CHAPTER 5

Storage and Transport of Magma in the Layered Crust—Formation of Sills and Related Flat-Lying Intrusions


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5.1 INTRODUCTION

Volcanic and igneous plumbing systems exhibit numerous components of various shapes, including sheet intrusions (dykes, cone sheets and sills) and more massive intrusions (laccoliths, plugs, plutons, etc.). Even though dykes are the main magma pathways from the lower crust to the Earth’s surface, recent research has highlighted that igneous sills represent significant
parts of volcanic plumbing systems (Planke et al., 2005) and substantially contribute to lateral magma transport and storage at various levels in the Earth’s crust (Magee et al., 2016).

Sills have been known and described for more than a century (Gilbert, 1877; Tweto, 1951). However, it is only the last two decades of research that have highlighted the abundance of sills worldwide and thus their global scientific significance. Indeed, large-scale seismic surveys dedicated to hydrocarbon exploration along continental passive margins revealed the presence of voluminous sill complexes in numerous sedimentary basins (Planke et al., 2005; Svensen et al., 2012; Magee et al., 2016). This chapter describes sills as essential components of volcanic plumbing systems, how they form and how they contribute to magma transport and storage in the Earth’s crust.

### 5.2 WHAT ARE SILLS? DEFINITIONS AND MORPHOLOGIES

The original definition of a sill is a tabular sheet intrusion that is concordant to the layering of the host rock. This layering includes strata in sedimentary basins, layers of lava and other erupted volcanic products in volcanic areas as well as foliation in metamorphic rocks. Since sills are often found in sedimentary strata, they are commonly sub-horizontal (Fig. 5.1). However, in cases of deformed sedimentary sequences, sills can be inclined, and even vertical.

**Figure 5.1** (A) Field photograph of basaltic dyke-fed sill emplaced in lake sediments (yellow formation) in the Breidavik volcano, NE Iceland (photograph: Elodie Saubin). (B) Orthomosaic of geological section exposing doleritic sills (white ‘s’), Traill Ø, East Greenland (photographs: Sverre Planke). (C) Panoramic image of Miocene andesitic sills (white ‘s’) emplaced in organic-rich shale, northern Neuquén Basin, Mendoza province, Argentina (photographs: Olivier Galland) (Senger et al., 2017).
This rigorous definition is based on outcrop-scale observations, which are usually limited in extent (tens of meters to hundreds of meters). However, sills can extend over kilometres, and even tens of kilometres (Fig. 5.1), and it is common to observe that sills are locally discordant (Polteau et al., 2008b). Therefore, a more general definition entails sills as intrusions that are dominantly concordant with the layering of the host rock.

Depending on their degree of concordance to the host-rock layering, observations of sills worldwide lead to a classification of distinct types of intrusions (Planke et al., 2005; Jackson et al., 2013) (Fig. 5.2), mostly based on interpretation of seismic data of sill complexes.
- Strata-concordant sills fulfil the original definition of sills, that is, they correspond to continuous sheets that remain concordant with the layering of the host rock. These intrusions commonly form deeper than the other types of sills described below.
- Transgressive sills are sheets that step to stratigraphically higher levels with oblique angle with respect to host-rock layering. The transgressive parts of the intrusions can be straight,

Figure 5.2 (A) Schematic drawings illustrating distinct sill and flat-lying intrusion morphologies as defined from seismic data. See text for morphological description. (B) Characteristic seismic profile of Gleipne Sill Complex, Vøring Basin, mid-Norwegian margin, exhibiting several sill and flat-lying intrusion (strong reflectors) morphologies (Planke et al., 2005).
indicating an overall discordant sheet at an angle to the host-rock layering, or step-wise, the latter indicating alternating concordant and steeply dipping discordant segments.

- Saucer-shaped sills are roughly symmetric intrusions with (1) a concordant, lower inner sill, (2) transgressive, climbing outer inclined sheets, which (3) flatten out to outer sills. Saucer-shaped sills are usually thicker at their centre and taper toward their tips.

- V-shaped intrusions correspond to saucer-shaped sills, the inner sills of which are limited in extent, such that mostly the inclined sheets are present. These intrusions commonly form at shallow levels of the crust.

- Hybrid sills exhibit mixed characteristics of transgressive, saucer-shaped and V-shaped intrusions.

Other types of flat-lying igneous intrusions include laccoliths. Similar to sills, their basal contact is strata-concordant and usually flat (Gilbert, 1877; Corry, 1988). The pressure and volume of magma are such that the overlying rocks are forced upward, giving the roof of the laccolith a dome-like shape (see Chapter 6). It is assumed that laccoliths initiate from the emplacement of one or several sills that subsequently grow and inflate as magma influx continues (Jackson, 1997). However, a robust definition of the transition between a sill and laccolith does not exist, which is why many igneous bodies can be called both sills and laccoliths. The characteristics of laccolith intrusions are addressed in Chapter 6.

5.3 WHERE DO SILLS OCCUR?

Sills are found in various geological settings where magmatism has occurred: central volcanoes, sedimentary basins and the layered lower crust (Fig. 5.3). Note that the distinction between sills emplaced in these settings is done for classification purposes only and does not represent exclusive relations. For example, central volcanoes can be located in sedimentary basins (Indonesia, East African rift, Kamchatka) and it is likely that lower crust sills are part of the deep plumbing systems of central volcanoes (see Chapter 2).

Figure 5.3 Schematic drawings showing the main geological settings where sills are encountered: (A) central volcanoes, such as in volcanic rifts and oceanic islands, (B) sedimentary basins and (C) the layered lower crust.
5.3.1 Sills in the Lower (Layered) Crust

Crustal-scale seismic profiles often show strong sub-horizontal reflectors in the lower crust (White et al., 2008). Such reflectors are usually not present in the lower crust of cratonic regions, however they are imaged in geological settings that involve thermal activation of the lithosphere, that is, magmatic input (Allmendinger et al., 1987). This seismic layering is therefore interpreted to indicate the occurrence of mafic sills emplaced at the base of the crust. The emplacement of these lower crustal mafic sills, e.g. offshore Scotland and the Faroe Islands, is probably the main process of magma underplating as a result of massive input of magma related to the North Atlantic large igneous province, prior to continental break-up. Offshore Scotland and the Faroe Islands, where continental break-up was preceded by massive input of magma related to the North Atlantic large igneous province, the supposed emplacement of large lower crustal sills is a plausible mechanism for magmatic underplating (White et al., 2008).

Obviously, outcrops of the lower layered crust are not common. It is therefore challenging to collect direct geological observations of the structures responsible for the seismic layering. An exceptional locality is the Oman ophiolite, where an oceanic lithosphere has been obducted on top of the margin of the Arabian plate. There, geological studies highlight the presence of numerous mafic sills close to the former Moho. These sills have greatly contributed to the migration of magma from the partially molten mantle to the crust (see also Chapter 2).

5.3.2 Sills in Central Volcanoes

Classic views of volcanic and igneous plumbing systems have considered dykes and central conduits as the main feeders of fissure eruptions and summit eruptions at central volcanoes (see also Chapter 4). However, plumbing systems in active central volcanoes appear much more complex, including numerous, co-existing intrusions of contrasting shapes, such as sills.

In eroded volcanic systems, the main difficulty in observing sills is that they commonly have the same lithology as their host rock. It can therefore be challenging to distinguish a thick lava flow from a sill. Detailed field observations, however, show the presence of abundant sills in central volcanoes, for example, in Iceland (Pasquare and Tibaldi, 2007; Burchardt, 2008).

In active central volcanoes, the obvious challenge is that the magmatic plumbing system is inaccessible in the sub-surface and thus not directly observable. However, geophysical and geodetic monitoring techniques provide considerable insights into the dynamics and shapes of magmatic intrusions. In particular, geodetic surface deformation patterns monitored at numerous active volcanoes highlight that the measured deformation can often be interpreted in terms of a growing sill in the sub-surface (Amelung et al., 2000; Pagli et al., 2012). In the case of Eyjafjallajökull volcano in Iceland, the successive emplacement of sills is thought to have triggered the infamous 2010 eruption, which disrupted the air traffic over Europe and North America (Sigmundsson
et al., 2010). In numerous examples, the emplacement of sills at depth preceded an eruption, which suggests that sills act both as shallow-depth magma storage reservoirs and as feeders of successive eruptions (Kavanagh et al., 2015). Hence, they are important components of volcanic plumbing systems and need to be considered for volcanic hazard assessments. While the examples above relate to individual magma injections, geodetic surveys at several large volcanic systems (e.g. Yellowstone and Sorrocco magma body, USA; Campi Flegrei, Italy) suggest that magma reservoirs likely exhibit sill-like shapes.

As sills represent significant components of volcanic plumbing systems in central volcanoes, substantial lateral transport of magma happens at the root of these volcanoes (Galland et al., 2007), in contrast to the classic idea that magma migrates mainly vertically up from depth.

### 5.3.3 Sills in Sedimentary Basins

Petroleum exploration in numerous sedimentary basins worldwide unravelled the presence of voluminous sill complexes (Planke et al., 2005; Magee et al., 2016), which appear as strong reflectors on seismic data (Fig. 5.2). The most voluminous sill complexes emplaced in sedimentary basins are those resulting from the rapid emplacement of large igneous provinces (LIPs). Good examples are the Karoo-Ferrar igneous province (Fig. 5.4), the North Atlantic igneous province (Rockall basin offshore Ireland, Møre and Voring basins offshore Norway, Greenland margin) and the Siberian igneous province (Tunguska basin) (Magee et al., 2016, and references therein). In these settings, sills usually occur as columnar jointed doleritic intrusions of up to several hundred metres thickness. These sills are likely the main feeders of flood basalts provinces associated with LIPs (Muirhead et al., 2014), such as those of the Deccan Traps and Lesotho Plateau (Fig. 5.4).

Sills also represent essential constituents of volcanic plumbing systems of arc and back-arc volcanoes within sedimentary basins. In contrast to LIP-type volcanism, arc- and back-arc-related sills usually exhibit andesitic compositions (Fig. 5.1B). Classic examples are the sills associated with the type locality of laccoliths in the Henry Mountains (Gilbert, 1877) and in the San Rafael subvolcanic field (Walker et al., 2017), Utah. There, the sills were dominantly emplaced in sandstone formations. Another spectacular example is the Neuquén Basin, Argentina, where voluminous Miocene back-arc volcanism led to the emplacement of numerous sills in the Mesozoic sedimentary sequences of the basin, dominantly in organic-rich shale formations (Rossello et al., 2002; Spacapan et al., 2017; Witte et al., 2012) (Fig. 5.1C).

### 5.4 HOW DO SILLS FORM?

Because of the scale and shape of sills, conclusive field studies of sill emplacement mechanisms require favourable outcrop conditions, which are hard to find. Conversely, most recent studies of sill complexes are based on seismic interpretation, which offers insights into the three-dimensional geometry of sills, but suffers from critical resolution problems
and imaging challenges (Eide et al., 2017). Therefore, large parts of the geology and physics of sill emplacement mechanisms and evolution remain poorly understood. In the following paragraphs, we describe and discuss the processes governing sill emplacement in a chronological order, that is, from sill initiation, sill propagation, to subsequent sill evolution to inclined sheets or laccoliths (Galland et al., 2018).

### 5.4.1 The Feeders of Sills

A key aspect for understanding the initiation of sills is the nature of their feeders and the feeder-to-sill relationships. However, there are very few direct outcrop observations of feeder-to-sill relationships. A common tool to study sill complexes is seismic imaging, but because this method has been designed for imaging sub-horizontal structures, it is not suitable for imaging feeders, especially if these are sub-vertical dykes.
In most laboratory and numerical models of sill emplacement, dykes are assumed to be the main feeders for sills (Kavanagh et al., 2006, 2017). However, clear examples of dykes feeding sills are rare. The clearest direct field observations of dykes feeding sills have been recently provided by Eide et al. (2016) (see also Fig. 5.1B). Spectacular images of a 25-km-long section unambiguously display sub-vertical dykes feeding sills, the dyke-to-sill transition being very sharp (Fig. 5.5A). Indirect structural and geochemical evidence of a dyke feeding saucer-shaped sills have been collected in the Karoo basin by Galerne et al. (2011), who showed that the elliptical saucer-shaped sills of the Golden Valley Sill Complex have been likely fed by dykes located below the long axis of the ellipse (see also Fig. 5.12).

Conversely, field and seismic studies suggest that sills, in particular, inclined sheets, can feed other sills through a sill complex. Several examples in Greenland (Eide et al., 2016) and Antarctica (Muirhead et al., 2012; Airoldi et al., 2016) show how sills are connected to underlying sills via gently dipping inclined sheets (Fig. 5.5B). Such a structural relationship has been widely described on seismic data of sill complexes that display features that resemble junctions between sills (Hansen et al., 2004). The wide occurrence of such junction features may even suggest that all sills of a sill complex were interconnected through sill-to-sill feeding relationships at the time of their emplacement (Cartwright and Hansen, 2006). However, systematic interpretations of sill junctions and associated feeding relationships require some caution. Galerne et al. (2011) provided field and geochemical evidence that show that two sills in contact in the Golden Valley Sill Complex, Karoo Basin, South Africa, were emplaced at distinct times and did not exhibit the same geochemical compositions. Even if such a contact would appear as a sill junction on seismic data, it is not indicative of a magma feeding relationship. This implies that the junctions between sills visible on seismic data should not be interpreted as feeding junctions by default. To summarize, sill complexes can be fed by both dykes and underlying sills and inclined sheets.

Figure 5.5  (A) Schematic drawing of a dyke feeding sills. (B) Schematic drawing of sills feeding sills via inclined sheets (modified from Airoldi et al., 2016). Note that in both cases, feeder-to-sill transitions occur abruptly at favourable stratigraphic levels.
Depending on the geometric relation between a sill and its feeder, several models for sill-feeding mechanisms have been proposed. A common model assumes that sills, and in particular saucer-shaped sills, are fed centrally such that the magma flows radially outward and upward (Polteau et al., 2008b). This model is supported by morphological flow indicators highlighted by 3D seismic data (Magee et al., 2016) and by anisotropy of magnetic susceptibility (AMS) data (Polteau et al., 2008a). The central feeding model explains, for instance, the symmetrical shapes of saucer-shaped sills. In contrast, geological observations show that sills can also be fed from the sides (Eide et al., 2016), leading to asymmetrical sill morphologies (Fig. 5.5).

5.4.2 Factors Controlling Sill Initiation

A classic model for sill emplacement states that the magma spreads horizontally along its level of neutral buoyancy (LNB) (Francis, 1982). Even if this model has been popular, numerous arguments show that it does not apply for the emplacement of sills, for the following reasons (see detailed discussion by Thomson and Schofield, 2008):

- When present, sills are emplaced at many stratigraphic levels, implying unrealistically many different LNBs.
- If the magma reaches the LNB, it should have no driving pressure, that is, the magma should stop propagating (Hogan et al., 1998). However, field observations and seismic data show that sills commonly trigger doming of their overburden, showing that the magma was over-pressured and not neutrally buoyant.
- Inclined sheets fed by sills show that even if magma spreads horizontally, it is sufficiently 'buoyant' to keep ascending subsequently.

Another classic model states that sills open parallel to the least principal stress \( \sigma_3 \): the horizontal orientation of sills implies that \( \sigma_3 \) is vertical, which is typical for compressional tectonic stresses (Hubbert and Willis, 1957). However, most sills associated with LIPs formed in un-stressed basins, often prior to rifting, where the stress is dominantly lithostatic and \( \sigma_3 \) is horizontal. Sills are even emplaced in active rifts, where \( \sigma_3 \) is horizontal parallel to extension and is expected to control the formation of vertical dykes. Even if a compressional tectonic stress regime might favour sill emplacement, it is likely not the primary controlling factor.

Alternative models that explain the emplacement of sills are based on the key observations that most sill complexes are found in layered host rock, either sedimentary strata or layered volcanic deposits, and that sills are overall strata-concordant. These first-order observations strongly suggest that sills form when a magma feeder hits a layer that is favourable for the magma to flow along. There are several possible mechanisms that explain how mechanical layering may lead to sill formation:

- Static mechanical models calculate the elastic stresses induced by a pressurized feeder dyke, the tip of which reaches a boundary between two layers, the upper one being more rigid, that is, higher Young’s modulus, than the lower one (Barnett and Gudmundsson, 2014). These models calculate complex stress distributions, with rotation
of the principal stresses that become favourable to sill growth along the boundary between the two layers.

- In addition to the rigidity contrast of the host–rock layers above and below an interface, the strength of the interface itself may play a significant role during sill initiation (Burchardt, 2008). In particular, weak interfaces between elastic rock layers strongly favour the rotation of a feeder dyke to a sill when the dyke reaches the interface (Kavanagh et al., 2017).

- The models above only consider the elastic properties of the layered host rock on sill initiation. However, sills are common within shale formations, the deformation of which can be strongly inelastic. It is therefore likely that inelastic deformation, that is, brittle shear deformation and ductile deformation, control the initiation of sills to a large degree (Schofield et al., 2012; Spacapan et al., 2017). The observation that sills are abundant in organic-rich shale formations also suggests that pore fluid pressure resulting from the maturation of organic matter might control sill initiation (Gressier et al., 2010). In this model, the local fluid overpressures lead to significant vertical fluid pressure gradients associated with fluid migration. Such pressure gradients generate vertical seepage forces that significantly reduce the vertical effective stress, such that the vertical effective stress becomes smaller than the horizontal effective stress, which is favourable for horizontal fracturing.

### 5.4.3 Sill Propagation Mechanisms

Various models of sill propagation have been proposed. Each model is associated with contrasting shapes of intrusion tips and associated structures in the host rock (Fig. 5.6). The following paragraphs describe the characteristics of each model and the expected intrusion shapes and structures in the host rock.

The most established propagation model, also called the splitting model, assumes that sills propagate through tensile linear elastic fracture mechanics (LEFM; Fig. 5.6A). Since sills are sheet intrusions, they are assumed to be hydraulic fractures propagating through a purely elastic host rock (Kavanagh et al., 2006; Bunger and Cruden, 2011; Michaut, 2011; Galland and Scheibert, 2013). In the splitting model, the tip propagates by tensile opening of the host rock, such that the opening vector is dominantly perpendicular to the contacts. The displaced host rock layers should therefore mimic the intrusion shape, and in the case of concordant sills, the strata should have the same thickness along the sill as ahead of the sill tip (Fig. 5.6G). This also implies that the displaced layers are expected to have a constant thickness along strike. The LEFM splitting model assumes that sill tips are sharp and thin. Hence, viscous magma should be unable to flow into the narrow, sharp tips of sills, which should result in a tip cavity to form between the magma front and the intrusion tip. This cavity is expected to be filled with volatiles either exsolved from the magma or from the host rock (Lister, 1990).
Figure 5.6  Schematic drawings of existing sill propagation mechanisms. (A) Linear elastic fracture-splitting model (e.g. Lister, 1990), which considers sill propagation by tensile failure, purely elastic deformation of the host rock, sharp tip of the propagating sill and the presence of a tip cavity between the magma front and the sill tip. (B) Elastic tensile fracture with a Barenblatt cohesive zone (Rubin, 1993). (C) Brittle faulting model and (D) ductile faulting model (Pollard, 1973). In both models, the magma pushes its host rock, which fails in shear manner. (E) Fluidization model triggered by rapid boiling of pore fluids as magma intrudes the host rock (Schofield et al., 2012). (F) Viscous indenter model (Merle and Donnadieu, 2000; Spacapan et al., 2017). In this model, the shear stresses due to highly viscous magma flow lead to shear (brittle and ductile) failure of the host rock. In this mode, the magma appears as rigid as, or even more rigid than, the host rock. (G) Helicopter field photograph of a sill tip in Traill Ø, Eastern Greenland. The outcrop shows that the tip of the mafic sill (dark) is sharp, and its propagation is dominated by tensile opening and elastic bending of the layered sandstone host rock.
Common rocks of the brittle crust that host sills, such as volcanic tuffs and sedimentary shale formations, do not deform elastically, and field observations show that significant inelastic deformation can accommodate sill propagation and emplacement. Thus, several propagation mechanisms accounting for inelastic deformation have been proposed. (1) the LEFM–Barenblatt cohesive zone model (Fig. 5.6B) is an extension of the LEFM splitting elastic model (Rubin, 1993). In this model, intrusion propagation occurs by tensile failure with simultaneous plastic deformation in a cohesive zone in the host rock beyond the tip of the propagating sill (Scheibert et al., 2017). (2) The brittle and ductile faulting–viscous indenter models (Fig. 5.6C and D) suggest that the host rock ahead of the intrusion tips fails in a shear manner, that is, is faulted, by the propagation of the magma. The brittle and ductile faulting models (Pollard, 1973) represent two end-member models of host-rock deformation, that is, brittle and ductile, respectively. However, they are phenomenologically similar in that they account for the push of the magma, which ‘bulldozers’ the host rock at the intrusion tip, so that the structures that form at the tip of the intrusions accommodate compression (Spacapan et al., 2017) (Fig. 5.6H). The viscous indenter model assumes both brittle (Fig. 5.6C) and ductile (Fig. 5.6D) shear failure of the host rock and implies that the viscous shear stresses near the tip of a propagating intrusion are high enough to overcome the strength of the host rock. Hence, the propagating magma pushes its host rock ahead like an indenter with a blunt or rectangular tip. In this model, the deformation associated with tip propagation consists of conjugate shear faults that accommodate shortening of the host ahead of the tip. The viscous-indenter model has been mainly applied to viscous magmas, for example, of rhyolitic compositions (Merle and Donnadieu, 2000). However, similar features have been observed associated with dykes of lower viscosity magma, that is, of basaltic and andesitic compositions. (3) Finally, the fluidization model (Fig. 5.6E) assumes that the heat brought by magma into the host rock can generate pore fluid pressure build-up
in the host at the vicinity of the intrusion (Schofield et al., 2012). The pressure build-up is such that it can trigger fluidization of the host, the transport of which accommodates the emplacement of the magma. Rock fluidization produces incoherent disruption of the fluidized rocks, easily recognizable in the field.

Sill propagation does not usually occur as one coherent magmatic sheet, but instead as multiple, slightly offset segments connected closer to the feeder. These segments are equivalent to en-échelon dyke segments commonly observed in the field (see Chapter 3). Sill segments are assumed to be elongated in the magma propagation direction and can therefore be used as magma flow indicators, in particular, on 3D seismic data (Fig. 5.7C) (Thomson, 2007). The morphology of sill segments and their connections strongly depends on the lithology and rheology of the host rock. If the host is competent, the sections of the magma segments are usually rectangular, the transition between them being very sharp and accommodated by complex brittle bridge structures (Fig. 5.7A) (Hutton, 2009). Conversely, if the host is much weaker, significant ductile deformation is expected, and the segment sections are elliptical and called magma fingers (Figs. 5.6H and 5.7B) (Pollard et al., 1975; Schofield et al., 2012; Spacapan et al., 2017).

### 5.4.4 Other Factors Influencing Sill Emplacement

Sill emplacement is largely controlled by the layering of the host rock. It is therefore likely that other types of mechanical heterogeneities, such as faults, also influence the emplacement of sills. Indeed, sills emplaced in rifted basins show clear evidence that normal faults affect the morphology of sills, as concordant sill segments are connected by intrusive segments emplaced along faults (Magee et al., 2013). In foreland basin settings, sill emplacement may also be controlled by thrust faults and ramps (Galland et al., 2007; Ferré et al., 2012).

Magma viscosity is another important parameter that controls sill emplacement. Most sills are of mafic to intermediate compositions (basaltic to andesitic), that is, composed of low-viscosity magma. In contrast, felsic intrusions (rhyolitic) dominantly exhibit laccolithic shape due to the high viscosity of the magma (Bunger and Cruden, 2011). Moreover, cooling of the magma at the contact with the cold host rock leads to significant viscosity increase near the propagating tips of sills, which considerably affects emplacement and propagation dynamics. This phenomenon results in thicker sills (Thorey and Michaut, 2016), which can also develop lobate morphology (Chanceaux and Menand, 2014).

### 5.4.5 How Do Sills Evolve? From Sills to Saucer-Shaped Sills or Laccoliths

Numerous sills in sedimentary basins resemble saucers in shape, that is, they consist of a flat-lying lower, inner sill connected to outer inclined sheets and outer sills. Typical examples are found in the Karoo basin, South Africa, offshore mid-Norway in the Vøring and Møre basins, and offshore Scotland in the Rockall Basin (see review by Polteau et al., 2008b). The most characteristic feature of saucer-shaped sills is the sharp
Figure 5.7 (A) Schematic drawing of the relations between sill segments, bridges between the segments and magma flow direction. The straight and geometric shapes of the segments highlight the brittle deformation of the host rock. (B) Schematic drawing of the relations between sill fingers and magma flow direction. The rounded sections of the fingers highlight the ductile deformation of the host rock. (C) 3D visualization of the saucer-shaped geometry of the top Tulipan sill horizon, Møre Basin, Offshore Norway (Schmiedel et al., 2017). Radial magma flow indicators mark edges of reflection segments representing upward, outward transgressing, igneous inclined sheets.
transition from the flat inner sill to the inclined sheets (Fig. 5.2A). Systematic observations of saucer-shaped sills worldwide show that (1) they are almost systematically associated with dome structures in their overburden (Fig. 5.8) and (2) the diameter
of the inner sill increases with increasing emplacement depth, the deepest sills being strata-concordant (Polteau et al., 2008b). These observations led to the hypothesis that saucer-shaped sills result from the mechanical interaction between the growing sill and the near free surface.

Saucer-shaped intrusions are proposed to form in the following way (Fig. 5.9): (1) a shallow sill grows and spreads along a layer, parallel to the free surface, (2) the sill deforms its overburden by doming, (3) differential uplift at the edges of the dome results in asymmetric stresses at the sill tip and (4) when the inner sill reaches a critical diameter, an inclined sheet

Figure 5.9 (A) Aerial photograph of the Golden Valley Sill, Karoo Basin, South Africa (photograph: Stéphane Polteau). (B) Satellite image of the part of Karoo Basin in the area of Golden Valley sill. The image displays numerous rings, which are exposed inclined sheets of saucer-shaped sills. (C) Schematic diagram illustrating emplacement mechanism of saucer-shaped sills (modified from Galland et al., 2009). (D) Example of rigid perfect plastic modelling showing the expected distribution of shear damage in the overburden of a 20-km-radius over-pressurized sill at 2 km depth (Haug et al., 2017). The shear damage zone mimics inclined sheets, suggesting that it is an important mechanical precursor for their emplacement.
initiates. The most common mechanical model of the transition from inner sill to inclined sheet considers tensile elastic stresses in the host rock at the vicinity of the propagating sill tip: when the stress reaches the tensile strength of the host rock, tensile failure occurs and guides the upward propagation of an inclined sheet (Fig. 5.8B and C) (Goulty and Schofield, 2008; Galland and Scheibert, 2013). Nevertheless, seismic and field observations suggest that shear failure, at least partly, controls the initiation of inclined sheets from sills (Figs. 5.8C and 5.9). In addition, rigid perfect plastic models show that over-pressurized shallow sills can trigger inelastic damage zone that mimics the shape of inclined sheets (Fig. 5.9D) (Haug et al., 2017); these models strongly suggest that shear damage can be a first-order controlling factor for the emplacement of inclined sheets (Fig. 5.9).

The formation of saucer-shaped sills likely influences the distribution of volcanism at the Earth’s surface. In the Central Andes of northern Chile, for example, an elliptical distribution of stratovolcanoes may suggest that they are fed by inclined sheets connected to a sill-like reservoir at depth (Mathieu et al., 2008). In the Danakil depression, Afar rift, Ethiopia, radial lava flows are fed by volcanic vents concentrated at the edge of the Aludome, suggesting that the volcanic feeders are inclined sheets fed by multiple sills that jacked up the dome (Magee et al., 2017).

It is interesting to note that igneous saucer-shaped sills exhibit the same shapes as those of saucer-shaped sand injectites that result from the injection of fluidized sand due to large pore fluid pressures (Szarawarska et al., 2010). The occurrence of both igneous and sedimentary intrusions of saucer shapes show that such structures are natural and fundamental results of growing flat-lying intrusions at shallow depth.

Large flat-lying intrusions do not systematically produce saucer shapes, especially when the magma has relatively felsic compositions (andesitic to rhyolitic), that is, of significantly higher viscosity. High-viscosity magma cannot flow over large distances, but it accumulates and inflates by substantial doming of the overburden, leading to the formation of laccoliths. The mechanisms associated to laccolith emplacement will be addressed in Chapter 6.

5.5 SCIENTIFIC AND ECONOMIC RELEVANCE OF SILLS

The above sections highlight that sills are essential components of volcanic plumbing systems. Due to their sub-horizontal shapes, they greatly contribute to lateral magma transport and magma stalling and accumulation at depth, strongly impacting volcanic activity at the surface. Accounting for sills in models of volcanic plumbing systems is a major improvement with respect to classic textbook views of vertical magma pathways.

The last two decades of research have shed light on the tremendous implications of sills emplaced in sedimentary basins. When sills are emplaced in prospective sedimentary basins, that is, those that contain all the components of petroleum systems, they may have strong effects on exploration and production of hydrocarbons (Fig. 5.10) (Rateau
et al., 2013; Senger et al., 2017). These effects concern all elements of the petroleum system, including source rock maturation, fluid migration, reservoir, trap and seal. (1) Sills are preferentially emplaced along stratigraphic levels such as organic-rich shale, that is, hydrocarbon source rocks, where the heat provided by the magma locally matures the organic matter in the surrounding sediments. (2) The injection of high-pressure magma may cause uplift and deformation of the host rock, forming broad domes, or ‘forced folds’, in their overlying strata (Fig. 5.8), some of which represent hydrocarbon traps. (3) The damage induced by the emplacement of magma in the host rock produces abundant fractures that enhance permeability and fluid flow (Fig. 5.8). (4) Solidified igneous intrusions are heavily fractured due to cooling, for example, the characteristic columnar jointing of sills. Therefore, the intrusions can be highly productive hydrocarbon reservoirs and migration pathways for hydrocarbons. Since sills have good reservoir properties, they also act as aquifers in arid parts of the world, such as the Karoo basin, South Africa (Chevallier et al., 2004).
The voluminous sill complexes resulting from LIPs within sedimentary basins were emplaced during short geological time intervals (<1 Ma). Several times during the Earth’s history, the enormous amount of heat brought by the sills triggered rapid degassing of the sedimentary host-rock formations, which resulted in the voluminous release of methane, CO$_2$ and/or poisonous gases (Fig. 5.11). These gases are released into the atmosphere through numerous hydrothermal vent complexes rooted in the metamorphic aureoles.
around the sills (Fig. 5.11) (Jamtveit et al., 2004). This mechanism had catastrophic consequences in the Earth’s climate and life conditions (Svensen et al., 2004), probably triggering major mass extinctions in Earth’s history (Courtillot and Renne, 2003). The most emblematic example is the Permo-Triassic mass extinction coeval with the Siberian LIP emplaced in the Tunguska Basin, Siberia, which triggered the extinction of 95% of the marine and 70% of the continental species. Other examples are the end-Triassic extinction associated with the Central Atlantic Magmatic Province, the early Toarcian climatic excursion associated with the Karoo-Ferrar Magmatic Province and the late Paleocene climatic excursion associated with the North Atlantic Igneous Province.

5.6 SUMMARY

Igneous sills are common magmatic intrusions and mainly occur in the layered crust. Sills have been studied in various volcanic settings, principally in sedimentary basins and central volcanoes in volcanic rifts and oceanic islands. Given that sills mainly form in the layered crust, it is assumed that the mechanical layering of the host rock dominantly controls their formation. The propagation mechanisms highly depend on the lithology and rheology of the host rock and span from tensile elastic fracturing for sills emplaced in competent rocks to shear brittle and ductile failure in weaker rocks. At shallow depth, growing sills may develop typical saucer shapes because of the mechanical interaction between the growing sill and the doming of the overburden. Better understanding of sill emplacement and evolution proves essential for assessing volcanic hazards in active volcanoes and exploring hydrocarbons in sedimentary basins. The massive and fast emplacement of sills associated with LIPs in sedimentary basins triggered catastrophic climate changes and mass extinctions in Earth’s history.

FIELD EXAMPLE: THE GOLDEN VALLEY SILL COMPLEX, KAROO BASIN, SOUTH AFRICA

The Karoo Basin in South Africa is likely the best natural laboratory to investigate sill emplacement mechanisms in a layered sedimentary basin because erosion under arid conditions has exposed hundreds of saucer-shaped sills (Fig. 5.4). Among these, the Golden Valley Sill Complex has excellent exposures of four main sills and some dykes of basaltic composition (Fig. 5.12). The Golden Valley Sill Complex has been the subject of ambitious research efforts integrating structural mapping, measurements of AMS and geochemical composition through extensive sampling campaigns, such that it is likely the best-studied sill worldwide. The multi-disciplinary research implemented at the Golden Valley Sill Complex intended to (1) constrain magma flow directions in the sills to understand their emplacement dynamics, (2) test whether nearby sills are connected to constrain sill-feeding mechanisms, (3) study post-emplacement magma differentiation within sills and (4) better understand the permeability of sill intrusions.
The main method to constrain magma flow directions is AMS. The basis of the AMS method is to measure the preferred orientation of magnetic minerals (i.e., the magnetic fabric) in a rapid and accurate manner. The magnetic fabric corresponds to the petrofabric and can be interpreted in terms of viscous shear induced by magma flow. Therefore, the AMS method applied to the Golden Valley Sill is used to estimate the magma flow direction during emplacement. A total of 665 samples were collected in situ at 113 localities that cover homogeneously the Golden Valley Sill and the connections with adjacent sills (Polteau et al., 2008a). The AMS results indicate that the emplacement of magma in saucer-shaped sills is an extremely dynamic process with inflation and deflation cycles. The AMS measurements at opposite margins of the finger-like structures show an outward magma flow direction. The fingers may have represented long-term magma channels with active magma flow at the time when the remaining sill was crystallizing.

To test whether the different sills of the complex were connected at the time of their emplacement, that is, whether they were feeding each other, statistical analysis of geochemical compositions from 327 rock samples was performed (Galerne et al., 2008). Geochemical variation diagrams for the different sills of the Golden Valley Sill Complex showed similar compositional ranges for the sills, but some differences in ratios between incompatible elements. These differences are statistically relevant and imply distinct, characteristic geochemical signatures among the sill populations. Each geochemical signature most likely represents a magma batch of distinct chemical characteristics. Notably, most sills of the Golden Valley Sill Complex exhibit significantly distinct chemical signatures, showing that each sill was fed by a distinct magma batch, with the exception of two sills that were likely connected.

The post-emplacement magma differentiation within the sills was studied through chemical analyses of compositional variations along profiles from the Golden Valley Sill (Galerne et al., 2010). In total, 18 whole-rock compositional profiles were sampled along the inclined sheets of the saucer-shaped sill (Fig. 5.12). The profiles show that different compositional patterns, previously described in distinct mafic–ultramafic sills elsewhere, may be found in different parts of a single saucer-shaped sill. The detailed examination of the mineral grain assemblage and compositions suggests that processes within 100-m-thick sills relate to early and late fractional crystallization. The observations in the Golden Valley Sill suggest that a significant part of the fractionation takes place at a late stage of cooling when a crystalline skeleton or mush zone forms. These results suggest that the process of post-emplacement melt flow regionally overprinted compositional patterns produced by earlier crystal segregation from the cooling magma at fluid-like stages during the emplacement.

To improve the understanding of fractures associated with intrusive bodies emplaced in sedimentary basins, quantitative analysis of fracturing in the sills and in the nearby host rock was performed through integration of field data, high-resolution Lidar virtual
outcrop models and image processing applied to key outcrops of the Golden Valley Sill (Senger et al., 2015). Fracture mapping highlights two main fracture sets oriented parallel and perpendicular to the contact, respectively. Finally, the fracture frequency in the host rock increases towards the sill contacts, showing permeability enhancement and a high potential for fluid flow channelling along the intrusion–host rock interfaces. The study of Senger et al. (2015) highlights how sills can considerably affect the permeability architecture of sedimentary basins.
REFERENCES


Storage and Transport of Magma in the Layered Crust—Formation of Sills and Related Flat-Lying Intrusions


**FURTHER READING**