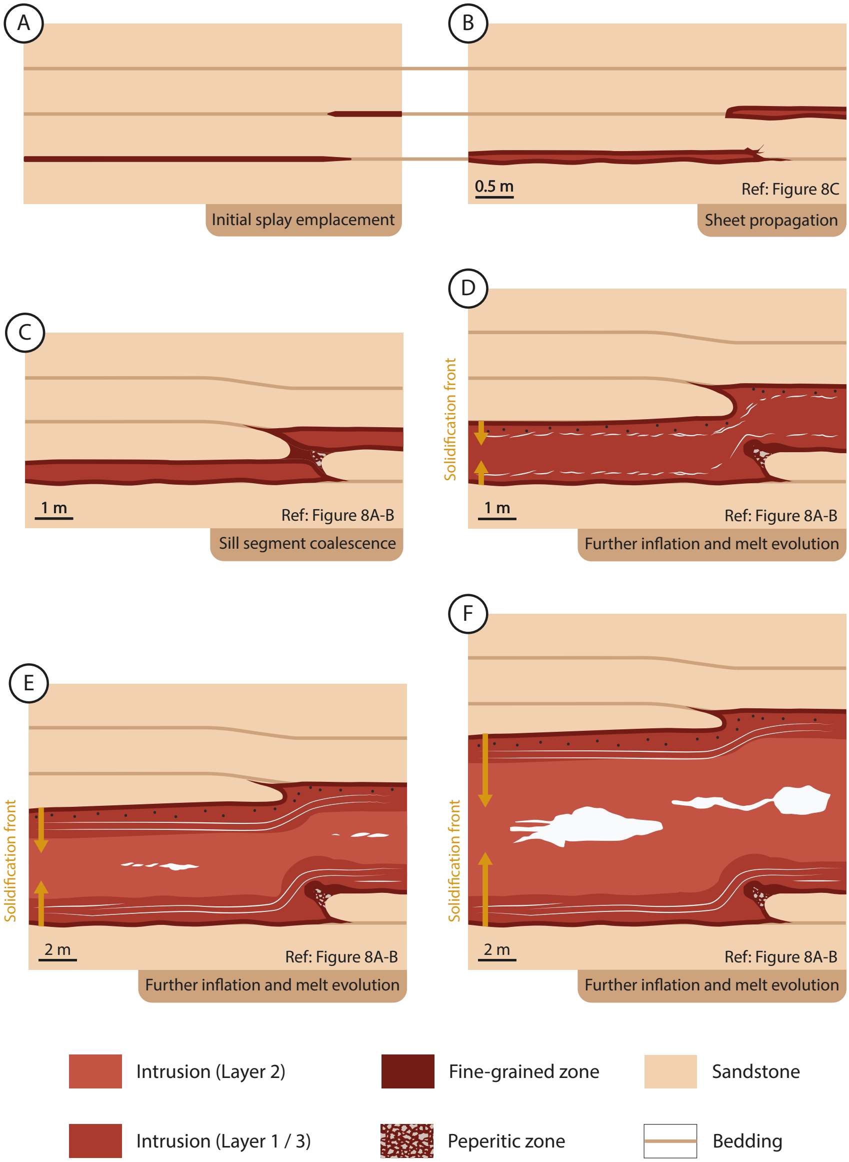

Figure 11: Schematic illustration showing the emplacement of the Mussentuchit Wash Sill. A: Stage 1, magma propagates as a series of offsets along bedding of the host rock. B: Stage 2, further propagation of individual magma splays, and we get overlapping bodies. C: Stage 3, the magmatic bodies begin 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.

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:

- 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.
- 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.
- Geochemical and groundwater-related effects may lead to different internal geometries within igneous sill intrusion.
- 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.
- 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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References

Baer, G., 1991. Mechanisms of dike propagation in layered rocks and in massive, porous sedimentary rocks. Journal of Geophysical Research: Solid Earth, 96(B7), pp.11911-11929.

Carman Jr, M.F., 1994. Mechanisms of differentiation in shallow mafic alkaline intrusions, as illustrated in the Big Bend area, western Texas. Journal of Volcanology and Geothermal Research, 61(1-2), pp.1-44.

Curtis, M.L. and Riley, T.R., 2003. Mobilization of fluidized sediment during sill emplacement, western Dronning Maud Land, East Antarctica. Antarctic Science, 15(3), pp.393-398.

Delaney, P.T. and Gartner, A.E., 1997. Physical processes of shallow mafic dike emplacement near the San Rafael Swell, Utah. Geological Society of America Bulletin, 109(9), pp.1177-1192.

Díez, M., Connor, C.B., Kruse, S.E., Connor, L. and Savov, I.P., 2009. Evidence of small-volume igneous diapirism in the shallow crust of the Colorado Plateau, San Rafael Desert, Utah. Lithosphere, 1(6), pp.328-336.

Doelling, H.H., 2004. Interim Geologic Map of the East Half of the Salina 30′ X 60′ Quadrangle, Emery, Sevier, and Wayne Counties, Utah. Utah Geological Survey.

Dragoni, M., Lanza, R. and Tallarico, A., 1997. Magnetic anisotropy produced by magma flow: theoretical model and experimental data from Ferrar dolerite sills (Antarctica). Geophysical Journal International, 128(1), pp.230-240.

Duffield, W.A., Bacon, C.R. and Delaney, P.T., 1986. Deformation of poorly consolidated sediment during shallow emplacement of a basalt sill, Coso Range, California. Bulletin of Volcanology, 48(2), pp.97-107.

Eide, C.H., Schofield, N., Jerram, D.A. and Howell, J.A., 2017. Basin-scale architecture of deeply emplaced sill complexes: Jameson Land, East Greenland. Journal of the Geological Society, 174(1), pp.23-40.

Eide, Christian Haug; Schofield, Nick; Howell, John; Jerram, Dougal A., 2021. Transport of mafic magma through the crust and sedimentary basins: Jameson Land, East Greenland. Journal of the Geological Society. Pages jgs2021-043.

Frid, V., Bahat, D. and Rabinovich, A., 2005. Analysis of en echelon/hackle fringes and longitudinal splits in twist failed glass samples by means of fractography and electromagnetic radiation. Journal of Structural Geology, 27(1), pp.145-159.

Galland, O., Planke, S., Neumann, E.R. and Malthe-Sørenssen, A., 2009. Experimental modelling of shallow magma emplacement: Application to saucer-shaped intrusions. Earth and Planetary Science Letters, 277(3-4), pp.373-383.

Galland, O. and Scheibert, J., 2013. Analytical model of surface uplift above axisymmetric flat-lying magma intrusions: Implications for sill emplacement and geodesy. Journal of Volcanology and Geothermal Research, 253, pp.114-130.

Galland, O., Spacapan, J. B., Rabbel, O., Mair, K., Soto, F. G., Eiken, T., ... & Leanza, H. A. (2019). Structure, emplacement mechanism and magma-flow significance of igneous fingers–Implications for sill emplacement in sedimentary basins. Journal of Structural Geology, 124, 120-135.

Gerjarusak, S., Peters, W.A. and Howard, J.B., 1991. Coal plasticity at high heating rates and temperatures. Y (No. DOE/PC/89773-5; FE-MIT-89773-5). Massachusetts Inst. of Tech., Cambridge, MA (United States).

Germa, A., Koebli, D., Wetmore, P., Atlas, Z., Arias, A., Savov, I.P., Diez, M., Greaves, V. and Gallant, E., 2020. Crystallization and Segregation of Syenite in Shallow Mafic Sills: Insights from the San Rafael Subvolcanic Field, Utah. Journal of Petrology, 61(9), p.egaa092.

Ghodke, S.S., Rathna, K., Kokandakar, G.J., Nagaraju, B., More, L.B., Bhosle, M.V. and Kumar, K.V., 2018. Emplacement and growth of alkaline dikes: Insights from the shonkinite dikes (Elchuru alkaline complex, SE India). Journal of Structural Geology, 117, pp.219-236.

Gilluly, J., 1927. Analcite diabase and related alkaline syenite from Utah. American Journal of Science, 5(81), pp.199-211.

Gonzales, D.A. and Lake, E.T., 2017. Geochemical constraints on mantle-melt sources for Oligocene to Pleistocene mafic rocks in the Four Corners region, USA. Geosphere, 13(1), pp.201-226.

Hansen, D.M. and Cartwright, J., 2006. Saucer-shaped sill with lobate morphology revealed by 3D seismic data: implications for resolving a shallow-level sill emplacement mechanism. Journal of the Geological Society, 163(3), pp.509-523.

Hansen, J. (2015). A numerical approach to sill emplacement in isotropic media: Do saucer-shaped sills represent 'natural'intrusive tendencies in the shallow crust?. Tectonophysics, 664, 125-138.

Haug, Ø. T., Galland, O., Souloumiac, P., Souche, A., Guldstrand, F., Schmiedel, T., & Maillot, B. (2018). Shear versus tensile failure mechanisms induced by sill intrusions: Implications for emplacement of conical and saucer-shaped intrusions. Journal of Geophysical Research: Solid Earth, 123(5), 3430-3449.

Humphreys, E.D., 1995. Post-Laramide removal of the Farallon slab, western United States. Geology, 23(11), pp.987-990.

Hutton, D.H.W., 2009. Insights into magmatism in volcanic margins: bridge structures and a new mechanism of basic sill emplacement–Theron Mountains, Antarctica. Petroleum Geoscience, 15(3), pp.269-278.

Jerram, D.A. and Bryan, S.E., 2015. Plumbing systems of shallow level intrusive complexes. In Physical geology of shallow magmatic systems (pp. 39-60). Springer, Cham.

Jerram, D.A. and Stollhofen, H., 2002. Lava–sediment interaction in desert settings; are all peperite-like textures the result of magma–water interaction?. Journal of Volcanology and Geothermal Research, 114(1-2), pp.231-249.

Kavanagh, J.L., Menand, T. and Sparks, R.S.J., 2006. An experimental investigation of sill formation and propagation in layered elastic media. Earth and Planetary Science Letters, 245(3-4), pp.799-813.

Kavanagh, J. L., Rogers, B. D., Boutelier, D., & Cruden, A. R. (2017). Controls on sill and dyke-sill hybrid geometry and propagation in the crust: The role of fracture toughness. Tectonophysics, 698, 109-120.

Kiyosugi, K., Connor, C.B., Wetmore, P.H., Ferwerda, B.P., Germa, A.M., Connor, L.J. and Hintz, A.R., 2012. Relationship between dike and volcanic conduit distribution in a highly eroded monogenetic volcanic field: San Rafael, Utah, USA. Geology, 40(8), pp.695-698.

Kokandakar, G.J., Ghodke, S.S., Rathna, K., More, L.B., Nagaraju, B., Bhosle, M.V. and Kumar, K.V., 2018. Density, viscosity and velocity (ascent rate) of alkaline magmas. Journal of the Geological Society of India, 91(2), pp.135-146.

Kokelaar, B.P., 1982. Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. Journal of the Geological Society, 139(1), pp.21-33.

Luedke, R.G. and Smith, R.L., 1984. Map showing distribution, composition, and age of late Cenozoic volcanic centers in the western conterminous United States (No. 1523).

Magee, C., Briggs, F. and Jackson, C.A., 2013. Lithological controls on igneous intrusion-induced ground deformation. Journal of the Geological Society, 170(6), pp.853-856.

Magee, C., Muirhead, J.D., Karvelas, A., Holford, S.P., Jackson, C.A., Bastow, I.D., Schofield, N., Stevenson, C.T., McLean, C., McCarthy, W. and Shtukert, O., 2016. Lateral magma flow in mafic sill complexes. Geosphere, 12(3), pp.809-841.

Magee, C., Muirhead, J., Schofield, N., Walker, R. J., Galland, O., Holford, S., ... & McCarthy, W. (2019). Structural signatures of igneous sheet intrusion propagation. Journal of Structural Geology, 125, 148-154.

Malthe-Sørensen, A.S.H.B.C., Planke, S., Svensen, H., Jamtveit, B., Breitkreuz, C. and Petford, N., (2004). Formation of saucer-shaped sills. Physical geology of high-level magmatic systems. Geological Society, London, Special Publications, 234, pp.215-227.

Ni, N., Chen, N., Ernst, R.E., Yang, S. and Chen, J., 2019. Semi-automatic extraction and mapping of dyke swarms based on multi-resolution remote sensing images: Applied to the dykes in the Kuluketage region in the northeastern Tarim Block. Precambrian Research, 329, pp.262-272.

Nicholson, R. and Pollard, D.D., 1985. Dilation and linkage of echelon cracks. Journal of Structural Geology, 7(5), pp.583-590.

Pederson, J.L., Mackley, R.D. and Eddleman, J.L., 2002. Colorado Plateau uplift and erosion evaluated using GIS. GSA TODAY, 12(8), pp.4-10.

Pollard, D.D., 1973. Derivation and evaluation of a mechanical model for sheet intrusions. Tectonophysics, 19(3), pp.233-269.

Pollard, D.D., Muller, O.H. and Dockstader, D.R., 1975. The form and growth of fingered sheet intrusions. Geological Society of America Bulletin, 86(3), pp.351-363.

Pollard, D.D. and Muller, O.H., 1976. The effect of gradients in regional stress and magma pressure on the form of sheet intrusions in cross section. Journal of Geophysical Research, 81(5), pp.975-984.

Pollard, D.D., Segall, P.A.U.L. and Delaney, P.T., 1982. Formation and interpretation of dilatant echelon cracks. Geological Society of America Bulletin, 93(12), pp.1291-1303.

Reid, M.R., Bouchet, R.A., Blichert-Toft, J., Levander, A., Liu, K., Miller, M.S. and Ramos, F.C., 2012. Melting under the Colorado Plateau, USA. Geology, 40(5), pp.387-390.

Richardson, J.A., Connor, C.B., Wetmore, P.H., Connor, L.J. and Gallant, E.A., 2015. Role of sills in the development of volcanic fields: Insights from lidar mapping surveys of the San Rafael Swell, Utah. Geology, 43(11), pp.1023-1026.

Rickwood, P.C., 1990. The anatomy of a dyke and the determination of propagation and magma flow directions. In International dyke conference. 2 (pp. 81-100).

Rittersbacher, A., Howell, J. A., & Buckley, S. J. (2014). Analysis of fluvial architecture in the Blackhawk Formation, Wasatch Plateau, Utah, USA, using large 3D photorealistic models. Journal of Sedimentary Research, 84(2), 72-87.

Rogers, R.D. and Bird, D.K., 1987. Fracture propagation associated with dike emplacement at the Skaergaard intrusion, East Greenland. Journal of Structural Geology, 9(1), pp.71-86.

Rotevatn, A., Fossen, H., Hesthammer, J., Aas, T.E. and Howell, J.A., 2007. Are relay ramps conduits for fluid flow? Structural analysis of a relay ramp in Arches National Park, Utah. Geological Society, London, Special Publications, 270(1), pp.55-71.

Schmiedel, T., Galland, O., & Breitkreuz, C. (2017). Dynamics of sill and laccolith emplacement in the brittle crust: role of host rock strength and deformation mode. Journal of Geophysical Research: Solid Earth, 122(11), 8860-8871.

Schofield, N., 2009. Linking sill morphology to emplacement mechanisms (Doctoral dissertation, University of Birmingham).

Schofield, N., Stevenson, C. and Reston, T., 2010. Magma fingers and host rock fluidization in the emplacement of sills. Geology, 38(1), pp.63-66.

Schofield, N.J., Brown, D.J., Magee, C. and Stevenson, C.T., 2012. Sill morphology and comparison of brittle and non-brittle emplacement mechanisms. Journal of the Geological Society, 169(2), pp.127-141.

Schofield, N., Heaton, L., Holford, S.P., Archer, S.G., Jackson, C.A.L. and Jolley, D.W., 2012b. Seismic imaging of ‘broken bridges’: linking seismic to outcrop-scale investigations of intrusive magma lobes. Journal of the Geological Society, 169(4), pp.421-426.

Schofield, N., Alsop, I., Warren, J., Underhill, J.R., Lehné, R., Beer, W. and Lukas, V., 2014. Mobilizing salt: Magma-salt interactions. Geology, 42(7), pp.599-602.

Schofield, N., Holford, S., Millett, J., Brown, D., Jolley, D., Passey, S.R., Muirhead, D., Grove, C., Magee, C., Murray, J. and Hole, M., 2017. Regional magma plumbing and emplacement mechanisms of the Faroe-Shetland Sill Complex: implications for magma transport and petroleum systems within sedimentary basins. Basin Research, 29(1), pp.41-63.

Skilling, I.P., White, J.D. and McPhie, J., 2002. Peperite: a review of magma–sediment mingling. Journal of Volcanology and Geothermal Research, 114(1-2), pp.1-17.

Spacapan, J.B., Galland, O., Leanza, H.A. and Planke, S., 2017. Igneous sill and finger emplacement mechanism in shale-dominated formations: a field study at Cuesta del Chihuido, Neuquén Basin, Argentina. Journal of the Geological Society, 174(3), pp.422-433.

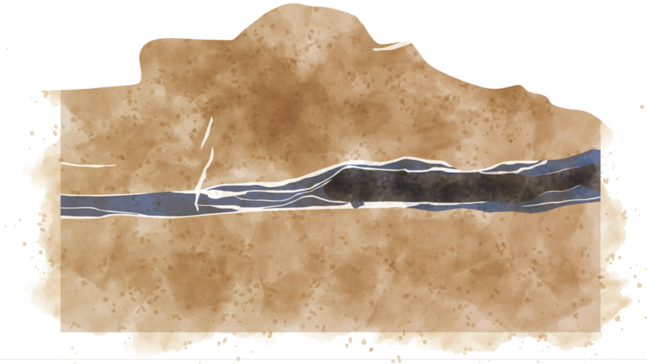
Spera, F.J., 1984. Carbon dioxide in petrogenesis III: role of volatiles in the ascent of alkaline magma with special reference to xenolith-bearing mafic lavas. Contributions to Mineralogy and Petrology, 88(3), pp.217-232.

Stephens, T. L., Walker, R. J., Healy, D., & Bubeck, A. (2020). Segment tip geometry of sheet intrusions, II: Field observations of tip geometries and a model for evolving emplacement mechanisms.

Thompson, G.A. and Zoback, M.L., 1979. Regional geophysics of the Colorado Plateau. Tectonophysics, 61(1-3), pp.149-181.

Tingey, D.G., Christiansen, E.H., Best, M.G., Ruiz, J. and Lux, D.R., 1991. Tertiary minette and melanephelinite dikes, Wasatch Plateau, Utah: Records of mantle heterogeneities and changing tectonics. Journal of Geophysical Research: Solid Earth, 96(B8), pp.13529-13544.

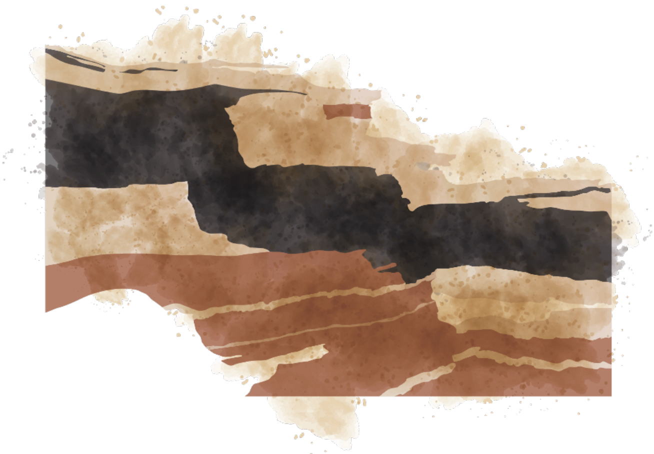
Wilcox, W.T. and Currie, B.S., 2008. Sequence Stratigraphy of the Jurassic Curtis, Summerville, and Stump Formations, Eastern Utah and Northwest Colorado.



Paper 2: Lithological controls on emplacement structures of sills in sedimentary basins: controls and recognition in reflection seismic data.

Martin Kjenes, Christian Haug Eide, Agustin Arguello Scotti, Isabelle Lecomte, Nick Schofield, Anna Bøgh.

In review at Basin Research.



Paper 3: Geometry of Igneous Sills in Sedimentary Basins: a comparison of igneous systems

Martin Kjenes, Christian Haug Eide, Kim Senger, Albina Gilmullina, Ole Rabbel, Nick Schofield.

Manuscript in preparation for submission to Journal of Geological Society of London.

III

Chapter 5

Synthesis

The main focus of this thesis has been the role of lithology related to emplacement of sills, and more specifically how intrusions are emplaced in heterogeneous sedimentary basins. This theme is covered in all papers included in this thesis, with each paper having a separate focus on different aspects of the relationship between host rock and igneous intrusion. The first paper focuses on sill architecture, textures and structures associated with emplacement. The second paper provides an qualitative and quantitative study of sills geometry, associated emplacement structures, geometry and relationship with the host rocks. The third paper compiles the observations from the first two papers and compares them to other field studies. The dataset for the third paper involves high-quality virtual outcrop models, which includes observations from previous studies.

Main Results

In this section, the main findings from this thesis are synthesised in context of the 4 research objectives presented in Chapter 1:

Objective 1: *investigate and describe qualitatively internal sill architecture and marginal contacts between igneous sills and sedimentary host rocks.*

The core objective of this thesis is to investigate the relationship between sills and their host rocks. Key observations of this relationship are documented along the contacts between magma and sediment. This is demonstrated in detail in **Paper 1** and in **Paper 2**. Here we show that sills do not always conform to either brittle or non-brittle emplacement, which was reflected by different types of magmatic textures found within the sills and along marginal contacts between the sill and host rock. These textures include massive trachybasalt, chilled margins, fine-grained zones and peperitic zones, and are described in detail in **Paper 1**. In general, chilled margins and fine-grained zones are associated with brittle emplacement of sills, while peperitic textures are related to non-brittle emplacement. Chilled margins are developed as warm magma are emplaced into colder host rocks, in which the igneous intrusion crystallizes rapidly. The fine-grained zones resemble breccia owing to its fractured appearance, but features rounded rather than angular magmatic material. They are also similar to chilled margins, as they form along the marginal contacts to the host rock in broken bridges and are comprised of fine-grained minerals, such as olivine and pyroxene. The peperitic textures, however, form due to magma-sediment mingling during emplacement. This process is typically initiated by boiling of pore fluids or volatiles, through heating and dewatering of host rock. Peperitic zones are mainly found around broken bridges and appear to originate from sedimentary xenoliths within the bridge.

Paper 1 also includes a detail description of the two main types of marginal contact between the sill and host rocks: (i) planar/concordant to sedimentary strata, (ii) irregular to strata. In **Paper 2**, however, a third marginal contact is introduced: (iii) strata discordant. Firstly, the planar/concordant sill contacts are represented by sills following sedimentary bedding and discontinuities within the host rocks. For instance, sills may either follow interfaces between different beds within the host rocks or sedimentary structures such as cross-bedding. In general, this type of marginal contact shows sharp boundaries, which indicates that the sill propagated and exploited fractures along discontinuities in the host rock. The second type of contacts, irregular to strata, is represented by undulating contacts which appear to have formed without any fracturing. These bedding contacts appear to be limited to tens of centimeters (up to 30 centimeters), suggesting that irregular bedding contacts form locally along the sill. The third type of contact, strata-discordant, was first observed in homogenous sandstones in Cedar Mountains. These sandstones do not exhibit any internal discontinuities for the sill to exploit, and thus the sills appear to be transgressing through these layers as *en echelon* type splays within the horizontal host rock.

Objective 2: *identify geometries and quantify potential preferential pathways for igneous intrusions in heterogeneous sedimentary strata.*

This study has thoroughly investigated the marginal contacts between sills and host rocks to quantify which sedimentary rocks most often host igneous intrusions. This was the main topic of **Paper 2**. In general, sills emplaced within mudstone display a strata concordant sill, with sharp contact between the igneous intrusion and host rock. These sills exhibit smaller vertical jogs but are usually limited to a few meters. In heterolithic intervals, sills tend to be strata-concordant but also exhibits multiple splays and sill segments separated by broken and unbroken bridges, most likely due to multiple mechanical weak layers that occur within this sedimentary host rock. In homogeneous sandstones, sills typically exhibit strata-discordant base contact to the host rock, in which the sills transgress sub-vertically through the sandstones. Sandstones with discontinuities, such as mud-draped cross-beds, will have sills intruding along the weaknesses in the host rocks. Furthermore, potential pathways of igneous intrusion were investigated by quantifying the lengths of sills found in each type of host rocks. The measurements presented in **Paper 2** show that the sills found in North Cedar Mountains are 3.5 times more likely to intrude along mudstone layers, compared to heterolithic intervals and sandstones.

Objective 3: *compare synthetic seismic models created from virtual outcrops with real seismic data from natural sills in sedimentary basins and investigate if sill geometries can be used to predict lithology in seismic datasets with limited or no well information.*

The North Cedar Mountain locality features a seismic scale exposure of sills and their respective host rocks, which can be used as a field analogue for sills found in seismic datasets. The virtual outcrops from Cedar Mountains were used as baseline for synthetic seismic modelling, which was presented in **Paper 2**, providing a high-quality analogue with strong control on marginal sill features that fall beneath seismic resolution. For instance, broken and unbroken bridges (i.e., overlapping sill segments) are difficult to image in seismic data, and especially sill splays due to their thickness and because they are often found in sedimentary intervals beneath the main sill. This study shows that maximum imageable dip of strata is a key factor in detecting sill marginal features and sill segments. For instance, most bridges with a vertical jog of less than 10 meter often fall beneath seismic resolution. However, the overall geometries of sills found in the synthetic seismic model were consistent with the ones observed in the virtual outcrops and presented in Objective 2. In general, strata-concordant sills suggest mudstones or heterolithic intervals, in which heterolithic intervals ca be distinguished due to the presence of detectable vertical jogs. While strata-discordant sills often suggest homogeneous sandstone layers with little-to-no discontinuities or sedimentary structures. This provides insights on how to interpret sills in seismic datasets without existing well logs to predict host rock lithology based on geometry of the sills. However, it is important to note that this is based alone on observations between the virtual outcrops and the synthetic seismic models, and basin history and lithology should always be investigated prior to interpretation of sills.

Objective 4: *compare different igneous intrusions from sedimentary basins and use this to understand how host rock strata may influence magmatic expression of sills.*

This thesis has focused on sills found in San Rafael Volcanic Field. While case studies are valuable, they may exhibit a restricted view on isolated instances of sill emplacement. Thus, it becomes paramount to investigate and compare findings from this thesis to other studies of sill emplacement in sedimentary host rocks. As a solution to this limitation, four field outcrops with similar scale exposures (approximately 10 kilometers by 100 meters) of sills were compared to the virtual outcrop from Cedar Mountains. This is presented in **Paper 3**, which shows that the geometries of sills appear to be similar in the same lithologies. For instance, study of all five sill complexes suggests that sills emplaced in mudstones or shales typically show strata-concordant geometries, heterolithic intervals show strata-concordant geometries with abundant broken bridges and splays, and sills emplaced in homogeneous sandstones typically shows strata-discordant geometries. The different sills chosen for this study exhibited different viscosities (four mafic and one andesitic) and emplacement depths (0.7 to 3 kilometers). Interestingly, emplacement depth does not seem to affect the sill geometries in the studied outcrops as all sills did not exhibit any differences in geometry within corresponding lithologies. For instance, the most shallowly emplaced sills in Cedar Mountains (less than 1 kilometer emplacement depth) and Hurry Inlet (c. 3-kilometer emplacement depth) exhibits the same geometries in similar lithologies, and both includes peperitic textures in poorly cemented lithologies. However, it should be noted that the host rocks in all studied areas had undergone extensive burial, in which the host rocks have been subjected to quartz cementation prior to emplacement of intrusions. The only expectation is the sills emplaced in Botneheia, but these intrusions are mostly emplaced in shales or at mechanically weak interfaces between shales and sandstones. The result from this study suggests that it is important to consider the state of the host rocks at the time of magma emplacement, rather than just the emplacement depth. In addition, the observations of both brittle and non-brittle emplacement of sills in sedimentary basins further strengthens the idea that sills have a dynamic response to the conditions of the host rocks during emplacement.

Perspectives and future work

More extensive datasets

A key product from this thesis is to highlight the importance and influence of lithology in terms of emplacement and propagation of igneous intrusions in sedimentary basins. Sedimentary host rocks are complex and often show great lateral variability. Thus, the emplacement of igneous intrusions is equally complex due to their dynamic response to sedimentary host rocks. However, most of the detailed descriptions of the different sedimentary strata are focused on logs from Cedar Mountains. It would be useful to conduct more in-depth study of different sedimentary facies and the emplacement processes of sills that intrude within these facies. This is currently being conducted in two associated MSc thesis projects at the University in Bergen, in which the students are focusing more on depositional processes and accurate facies descriptions of the intruded units found in San Rafael Volcanic Field, and how this relates with the emplaced intrusions.

This thesis has documented that igneous intrusions may propagate through both brittle and non-brittle fashion in sedimentary basins. This implies a dynamic relationship between the host rock conditions and the magma, which is reflected by the textures found within the sills (e.g., fluidization). Thus, a stronger geochemical approach to the development of multiple textures (e.g., fluidization) described in **Paper 1** would be of interest to investigate what is the dominant propagation factor during development of fluidized sill textures. There is also an aspect of geomechanical questions regarding the discoloration and bleaching caused by thermal alteration of the host rocks. Although this has been briefly studied in terms of CO_2 fluid alteration (e.g., Major et al., 2018; Skurtveit et al., 2021), it would be of interest to investigate if thermal alteration of host rocks has an impact of the preferential pathway of sill emplacement. For instance, to see if changes in fracture toughness and porosity for a host rock due to thermal alteration would alter or influence the propagation pathway of a sill. A few thin sections of unaltered and altered host rocks were collected, but the dataset remains too small to be included in the current study. Hence, more field work and subsequently a larger dataset of thin sections and rock samples for shear strength testing would be of interest.

The sills presented in this study exhibits multiple magmatic textures, such as fine-grained zones and peperitic zones. These have been established to be related to non-brittle emplacement. However, fluidization and brecciation of host rocks have been found to be related to hydrothermal vent complexes that originate in contact metamorphic aureoles around sill intrusions (e.g., Svensen et al., 2006). The sills presented in this study exhibit such contact aureoles, represented by the bleached host rocks. It would be of interest investigate the processes of hydrothermal vent complexes with non-brittle fashion emplacement of sills, as the hydrothermal mineral zeolite is found within the sills in Mussentuchit Wash. An open question that remains is if the phreatic eruption of hydrothermal vent complexes and development of fluidization of sills are connected in Cedar Mountains.

Numerical and analogue modelling

This thesis contributes to the data base needed to develop and enhance numerical and analogue modelling to study emplacement of sills in multi-layered models. The main results suggests that lithology, and consequently their fracture properties, are a key contributing factor in emplacement and end-member sill geometries. This implies that the spectrum of host rock rheology and properties should be a topic of future work involving numerical and laboratory modelling of sill intrusions (also suggested by Kavanagh et al. 2018). For instance, the emplacement of multiple segments and splays observed in the heteroliths at Cedar Mountains are poorly constrained from an evolutionary perspective. It would be of interest to conduct modelling of emplacement in interbedded host rocks to study how these sill segments are interacting with each other. This could assist in the understanding on deformation of host rocks in terms of mechanical layering, and how local or regional stress perturbations of multiple sills affect each other and overall propagation of magma. However, it should be noted that modifications to the intrusion geometry and associated style of host rock deformations occur during emplacement due to increasing magma viscosity during cooling (e.g., Burchardt et al. 2019). These modifications are important to understand, as late-stage processes have the potential to overprint early structures, which implies that segment geometries as observed in the field may be representative only of the final stage of emplacement, rather than the emplacement process as a whole (Stephens et al. 2021; Walker et al. 2021).

Data integration and shallow 3D seismic

Virtual outcrop studies are often limited by the lack of true three-dimensional control and continuity of sills, due to the orientation of the exposed cliffs in outcrops. Most, if not all, outcrops presented in this study are oriented parallel to propagation, as shown by the presence of broken bridges. The 2D limitation is a common problem in outcrop-based studies and is difficult to counter. However, shallow 3D seismic datasets do not exhibit such limitations and are great ways to study sills to their full extent. It would be of interest to find and interpret seismic dataset of sills that are good analogues to the sills presented in this study. For instance, the sills found in Hurry Inlet and Svinhufvuds Bjerge are direct analogues to sills found in the Vøring-Møre Basin, and Botneheia is an analogue to sills found in the eastern Barents Sea Basin. Synthetic seismic models could be developed by using the basis of the virtual outcrops, which again could be directly compared to the real seismic of the analogues. This would provide us with a strong control on geometries in associated lithologies, and emplacement structures that fall beneath seismic resolution.

The observations that sills may propagate and emplace through brittle and non-brittle fashion contemporaneously infer implications on monitoring of active igneous intrusions (e.g., Schofield et al. 2014). This duality of sill emplacement is evident by the linear elastic fracture mode propagation of sills with presence of fluidization at broken bridges. This highlights the notion that magma intruding into sedimentary basins have a dynamic relationship with the host rocks, which has consequences in terms of subsurface magma monitoring. Present-day monitoring involves InSAR and seismic measurement (e.g., Barsotti et al. 2023), which assume that the magma emplacement causes brittle failure that can be detected. However, sills intruding into semi-consolidated interbeds, or groundwater, will not produce any seismic signals. Therefore, it would be of interest to map areas of recent magmatic activity and correlate the presence of sills with seismic measurements of that area when it was active.

References cited in Introduction and Synthesis

Abdelmalak, M. M., Mourgues, R., Galland, O., & Bureau, D. (2012). Fracture mode analysis and related surface deformation during dyke intrusion: Results from 2D experimental modelling. Earth and Planetary Science Letters, 359, 93-105. Borton, J. & Clay, E. (1986): "The African Food Crisis of 1982-1986", Disasters, Vol. 10: 258-72.

Agirrezabala, L. M., Permanyer, A., Suárez-Ruiz, I., & Dorronsoro, C. (2014). Contact metamorphism of organic-rich mudstones and carbon release around a magmatic sill in the Basque-Cantabrian Basin, western Pyrenees. Organic Geochemistry, 69, 26-35.

Archer, A. W. (2005). Review of Amazonian depositional systems. Fluvial sedimentology VII, 17-39.

Barenblatt, G. I. (1962). The mathematical theory of equilibrium cracks in brittle fracture. Advances in applied mechanics, 7, 55-129.

Barsotti, S., Parks, M. M., Pfeffer, M. A., Óladóttir, B. A., Barnie, T., Titos, M. M., ... & Sigurðsson, E. M. (2023). The eruption in Fagradalsfjall (2021, Iceland): how the operational monitoring and the volcanic hazard assessment contributed to its safe access. Natural Hazards, 116(3), 3063-3092.

Bjørlykke, K., & Egeberg, P. K. (1993). Quartz cementation in sedimentary basins. AAPG bulletin, 77(9), 1538-1548.

Bundschuh, J., & Maity, J. P. (2015). Geothermal arsenic: occurrence, mobility and environmental implications. Renewable and Sustainable Energy Reviews, 42, 1214-1222.

Bunger, A. P., & Cruden, A. R. (2011). Modeling the growth of laccoliths and large mafic sills: Role of magma body forces. Journal of Geophysical Research: Solid Earth, 116(B2).

Burchardt, S., Mattsson, T., Palma, J. O., Galland, O., Almqvist, B., Mair, K., ... & Sun, Y. (2019). Progressive growth of the Cerro Bayo cryptodome, Chachahuén volcano, Argentina—Implications for viscous magma emplacement. Journal of Geophysical Research: Solid Earth, 124(8), 7934-7961.

Carman Jr, M.F., 1994. Mechanisms of differentiation in shallow mafic alkaline intrusions, as illustrated in the Big Bend area, western Texas. Journal of Volcanology and Geothermal Research, 61(1-2), pp.1-44.

Cartwright, J., and Møller Hansen, D. (2006). Magma transport through the crust via interconnected sill complexes. Geology, 34(11), 929-932.

Crabaugh, M., & Kocurek, G. (1993). Entrada Sandstone: an example of a wet aeolian system. Geological Society, London, Special Publications, 72(1), 103-126.

Crabaugh, M., & Kocurek, G. (1998). Continental sequence stratigraphy of a wet eolian system: a key to relative sea level change. SPECIAL PUBLICATION-SEPM, 59, 213-228.

Delaney, P. T., & Gartner, A. E. (1997). Physical processes of shallow mafic dike emplacement near the San Rafael Swell, Utah. Geological Society of America Bulletin, 109(9), 1177-1192.

Delaney, P. T., & Pollard, D. D. (1981). Deformation of host rocks and flow of magma during growth of minette dikes and breccia-bearing intrusions near Ship Rock, New Mexico (No. 1202). USGPO.

Dickinson, W. R., & Gehrels, G. E. (2009). U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment. Geological Society of America Bulletin, 121(3-4), 408-433.

Dickinson, W. R., & Gehrels, G. E. (2010). Insights into North American paleogeography and paleotectonics from U–Pb ages of detrital zircons in Mesozoic strata of the Colorado Plateau, USA. International Journal of Earth Sciences, 99, 1247-1265.

Díez, M., Connor, C. B., Kruse, S. E., Connor, L., & Savov, I. P. (2009). Evidence of small-volume igneous diapirism in the shallow crust of the Colorado Plateau, San Rafael Desert, Utah. Lithosphere, 1(6), 328-336.

Donnadieu, F., & Merle, O. (1998). Experiments on the indentation process during cryptodome intrusions: new insights into Mount St. Helens deformation. Geology, 26(1), 79-82.

Duffield, W. A., Bacon, C. R., & Delaney, P. T. (1986). Deformation of poorly consolidated sediment during shallow emplacement of a basalt sill, Coso Range, California. Bulletin of Volcanology, 48, 97-107.

Eide, C. H., Schofield, N., Jerram, D. A., & Howell, J. A. (2017). Basin-scale architecture of deeply emplaced sill complexes: Jameson Land, East Greenland. Journal of the Geological Society, 174(1), 23-40.

Eide, C. H., Schofield, N., Howell, J., & Jerram, D. A. (2022). Transport of mafic magma through the crust and sedimentary basins: Jameson Land, East Greenland. Journal of the Geological Society, 179(3).

Galland, O., Burchardt, S., Hallot, E., Mourgues, R., & Bulois, C. (2014). Dynamics of dikes versus cone sheets in volcanic systems. Journal of Geophysical Research: Solid Earth, 119(8), 6178-6192.

Galland, O., Spacapan, J. B., Rabbel, O., Mair, K., Soto, F. G., Eiken, T., ... & Leanza, H. A. (2019). Structure, emplacement mechanism and magma-flow significance of igneous fingers–Implications for sill emplacement in sedimentary basins. Journal of Structural Geology, 124, 120-135.

Gartner, A. E. (1986). Geometry, emplacement history, petrography, and chemistry of a basaltic intrusive complex, San Rafael and Capitol Reef Areas, Utah (No. 86-81). US Geological Survey.

Germa, A., Koebli, D., Wetmore, P., Atlas, Z., Arias, A., Savov, I. P., ... & Gallant, E. (2020). Crystallization and segregation of syenite in shallow mafic sills: insights from the San Rafael Subvolcanic field, Utah. Journal of Petrology, 61(9), egaa092.

Gill, S. P. A., and Walker, R. J. (2020). The roles of elastic properties, magmatic pressure, and tectonic stress in saucer-shaped sill growth. Journal of Geophysical Research: Solid Earth, 125(4), e2019JB019041.

Gudmundsson, A. (2011). Deflection of dykes into sills at discontinuities and magma-chamber formation. Tectonophysics, 500(1-4), 50-64.

Hansen, D. M., & Cartwright, J. (2006). Saucer-shaped sill with lobate morphology revealed by 3D seismic data: implications for resolving a shallow-level sill emplacement mechanism. Journal of the Geological Society, 163(3), 509-523.

Haug, Ø. T., Galland, O., Souloumiac, P., Souche, A., Guldstrand, F., & Schmiedel, T. (2017). Inelastic damage as a mechanical precursor for the emplacement of saucer-shaped intrusions. Geology, 45(12), 1099-1102.

Hayba, D. O., & Ingebritsen, S. E. (1997). Multiphase groundwater flow near cooling plutons. Journal of Geophysical Research: Solid Earth, 102(B6), 12235-12252.

Healy, D., Rizzo, R. E., Duffy, M., Farrell, N. J., Hole, M. J., & Miurhead, D. (2018). Field evidence for the lateral emplacement of igneous dykes: Implications for 3D mechanical models and the plumbing beneath fissure eruptions. Volcanica, 1(2), 85105.

Hintze, L.F., Willis, G.C., Laes, D.Y.M., Sprinkel, D.A., and Brown, K.D., 2000, Digital Geologic Map of Utah: Utah Geological Survey, Map 179DM, scale 1:500,000.

Hudson, T. S., White, R. S., Greenfield, T., Ágústsdóttir, T., Brisbourne, A., & Green, R. G. (2017). Deep crustal melt plumbing of Bárðarbunga volcano, Iceland. Geophysical Research Letters, 44(17), 8785-8794.

Hutton, D.H.W., 2009. Insights into magmatism in volcanic margins: bridge structures and a new mechanism of basic sill emplacement–Theron Mountains, Antarctica. Petroleum Geoscience, 15(3), pp.269-278.

Jackson, C. A., Schofield, N., & Golenkov, B. (2013). Geometry and controls on the development of igneous sill–related forced folds: A 2-D seismic reflection case study from offshore southern Australia. Bulletin, 125(11-12), 1874-1890.

Jamtveit, B., Svensen, H., Podladchikov, Y. Y., & Planke, S. (2004). Hydrothermal vent complexes associated with sill intrusions in sedimentary basins.

Jerram, D. A., & Bryan, S. E. (2018). Plumbing systems of shallow level intrusive complexes. Physical Geology of Shallow Magmatic Systems: Dykes, Sills, and Laccoliths, 39-60.

Jerram, D.A. and Stollhofen, H., 2002. Lava–sediment interaction in desert settings; are all peperite-like textures the result of magma–water interaction?. Journal of Volcanology and Geothermal Research, 114(1-2), pp.231-249.

Kavanagh, J. L., & Sparks, R. S. J. (2011). Insights of dyke emplacement mechanics from detailed 3D dyke thickness datasets. Journal of the Geological Society, 168(4), 965-978.

Kavanagh, J. L., Menand, T., & Sparks, R. S. J. (2006). An experimental investigation of sill formation and propagation in layered elastic media. Earth and Planetary Science Letters, 245(3-4), 799-813.

Kavanagh, J. L., Rogers, B. D., Boutelier, D., & Cruden, A. R. (2017). Controls on sill and dyke-sill hybrid geometry and propagation in the crust: The role of fracture toughness. Tectonophysics, 698, 109-120.

Kavanagh, J. L., Engwell, S. L., & Martin, S. A. (2018). A review of laboratory and numerical modelling in volcanology. Solid Earth, 9(2), 531-571.

Kempton, P. D., Fitton, J. G., Hawkesworth, C. J., & Ormerod, D. S. (1991). Isotopic and trace element constraints on the composition and evolution of the lithosphere beneath the southwestern United States. Journal of Geophysical Research: Solid Earth, 96(B8), 13713-13735.

Kjenes, M., Eide, C. H., Schofield, N., & Chedburn, L. (2023). Alkaline sill intrusions in sedimentary basins: emplacement of the Mussentuchit Wash Sill in San Rafael Swell, Utah. Journal of the Geological Society, 180(1).

Kokelaar, B.P., 1982. Fluidization of wet sediments during the emplacement and cooling of various igneous bodies. Journal of the Geological Society, 139(1), pp.21-33.

La Felice, S., Montanari, D., Battaglia, S., Bertini, G., & Gianelli, G. (2014). Fracture permeability and water–rock interaction in a shallow volcanic groundwater reservoir and the concern of its interaction with the deep geothermal reservoir of Mt. Amiata, Italy. Journal of volcanology and geothermal research, 284, 95-105.

Lenhardt, N., Götz, A. E. J. J. o. V., and Research, G., 2011, Volcanic settings and their reservoir potential: An outcrop analog study on the Miocene Tepoztlán Formation, Central Mexico, v. 204, no. 1-4, p. 66-75.

Lister, J. R. (1990). Buoyancy-driven fluid fracture: the effects of material toughness and of low-viscosity precursors. Journal of Fluid Mechanics, 210, 263-280.

Liu, J., Wang, P., Zhang, Y., Bian, W., Huang, Y., Tang, H., & Chen, X. (2012). Volcanic rock-hosted natural hydrocarbon resources: a review. IntechOpen.

Magee, C., Maharaj, S. M., Wrona, T., & Jackson, C. A. L. (2015). Controls on the expression of igneous intrusions in seismic reflection data. Geosphere, 11(4), 1024-1041.

Magee, C., Muirhead, J.D., Karvelas, A., Holford, S.P., Jackson, C.A., Bastow, I.D., Schofield, N., Stevenson, C.T., McLean, C., McCarthy, W. and Shtukert, O. (2016). Lateral magma flow in mafic sill complexes. Geosphere, 12(3), 809-841.

Magee, C., Muirhead, J., Schofield, N., Walker, R. J., Galland, O., Holford, S., ... & McCarthy, W. (2019). Structural signatures of igneous sheet intrusion propagation. Journal of Structural Geology, 125, 148-154.

Major, J. R., Eichhubl, P., Dewers, T. A., & Olson, J. E. (2018). Effect of CO2–brine–rock interaction on fracture mechanical properties of CO2 reservoirs and seals. Earth and Planetary Science Letters, 499, 37-47.

Mathieu, L., De Vries, B. V. W., Holohan, E. P., & Troll, V. R. (2008). Dykes, cups, saucers and sills: Analogue experiments on magma intrusion into brittle rocks. Earth and Planetary Science Letters, 271(1-4), 1-13.

Merle, O., & Donnadieu, F. (2000). Indentation of volcanic edifices by the ascending magma. Geological Society, London, Special Publications, 174(1), 43-53.

Peterson, F. (1988). Pennsylvanian to Jurassic eolian transportation systems in the western United States. Sedimentary Geology, 56(1-4), 207-260.

Planke, S., Symonds, P. A., Alvestad, E., & Skogseid, J. (2000). Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins. Journal of Geophysical Research: Solid Earth, 105(B8), 19335-19351.

Pollard, D. D. (1973). Derivation and evaluation of a mechanical model for sheet intrusions. Tectonophysics, 19(3), 233-269.

Pollard, D.D., Muller, O.H. and Dockstader, D.R., 1975. The form and growth of fingered sheet intrusions. Geological Society of America Bulletin, 86(3), pp.351-363.

Poppe, S., Galland, O., de Winter, N. J., Goderis, S., Claeys, P., Debaille, V., ... & Kervyn, M. (2020). Structural and geochemical interactions between magma and sedimentary host rock: the Hovedøya case, Oslo Rift, Norway. Geochemistry, Geophysics, Geosystems, 21(3), e2019GC008685.

Rateau, R., Schofield, N., & Smith, M. (2013). The potential role of igneous intrusions on hydrocarbon migration, West of Shetland. Petrol. Geosci., 19, 259–272.

Reid, M. R., Bouchet, R. A., Blichert-Toft, J., Levander, A., Liu, K., Miller, M. S., & Ramos, F. C. (2012). Melting under the Colorado Plateau, USA. Geology, 40(5), 387-390.

Richardson, J. A., Connor, C. B., Wetmore, P. H., Connor, L. J., & Gallant, E. A. (2015). Role of sills in the development of volcanic fields: Insights from lidar mapping surveys of the San Rafael Swell, Utah. Geology, 43(11), 1023-1026.

Rickwood, P.C., 1990. The anatomy of a dyke and the determination of propagation and magma flow directions. In International dyke conference. 2 (pp. 81-100).

Rocchi, S., & Breitkreuz, C. (2018). Physical geology of shallow-level magmatic systems—an introduction. Physical Geology of Shallow Magmatic Systems: Dykes, Sills and Laccoliths, 1-10.

Rotevatn, A., Fossen, H., Hesthammer, J., Aas, T.E. and Howell, J.A., 2007. Are relay ramps conduits for fluid flow? Structural analysis of a relay ramp in Arches National Park, Utah. Geological Society, London, Special Publications, 270(1), pp.55-71.

Rubin, A. M. (1993). Tensile fracture of rock at high confining pressure: implications for dike propagation. Journal of Geophysical Research: Solid Earth, 98(B9), 15919-15935.

Rubin, A. M. (1995). Propagation of magma-filled cracks. Annual Review of Earth and Planetary Sciences, 23(1), 287-336.

Saffman, P. G., & Taylor, G. I. (1958). The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous liquid. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 245(1242), 312-329.

Schmiedel, T., Galland, O., & Breitkreuz, C. (2017). Dynamics of sill and laccolith emplacement in the brittle crust: role of host rock strength and deformation mode. Journal of Geophysical Research: Solid Earth, 122(11), 8860-8871.

Schmitt, R. R., Andrews, G. D., Moore, J., Paronish, T., Workman, S., Gumowski, L. M., ... & Neubaum, J. (2023). Self-sealing mafic sills for carbon and hydrogen storage. Geological Society, London, Special Publications, 528(1), SP528-2022.

Schofield, N., Stevenson, C., & Reston, T. (2010). Magma fingers and host rock fluidization in the emplacement of sills. Geology, 38(1), 63-66.

Schofield, N. J., Brown, D. J., Magee, C., & Stevenson, C. T. (2012). Sill morphology and comparison of brittle and non-brittle emplacement mechanisms. Journal of the Geological Society, 169(2), 127-141.

Schofield, N., Alsop, I., Warren, J., Underhill, J.R., Lehné, R., Beer, W. and Lukas, V., 2014. Mobilizing salt: Magma-salt interactions. Geology, 42(7), pp.599-602.

Schofield, N. et al. (2017) Regional magma plumbing and emplacement mechanisms of the Faroe-Shetland Sill Complex: implications for magma transport and petroleum systems within sedimentary basins. Basin Research, 29(1), pp. 41-63.

Schofield, N., Jerram, D. A., Holford, S., Archer, S., Mark, N., Hartley, A., ... & Stevenson, C. (2018). Sills in sedimentary basins and petroleum systems. Physical Geology of Shallow Magmatic Systems: Dykes, Sills and Laccoliths, 273-294.

Scott, S., Driesner, T., & Weis, P. (2015). Geologic controls on supercritical geothermal resources above magmatic intrusions. Nature communications, 6(1), 7837.

Senger, K., Roy, S., Braathen, A., Buckley, S. J., Bælum, K., Gernigon, L., ... & Tveranger, J. (2013). Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications for CO2 sequestration. Nor. J. Geol., pp. 143-166.

Senger, K., Millett, J., Planke, S., Ogata, K., Eide, C. H., Festøy, M., ... & Jerram, D. A. (2017). Effects of igneous intrusions on the petroleum system: a review. First Break, 35(6).

Sigmundsson, F., Parks, M., Hooper, A., Geirsson, H., Vogfjörd, K. S., Drouin, V., ... & Ágústsdóttir, T. (2022). Deformation and seismicity decline before the 2021 Fagradalsfjall eruption. Nature, 609(7927), 523-528.

Skilling, I. P., White, J. D., & McPhie, J. (2002). Peperite: a review of magma–sediment mingling. Journal of Volcanology and Geothermal Research, 114(1-2), 1-17.

Skurtveit, E., Torabi, A., Sundal, A., & Braathen, A. (2021). The role of mechanical stratigraphy on CO2 migration along faults–examples from Entrada Sandstone, Humbug Flats, Utah, USA. International Journal of Greenhouse Gas Control, 109, 103376.

Spacapan, J. B., Galland, O., Leanza, H. A., & Planke, S. (2017). Igneous sill and finger emplacement mechanism in shale-dominated formations: a field study at Cuesta del Chihuido, Neuquén Basin, Argentina. Journal of the Geological Society, 174(3), 422-433.

Stephens, T. L., Walker, R. J., Healy, D., & Bubeck, A. (2021). Segment tip geometry of sheet intrusions, II: Field observations of tip geometries and a model for evolving emplacement mechanisms.

Svensen, H., Planke, S., Malthe-Sørenssen, A., Jamtveit, B., Myklebust, R., Rasmussen Eidem, T., & Rey, S. S. (2004). Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. Nature, 429(6991), 542-545.

Svensen, H., Jamtveit, B., Planke, S., & Chevallier, L. (2006). Structure and evolution of hydrothermal vent complexes in the Karoo Basin, South Africa. Journal of the Geological Society, 163(4), 671-682.

Svensen, H., Planke, S., Polozov, A. G., Schmidbauer, N., Corfu, F., Podladchikov, Y. Y., & Jamtveit, B. (2009). Siberian gas venting and the end-Permian environmental crisis. Earth and Planetary Science Letters, 277(3-4), 490-500.

Tarasewicz, J., White, R. S., Woods, A. W., Brandsdóttir, B., & Gudmundsson, M. T. (2012). Magma mobilization by downward-propagating decompression of the Eyjafjallajökull volcanic plumbing system. Geophysical Research Letters, 39(19).

Thompson, G. A., & Zoback, M. L. (1979). Regional geophysics of the Colorado Plateau. Tectonophysics, 61(1-3), 149-181.

Walker, R., Stephens, T., Greenfield, C., Gill, S., Healy, D., & Poppe, S. (2021). Segment tip geometry of sheet intrusions, I: Theory and numerical models for the role of tip shape in controlling propagation pathways. Volcanica, 4(2), 189-201.

Witte, J., Bonora, M., Carbone, C., & Oncken, O. (2012). Fracture evolution in oil-producing sills of the Rio Grande Valley, northern Neuquén Basin, Argentina. AAPG bulletin, 96(7), 1253-1277.

Zuchuat, V., Midtkandal, I., Poyatos-Moré, M., Da Costa, S., Brooks, H. L., Halvorsen, K., ... & Braathen, A. (2019). Composite and diachronous stratigraphic surfaces in low-gradient, transitional settings: The J-3 “unconformity” and the Curtis Formation, east-central Utah, USA. Journal of Sedimentary research, 89(11), 1075-1095.

Zuchuat, V., Sleveland, A. R., Pettigrew, R. P., Dodd, T. J., Clarke, S. M., Rabbel, O., ... & Midtkandal, I. (2019). Overprinted allocyclic processes by tidal resonance in an epicontinental basin: the Upper Jurassic Curtis Formation, east-central Utah, USA. The Depositional Record, 5(2), 272-305.

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Do I really have to finish?

Do returns always diminish?

R.P. Burnham

Everything that happens is from now on.

J. Vernon

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