Viscous-brittle deformation of shallowly emplaced silicic magma

Implications for outgassing and volcanic hazards

TAYLOR WITCHER
Dissertation presented at Uppsala University to be publicly examined in Hambergsalen, Geocentrum, Villavägen 16, Uppsala, Wednesday, 8 May 2024 at 09:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Edward Llewellin (Durham University).

Abstract

Silicic magma in the shallow crust has the potential to violently erupt, depending on its ability to release overpressures caused by magmatic volatiles (outgassing). Deformation-induced outgassing is prevalent along volcanic conduit margins, where ascending magma is sheared at high rates. However, this mechanism limits outgassing to the contact with the host rock, leaving the bulk of the magma untouched and full of volatiles. This thesis presents a different mechanism of silicic outgassing that affects the interior volume of a magma body as well as the margins. Here, we present a case study of deformation features within the Miocene Sandfell laccolith, Eastern Iceland: a 0.57 km$^3$ dome-shaped rhyolitic magma body with ~5 vol% phenocrysts and a microcrystalline groundmass. Similar textures have been reported in lava domes and intrusions with various compositions and crystallinities.

The range of deformation features are 1. porous flow bands, 2. elongated pores within flow bands, 3. 1–5 cm long tensile fractures aligned in bands, 4. 5–20 cm fractures within bands (often multiple fracture sets), and 5. breccia (densely spaced bands that are no longer distinguishable). The bands in each category range in length from ‘lenses’ (~15 cm) to laterally expansive (several meters), and usually taper at the tips. The bands are interlayered with coherent, undeformed rhyolite, and their morphology varies between planar, undulating, and anastomosing. The chapters within this thesis characterize the spatial distribution of each stage of ‘fracture banding’ and interpret their role in magma emplacement (Paper I); analyze the textures of each deformation stage on a micro-scale to interpret the rheology of the magma during formation (Paper II); investigate the mineral assemblage of fracture fillings and apply results to metal separation from parent magma in early ore systems (Paper III); and attempt to experimentally recreate fracture bands in a laboratory setting (Paper IV).

The results of these chapters suggest the deformation features formed from a rheological contrast between flow bands with different crystallinity. Emplacement-related stress localized along the weaker, more melt-rich flow bands, driving the ductile magma to deform through viscous and brittle processes. The fractures arrested against the stiffer rhyolite in the more crystalline flow bands, while drawing in surrounding melt and fluids. This, plus the interconnectedness of the fracture bands, implies an efficient outgassing system.

Here we show that fracture banding is an outgassing mechanism taking place in silicic magma undergoing deformation.

Keywords: magma deformation, magmatic outgassing, magmatic intrusions, rhyolite, Sandfell laccolith, crystal mush, volcanic hazards

Taylor Witcher, Department of Earth Sciences, Mineralogy Petrology and Tectonics, Villavägen 16, Uppsala University, SE-75236 Uppsala, Sweden.

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ISSN 1651-6214
URN urn:nbn:se:uu:diva-524861 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-524861)
Heaven is under our feet as well as over our heads.

—Henry David Thoreau
Walden
1854
Magma is a complex material that spans a vast range of physical properties, depending largely on its proportion of solid crystals and gas bubbles suspended in the liquid silicate melt. Magma will either erupt at the surface, or remain in the Earth’s crust. The conditions that dictate one outcome over the other stem from the way magma moves, or its ‘rheology’. Also, whether magma will erupt explosively or not, is controlled by the magmas ability to release pressure built up from gas leaving the magma, much like a champagne bottle. How gas leaves magma depends on the magma rheology, meaning how the magma reacts to stress: if the magma is fluid enough, gas bubbles can rise through the magma surface and escape. However, thicker magma does not allow bubbles to rise and pressure builds up in the magma. This pressure build up can manifest in catastrophic explosive eruptions, like Pinatubo in 1991. Therefore, volcanoes with thick, silica-rich (silicic) magma pose a threat to nearby communities and air traffic with ash-generating eruptions. However, silicic magma also erupts in effusive lava domes that do not necessarily represent a risk. The difference between these eruption styles lies in whether gas can escape the magma in sufficient amount. Understanding the mechanisms that allow gas-escape from silicic magma is the overarching aim of this thesis.

Here, I present both experiments and a case study of a solidified silicic magma chamber in Eastern Iceland: the Sandfell laccolith. The textures preserved in the solidified magma include bands of cm to dm-scale fractures organized in bands like books on a shelf. When they were first observed, it was suggested that the fracture bands formed when the magma was still hot and liquid. In this thesis, I therefore investigated the following research questions:

- How did the fracture bands in Sandfell form? What was the rheology of the magma—pure melt? Nearly solid?
- Why are the fracture bands so uniformly organized? What controlled their confinement to bands?
- What role did they play in the growth of the Sandfell laccolith?
- Were they a pressure valve that allowed gas to escape from the magma, enough to avoid an eruption?

The thesis is divided into four chapters. In Paper I, my collaborators and I mapped the distribution of deformation in the rhyolite of the Sandfell
laccolith. We took structural measurements of flow bands, fracture bands, and fractures within them. We collected rock samples to analyze the microstructure of each deformation type, and present those results in Paper II. We analyzed unique mineral fillings of the fractures in Paper III, by measuring element distribution and relative abundances, as well as 3D imaging of the fracture bands and porosity/permeability measurements. Finally, Paper IV is an experimental deformation study. We heated rock samples from Sandfell to magmatic conditions and deformed them by torsion to try to reproduce fracture bands in the laboratory, in order to constrain the conditions necessary to form them.

Based on the results of these four chapters, I confirm that the fracture bands formed during magma pooling in the Sandfell magma chamber below the surface of a volcano. The flow of magma into the chamber separated layers with more and less melt, similar to the structure of a lasagna. While more and more magma entered the chamber, the layers with more melt (sauce layers in the lasagna) took up most of the stress. But even these layers crystallized more and more, which changed the magma rheology. At some point, the rheology resembled that of ooblek, a mixture of cornstarch and water. In this state, the magma could still flow when it was not stressed. But when new magma entered the chamber, the magma reacted by breaking and producing fractures. The fractures also allowed gases to escape from the magma and so prevented the Sandfell magma chamber from erupting.

Textures like those at the Sandfell laccolith have been found in other places around the world, meaning they are not unique to Sandfell. The mechanisms of magma fracturing is important for assessing the risk of explosive volcanic eruptions, understanding how valuable elements are extracted from magma, how geothermal systems form, and how groundwater moves long after the magma has solidified.
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Additional Papers

In addition, the author has contributed to the following papers, which are not included in the thesis:


Contributions

The papers included in this thesis are the result of collaboration between myself, my supervisors, and many co-authors. The contributions to each paper are summarized below:

I. 80% of the total effort. Steffi Burchardt (SB) initiated the study. Tobias Mattsson (TM) carried out AMS analysis along with William McCarthy. Together, SB and I carried out field mapping. I analyzed the data, wrote the text and created figures. Michael J. Heap (MJH) added constructive feedback to the manuscript. SB and TM contributed to the interpretations and final versions of the text and figures.

II. 80% of the total effort. SB and I decided to create a ‘part 2’ of the field study (Paper I), focusing only on the microstructures. SB and I collected samples during the field campaign in 2021. I prepared samples for thin section production and carried out subsequent microscopy analyses. Anne Pluymakers (AP), Kai Li (KL) and MJH contributed to the methodology. I created the figures and wrote the text. All coauthors provided input to the interpretation and final versions of the text and figures.

III. 80% of the total effort. The research question was formulated by SB and myself. Pim Kaskes, Philippe Claeys, Johan Lissenberg, MJH, and AP contributed to the methodology. Iain Pitcairn assisted with mass balance calculations, and together with Shaun Barker offered expertise related to metal transport in volcanic and magmatic fluids. I created the figures and wrote the text. All coauthors provided input to the interpretation and final versions of the text and figures.

IV. 75% of the total effort. The research question was formulated by myself, SB, MJH, Alexandra R. L. Kushnir (ARLK), Bjarne Almqvist, Rémi Champallier (RC), and Laurent Arbaret (LA). Methodology was carried out by myself and RC, ARLK, MJH and LA. Processing of the experimental products was done by myself and LA. I created the figures and wrote the text with constructive input from ARLK. All coauthors provided input to the interpretation and final versions of the text and figures.
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### Abbreviations

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<tr>
<td>$\sigma$</td>
<td>stress</td>
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<tr>
<td>$\tau$</td>
<td>shear stress</td>
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<tr>
<td>$\gamma$</td>
<td>strain</td>
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<td>$\dot{\gamma}$</td>
<td>strain rate</td>
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<td>$\mu$</td>
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<td>$\eta$</td>
<td>apparent viscosity</td>
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<tr>
<td>$\phi_c$</td>
<td>crystal fraction</td>
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<tr>
<td>$\theta$</td>
<td>radial displacement</td>
</tr>
<tr>
<td>$\mu m$</td>
<td>micrometer ($10^{-6}$ m)</td>
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<tr>
<td>$Ma$</td>
<td>mega-annum (million years)</td>
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<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>HPHT</td>
<td>high pressure high temperature</td>
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<tr>
<td>AMS</td>
<td>anisotropy of magnetic susceptibility</td>
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<tr>
<td>EMP</td>
<td>electron microprobe</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscopy</td>
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<tr>
<td>BSE</td>
<td>backscattered electron image</td>
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<tr>
<td>$\mu$CT</td>
<td>micro-computed tomography</td>
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<tr>
<td>$\mu$XRF</td>
<td>micro-X-ray fluorescence</td>
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<td>EDS</td>
<td>electron dispersion spectroscopy</td>
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Terminology

Magma
Molten rock consisting of liquid silicate melt with various proportions of solid crystals and gas bubbles

Magma body
Any volume of magma within the Earth’s crust

Magma chamber
A non-planar cavity in the crust filled with magma

Pluton
A large magma body (>2 km³)

Dyke
A vertical planar magma body

Sill
A horizontal planar magma body

Laccolith
A magma body with a flat bottom and domed top, deforming overlying host rocks through folding or faulting

Pore
Discrete void within a rock

Fracture
Planar pore with two discrete sides and a high aspect ratio (length/width ≫ 1)

Bubble
An originally spherical volume of gas in liquid magma

Vesicle
A small cavity in an igneous rock formed by expansion of a bubble of gas during solidification of the rock

Phenocryst
Euhedral crystal that formed and grew early in the magma’s history; large in comparison to groundmass

Microcryst/microlite
Small (<50 µm) crystals formed within the groundmass of an igneous rock
Volcanoes exist on every continent on Earth. Humans have lived among volcanoes for millennia, benefiting from the fertile soil caused by erupted magma. Throughout time, resident communities acknowledged the source of such fertility, and developed an intimate connection with their respective volcanoes. Through generations of observation, they got to know its ‘personality:’ eruptive patterns and signals of unrest. An active volcano is an enormous presence, usually an isolated mountain that ‘breathes’—swells and contracts with magma movement, and outgasses clouds of steam through vents. It rumbles and jostles the ground with earthquake swarms, and, of course, erupts clouds of ash, fountains of bombs and pyroclasts, or rivers of lava. It’s no surprise, then, that volcanoes and their eruptions imprinted themselves on the culture of any nearby people. If you, the reader, have ever witnessed an eruption yourself, you’ll easily recall the incandescence of the lava, the almost-tangible heat, and the thunderous sounds of hot gas rushing into the atmosphere. The phenomenon invokes awe and fascination in us modern folk, with our technology and scientific understandings. To early peoples, such ferocious displays could only be explained by acts of the gods.

Here I have compiled various legends from cultures around the world who have lived among volcanoes for generations. I include it in this thesis as an homage to ‘early volcanology’: observation, interpretation, and distribution. Through these myths and legends, significant eruptions were recorded along with key elements: eruption type (ash plume, lava fountains, effusive lava flow), vent geometry (fissure vs crater), extent of eruptive products (distance lava traveled, distance bombs ejected, extent of ash deposition) eruption duration, and often loss of life. They explained the cause of such disasters with the tools they had available: stories. The cast of characters were often powerful beings who also controlled other essential natural events like rain, tides, hunting success, and wind. Through oral storytelling, elders would recount volcanic events to younger generations, who could compare it to their own personal experiences with the volcano, and so developed a unique monitoring and outreach system.

In my opinion, volcanology today is not much different: we make observations of natural processes, interpret those observations with the tools available to us
(nowadays: analytical methods), and disperse our conclusions to the wider community. Volcanology is ever-changing. We have come a long way in un-tangling the mysteries that drive liquid rock to the surface of the Earth, and still have so much to learn.

I believe that there is ancient wisdom in the stories of the people who lived among volcanoes, and their records deserve a place among the rigid science of our field. Descendants of the creators of these stories may still be living next to the same volcano, researching it actively as professionals or through passive observation. As someone who comes from the intermountain western USA, my local volcanoes are only fossils, Triassic in age. I acknowledge my immense privilege to be partaking in and contributing to the field of volcanology at Uppsala University in Sweden, where there are also only fossil volcanoes. The preface to this thesis aims to acknowledge the expanse of volcanology interwoven into cultures of which I am not a part, and is a collection of stories gathered from published works. I present it with utmost respect and reverence, and hope I adequately give credit where credit is due. Furthermore, I recognize the dominantly white, Western, and cis-gendered male voices that currently make up the bulk of modern volcanology, and commit to including researchers local to any field areas of interest in my future endeavors. We are guests in their home, and need to break the colonialist mindset of entitlement, in this field and every field.

The following stories are paraphrased by me from the paraphrasing of others, which were all translated to English from their original language, so certainly some inaccuracies are present. I hope you will enjoy reading them as much as I enjoyed writing them down; the vivid imagery transported me around the world to the site of every story. These act as inspirational reminders for why I’ve spent five years of my life on this PhD project: volcanoes are awesome. They’ve always been awesome. And the creativity required to interpret volcanic activity (especially in these stories, but in modern times as well) is a testament to the human component of volcanology—we’re pretty awesome too.

**Pinatubo (Philippines)**

Pinatubo famously erupted in 1991. What follows is an oral folk memory of an ancient eruption of Pinatubo from the Ayta people, who were early inhab-"

...
the event will likely repeat in the future. This has weight because the last two eruptions of Pinatubo before 1991 were 3 ka and 1 ka. The Ayta people must have lived around Pinatubo in the quiescent period between these two events and passed on the folk memory over the next millennium.

Bacobaco was the “terrible spirit of the sea,” and took the form of a huge turtle that could breathe fire. He would often feast on deer in the hunting grounds of the other gods. When the other gods had finally had enough, they launched an attack on Bacobaco, and he retreated to the lake at the foot of Mount Pinatubo and jumped in. The clear water provided no cover, so he climbed up the mountain in exactly 21 tremendous leaps. When he reached the top, he began burrowing down. Showers of rocks, mud, and ash were launched from his digging. In his rage, he howled so loudly the earth shook, and the fire that escaped his mouth became so thick and so hot that the attacking party had to turn away. For three days the turtle burrowed itself, roaring and launching debris out of the mountain. Finally, all was quiet, but the once clear lake was now filled with mud, and a giant hole was smoking at the top of Pinatubo.

“But now, you do not see smoke coming out of the Pinatubo mountain… and many believe that the terrible monster is already dead; but I think that he is just resting after his exertions, and that someday he will surely come out of his hiding place again…”


Merapi (Java, Indonesia)

Merapi volcano on Java, Indonesia, is known in Javanese mythology as the site of a ghost kingdom, with a kraton (palace) filled with rulers, soldiers, servants and farmers. The residents live simple ghostly lives, herding cattle, working rice fields and living in kampung (villages). The ghost kingdom of Merapi has alliances with other ghost kingdoms, in particular that of the Spirit Queen of the southern (Indian) ocean.

The Spirit Queen’s kingdom and Merapi’s kingdom are connected by the Progo River. Occasionally, spirits called lampors will drive horse-drawn carts through the water to visit each other, and the disturbance creates great sudden rushes and floods. These visits are records of volcanic mudflows coming downstream from Merapi, and effects of tsunami that surge upstream after an offshore earthquake.
The Javanese have focused on the beneficial aspects of volcanism in their mythology. In particular, the Ghost King of Merapi and the Spirit Queen of the ocean have a loving sexual relationship in the mythology. Eruptions of Merapi that reach the ocean are celebrated as fertilization events. This myth reflects the Javanese people’s long-standing awareness of the mineralogical enrichment of coastal waters by volcanic ash and mud, increasing yields of fish and other seafood.


Kilauea (Hawaii)

Hawaii is famous for its rich mythology surrounding Kilauea and its other volcanoes. Pele is the goddess of volcanoes and fire, and is responsible for the creation of the Hawaiian Islands in the mythology. Pele’s spirit is said to take the form of the glowing clouds rising from the volcanic crater, their undersides illuminated pink by the lava below. In Hawaiian stories, Pele often interacts with the people around her home of Kilauea, and she has a short and fiery temper. A great fan of games and sports, Pele is competitive and loves to challenge the village chiefs to show off her power. Occasionally, she has lost, which would entice the chiefs to boast and taunt her. That rarely ended well for the chiefs.

Selecting one Pele myth out of the impressive collection documented in the literature was difficult. Many stories describe her arrival to Hawaii, epic battles with her sisters or lovers, and the details of her home and servants within the lava lake. But the story that follows stood out to me because it speaks to the humanity of Pele, and the evident fondness the Hawaiian people have toward her despite her dangerous tendencies.

An old Hawaiian proverb is “never abuse an old woman; she might be Pele.”

One legend that the saying applies to is that of Kaha-wali, who was a chief on the island of Kauai, where volcanic activity had ceased and it was therefore known as “The Garden Island.” Its steep, grassy hills were ideal for sled-riding, or heeholua. The sleds (holua) were made of polished wood and were between 2 and 6 m long, but only 15 cm wide. At the top of the hill, the rider would get a running start and then hop on, sometimes riding for hundreds of meters before stopping. The difficulty of balancing on the sled made it quite a challenge to ride a long distance, and so racing was a grand event that chiefs and entire villages gathered to take part in.

Kaha-wali was an excellent holua rider, so much so that he took his closest friends and possessions to travel to other islands for more challengers. He had
heard of a beautiful young chiefess on the distant island of Hawaii named Pele, who was also a renowned rider, and sought to find her.

His arrival on Hawaii was welcomed by the locals, and they all climbed the vegetated lava hills and began the holua races. Festivities took place all around, including dancing, music, feasting, wrestling and boxing, and more and more travelers came to the party. Kaha-wali and his best friend Ahua were racing together, and as they prepared for another run at the top of the hill they were approached by an elderly woman. She said to Kaha-wali, “I wish to ride. Let me borrow your holua.” The chief replied, “What does an old woman like you want with a holua? You do not belong to my family, that I should let you take mine.” She then turned to his friend, Ahua, and asked for his holua. He let her have his, and she and the chief got their running start and set off down the steep hill. Soon the woman lost her balance, and was thrown from her holua and rolled some distance. Once she caught up to Kaha-wali, who had made it to the bottom, she challenged him to a rematch. Again, when they reached the top of the hill, she asked to use his holua. Since Kaha-wali thought she was a common villager, he roughly refused her request, "Are you my wife [i.e., my equal rank], that you should have my holua?" and swiftly sped down the slope, leaving her behind.

Rage flashed across the face of the woman at his insulting departure, desiring her after accepting the challenge of a race. Her eyes burned like red hot coals. She stamped her feet on the ground, and it opened beneath her. She summoned a flood of lava to lift her up and race down the hillside after her opponent. Now taking the form of her true self, the beautiful goddess of fire, she rode her own holua at the front of the waves of lava. Her black hair billowed behind her in clouds of smoke, her eyes and body flaming as she leaned forward, rushing to catch up with Kaha-wali.

Lava poured into the valley, swallowing up all the people and houses. Seeing the terrible sight behind him, Kaha-wali reached the bottom of the hill, jumped off his holua, and fled to the sea. On his way he met his mother, wife, children, and favorite pet pig, saluted each of them by touching noses, and told them their death was coming, that “Pele comes devouring.” He made it to the sea with his best friend Ahua, and they jumped in a canoe and paddled into the water. Pele stood at the shore, launching red-hot rocks at them, which can still be seen at the bottom of the sea.

And that’s how Kaha-wali learned that he must not abuse an old woman, for she might be Pele.

Mount Mazama (Oregon, USA)

*Tum-sum-ne* in Klamath

Crater Lake is the deepest lake in the US, at 594 m. It’s a volcanic caldera spanning 9 km in the northwestern state of Oregon, created by an eruption of Mt Mazama around 5700 BCE. The present-day Klamath Tribe are native to the area surrounding Mazama, and are descendants of the ancient Makalak people. This oral legend likely describes the eruption which formed Crater Lake nearly 7700 years ago:

The Chief of the Below World, Llao, would often come up to the surface of the Earth to stand atop Mt Mazama, one of the highest peaks in the Cascade Range at the time. One day, while surveying the land, he saw the daughter of the Makalak chief and instantly fell in love with her. He approached her, and promised immortality if she would join his side beneath the mountain. When she refused, Llao became enraged and threatened her people with death by fire. He stormed back to the peak of Mt Mazama, burst through the entrance to the Below World, and made true his promise.

“Mountains shook and crumbled. Red hot rocks as large as hills hurtled through the skies. Burning ashes fell like rain. The Chief of the Below World spewed fire from his mouth. Like an ocean of flame, it devoured the forests on the mountains and in the valleys. On and on the Curse of Fire swept until it reached the homes of the people.”

Skell, the Chief of the Above World, who creates laws and destroys evil beings, witnessed this event and stepped in to defend the people from Llao. Skell awoke the neighboring volcano, Mt Shasta, and the two spirits battled ferociously. Throwing incandescent boulders the size of houses, landslides of fire (pyroclastic currents), and shaking the earth, the terrified people fled to the waters of Klamath Lake to seek refuge.

Two seers among the Makalak people sought to quell Llao’s fury by sacrificing themselves to the fires at the peak of Mazama. The sight of their courage moved Skell, and fueled him to advance on Llao. This charge drove Llao to retreat into Mt Mazama with a spectacular explosion. When everything settled, at sunrise the next day, the once-towering mountain had disappeared. It fell in on Llao, leaving a gaping hole in the earth. Llao no longer comes to the surface world; he remains under Crater Lake, “rather octopoidal and of a dirty white color.”

Apart from the accurate description of a caldera-forming eruption, evidence that this story describes the formation of Crater Lake is found through an abundance of tools carved from obsidian dated to be this age, as well as “a pair of Makalak sandals found entombed beneath the pumice.”
Mount Etna (Italy & Greece)

In Greek mythology, Titans were huge man-creatures whose purpose was to challenge the gods. Some were imprisoned under volcanically active regions and were thought to be the cause of eruptions. For example, Typhon was a particularly powerful Titan, firstborn of Mother Earth (Gaia) and Zeus. He was by far the largest of the Greek monsters; when he spread out his arms, they spanned one hundred leagues (483 km), fire flashed from his eyes and he could hurl flaming rocks from his mouth. The gods of Olympus feared Typhon, and eventually he became aware of his power over them. One day, Typhon rebelled against his father, Zeus, and challenged the gods to a battle. Zeus, in answer, hurled Mount Etna at Typhon, trapping him under the mountain. In his fury, Typhon grew a hundred dragon’s heads from his shoulders. Each dragon had flaming eyes and a long black tongue, and wailed in a chorus of terrible voices, but Typhon remained imprisoned. Etna’s subsequent activity was attributed to the stirring and shifting of the Titan in his chamber, the more violent eruptions were his attempts at escape.

It has been recorded that the 5th century BCE natural philosopher Anaxagoras interpreted volcanic eruptions to be driven by “great winds stored inside the earth.” He estimated that the velocity of those winds rushing through narrow openings in the rocky crust would create frictional heat sufficient to melt the rocks, creating lava. This hypothesis was passed down for centuries, through Aristotle (384–322 BCE), and continued to be accepted into the Middle Ages (~500–1500 CE).

Aristotle, in fact, applied these wind-driven mechanics to the generation of earthquakes as well. He wrote in Meteorologica, “the earth possesses its own eternal fire,” which heats and disturbs trapped air and moisture, and leads to earthquakes and volcanic eruptions. His logic for this theory came from the comparison of the earth with human anatomy, relating ‘internal wind’ to both systems: “For we must suppose that the wind in the earth has effects similar to those of the wind in our bodies, whose force when it is pent up inside us can cause tremors and throbblings.”
Popocatépetl, Iztaccíhuatl, and Nevado de Toluca (Mexico)

An Aztec legend describes the origin story of the volcanoes Popocatépetl and Iztaccíhuatl. Long ago, a great warrior Popoca was engaged to the Princess Izta. They were set to be married upon Popoca’s return from battle. An envious member of society wrongfully informed Izta that Popoca died on the battlefield, and she grieved so severely she died of a broken heart. Popoca later returned to the city and was shocked to find his beloved no longer living. In his grief, he carried her body out of town and laid her on a beautiful table, keeping watch over her day and night with a torch. The gods saw these events unfold, and were so moved by his devotion that they turned both Popoca and Izta into great mountains. Popoca's torch continues to burn for Izta at the top of his mountain.

A story from the Tetelcingo, Morelos region of Mexico involves the same volcanoes plus a third player, and seems to recount a specific volcanic event:

Iztaccíhuatl translates in English to ‘White Woman,’ because the mountain resembles the figure of a sleeping woman and is often covered in snow. Popocatépetl translates to ‘Smoking Mountain.’ In this story, the mountain Iztaccíhuatl is the wife of the mountain Popocatépetl. Another volcano nearby, Nevado de Toluca, desired Popocatepetl’s wife, and wanted to take her away from him, but Popoca wouldn’t let him. So, they got into a fight and hurled pieces of ice and rock at each other. After they had thrown a great deal, Popoca got angrier than ever and threw a huge piece of ice, aimed right at Toluca’s neck, and decapitated him. This ended the fight, and explains why Nevado de Toluca has a flat top, resembling shoulders without a head.


Picchu Picchu, Chachani, and Misti (Peru)

Three volcanoes ‘guard’ the northeastern border of the Peruvian town of Arequipa in a line. The two end volcanoes are Picchu Picchu and Chachani. Legend says that they used to be the only two volcanoes on guard, and they fell in love. The gods did not approve, so they erected a third, larger volcano directly between them so they could no longer see each other. This volcano was Misti. Picchu Picchu was angry at the gods’ interference, and attempted to stand up to fight them. This was a struggle, and Picchu Picchu fell backwards. As
punishment for his defiance, the gods froze him in his lying-down position for eternity.

The peaks of Picchu Picchu resemble that of a man lying down, and Misti is geologically the youngest of the three volcanoes.

*Directly transcribed from oral storytelling by Carolina Segami (Peruvian friend)*

**Grimsvötn (Iceland)**

Bergbúa þátr (pronounced baig-booa thowt) translates to ‘Tale of the Mountain Dweller,’ and is a short 13th century Icelandic narrative. It tells the story of two young men who got lost on their way to church one winter and took shelter inside a cave. Once inside, two bright eyes appeared at the back of the cave and a voice rang out. The voice claimed to be a giant, and spoke the poem written below three times in a row. The giant warned that the two young men should memorize the poem or else tragedy will befall them. One man does remember it, but the other does not, and dies the following year.

The age of the giant’s poem (titled Hallmundarkviða) is thought to be older than Bergbúa þátr, and likely describes the 910 CE eruption of Grimsvötn.

“Stones fly at the giant step, steep cliffs tilt and teeter,
Little peace is to be found in the tall heath Fenrir’s hall.
Round the high crags hastens the hoary one; echoes roar:
Hallmundr, through the rocks
Resounding, treads loudly,
Resounding, treads loudly.

Dark flames spit and drive, split the mountain ridge,
Harshly rumble round the swarthy treasure strewer.
Embers shoot, I say, rushing, black straight upwards
round Hrungnir’s hall is heard
The roaring of the spark storm,
The roaring of the spark storm.

Crags and boulders burst, bringing death to many;
Tremors rack the rockscape, resounding in the mountains.
Thundr’s hall echoes also: I’ve stamped across the stream bed
but others, too, are helping
Quickening the quaking,
Quickening the quaking.

The earth-neck’s raging streams rush in heavy rubble.
One marvel more for men: to learn of glaciers burning.
But the oak of battle knows an older wonder; greater far, its traces
Will always stand in Snow-land,
Will always stand in Snow-land.

Dim cliffs break; the flame tongs blaze at faster paces.
From the ground begins a strange new clay to flow.
The heavens crack and split; giants come to life.
Twilight comes from torrents,
Till the world’s extinguished,
Till the world’s extinguished.

Harm is done by Thor. A warning often heard is:
Vex him, you regret it. The glacier-kindler’s killed.
Fewer are the rock-folk. my spirits sink – with reason –
on my way earth-inward
To black Surtr’s conflagration,
To black Surtr’s conflagration.

World to world, like snowfall, I fly; the air is ashen.
Thick rocks crash. Thor’s moving; only he could cause this.
Sorrows broadly written beneath the stone-elf’s brow,
my brow, when I travel;
My sturdy eye-shields tremble,
My sturdy eye-shields tremble.

Alone in stony home I live, without a visit.
I never was adept at entertaining humans
Learn by heart this flokkr, fighters! If you fail, punishment you’ll suffer
Aurnir’s well is dry now
Aurnir’s well is dry now.”

Introduction

Volcanism is the surface manifestation of a living earth.

—Jelle Zeilinga de Boer & Donald Sanders

Volcanoes in Human History 2002

Shallow magmatic systems are an elusive danger to surface-dwelling life. More than that, they are a source of life (likely the source of life on Earth, at ocean ridge vents), providing nutrients to soil, ore for mining, and creating more land for dwelling. People and volcanoes have lived in close proximity for millennia, and a large part of our fascination with them has come from the mystery of the hidden processes occurring at depth: Where is the hot, glowing, molten rock coming from? Why does it erupt at the surface, sometimes gently and sometimes violently? What forces are causing such explosions, to create ash that lifts hundreds to thousands of meters into the sky? These fundamental questions are still being researched today; we now know magma comes primarily from the decompression of the Earth’s mantle or the heating of fluid-rich subducting crust, which migrates upward because of buoyant forces. We know it erupts to the surface when the path of least resistance leads it there, and the enormous driving forces that cause explosive eruptions come from build-up and release of pressure in the volcanic and igneous plumbing system (Fig. 1) (Burchardt, 2018).

Active volcanoes and their plumbing systems, i.e. the network of magma transport and storage structures in the Earth’s crust, are being intensely monitored, especially when there are communities living nearby. Volcanology as a science aims to improve the understanding of volcanoes, magma, lava, and geological processes that are associated with volcanism. One purpose of volcanology as a science is to improve eruption forecasting abilities to the end of providing adequate time for humans to evacuate high-risk areas. Admittedly, there is also a significant part of the motivation that is more mystical: the inherited fascination of these dynamic, beautiful, and dangerous portals into the deep.
Figure 1. Anatomy of the volcanic and igneous plumbing system. a. Silicate melt at the crust-mantle boundary; b. Pluton or batholith, with thermal convection; c. Stopped block; d. Thermal aureole in the host rock; e. Sill; f. Dyke; g. Laccoliths; h. Magma chamber growth through stacking sills; i. Older, solidified plumbing system components; j. Saucer-shaped sill; k. Volcanic vents; l. Lava dome; m. Volcanic conduit, surrounded by dyke swarm; n. Cone sheet.
The volcanic and igneous plumbing system

Below the volcano expands a network of channels through which the magma has traveled or is traveling (Fig. 1). These channels have various geometries and sizes, similar to a system of pipes and tanks connected to a drain. Solidified plumbing systems have been studied in the field since the early days of modern geology; since it is impossible to observe in active systems, researchers must seek out exposures around the world of so-called ‘fossilized’ sub-volcanic systems, which are old, solidified magma bodies in the upper crust that are exposed from erosional processes (Burchardt & Galland, 2016). Quality and access to those exposures can be limited, so researchers have had to work with what’s available to them and collaborate internationally to patch together a general picture of what lies beneath.

Molten rock percolates through the Earth’s mantle and lower crust (Fig. 1) (Grove & Till, 2015), driven by buoyancy forces the liquid migrates upward toward the surface (Petford et al., 2000; Sparks et al., 2019). The silicate melt coalesces with other melt droplets and can eventually form large-scale magma bodies, the largest of which are plutons or batholiths (Fig. 1b) that are able to assimilate surrounding crust (Fig. 1c). The geometry of these magma bodies is strongly controlled by the mechanical properties of the host rock (Fig. 1d)—any weakness will be found and used by the ascending magma (Cruden & Weinberg, 2018). In addition, magma is able to create its own pathways through the crust (Kavanagh, 2018). During most of its lifetime, magma within the various parts of the volcanic plumbing system exist in the state of a crystal mush, which is a densely packed crystalline framework (about 50% crystals), lubricated along crystal grain boundaries by silicate melt (e.g. Cashman et al., 2017). The brittle regime in the upper crust is where structural control of the host rock on magma transport and storage are most prevalent. Dykes are the primary way to transport magma through the Earth’s crust (Fig. 1f), driven by internal fluid pressure under the influence of local and regional stress fields and preexisting discontinuities, like faults or fractures (Greiner et al., 2023; Poppe et al., 2020).

Dykes may divert into sills that follow a discontinuity (Fig. 1e), often between sedimentary beds or lavas (Schmiedel et al., 2019). Near the Earth’s surface where the overburden pressure is low, propagating sills may reach a point where it becomes more mechanically favorable to uplift the overburden rather than propagate further (Schmiedel et al., 2017). The continued intrusion of magma then deforms the overlying host rock by folding or faulting, forming a mushroom-shaped magma body that was first described by Gilbert (1877) in the Henry Mountains, Utah, USA. These features are called laccoliths, coming from the Greek ‘lakkos’ (reservoir) and ‘lith’ (stone; Fig. 1g). Different types of laccoliths exist, and are illustrated in Figure 2. The traditional domed geometry comes from folding the overlying host rock (Fig. 2a), but if at some point the host rock fails and there is one faulted side, that creates a ‘trap door’
laccolith (Fig. 2b). If more than one side faults and the host rock moves upwards as a piston, it creates a ‘punched’ laccolith (Fig. 2c) (Corry, 1988).

Figure 2. Laccolith geometries, modified from Schmiedel et al. (2019). a. Domed laccolith; b. Trap-door laccolith; c. Punched laccolith.

Laccoliths have made history more than once. Most famous is probably the 1980 eruption of Mt St Helens in the USA, when a laccolith grew within the edifice of the central volcano (in such a setting, the laccolith is sometimes called a ‘cryptodome’), inflating the surface at a rate of 2 m/day (Moore & Rice, 1984). An earthquake triggered a landslide on the steepened slope, and the sudden removal of material caused rapid decompression of the laccolith, which resulted in a violent and unexpected explosion (Moore & Rice, 1984). That eruption was a tragic wake-up call to the hazard posed by magma intruding into the shallow subsurface. While the Mt St Helens laccolith uplifted about 30 meters vertical height in just over a month, in 2010 the volcano Cordón Caulle was erupting in Chile and a laccolith rapidly inflated near the eruptive vent to ~100 meters in height in just one month (Castro et al., 2016). The observatories braced themselves for a potential explosion, but none came.

Arguably one of the largest difficulties in the volcano monitoring community is knowing when to sound the alarm. The cases of these two laccoliths exemplifies the uncertainties faced by volcanologists. Comparisons between volcanoes—even between eruptions of the same volcano—must be made with extreme caution. Coming back to the cases of the two laccoliths: both were very shallow (<1 km), were made of silicic magma (dacite and rhyolite), and had an extremely fast growth rate (vertically uplifted tens to hundreds of meters in one month). One was the realization of the hazard posed by viscous
magma so near to the surface, and one remained underground. Understanding the mechanical behavior of silicic magma is key to confronting future scenarios such as these.

The overarching research questions that are addressed in this thesis are:

- How does silicic magma deform during ascent and displacement?
- How does magma rheology affect magma degassing and outgassing?
- How does magma rheology affect the style of magma emplacement, and a magma’s explosive potential?

An improvement of assessing the risk associated with cases of shallow silicic magma intrusion will come with 1) more data collected on active volcanoes, 2) thorough analysis of solidified plumbing systems, and 3) models and experiments to identify and quantify the controlling physics. Since the plumbing system of active volcanoes is inaccessible to direct observations, studying solidified plumbing systems can provide a wealth of information on the behavior of the magma before it solidified. Some argue that what is observable in outcrop is the sum of all the processes that affected the system before it became extinct and therefore difficult to apply to an active system. This is certainly a point to always keep in mind, and still, careful observation and interpretations can allow us to detangle the complex history recorded in magmatic rocks. Some might further argue that studying solidified magmatic systems does not allow access to the dynamic processes and controlling forces that steered the behavior of the system when it was still active. This is where experiments and models come in as a complement to observations in nature. Specifically, deformation experiments can explore the influence of individual physical parameters on the behavior of geologic systems. It is through both the study of a solidified magmatic intrusion and deformation experiments that this thesis confronts the above research questions.

Project focus and aims

The crux of my PhD project is an array of tensile fractures (termed ‘fracture bands’) preserved in the Sandfell laccolith, located in eastern Iceland and first described by Mattsson et al. (2018). Similar features have been observed in other magmatic settings (Burchardt et al., 2019; Galland et al., 2023; Smith et al., 2001), but none as spectacularly displayed as at Sandfell. Using Sandfell as a case study, the following specific research questions are addressed in the thesis in order to contribute to an understanding of the overarching questions mentioned above:

- How did the fracture bands in Sandfell form? What was the rheology of the magma—pure melt? Nearly solid?
Why are the fracture bands so uniformly organized? What controlled their confinement to bands?
What role did they play in the growth of the Sandfell laccolith?
Do they represent a magma outgassing network? Could they significantly remove exsolved volatiles (and pressure) from the system, enough to avoid an eruption?

These questions were investigated before, during, and after the Covid-19 pandemic, which derailed our early plans for fieldwork and deformation experiments abroad. We adapted by analyzing the few samples we had previously collected, which brought a whole new suite of research questions: the larger fractures were filled by unexpected mineral assemblages, including particularly puzzling high concentrations of rare-Earth elements (REE).

The questions listed have been addressed in the four chapters in this thesis:

**Paper I** describes the results of our field mapping, where we systematically documented the deformation present in the Sandfell laccolith. The distribution of viscous-dominated and brittle-dominated deformation features (including fracture bands) were paired with analyses of magnetic fabrics within the rhyolite. Hence, Paper I addresses the questions, “How are the fracture bands distributed? How do they relate to the magnetic fabric of the Sandfell laccolith? What role did fracture bands play in laccolith growth?”

**Paper II** is a companion to Paper I, and investigates the deformation features mapped in the field on a microscopic level. The textures preserved shed light on the material properties of the magma at the time of fracture band formation. Paper II addresses the questions, “How did the fracture bands form? Why in such uniform geometries? Were they magma degassing features? Outgassing pathways? What was the rheology of the magma when it was deformed?”

**Paper III** addresses the mineral fillings of the fractures. Departing from the mechanical focus of the other three papers, this paper investigates ore genesis and geochemistry. Hydrothermal brines and fluids precipitate minerals according to the pressure, temperature, oxidation state and salinity of the system, as well as availability of certain elements on which others can bind during precipitation. The Sandfell fracture fills show an enrichment of a suite of elements atypical to rhyolites in this geological setting. This paper addresses the questions, “Where did the elements in the fracture fill come from? Are the fracture bands a window into mechanisms of metal liberation? Is this how magmatic ore-forming elements get separated from parent magma before being transported away to form a deposit?”

Finally, **Paper IV** is a preliminary study reporting our attempt to recreate tensile fracture bands in natural rhyolite. With the guidance and supervision of my collaborators, I conducted high-temperature, high-pressure experiments that deformed the re-melted Sandfell rhyolite in torsion at controlled rates. This was done during a one-month visit to the University of Orléans, France.
While we did not manage to fracture the molten rhyolite, the results provided valuable information on the behavior of 3-phase (solid crystals, gas bubbles, liquid melt) natural magma under simple shear and a starting point for future experiments to successfully produce tensile fractures in magma.
Background

The earth hath bubbles, as the water has…

—William Shakespeare Macbeth Act I.III
1606

The Oxford English Dictionary defines *rheology* as “the branch of science that deals with the deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids.” A liquid (or fluid) is considered Newtonian when the applied shear stress $\tau$ is linearly related to the rate of deformation, the strain rate $\dot{\gamma}$ (Fig. 3). A fluid’s *viscosity* is its resistance to flow, i.e. low viscosity fluids flow with ease. Viscosity is defined in Newtonian fluids as the slope of the flow curve, $\mu = \tau / \dot{\gamma}$ (Fig. 3), and is independent of $\dot{\gamma}$.

Non-Newtonian fluids exhibit non-linear flow curves (Fig. 3), where increasing $\dot{\gamma}$ results in $\tau$ values that do not increase at a constant rate. Non-Newtonian rheology is the result of a material’s internal structure trying to ‘catch up’ to the deformation rate, dissipating stress within its molecular network more slowly than the applied rate of strain. While some pure liquids are non-Newtonian like toothpaste and blood, the addition of particles to a Newtonian liquid will typically result in non-Newtonian rheology. The measurement of non-Newtonian viscosity is done with the term $\eta$, or *apparent* viscosity, through $\eta = \tau / \dot{\gamma}$. This term measures the bulk response of the material to $\dot{\gamma}$ in the same way as Newtonian viscosity $\mu$, but with the caveat that the value of $\eta$ will change with different applied strain rates in a non-Newtonian material.

Defining this terminology is pertinent to the study of magma, because magma is almost always a suspension of gas bubbles and/or solid crystals in a liquid silicate melt. Understanding the material properties of magma and how it flows (i.e., its rheology) allows us to more accurately model its movement within the crust and at the surface. Magma has an expansive range of inherent parameters that affect its rheology, the most important of which are temperature and the contents of silica, water, crystals, and bubbles (Kolzenburg et al., 2022).
Silicate melt is the suspending medium in almost all magmas, with or without crystals and bubbles. The rheology of silicate melt is unique in that, at low strain rates, it has a Newtonian rheology until a critical $\dot{\gamma}$ that exceeds the relaxation time $\lambda_r$ of the melt. The relaxation time, $\lambda_r$, is given by the Maxwell relationship $\lambda_r = \mu/G_\infty$, where $G_\infty$ is the shear modulus of silicate melt and has a value of $\sim 10^{10}$ Pa determined by Dingwell & Webb (1989). $\lambda_r$ describes the time it takes for the internal network of silica to rearrange in the presence of applied stress. When the deformation time, $\lambda = 1/\dot{\gamma}$, is lower than $\lambda_r$, the silicate melt viscously flows. When $\lambda \gg \lambda_r$, the rate of applied strain is too rapid for the silica network to reorganize, resulting in microstructural lock-up and stress release through elastic failure instead of viscous flow (Webb & Dingwell, 1990). This phenomenon is known as viscoelasticity, which, in silicate melt, forms the foundation of magma rheology.

Complexity of magma rheology increases with the addition of solid crystals and gas bubbles, as these ‘particles’ will also require rearrangement under applied shear in addition to the microstructural silica network (Mader et al., 2013). The fraction of crystals and bubbles in magma varies with time: crystal volume fraction $\phi_c$ increases as magma cools, grading from a dilute suspension ($\phi_c < 0.5$), into a mush ($0.5 < \phi_c < 0.7$), until the maximum packing fraction $\phi_m$ is reached and the bulk magma behaves as a solid (Fig. 4). The value of $\phi_m$ is dependent on the shape of the particles, the dispersion of particle sizes, and can change with the introduction of flow (Cimarelli et al., 2011; Mader et al., 2013; Petford, 2009). It has been shown that, at a given $\dot{\gamma}$, magma with dilute crystal suspensions will have Newtonian rheology until a critical crystal fraction $\phi^*$ marks the onset of non-Newtonian rheology (Fig. 4). At crystal fractions higher than $\phi^*$, $\eta$ increases exponentially due to crystal interaction inhibiting flow (Frontoni et al., 2022; Okumura et al., 2016). After $\phi_m$, in the ‘hyper-concentrated’ regime, $\eta$ levels off (Fig. 4), perhaps due to
crystals locally increasing $\dot{\gamma}$ enough to fracture, and strain localizing on the fracture planes or redistributing the smaller grains of broken crystals (Frontoni et al., 2022; Laumonier et al., 2011). In general, the addition of crystals or bubbles lowers the applied $\tau$ or $\dot{\gamma}$ value required for magma to fracture (Cordonnier et al., 2012).

**Figure 4.** Solidification front in a crystallizing magma, and relative viscosity increase with crystal fraction. Modified from Marsh et al., (2002) and Frontoni et al., (2022). Lower part of figure is pure melt, with the highest temperature. Once the magma cools past the liquidus temperature ($T_{\text{liquidus}}$), crystallization begins. After a critical crystal fraction $\phi^*$, viscosity becomes non-Newtonian. Crystal fraction increases as temperature decreases, and viscosity levels off toward a constant value past the maximum packing fraction $\phi_m$.

Mush rheology is an ongoing area of research, combining deformation experiments (Caricchi et al., 2007; Champallier et al., 2008; Cordonnier et al., 2012; Laumonier et al., 2011; Pistone et al., 2012; Van Der Molen & Paterson, 1979) and rheological models (Costa et al., 2009; Frontoni et al., 2022; Pistone et al., 2016) to quantify the flow behavior of crystal-rich magmas in nature. Simple-shear deformation experiments have shown strain partitioning features that developed in crystal-rich suspensions, in the form of melt segregation, bubble concentration, and crystal cataclasis (Forien et al., 2011; Holtzman et al., 2003; Laumonier et al., 2011; Picard et al., 2013; Pistone et al., 2012;
Segregation of melt from crystal-rich magma will cause strain rates to locally increase with respect to the bulk system, and porosity will migrate from areas of low strain towards areas of higher strain (Laumonier et al., 2011). Bubbles suspended in the melt will reflect strain in their shape (Rust et al., 2003), sometimes coalescing with neighboring bubbles (Okumura et al., 2008) or breaking down into smaller bubbles (Stone, 1994) when intensely sheared. This interplay between deformation and phase separation leads to significant implications for magma degassing and outgassing processes.

Degassing and outgassing

The decoupling of magmatic volatile phases (MVPs) from the silicate melt is known as degassing. Magma degassing commonly occurs through bubble formation (Sparks, 1978), which is driven by the different solubilities of MVPs in the decreasing confining pressure of ascending magma (Blake, 1984; Tait et al., 1989). H2O is the most abundant MVP, generally followed by CO2, and traces of other species (H2S, SO2, HCl, and HF; Gardner et al., 2023; Papale et al., 2006). In rhyolitic melts, bubbles tend to preferentially nucleate on magnetite crystals (Hajimirza et al., 2021). First boiling is the term that refers to MVP exsolution during decompression, and second boiling is an MVP exsolution event driven by the chemical evolution of the silicate melt during crystallization. Elements are removed from the melt phase when they join the solid crystal phase, which gradually increases the proportion of undersaturated MVPs in the melt until they ultimately become saturated, and exsolve into bubbles (Newman & Lowenstern, 2002).

Often there is feedback between rheological parameters. Consider, for example, a slowly ascending magma that reaches the pressure where the saturation level of H2O is reached, and so gas bubbles form in the silicate melt. The addition of a gas phase adds buoyancy to the bulk magma, and so increases its ascent rate, which decreases the confining pressure further, which drives the bubbles to expand. The magma’s gas fraction increases, which accelerates ascent, and so on (Abdullin et al., 2024). This case exemplifies the significance that degassing can have on magma not only physically, but also chemically. Removal of MVPs from the silicate melt will increase the melt’s viscosity (Hess & Dingwell, 1996), which will drive it towards non-Newtonian rheology. In a dehydrated melt, the applied stress from an expanding bubble, for example, may overcome the melt’s relaxation time and result in a fracture (Gonnermann, 2015; Sparks, 2003). This is the process of magma fragmentation, which generates ash (broken bubble walls) that gets ejected into the atmosphere from volcanic vents. The driving force behind such violent eruptions is related to MVPs: if they degas from the magma cannot be expelled, pressure continues to build until a potentially catastrophic release.
Outgassing
Outgassing is the removal of MVPs from the magmatic system. It is the open pressure valve that allows degassed volatiles to escape into the surrounding host rock or into the atmosphere, in some settings carrying with them precious metals and ore minerals (Blundy et al., 2021; Halter et al., 2005; Williams-Jones et al., 2002). In magmas like basalt, the low viscosity of the silicate melt allows for bubble migration through buoyancy forces, and MVPs can rise to the surface of the magma body and outgas with ease (Colombier et al., 2021; Lo et al., 2023). Magmas with higher viscosity (silica-rich and/or crystal-rich) sustain more sluggish bubble migration and so outgas more efficiently through the development of permeable networks. Connected pathways along which MVPs can travel through and out of the magma can form by bubble coalescence (Eichelberger et al., 1986; Lamy-Chappuis et al., 2020; Okumura et al., 2008), fracture networks (Kushnir et al., 2017; Shields et al., 2016), or other types of porosity development discussed in the next section.

The volcanic conduit margin
As mentioned earlier, magma will fracture when strain rates overcome its shear strength. Magmatic strain rates are highest in the volcanic conduit, specifically on the margins, from shear against the host rock (Lavallée et al., 2013). Strain rates applied to magma in the upper conduit have been estimated to range from $\dot{\gamma} = 10^{-6}–10^{-2}$ s$^{-1}$ (Tuffen et al., 2003). These $\dot{\gamma}$ values straddle the viscous-brittle transition of single- and multi-phase magma (Wadsworth et al., 2018). Corroboration between deformation experiments, textures of erupted magma, and direct observations of high-energy bursts during effusive eruptions has led researchers to the conclusion that fracturing is a viable outgassing mechanism taking place in the volcanic conduit (Castro et al., 2012; Farquharson et al., 2022; Lavallée et al., 2013; Schipper et al., 2013).

One common fracture-induced outgassing mechanism is the tuffisite, which is a fracture that draws in MVPs from the surrounding magma so rapidly that the magma fragments and the fracture is soon clogged with ash and pyroclasts (Heiken et al., 1988; Tuffen & Dingwell, 2005). Tuffisites form in the magma but can also propagate into the host rock (Stasiuk et al., 1996). The outgassing potential of tuffisites is high, but limited in space to the surface area of the fracture, and in time to the eventual closing of the fracture through sintered particles (Heap et al., 2019). Conditions required to generate tuffisites are: 1. High strain rates and stresses to rupture the magma; 2. High melt fraction, in order to rapidly exsolve volatiles through pressure-gradient diffusion that can drag fragments of magma along, and 3. A sufficiently high volatile content, to rush into the fracture (Kendrick et al., 2016). Not all magmas will meet these criteria, and in those cases, there must be other outgassing mechanisms at play.
Furthermore, strain localization along the conduit margin only allows for a small fraction of the magma volume to outgas. Some models account for this by arguing extruding lava is indeed not outgassed, but ascending as a ‘plug’ that’s been lubricated by the intense shearing along the conduit walls (Lavallée et al., 2013). However, not all ascending magma reaches the surface, nor does it have an open vent to exploit. There must be ways in which entire volumes of high-viscosity magma sufficiently outgas while remaining in the crust.

**Beyond the conduit margin**

Porosity in magma can develop in other ways besides bubble formation and fracture. When a magma approaches its maximum packing fraction $\phi_m$, it behaves like a ‘ductile solid’ and its material properties are comparable to other granular materials (Petford et al., 1998). Water-saturated soil, for example, undergoes a pore-volume increase when sheared, in a phenomenon first described by Reynolds (1885) as shear-induced dilation. To summarize, the contacts between solid grains transmit the stress applied to the bulk system and roll against one another which increases the pore space between them (Fig. 5a). The occurrence of this effect in soil has been studied at length (Bernard et al., 2002; Powrie, 2018; Schofield & Wroth, 1968), and has crossed over into the magma mush community (Caricchi et al., 2007; Petford et al., 2020; Pistone et al., 2012; Rutter et al., 2006). The application to magmatic systems is significant in that, along with the pore volume increase comes a decrease in pore pressure, which will draw in any surrounding fluids, namely exsolved MVPs or silicate melt (Marsh, 2004; Oppenheimer et al., 2015; Petford et al., 2007). The resulting concentration of melt would have a unique composition that, upon crystallizing, would result in a different mineral assemblage than that of its mush host, as proposed by Bowen (1920) as ‘deformation-induced differentiation’.

Metal alloy research has also explored the effect of Reynolds dilation from critical soil mechanics (Fonseca et al., 2013; Meylan et al., 2010; Su et al., 2019). Material properties (especially strength) of different metal alloys are intensely studied for the sake of engineers to plan structures safe for human use. One benefit of this wealth of rheological research is an abundance of textures to compare to magmatic rocks. Along with dilatant shear bands (Gourlay & Dahle, 2007), a higher degree of deformation produces cavitation features, also referred to in metal alloys as ‘hot tears’ (Nicolaou & Semiatin, 2007; Rappaz et al., 1999; Tanaka & Higashi, 2004). Cavitation in liquids is the formation of a bubble in low-pressure regions, most commonly at the trailing edge of boat propellers (Mishima & Kinnas, 1997). In ductile solids, however, cavitation is simply ductile tearing (or fracture) in response to tension, usually propagating from an original defect like a solid grain boundary (Boccaccini et al., 1998; Iwasaki et al., 1998) (Fig. 5b, c). Cavitation has been observed propagating parallel (Yousefiani & Mohamed, 1999) and oblique (Iwasaki et al.,
Cavitation, or ductile fracture, is being considered to commonly occur in geological environments like the lower crust (Katz et al., 2006; Rybacki et al., 2008), in earthquake hypocenters (Shigematsu et al., 2004), and crystal-rich magmas (Farquharson et al., 2016; Hornby et al., 2019; Smith et al., 2001).

**Figure 5.** Porosity development mechanisms not associated with brittle fracture or bubble formation. a. Reynolds dilatancy, where pore space (red) between rolling grains (black) increases as a result of shear; b. Drawing of the onset of cavitation (red) in a ductile solid localized at solid particle interfaces (black); c. Mature cavitation pore geometry in a ductile solid, also known as ‘ductile fractures.’ b. and c. are drawings of experimental products by Iwasaki et al. (1998).
It burns so as to recreate,  
The glow of fire becomes an embrace…  
That destroys and rebuilds, tears and will mend, burns  
And will make green again.

—Max Gérard, *Volcano*  
1975

Iceland is volcanically active due to magma source contributions from an underlying mantle plume and the Mid-Atlantic Ridge (Thordarson & Larsen, 2007). The active rift zones in Iceland are creating crust that increases in age towards the east and west of the country (Burchardt et al., 2022). The result of this pattern means the oldest rocks in Iceland (10–13 Ma) are on the eastern and western coasts (Fig. 6). Tectonic uplift and glacial erosion have cut down into the crust in the eastern fjords, revealing the interiors of volcanic systems that are considered analogous to those in the modern rift system (Fig. 6b; Thordarsson & Höskuldsson, 2014).

The Sandfell laccolith is located on the flanks of the Reydarfjörður (RAY-dar-fyar-dur) volcano, on the southern shore of Fáskrúðsfjörður (FOW-skrooths-fyar-dur) (Fig. 6b). The Reydarfjörður volcano was active between 12.2 to 11.3 Ma in the Miocene rift zone (Eriksson et al., 2011; Martin et al., 2011). The area was mapped in detail by Gibson (1963), who distinguished six phases of silicic volcanic activity. Each phase typically consisted of an explosive eruption, which formed a fall-deposit, followed by effusive eruption of felsic, intermediate, and basaltic lavas (Gibson, 1963). During the fourth felsic phase of Reydarfjörður, rhyolite magma intruded beneath ~540 m of (mainly) basalt lavas from the second and third eruptive phases, nearly 10 km south of the central eruptive vent (Gibson, 1963; Gibson et al., 1966). The intruding rhyolite propagated along a felsic ignimbrite of the second eruptive phase of the volcano (called T2; Gibson, 1963), and domed the overlying strata to form the Sandfell laccolith 11.7 Ma (Martin et al., 2011; Padilla et al., 2015).
Figure 6. Geological setting of the Sandfell laccolith. a. Approximate locations of Iceland’s main rift zones over time. Modified from Martin et al. (2011). Eastern and Western Iceland contain the oldest preserved rocks, dating at 10–12 Ma (dark purple). Rock ages get progressively younger toward the interior of the island; b. Central volcanic and volcanic systems of the eastern fjords, modified from Mattsson et al. (2018). The Reydarfjörður volcanic system hosts the Sandfell laccolith, the study area.

The Sandfell laccolith

The Sandfell laccolith consists of a dome-shaped main laccolith body and two sill-like offshoots that extend to the east of the main body, called Upper Sill and Rauduhnausar. In addition to doming the overlying lava pile, the intruding rhyolite created at least one punch fault along the north margin (making it discordant), opening a ‘trap door’ to accommodate inflation (Fig. 7). Since the base of the laccolith follows the T2 ignimbrite and the top is partly preserved, Mattsson et al. (2018) were able to reconstruct the total volume of the Sandfell laccolith to be 0.57 km³.

After emplacement, the laccolith solidified and was undisturbed for millennia. Regional tilting affected the Sandfell laccolith and surrounding strata and resulted in a dip of about 10–15° to the WNW (Oskarsson & Riishuus, 2013). Additionally, three steeply dipping regional faults crosscut Sandfell, oriented ca. N-S (Fig. 7). The Heljara and Grákullor faults formed a graben which displaced the eastern half of the main body of the Sandfell laccolith (Lower Sandfell) downward by ca. 70–120 m (Gibson, 1963). This post-magmatic faulting exposed the interior of the laccolith close to the upper contact with the host rock, which provided key observations during our study.

The Sandfell rhyolite contains ~5% plagioclase feldspar phenocrysts and ~5% vesicles suspended in a microcrystalline groundmass. The low phenocryst content implies the magma was melt-rich as it ascended, and cooled rapidly in order to develop a microcrystalline groundmass, but not so rapid that any substantial amount of glass was quenched from the melt (cf. Befus et al., 2015). This texture is uniform throughout all accessible outcrops of the laccolith, but virtual outcrops created from photographs acquired from a low-flying airplane revealed discontinuities in the large-scale magmatic fabric under the northern roof contact (Fig. 8). We interpret these discontinuities as contacts between successively intruded magma pulses, possibly remnants of the initially intruded sill before inflation and subsequent magma batch intrusions (Fig. 8).
Figure 7. Map of the Sandfell laccolith, modified from Paper I. See Figure 6b for location. a. Concordant and discordant contacts are labeled, along with regional faults; b. Side perspective showing displacement caused by the Heljara fault, creating the offset in the laccolith roof between Upper and Lower Sandfell.

Deformation features

Fresh surfaces of rhyolite are a cool grey, while weathered surfaces are a warm tan, often with a veneer of iron probably sourced from the overlying basalt lavas. The microcrystallinity and sparse phenocrysts in the rhyolite allow for deformation textures to be clearly showcased. Deformation features range from flow bands, to systematic porosity within flow bands, to brittle deformation expressed in single-orientation fracture bands, to breccia. Detailed
descriptions of the deformation stages and subsequent interpretations are given in Papers I and II.

Fracture banding is pervasive at the Sandfell laccolith, and is the primary focus of this thesis. In the following sections I list the methods we used to investigate the distribution, mechanics, and possible effects of the fracture bands and associated deformation features within the Sandfell laccolith. The aims and results of those methods are explained in more detail in their respective papers, but a summary of each paper follows the Methods section.
Figure 8. Photo mosaic of the northern face of Upper Sandfell, modified from Mattsson et al. (*in prep*). a. Virtual outcrop based on drone photographs; b. Annotations highlighting faults and a textural discontinuity expressed as a slightly darker weathering color of the rhyolite, interpreted as the original sill; c. Two additional discontinuities interpreted from the orientation of platy parting (example photo) and palaeomagnetic data (not shown). The discontinuities are assumed to represent the boundaries between successively intruded magma batches.
Approach & methods

I smile when I hear my colleagues say “I discovered X.”
That’s kind of like Columbus saying he discovered America.
It was here all along, it’s just that he didn’t know it.
Experiments are not about discovery, but about listening and translating.

–Robin Wall Kimmerer
Braiding Sweetgrass, 2013

In this section I will summarize the general timeline of the PhD project, then explain each method in detail. The planned approach for this project in the beginning of my PhD (May, 2019) was:

1. An introduction to the Sandfell laccolith (2 days) in August 2019 as part of a field trip to Eastern Iceland. Initial sample characterization of samples collected during this trip and two previous trips by the supervisor.
2. Detailed field mapping of the Sandfell laccolith during a field campaign in summer 2020. Structural measurements would record the orientations of flow bands and fracture bands as well as any other significant structural features. Photography would document the outcrops and deformation features at centimeter to meter scale. Samples representative of deformation features would be collected for later microstructural analysis.
3. High-pressure, high-temperature (HPHT) experiments of the natural rhyolite in autumn 2020. We would deform samples at various strain rates and record the resulting deformation features. Ideally, brittle fracturing would take place and we could constrain the conditions that created them.

I described and processed the samples from 2019, but a few months later the world shut down as the Covid-19 pandemic began. Hence, I first focused on analyzing the available thin sections with the methods available at Uppsala University, i.e., optical microscopy, electron microprobe (EMP) analyses
with scanning electron microscopy (SEM) and back-scattered electron (BSE) imaging. BSE images revealed a high complexity of the mineral fillings within the fractures (Paper III), and the EMP analyses were inconclusive on their exact mineralogy. So, I contacted laboratories around Europe that remained open (usually with one single designated technician) to perform non-destructive measurements and shipped thin sections and pieces of samples to them. Thanks to the international postal service and email, I obtained thin sections, microcomputed tomography (µCT) scans, micro-X-ray fluorescence (µXRF) measurements, and large (thin-section) scale electron dispersive spectroscopy (EDS) scans. These methods were chosen to further follow the thread of the mysterious minerals filling the fractures within the fracture.

Finally, the travel restrictions lightened and travelling became possible as the vaccine rollout commenced. Our research group was able to carry out long-awaited field work in the summer of 2021. Five days of field mapping on the Sandfell laccolith permitted us to document the preserved deformation features at almost every accessible outcrop (Paper I). We took structural measurements, photographs, and rock samples while scrambling through the scree and dense fog. Microstructural analyses (Paper II) of samples taken during this campaign involved optical microscopy, BSE imaging, and EMP analyses. Porosity and permeability measurements characterized the fluid-flow potential of dense rhyolite compared to flow bands. Raman spectroscopy identified the silica polymorph present in the groundmass and pore-fillings of the rhyolite, and cathodoluminescence (CL) imaging distinguished zones in the silica associated with compositional changes during crystallization.

After several attempts that had to be cancelled due to repeated travel restrictions and partial lockdowns, I was finally able to visit the Université d’Orléans in France in March 2022 to experimentally deform the rhyolite samples and try to recreate the brittle deformation features (Paper IV). My collaborators and I used a Paterson-type torsion apparatus to heat samples to magmatic conditions, apply simple shear at a controlled twist rate, and measure the torque applied to the sample. Torque was later converted to stress and experiment duration was converted to strain. Microtextural analyses were paired with the mechanical data to interpret the rheology of a natural 3-phase magma under shear.

While the essential approaches to my project (field work and HTHP experiments) were postponed by one and two years, respectively, everything finally came together. As expected, we learned more about Sandfell’s fracture bands as we collected more data, but also had more and more questions. The first project I worked on (Paper III) was not supposed to be the first, but we had to adapt to the extreme situation presented to us. While the sequence of events took place out of the intended order, each approach presented challenges, surprises, setbacks and breakthroughs that lead to the overarching conclusions of this PhD project. An arguably more valuable outcome is the remaining questions, as they mark a path leading towards the next steps one could take to
continue to unravel the mysteries of the Sandfell laccolith’s fracture bands. These outlooks are described further in this chapter’s Conclusions.

Field mapping

We briefly collected samples at the Sandfell laccolith for two days during an Eastern Iceland excursion in 2019, and then a longer excursion took place for structural mapping during the Covid-19 pandemic in 2021. Structural measurements used in Paper I were taken using the FieldMOVE Clino application on an iPhone 7 (Fig. 9), which was calibrated to the local magnetic declination and global positioning system (GPS) location. The application took strike and dip measurements of flow bands, fracture bands, and the fractures within them. We checked the accuracy of the FieldMOVE measurements by comparing them to measurements taken by a geological compass every ca. 10 measurements; they were always within an error of 1°. Photographs taken through FieldMOVE Clino were automatically georeferenced. Photographs taken with a Nikon Z6II camera were later referenced by constraining the time stamps between two georeferenced FieldMOVE photos. Photographs were used to categorize each outcrop on the deformation scale defined in Paper I.
Sample collection and preparation

During the field campaigns, we collected samples with interesting deformation features directly from outcrops and also from the scree for microstructural analysis for Paper II. Hand samples with the least amount of weathering possible and features as complete as possible were selected, i.e., tips of fractures and tapered tips of fracture bands with substantial amounts of groundmass surrounding them. Samples were also collected for whole-rock and trace element geochemistry which was provided through the commercial service of ALS Geochemistry, Vancouver, Canada. Standard polished thin sections were produced for Papers II, III and IV by Precision Petrographics laboratories in Langley, Canada, and ERZ Labor in Freiberg, Germany. Blue epoxy was used in some samples to highlight porosity.

![Figure 10](image)

Figure 10. Examples of fracture bands in hand sample (a) and thin section (b, c).

Microstructural and chemical analysis

To study the textures of the deformation features and undeformed rhyolite, we employed transmitted and reflected light microscopy as well as a field emission source JEOL JXA-8530F Hyperprobe Scanning Electron Microscope (SEM) at the Department of Earth Sciences, Uppsala University. Backscatter electron images (BSE) were captured and analyzed (Fig. 11a). The SEM is also equipped with an electron microprobe (EMP), which applied wavelength dispersive spectroscopy (WDS) to quantitatively determine mineral compositions in Papers II, III and IV, and glass compositions in Paper IV. Raman spectra were acquired at Uppsala University to determine the polymorph of silica present in the groundmass and pore fillings of the Sandfell rhyolite (Paper II).
My international colleagues provided valuable methodology. Micro-x-ray fluorescence (µXRF) was measured on samples at the Department of Chemistry, Vrije University, Brussels, Belgium by Pim Kaskes. Semi-quantitative relative element abundance (Fig. 11b) and quantitative linescans were measured by a Bruker M4 Tornado benchtop micro-X-ray fluorescence instrument (Bruker Nano GmbH, Berlin, Germany). Element mapping was done by electron dispersive spectroscopy (EDS) on entire thin sections by Johan Lissenberg at the School of Earth and Environmental Sciences at Cardiff University, Wales (Fig. 11c). EDS was collected on a Zeiss Sigma HD scanning electron microscope equipped with dual 150 mm² Oxford Instruments Xmax EDS detectors with an acceleration voltage of 20 kV. More details on both methods can be found in Paper III. Micro computed tomography (µCT) was used to image rhyolite blocks in 3D at Delft University of Technology, Delft, the Netherlands by Anne Pluymakers. µCT scans were acquired using a Phoenix Nanotom X-ray microtomograph with a beam energy of 180 kV and a resolution of 22.5 µm/voxel (Fig. 11d). Porosity and permeability measurements were done on flow-banded rhyolite samples by Michael J. Heap at Institut Terre et Environnement de Strasbourg, Université de Strasbourg, France. A helium pycnometer was used to measure porosity and a benchtop nitrogen permeameter was used to measure permeability. More details of µCT and porosity/permeability methods can be found in Paper II.
Figure 11. Texture and chemistry of fracture bands. a. BSE image of a large fracture with branching smaller fracture. Black is void, grey is silicate minerals, white is Fe-rich minerals. b. µXRF element abundance map of Y on three samples; c. EDS element distribution map of Al; d. slice of µCT scan showing the interior of fracture banded rhyolite. Greyscale same as BSE image.
Torsion experiments

A Paterson-type torsion apparatus was used at Institute de Sciences et Terre d’Orléans (ISTO) in Orléans, France. Natural rhyolite was cored, trimmed, and polished in order to impart simple shear in the form of controlled torsion. The sample was heated to reach partial melting, then temperature was lowered to reach a target apparent viscosity before deformation commenced. Torsion was applied at a constant twist-rate by the external torsion motor, and torque on the sample was measured by the internal load cell (Fig. 12). Subsequent processing of the output data allowed for calculation of apparent viscosity, stress, strain rate, and strain of the sample. Details are found in Paper IV.

Figure 12. Schematic drawing of a Paterson-type torsion apparatus. Modified from Paterson & Olgaard (2000). Photograph of the sample assembly column with HTHP-stable materials on either side of the rhyolite sample.
Additional methods used in the project

Anisotropy of magnetic susceptibility (AMS) was used in **Paper I** as a proxy for magmatic fabric. A separate field campaign was conducted for sample collection by Tobias Mattsson, who carried out measurements along with William McCarthy at the University of St Andrews in Scotland. Additionally, at the University of St Andrews, cathodoluminescence (CL) images of quartz were acquired by a JEOL JXA isp-100 electron microprobe analyzer with a CLi detector in 5120 x 3840 resolution. A 3D model of the Sandfell laccolith was created in the Petroleum Experts MOVE v2019.1 software, to visualize and process structural data collected during field mapping. The MOVE software along with the Stereonet 11 program (Allmendinger et al., 2011; Cardozo & Allmendinger, 2012) were used to create the stereographic projections. Image analysis was done on BSE images with the ImageJ program.
Paper I: Field mapping

The main focus of this study was to map the distribution of deformation features at every accessible outcrop on the main body of the Sandfell laccolith. Through extensive field mapping and photography, we identified five different categories of deformation: 1. flow banding, 2. vertically elongated pores within flow bands, 3. small fracture bands (<5 cm thick or one fracture set), 4. large fracture bands (>5 cm thick or >1 fracture set), and 5. Breccia (Fig. 13).

Stage 1 flow bands are defined by an increased porosity and/or crystallinity with respect to the interlayered coherent rhyolite. Flow bands have a tan weathering color in contrast to the cool grey of coherent rhyolite (Fig. 13a,b). The elongated pores in Stage 2 are confined to flow bands, irregularly shaped and spaced, and are <1 cm long in cross section (Fig. 13c). The elongate pores in Stage 2 form channels when exposed in plan view (Fig. 13d), and so we term them ‘pore channels.’ Stages 1 and 2 are interpreted to be viscous-dominated features.

Stage 3 marks the onset of dominantly brittle deformation within the magma. Fractures within fracture bands are more planar, sharp-tipped, and remarkably evenly spaced and sized compared to Stage 2 features (Fig. 13e-g). Fractures terminate along upper and lower boundaries consistently, where no visible change in the groundmass is observed. The differences between Stages 3 and 4 are subtle: sometimes a single-orientation fracture band exists that’s 15 cm thick (Fig. 13h), and sometimes a multi-set fracture band exists that’s 3 cm thick (Fig. 13i). We therefore categorized ‘large’ fracture bands...
(Stage 4) as being >5 cm thick or containing >1 fracture set, since both cases would be evidence of a higher degree of deformation than small, single set fracture bands. The final Stage 5 describes outcrops with more fractured rock than coherent (Fig. 13k-m), as a result of the abundance of similarly-oriented fracture bands or brittle deformation preserved in random angular clasts resembling cataclasite.

Figure 13. Examples of deformation features in outcrop. a, b. porous flow bands; c, d. pore channels; e-g small fracture bands; h-j. large fracture bands; k-m. breccia.
We categorized each documented outcrop by its deformation stage and assigned it a corresponding color. We plotted the dots on a map of the Sandfell laccolith to represent the deformation distribution. (Fig. 14a) The concentration of dominantly-brittle deformation aligns with abrupt changes in magnetic fabric, as shown by the AMS results (arrows in Fig. 14a). Such abrupt magnetic fabric orientations are interpreted to be caused by strain partitioning. In order for the AMS fabrics to be preserved, deformation must have taken place at temperatures >580 °C, which is the blocking temperature of the magnetic minerals. We therefore interpret the different deformation stages as records of laccolith emplacement.

The mapped distribution of the five stages sheds light on the emplacement history of the main body of Sandfell. As shown by AMS results, areas of intense brittle deformation are associated with high degrees of shear recorded in the magnetic fabric of the magma. The combination of these two datasets reveals circumferential shear zones analogous to the mapped punch fault on the northern margin (Fig. 14a). We interpret these as early punch faults; absence of overlying host rock and its orientation leaves us to interpret the magmatic deformation independently. However, we confidently argue that punch faults similar to the north margin were developing higher up along the laccolith flanks, forming what we describe as a ‘tiered wedding cake’ model (Fig. 14b, c).

We envisage that stress applied by intruding magma initiated the onset of brittle fracture in the microcrystalline rhyolite, which localized in structurally weak areas (earlier shear zones: porous flow bands and pore channels, Stages 1 & 2). This resulted in the small fracture bands (Stage 3). From that point, the fracture bands were structurally weaker than the surrounding coherent rhyolite, and so further localized deformation. If the stress field remained dominantly compressive, the tensile fractures propagated vertically and formed large, single-orientation fracture bands. If the stress field shifted from earlier conditions, a new fracture set would be overprinted on the first fracture set. In both cases, continued applied stress from magma intrusion from below and the rigid host rock above further broke the sub-solidus rhyolite. Areas of highest stress localization resulted in the continued brittle deformation until the rhyolite was brecciated.

The increase of pore size from Stages 1–4 implies an increase in magma permeability. Moreover, the growth and linkage of fracture bands from Stages 3–5 would have formed an interconnected fracture network. This leads us to conclude that the Sandfell laccolith (and other fracture-banded magma bodies) have high outgassing potential associated with the development of brittle deformation.
Figure 14. Conceptual model of the growth of the Sandfell laccolith. a. compiling of field mapping and AMS data, with highlighted areas of high shear (dark pink) and low shear (light pink); b. schematic drawing of laccolith inflation and associated magmatic deformation features; c. virtual outcrop of the Sandfell laccolith with shear zones from (a) overlain.

**Paper II: Microstructures**

We collected samples containing the five deformation stages described in Paper I with the intent to closely analyze the microstructures, aiming to better understand the mechanisms behind their formation. Thin section preparation and core drilling were only feasible on Stages 1–3, so we focused on the microstructures of those stages: porous flow bands, pore channels, and small fracture bands.
Mineralogy of the rhyolite consists of mm-scale plagioclase phenocrysts in a groundmass of alkali feldspar microlites and poikilitic quartz (crystals that grew around microlites). Between microlites is a fourth phase with a darker greyscale in SEM than the other phases, but couldn’t be adequately chemically analyzed because the EMP beam has a larger diameter than the phase exposure. Few vesicles are preserved in the analyzed thin sections, but are identified by their circular shape and smooth walls. The majority of the pores within the flow bands have an approximate aspect ratio \( R \) of \( l/w \approx 1 \), but their appearance is far less circular than the vesicles, and they contain rough walls due to the protrusion of microlites into the pore space (Fig. 15a). Additionally, the flow bands have a higher concentration of poikilitic quartz than the surrounding coherent rhyolite, and porosity occurs preferentially between the quartz grains (Fig. 15b).

Pore channels have a long axis of \( \approx 500 \) µm, and distinct elongate shapes with aspect ratios of \( R > 1 \) (Fig. 15c). Poikilitic quartz is also present among the pore channels, but another quartz texture becomes more common than in the flow bands: euhedral quartz crystals that protrude into the pore space and are free of microlites (Fig. 15d, e). Since the pore must have existed before the quartz grew into it uninterrupted, we term the poikilitic quartz ‘groundmass quartz’ and the euhedral quartz ‘pore-filling quartz’. CL imaging show compositional growth zones in both quartz types. We measured Ti-content in both types of quartz to perform geothermometry, and results show both crystallized at \( T = 736 \pm 20 \) °C.

Fracture bands contain pores with two discrete sides that are often planar, and have aspect ratios of \( R \gg 1 \). Because of this we call them ‘fractures’. No visible offset can be identified on either side of the fracture, and their shape is generally largest in the middle and tapers towards the tips, and so we interpret that they were formed in opening mode (tension). Fractures are the largest in size of the analyzed pores, on average \( \approx 1 \) cm in length. Fracture tips are generally forked grade into groundmass, rather than being blunt or sharp like in typical elastic fractures (Fig. 15f, g). At the tips and on the edges, microlites are suspended with the interstitial melt removed, forming a diktytaxitic texture (Fig. 15h). Various minerals fill the fractures, including Fe-rich and Mn-rich oxides and calcite. More dark grey material is present in the pore channels and fracture bands, and based on its occurrence in trace amounts between euhedral microlites and occasional micron-scale vesicles preserved, we interpret this phase to be interstitial melt (Fig. 15h).
Figure 15. Examples of magmatic deformation features in BSE images and thresholding highlighting quartz. a, b. porous flow bands. Note vesicle and developing pore channel in (a); c-e. pore channels; f-h. fractures within fracture bands. Red arrows point to melt filaments between crystals that resemble bubble walls.
We compare the described textures to experimental products of deformed magma (natural and synthetic), and reports of similar porosity in other natural settings (laccoliths and lava domes). Based on our findings, we interpret the evolution of Sandfell’s rhyolite magma to have evolved in the following way:

I. At depth, sparse plagioclase phenocrysts crystallized in a low nucleation-rate, high growth-rate event.

II. As the magma ascended, it was undercooled to such an extent that microlite crystals began to form, in a high nucleation-rate, low growth-rate event.

III. Once crystal fraction reached ~45%, the shear caused by intrusion of the original sill caused strain to localize, segregating melt from the crystal network into melt-rich shear bands.

IV. Once emplacement of the magma batch ceased, crystallization continued. The segregated melt had a higher fraction of silica, and so quartz crystallized simultaneously with the alkali feldspar microlites. The magma between the shear bands had a higher crystal fraction, and so was rheologically stiffer than the shear bands.

V. Upon the next batch of magma emplacement beneath the first sill, stress was applied from below that compressed the first sill against the host rock. This stress localized in the softer shear bands, and resulted in various deformation:

a. Low degrees of simple shear caused dilation, increasing pore space between the rigid quartz crystals as they rolled against one another (Background, Fig. 5a). This is evidenced by quartz in flow bands being lined with microlites and pores preferentially occurring between quartz grains.

b. Moderate degrees of pure shear initiated cavitation at quartz grain boundaries, propagating a ductile tear parallel to the largest principle stress direction (Background, Fig. 5b). This is evidenced by irregularly shaped and spaced elongate pores in the pore channels.

c. High degrees of pure shear drove the magma to fracture, propagating parallel to the largest principal stress direction until intersecting the stiffer magma outside of the shear band.

The mineralization within the pores (pore-filling quartz, oxides and carbonates) are evidence that magmatic fluids migrated through them at high temperatures (~730 °C for the quartz). The preserved bubbles in the fractures (Fig. 15h) is evidence for degassing associated with fracture formation. Similar textures as the ones described in this study have been observed in lava domes and laccoliths in other geologic settings, with different crystallinities and magma compositions. This implies an efficient outgassing network developed at sub-solidus conditions that was driven by viscous-brittle magma deformation.
Figure 16. Conceptual model of the formation of the fracture bands. I. Melt-rich magma with plagioclase phenocrysts ascends from depth. II. Microcrystal-content increases during ascent, and at ~50% shear drives melt segregation into flow bands. III. Continued crystallization increases the quartz crystal fraction within the melt-rich bands, and subsequent shear causes dilation. IV. Continued stress from magma batch emplacement drives the ductile shear band to cavitate. V. Brittle fractures form when strain or strain rate are higher than the strength of the magma. Porosity arrests against stronger, nearly-solid rhyolite.
**Paper III: Mineral fillings**

Many types of ore are sourced from granitic magma bodies. Metals of interest like Cu, Fe, Zn, Au, and Pt exist in trace quantities of this composition of magma, and yet somehow depart from the system to collect in high concentrations like veins. Mechanisms that can partition such high quantities of trace metals from large volumes of parent magma are keenly debated.

The suite of minerals filling the fractures of the Sandfell laccolith is unusual for an Icelandic rhyolite. There is an abundance of Fe-rich and Mn-rich minerals that yielded inconclusive identification in the EMP. Interestingly, there is also a filling phase that returned high levels of the rare-Earth elements (REE) La, Ce, and Y. To investigate further, we measured the distribution and relative abundance of elements on polished thin sections (EDS) and unpolished rock slabs (µXRF). We also scanned the rock slabs in 3D using µCT, to visualize the distribution of fillings. EDS maps measured major elements: Si, Al, Mg, Na, Ti, K, Fe, Ca, P, and Cr. µXRF heat maps were able to measure trace elements in addition to the major elements.
Results showed that there is enrichment of La and Y in the fracture fillings, in both polished thin sections and unpolished rock slabs, ruling out any artefact of sample preparation. Additionally, a halo of Fe depletion surrounds each fracture, which results in a tan color in hand sample. No enrichment of elements associated with hydrothermal alteration products was observed surrounding the fracture, like Al, K, Na or Si. µCT results show randomly distributed filling phases throughout the whole volume of the fracture, and calculated ~80% of the pore volume is filled while ~20% remains open. Small, completely enclosed fractures were imaged in µCT that had mineral fillings. Permeability of unfractured, undeformed rhyolite was below the detection limit of the permeameter (<< 10⁻¹⁸ m²), which rules out the mineralization as a weathering product of surface processes.
Element transport through magma degassing is how economic elements decouple from their parent magma, to then be transported by fluids and carried off to form ore deposits. But the process by which elements in such trace quantities in the magma can concentrate enough in magmatic or hydrothermal fluids in the first place remains elusive. Here we argue that the Sandfell laccolith fracture bands have captured a snapshot of metal partitioning into the magmatic volatile phase (MVP). The drop in pressure associated with fracturing created a vacuum into which surrounding melt released MVPs, carrying with them elements that are incompatible to the crystal phases, such as Fe, Mn, and REEs. The small scale of each fracture means it didn’t have a significant surface area through which MVPs could diffuse, but the abundance of fractures within one fracture band, compounded with the abundance of fracture bands in the laccolith, means a significant volume of magma was affected by this degassing mechanism.

Once the metals had escaped the melt phase, they were either carried out of the magma body through the permeable network created by interlinking fracture bands, or remain trapped and slowly cooled and precipitated into what we observed in our samples. A likely cause for the preservation of the deformation features at the Sandfell laccolith is the low water content of the magma (estimated to be 1.77 wt% by using Krafla rhyolite as a proxy). In more hydrous magmas, sustained release of hydrothermal fluids would greatly alter the rock through which they travel, to the point of destroying evidence of discrete fracturing. We argue that metals decoupling from melt through magma fracturing may be taking place anywhere that silicic magma is moving through the crust, which may contribute to the concentration of metals required before ore deposit formation.
Figure 18. Conceptual model for metal partitioning into magmatic fractures.
Paper IV: Torsion experiments

Deformation experiments have explored the rheology of natural and synthetic magmas at many compositions, crystal and bubble fractions, and deformation types. Synthetic magma is appealing because it ensures control over chemical processes, composition, and distribution of particle size and shape. However, comparing results from controlled conditions to those using natural material is beneficial to maintain relevance. In this paper, we deform natural rhyolite from the Sandfell laccolith under simple shear at magmatic conditions in an attempt to create tensile fractures. An array of tensile fractures was created in synthetic bubble-bearing rhyolite using a Paterson-type torsion apparatus that closely resembled the fracture bands at the Sandfell laccolith. We used the study of Kushnir et al. (2017) as a model to apply their method to natural material, with the aim to create the same brittle features.

Samples were cored with a 14.99 mm inner-diameter drill bit out of a block of rhyolite devoid of any apparent deformation features (i.e., as homogenous as possible). The cored samples were trimmed to a length of ~15 mm and ~7 mm, to attain a 1:1 and 1:2 aspect ratio (which would affect the applied strain and strain rate). The ends were polished to 15 µm to have perfect contact with the materials that would transmit the applied torsion. Once assembled in the Paterson press, the system was pressurized to 100 MPa to simulate upper crustal conditions (equivalent depth ~5 km) and heated to 1150 °C and held for 1 hour to melt the sample. After the heating step, temperature was decreased to reach a target melt viscosity of ~10^{10} or ~10^{11} Pas before deformation.

Figure 19. BSE images of the starting material for Paterson torsion deformation. a. Natural, undeformed rhyolite. b. Rhyolite after 1 hour at the 1150 °C heating step.

We performed 9 successful experiments over the course of one month. Results showed that our starting material had a crystal content of ~26% (from SEM image analysis). Bubbles were heterogeneously distributed throughout the melt phase. Strain rates between $1.87 \times 10^{-3}$ and $2.92 \times 10^{-5}$ s^{-1} were applied at a constant twist rate, and torque on the sample was measured by the press. All experimental products exhibited viscous behavior in the mechanical data (on a whole-sample scale), but whether fracturing took place inside the
material requires further textural analyses. We converted torque to stress and viscosity through calculations explained in detail in Paper IV. In general, apparent viscosity $\eta$ decreased with increasing strain rate, and maximum stress slightly increased with increasing strain rate.

Figure 20. Textural analysis and rheology of deformed rhyolite. BSE image of deformed sample, red arrows point to relaxed bubbles (circular), yellow arrows point to sheared bubbles (ellipsoidal). Shape analysis of the three phases is on the right. b. Relative viscosity of experimental results with crystal fraction of 0.26 (measured solids from image analysis) and 0.42 (tracing rigid microlite clusters, in c). Results are plotted against rheological models of crystal suspensions at different strain rates (Frontoni et al., 2022).

Preliminary textural analyses have been done through SEM imaging and $\mu$CT of a 3 mm core. Results reveal inhomogeneous strain distribution within the 3-phase magma, primarily localizing in the melt that flowed around clusters of solid microlites (Fig. 19). Bubbles suspended in the melt range from highly deformed (elongate) to nearly relaxed (circular). We measured glass compositions of the melt phase and calculated its equivalent liquid viscosity ($\eta_l$), and determined the magma’s relative viscosity ($\eta_r = \eta / \eta_l$). We compared our rheological data with models of crystal suspensions, and found our $\eta_r$ values were higher than the models predict for a crystal content of 26%. We then traced the clusters of microlites around which the melt was flowing, since they apparently acted as rigid bodies interrupting flow. We calculated the area of
BSE images that microlite clusters covered to be, on average, 42%. This new ‘crystal content’ brought our data closer to projected $\eta_r$ values of the rheological models. We attribute the remaining discrepancy on the presence of bubbles in the system, which are known to affect apparent viscosity of crystal suspensions by either lubricating the system (shear-thinning) or acting as rigid particles (shear-thickening). Further analysis is required to better constrain the rheological parameters at play in these conditions.

Returning to the original aim of the study, we hypothesize that we failed to create fractures in the rhyolite because we ran the experiments at $\eta = 10^{10}$ Pas instead of $\eta_l = 10^{10}$ Pas. Fractures initiate within the melt phase even in crystal suspensions, and so at conditions favorable for magma failure $\eta$ must be higher than $10^{10}$ Pas. With this in mind, our future work on creating fractures in the natural rhyolite of the Sandfell laccolith includes:

I. Lowering the initial heating step to increase crystal fraction. This will create a more crystal-rich magma that’s analogous to the rheology we hypothesize created the deformation features preserved at Sandfell.

II. Lowering deformation temperature. This will increase the melt viscosity, which will fracture at lower strain rates compared to lower viscosity melt.

III. Increasing finite strain. Most of our experiments were deformed until strain values of $<1$ before the torsion system started to become unstable. This is likely because we approached the operational limits of the Paterson press with high strain rates, high temperature, and low pressure. If we employ the previous two conditions, temperature will be lower (and strain rates will also likely be lower), which will allow for longer duration of deformation. This will also allow the material to reorganize sufficiently as a response to shear, and develop strain localization textures.

Tensile fracture bands in shallow silicic magma has the potential to outgas significant volumes of the magma body. Understanding the mechanics behind how they form will contribute to the wider understanding of silicic and crystal-rich magmatic settings.
Conclusions and Outlook

What’s under the road?

—Taylor Witcher, age 4

This thesis presents a thorough investigation of magmatic deformation in the Sandfell laccolith, Eastern Iceland, and in deformation experiments. The results from the four chapters are applicable to the wider context of shallow magmatic systems, in that silicic magma is a dynamic material, the behavior of which is controlled by the feedback between emplacement, deformation, and rheology.

How does silicic magma deform during ascent and emplacement?

Magma is not a passive fluid. It is a complex material covering a wide range of physical properties based on composition, temperature, crystallinity, and volatile content. The interplay between all three phase components (silicate melt, crystals and volatile-filled bubbles) creates local variations in deformation, which contribute to the bulk response to stress but cannot always be identified through direct observation. Eruptive products are rapidly quenched and delivered directly to the Earth’s surface from within the magmatic plumbing system. So it is no surprise that the textures in eruptive products are snapshots of the magma’s final moments. What I offer in this thesis is the intrusive equivalent, 0.57 km$^3$ of magma that remained in the crust, and still retained emplacement-related deformation features on the millimeter to decimeter scale. Hence, the textures of the Sandfell rhyolite are proof that silicic magma has the capacity for strain memory, preserving a record of deformation in the magmatic state.

The reporting of similar textures in lava domes and laccoliths further support the significance of brittle deformation in crystal-rich silicic magma. Based on observations and deformation experimental results, this is how I envisage the fracture band formation begins:

I. Melt-dominated magma (<45-50% crystals overall) ascends and groundmass crystallization commences. As the crystal fraction...
increases to ~50%, shear localizes along weak planes and segregates melt from the crystalline framework (flow banding).

II. Crystallization continues throughout the flow-banded magma, but the rheological contrast between flow bands persists due to the offset in crystal content. Strain partitions preferentially into the low-viscosity melt-rich flow bands.

III. Subsequent emplacement of new magma batches applies stress to the previously emplaced magma. Once melt-rich flow bands reach a crystal fraction of >50%, deformation manifests viscously or brittlely, depending on sense of shear, strain rate, and total strain:
   a. Low degrees of simple shear deformation can result in dilation bands, increasing porosity and drawing in residual melt.
   b. Moderate degrees of pure shear initiates cavitation, propagating ductile tears vertically, parallel to the largest principle stress direction and opening parallel to the lowest stress direction.
   c. High degrees of pure shear cause brittle failure and produce fractures, which rapidly draw in interstitial melt and volatiles along with any remaining incompatible elements.

IV. Fracturing and cavitation cease at the boundary of rheologically stiff crystalline rhyolite (> 60–70% crystals), where the applied stress is high enough for the more melt-rich bands to fail, but lower than the strength of the more solid material. Fractures propagate vertically and join with over- and underlying bands, sometimes to the point of total brecciation.

How does magma rheology affect magma degassing and outgassing?

The presence of vesicles, though scarce, shows that the Sandfell rhyolite degassed in part through bubble nucleation and growth. The scarcity of bubbles testifies to the low magma volatile content. Hence, all other porosity present at the Sandfell laccolith was deformation-induced.

The results presented in this thesis delineate the conditions under which deformation-induced magma outgassing will take place: As shown in Paper IV, magma will not fracture if conditions are not favorable. Rheology directly affects the style of magma deformation. The porosity at Sandfell developed at ~500 m depth, and quartz crystals grew into the open pores around 730 °C. Such conditions are typical for the sub-volcanic regime. And deformation is a natural side effect of magma moving through the Earth’s crust.

Deformation-induced porosity then controls magma de- and outgassing: Preserved melt filaments stretching across the width of fractures (resembling bubble walls) show that the expansion of the pores drew in melt, or drove volatile exsolution from interstitial melt. The mineral filling within the fractures are evidence that fluids were migrating through the pathways provided by the porosity network, even at high temperatures (Papers II & III).
Reworked sedimentary textures of groundmass and oxides in the fracture fillings and pore channels suggest high-energy events (‘explosions’) took place on a micro-scale, potentially equivalent to microscopic tuffisites. Hence, local decreases in pressure associated with fracturing is enough to drive volatile exsolution directly into an interconnected magmatic fracture network. Therefore, the pervasive, small-scale fracturing is an efficient mechanism to outgas a large volume of magma moving in the upper Earth’s crust, which has the potential to prevent explosive volcanic eruptions. In fact, the deformation-induced outgassing of magma summarized in this thesis interrogates a significantly higher magma volume than shear-induced fracturing along a conduit wall, and should be considered as an additional outgassing mechanism in silicic magmatic settings.

Even after magma supply ceases, the permeable network formed by fracture banding can lead magmatic fluids from the inner confines of the magma out towards the host rock contact. Together with the partitioning of incompatible elements from the magma (Paper III), the permeable network creates the conditions for element transport towards locations where precipitation produces mineral deposits.

Permeability may even be long lasting. Galland et al. (2023) report an exposed laccolith with oil seeps exploiting the permeable magmatic fracture bands. Moreover, magmatic fracture banding has implications for geothermal fluid system development and may explain why cryptodomes are preferential sites for the formation of geothermal systems (Ishikawa, 1970).

How does magma rheology affect the style of magma emplacement, and a magma’s explosive potential?
The findings of this thesis demonstrate that processes taking place on the micro-scale (Paper II) govern the emplacement dynamics of entire magmatic intrusions (Paper I). In case of the Sandfell laccolith, the non-Newtonian magma rheology controlled the laccolith geometry: instead of continuing propagation as flat sills, magma rheology arrested the magma at the sill edges and instead forced vertical inflation. In turn, stress resulting from compression of the magma against the host rock during inflation overcame the strength of the weaker shear bands in the magma, which weakened the magma further. Continued shearing reduced areas of the rhyolite to breccia, and eventually the host rock failed at the north margin creating a steep, ‘punched’ laccolith geometry. Hence, host rock properties are not the only controls on the geometry of a magma body.

Given that explosive, ash-generating eruptions are driven by fragmentation caused by bubble expansion, low-volatile (or ‘dry’) magmas have a lower risk of explosively erupting. However, lava dome collapse is another mechanism by which ash is generated in locally hazardous block-and-ash flows. Since fracture bands have been described in lava domes (Smith et al., 2001), they
likely affect the structural integrity of lava domes, and can form weak zones that may localize failure.

In this thesis, I only touched upon the process and significance of fracture-band development. To sum up the work in one sentence: sub-solidus ‘ductile’ magma has the capacity to outgas by deformation-induced viscous and brittle porosity development in the shallow crust. Future work entails experimentally constraining rheological conditions that recreate the textures observed in nature.

**Figure 21.** Influence of physical and chemical parameters during silicic magma intrusion, based on the conclusions of this thesis. Aerial photo of the Sandfell laccolith from Landmælingar Íslands.

Här presenterar jag både experiment och en fallstudie av en stelnad kiselhaltig magmakammare på östra Island: Sandfell-lakoliten. De texturer som bevarats i den stelnade magman inkluderar bandfrakturer av cm till dm-skala organise-rade i band som böcker på en hylla. När de först observerades föreslogs det att sprickbanden bildades när magman fortfarande var varm och flytande. I detta examensarbete har jag därför undersökt följande forskningsfrågor:

Hur bildades brottbanden i Sandfell? Vad var magmans reologi - ren smälta? När man solid?
Varför är frakturbanden så enhetligt organiserade? Vad styrde deras begräns-nings till band?
Vilken roll spelade de i tillväxten av Sandfell-lakoliten?
Var de en tryckventil som tillåt gas att fly från magman, tillräckligt för att undvika ett utbrott?


Texturer som de på Sandfell laccolith har hittats på andra platser runt om i världen, vilket betyder att de inte är unika för Sandfell. Mekanismerna för magmasprickning är viktiga för att bedöma risken för explosiva vulkanutbrott, förstå hur värdefulla element utvinns ur magma, hur geotermiska system bildas och hur grundvatten rör sig långt efter att magman har stelnat.
A tale is but half told when only one person tells it.

— Jafnan er hálfsögd, Saga ef einn segir
Icelandic proverb

What a wonderful five years this has been. I could write another thesis acknowledging all the support I’ve gotten, but in the interest of the reader’s time I’ll do my best to summarize.

My deepest gratitude goes to my main supervisor Prof. Steffi Burchardt. You have been a shining model of leadership, curiosity, ambition, adventure, and fascination with all things magma. In this industry, PhD supervisors can sometimes have unsavory reputations, which makes my experience as your student even more extraordinary. Your prioritization of our one-on-one weekly meetings, manuscript feedback, and most importantly mental health through encouragement of breaks, holidays and flexible work hours has made my PhD journey not only successful but downright enjoyable. You’ve always been a human first and supervisor second, and for that I am forever grateful.

In the last five years you have enabled me to grow more confident both in my research abilities and myself in general. You have talked me off cliffs of anxiety, repeatedly reassured me of my capabilities, and introduced me to the Swedish cultural phenomenon Melodifestivalen. I will forever cherish our cozy knitting sessions in multiple countries, spontaneous skinny dips at every opportunity, and rewardingly miserable workouts. You have been an outstanding mentor and friend, and it has been an honor and a privilege to work, travel, hike, scramble, haul rocks, zoom, eat, drink, cry, learn and laugh with you.

To my second supervisor, Prof. Mike Heap, thank you for thinking of me when this project was crystallizing. Though ours was a long-distance relationship, having you on the team has been crucial and vastly rewarding. You also showed exceptional accessibility not matched by many other supervisors, and took your place as cheerleading captain when things got bleak. In all seriousness, your words of encouragement were lifelines when the manuscripts were piling up and the publication list remained empty. Your coaching on technical
writing has been invaluable, as well as your expertise of experimental environments and rock mechanics. Thanks also for letting me stay in your flat in the early days when it was 40°C in Strasbourg, and making me dinner while watching Super Troopers. You’re the man.

Thanks also to my third supervisor, Dr Bjarne Almqvist. While you were more hands-off as the project headed in a direction outside of your expertise, you always showed up as an advocate for me at every opportunity. You also provided the link to the Orléans group, which resulted in an essential chapter in my thesis. Thank you for the support and good vibes throughout the years.

I’d like to thank my many collaborators: Dr Alexandra Kushnir, thank you for stepping up as an honorary supervisor, and for your time and patience chatting over zoom trying to work out strain calculations. Your guidance through the Paterson journey was essential and I’m lucky to have you on the team. Drs Laurent Arbaret and Rémi Champallier at ISTO in Orléans, France, thank you for hosting me in March 2022 and dedicating your time to rapid-fire Paterson tests and subsequent sample analysis. It was a pleasure working with you. Dr Tobias Schmiedel, thank you for taking me under your wing at the start of the project and for remaining my academic big brother even after you moved to Delft. And thanks for connecting me with Dr Johan Lissenberg at a virtual EGU, who agreed to collaborate and produced some beautiful EDS scans of our thin sections. Dr Anne Pluymakers, thank you for the mesmerizing µCT scans of our fractures and steady supply of Dutch goodies. Dr Tobias Mattsson, thank you for laying the foundation for my work at Sandfell (sorry—the Sandfell laccolith), and for your contributions to the fracture band story. Thanks also for stepping up with pore shape analysis and magnetic fabric analysis; together we’re really patching the Sandfell picture into focus. Dr Peter Lazor, thank you for the ISP signatures, contract extensions, and Raman spectra. Dr Pim Kaskes in Belgium, thank you for the countless zoom meetings regarding the µXRF data that blew all our minds. And finally, to ‘the ore guys’ Drs Iain Pitcairn and Shaun Barker, thank you for walking me through basic geochemistry with patience, and reassuring me that what we’ve found is indeed cool.

To my international colleagues, thank you for discussions in the field, at conferences, and in the virtual realm: Hugh T., Holly U., Janine K., Kat, Caitlin, Fabian W., Dave M., Jenny S., Catherine A., Sandy C., Antony L., Adrian H., Ben K., Basil T.. Thank you Otterborg, Liljewalchs, and Ana Maria Lunden stipends for funding field excursions and conference attendances. Thank you to the Knut and Alice Wallenberg Foundation for funding the whole project.
Geocentrum has become a home away from home, and the community of expatriates has enriched daily life in Uppsala. To Orlando, Sonja, Thorben, Paula, Laura, Sebastian, Madeleine, Ben, Graham, Kristina, Manos, Michael, Andra, Alex H., Moho-sen, Christian, Tatiana, Pauline, Karin, Abi, Jarek, Julia, Daniel, Rémi, Alizée, Lucia, Christoffer, Chiara, Joshi, Braden, Pablo, and everyone else who shared lunch, fika, and/or beers with me over the years, thank you for your kindness. To the HR department, Fati
ma, Veronica, Tora, and Barbro, thank you for answering my Sweden-logistics questions, helping me with contract extensions and for reimbursing my travel expenses. Many thanks go to Lofi Girl on YouTube—your ‘beats to relax/study to’ was invaluable company during the many hours of writing.

My close friends in Uppsala, what a weird five years it’s been :) Swedish winters and pandemics did their best to dampen our spirits, and without all of you it would have been unbearable. To George, Leo, Faranak, Meghdad, Elisa, Sami, Alberto, Valentina, Zibi, Lea, Emma, Ginho, Boris, Caro, Yunus, and Gabriella, thank you all for putting up with my stupid jokes and forced costume parties. You’re all wonderful and I hope to see you someday in the western US or beyond.

To the Källsens, my ‘Swedish family,’ Pål, Malin, Svante, Björn, Nana, Gyoza and especially Sushi, thank you for inviting us into your lives and sharing your home with us. Thank you for the sauna, skis, garden, coffee mugs, firewood, and excellent company during the last three years. You’re a very cool family and I hope we stay in touch.

Home family! Thank you for enduring five (more) years of long distance while I studied rocks in Europe. Facetime and messaging apps have had great effect in closing the 8–9 hour time gap, but it’s the effort you’ve put in to not forgetting me that will get singing praise. Thank you Cory & Noah, Melanie, Diego and Flynn for the postcards, random texts, and phone calls. They’ve meant more than you’ll ever know. Molly, Jake, Anita, Jim, and Wiley: thank you for being my people and bringing joy to every morning when I woke up to a Wiley video. Grandma and Grandpa Witcher—Darleen and Butch—thank you for Wednesday yoga class and Facetime catch-ups. Grandma and Grandpa Grayson—Linda and Bill—thank you for seasonal garden photos and relentless holiday & birthday cards. Jeff and Garth, thank you for gifting us your skymiles and providing an oasis in California. Jack and Lily, my little tiny baby siblings, thank you for the texts and calls as you’ve navigated through your teenage years. I’ve thought about both of you every day, and I’m looking forward to being a more actively present big sister. Mom and Dad, what words can I possibly say to express my gratitude to you? Thank you for everything. For believing I could get a PhD long before I did. For encouraging me to take leaps even when they took me to far-off lands. Thank you.
Finally, to Adam. Thank you for following me to Sweden after two months of dating. Thank you for wanting to stay. Thank you for building a life for yourself and being so flexible, patient, and adaptable. Thank you for traveling with me, staying in with me, teaching me to flyfish, picking mushrooms with me, changing your insta to @spoonadddy_spoons, playing cards and video games and building fires and surprise birthday parties. Thank you for the relentless, unwavering support. You’re the light of my life. Thank you for being here with me, through all of it.
Wanna get married?


Acta Universitatis Upsaliensis

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