When the glacier left the volcano: Behaviour and fate of glaciovolcanic glass in different planetary environments

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Glacial ice and volcanic sands meet at the beach near the iceberg lake Jökulsárlón in South-West Iceland.
Chapter 1
Under the glacier

1. Introduction

Parallels between landscapes in Iceland and those at the surface of planet Mars allow studies of terrestrial landscape processes to be used for characterising Martian landform genetics. One of those landscape parallels is governed by magma-ice interactions that occur during volcanic eruptions underneath ice deposits. The materials created during such eruptions are characteristic for their formation environment and Icelandic volcanic glasses are therefore a unique Mars analogue material for use in process-oriented studies. However, substantial work on the environmental dynamics of these eruption products are lacking for properly understanding erosion, mobility and modification rates on Mars. This dissertation will therefore focus on the post-eruptive transport and the physical modification of glassy eruption products in different planetary environments.

The role of volcano-ice interactions in the formation of fragmental volcanic glass first became apparent in science after the Scottish Geographical Magazine published an article on the topic in 1900. In it, Helgi Pjetursson (1900)\(^1\) accounts his field studies in Iceland during which he discovered “that some rocks of the ‘tuff- and breccia formation’ may be formed due to the direct interaction of volcanic and glacial forces”. Later work by Peacock (1926) showed that basaltic glasses in these breccias were primarily formed by volcanic activity underneath ice sheets or inside lakes. With their observations, Pjetursson and Peacock were among the first to realise that magma-ice contact leads to the formation of a unique type of glassy breccia. The intercalation of these materials in larger landscape features such as steep-sided, table-shaped mountains helped to bolster the hypothesis that their origin was mainly related to subglacial volcanism and the ensuing magma-ice interactions (van Bemmelen and Rutten, 1955). Although the general characteristics of sub-ice and sub-marine eruptions are similar, confinement of eruptions by an ice body distinguishes these eruptions from sub-marine variants in terms of drainage and access of water to the volcanic vent (Moore and Calk, 1991;...

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\(^1\) Helgi Pjetursson (1872-1949) was the first Icelandic scholar to graduate with a PhD in Geology in 1905 and published extensively on the geology of Iceland between 1898-1910.
Smellie 2006). The discovery that pillow lavas are formed during the first eruption stage (Einarsson, 1960) and other units during successive stages (Jones, 1969, 1970) increased the understanding of basaltic sub-ice volcanism in the Icelandic landscape. Studies of rhyolitic subglacial volcanism are scarcer, yet have steadily increased over the past decade (McGarvie, 2009). Numerous studies have since given insight in the similarities and differences between basaltic (e.g. Furnes, 1978; Smellie and Skilling, 1994; Bourgeois et al., 1998; Wilson and Head, 2002; Tuffen, 2007; Smellie, 2008; Skilling, 2009) and rhyolitic subglacial volcanism (e.g. Furnes et al., 1980; Tuffen et al., 2001, 2002a, 2002b; McGarvie, 2009; McGarvie et al., 2006, 2007; Flude et al., 2008). The current state of art focuses on the interrelationships of geochemical and volatile composition with the confining and glaciostatic (or ice overburden) pressure of the overlying ice-mass for reconstructing eruption conditions and past glacial thicknesses (Dixon et al., 2002; Denton et al., 2009; Tuffen et al., 2010, Owen et al., 2012).

This first chapter sets out to review the geological and geomorphological developments reported in studies of subglacial volcanism; it explores the eruption types, resulting landforms and properties of materials in Iceland (paragraph 2). The focus is then shifted to Mars to show that similar glaciovolcanic eruptions occurred throughout the geologic history of the red planet and played an important role in its surface development (paragraph 3). These paragraphs highlight the similarities between eruption styles and the formation of glassy materials that are nowadays being widely observed on both planets. Such parallels justify the use of landforms and materials in Iceland as analogues for field and experimental studies to understand the landform genetics on Mars. With the planetary context set, this chapter continues with defining the relevant research questions and the structure of this dissertation (paragraph 4) and closes with a detailed description of the selected field site in Iceland (paragraph 5).

2. Tuyas, tindars and hyaloclastites

Recognising subglacial volcanic landforms can be quite straightforward in the Icelandic landscape (Fig. 1). Emergent subglacial volcanoes have developed into characteristic table-shaped mountains known as tuyas by the melting of magma upward to the ice-atmosphere interface of the glacier. They are by far the most visual illustration of basaltic and rhyolitic eruptions below ice masses during past glacierization of the Icelandic rift zones. Their formation usually starts as a fissure eruption that can develop edifices of considerable dimensions. The largest monogenetic tuya in Iceland (formed during one, possibly multi-phased, eruption) is Eiríksjökull, which has a 77 km² footprint and an average height of 1 km (Jakobsson and Gudmundsson, 2008). Although tuyas can be formed over the course of several eruptions such as the Herðubreið tuya (Werner et al., 1996; Werner and Schminke, 1999), their structure always consists of four basic units. A pedestal of (i.) pillow lavas is commonly found at the base, followed by (ii.) layers of glassy breccias and (iii.) a subaerial cap-rock formed when the eruption breached the air interface. These three units are often dissected by (iv.) irregular lava intrusions.

The formation of bedded layers of glassy breccias, also known as hyaloclastite, is principally driven by the explosive fragmentation and rapid quenching (thermal contraction and shattering) when erupting magma mixes with meltwater from the surrounding ice. While the historical definitions of hyaloclastite and the Icelandic equivalent móberg have been predominantly attributed to describing mafic volcanic glasses (Kjartansson, 1943; Fisher and Schmincke, 1984), the term glaciovolcanic glass is used in this dissertation in parallel as a wider
definition to cover all geochemical variations of glass formed during volcano-ice interactions. In the case of basaltic glass the hydrothermal instability makes it easily chemically weathered, which leads to the formation of a palagonite coating on the exterior (Nesbitt and Young, 1984; Gislason and Oelkers, 2003). This coating or ‘gel’ eventually cements the granular glass into a more cohesive rock compared to the initially loose granular glass. Further chemical weathering of palagonite rinds leads to the formation of secondary clay minerals that in turn causes consolidation and strengthening of these volcanic glass deposits as a result of the filling of vesicles and interparticle pore spaces (Frolava, 2008). Estimates from the Gjálp eruption in 2001 suggest that the entire consolidation process can occur within the first 1-2 years after the eruption (Jakobsson and Gudmundsson, 2008; Jarosch et al., 2008). Under conditions of smaller or variable thermal gradients chemical weathering and consolidation of the outer layers of an edifice can require several thousands of years (Fisher and Schminke, 1984). Basaltic tuyas are transformed by these chemical weathering processes into consolidated formations that are able to resist much of the erosive forces from glacier flow (Jakobsson and Gudmundsson, 2008).

The resistive nature of tuyas makes them potentially powerful palaeo-climatic markers due to the relation of their shape and height with the ice body in which they were formed. The first glacial reconstructions by Walker (1965) used the maximum summit elevations to determine possible ice profiles of past ice sheets. However, recent research indicates that the use of tuyas

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**Fig. 1** - The extent of glaciovolcanic formations in Iceland. Dark grey features outline the ‘Móberg’ formation (data from: Jakobsson and Gudmundsson, 2008), adjacent lighter grey areas delineate the Icelandic rift zones (data from: Einarsson and Sæmundsson, 1987) and white regions are present-day glaciers and ice caps (data from: Ahrendt et al., 2012). The dashed area outlines the Torfajökull caldera at the transition between the Eastern Volcanic Zone (EVZ) and the Southern Flank Zone (SFZ). Other volcanic zones in the figure include the Northern (NZV), Snæfellness (SVZ), Western (WVZ) and Öræfajökull (ÖVZ) Volcanic Zones. Black triangles highlight locations of confirmed and suspected rhyolitic subglacial eruptions that are younger than 0.8 Myr (locations from: McGarvie, 2009).
in glacial reconstructions is limited to a minimum ice thickness as the cap rock unit only accurately records the height of the water-air transition zone. This level water accumulating inside the cauldron above the growing edifice was shown to be 150-200 m lower the actual thickness of the surrounding ice (Jakobsson and Gudmundsson, 2008). Detailed dating studies using cosmogenic \(^{3}\)He exposure ages have shown that many tuyas formed during the last deglaciation of Iceland (Licciardi et al., 2007). Temporal clusters of these eruptions were found to coincide with episodes of ice sheet thinning during the Bølling warming (14.5 kyr) and at the end of the Younger Dryas (11.6 kyr) (Licciardi et al., 2007). The effect of a declining ice sheet and the associated isostatic rebound leads to a 30-100 fold increase in the magma supply over a period of 1-2 kyr (Jull and McKenzie, 1996; Slater et al., 1998; Maclennan et al., 2002). The formation of large tuyas therefore benefits from this consistent and continuous volcanic activity for the upward melting through the ice (Jakobsson and Gudmundsson, 2008).

Many of the early Holocene flood lavas in Iceland have been dated to the late Pleistocene and corroborate the effects of lithosphere unloading on increased eruption rates (Jull and McKenzie, 1996; Slater et al., 1998; Maclennan et al., 2002). These feedback mechanisms imply additionally that increased levels of explosive subglacial eruptions can be expected during the next centuries as a consequence of declining ice caps from climate change in Iceland.

Signs of tuya formation have been absent in nearly all recent subglacial eruptions (Jakobsson and Gudmundsson, 2008). These eruptions shared similar eruptions stages as tuyas in the sense that they also contain basal pillow formations and bedded deposits of hyaloclastites. However, they lack the characteristics cap rock layers from the filling of the cauldron with lavas in the subaerial eruption phase (Schopka et al., 2006). Landforms created in such subglacial low-volume fissure eruptions are known as tindars and after deglaciation they are recognisable as ridges composed of hyaloclastite (Chapman et al., 2000; Jarosch et al., 2008). Tindars are especially dominant features just north and south of the present ice margin of the Vatnajökull ice cap (Fig. 1) in the in the Northern Volcanic Zone and Eastern Volcanic Zone (Vilmundardóttir, 1997; Jakobsson and Gudmundsson, 2008).

### 2.1 Recent Icelandic subglacial eruptions

Many eruptions have occurred over the past few decades (Thodarson and Larsen, 2007) and recent examples of subglacial volcanism in Iceland include the eruptions of Eyjafjallajökull in 2010 and Grímsvötn in 2011. Eyjafjallajökull illustrated to the world that subglacial eruptions are still common in Iceland. This particular eruption was intensively studied due to well-developed ground and airborne research infrastructures and this led to various insights into the evolution of the subglacial eruption (Sigmundsson et al., 2010; Matoza et al., 2011; Borisova et al., 2012; Magnusson et al., 2012). The Eyjafjallajökull eruption also clearly illustrated the effects of the eruption environment on the volcaniclastic material properties of the formed eruption products (Donnovan and Oppenheimer, 2011; Gislason et al., 2011; Edwards et al., 2012). The first phase of the eruption sequence started with a subaerial eruption at the Fimmvörðuháls mountain pass from March to April 2010. This eruption formed the Goðahraun lava field with two scoria and spatter cones known by the names Magni and Móði (Edwards et al., 2012). Direct contact of lava with local snow and ice during this eruption was incomparable to the scale of magma-ice interactions of the subsequent eruption-phase. The dike intrusion in the subsurface extended during the eruption at Fimmvörðuháls and formed an eruption conduit underneath the Eyjafjallajökull ice cap. The resulting subglacial eruption had a Volcanic Explosivity Index (VEI) of 4 and started in April with activity lasting until September 2010 (Sigmundsson et al., 2010). Rapid quenching of magma by ice and
abundant meltwater caused considerable spalling and shattering of the magma (Magnússon et al., 2012). Fine glassy ashes were widely distributed across Iceland and carried aloft into European air space where it caused exceptional disruptions of air traffic (Gertisser, 2010). The eruptions at Fimmvörðuháls and under the Eyjafjallajökull glacier were roughly comparable in geochemical composition, yet their eruption environments differed significantly. The substantial differences between the eruption products are illustrated by rock and ash samples collected from the two eruptions (Fig. 2). The high explosivity of subglacial eruptions also makes these forms of eruptions inherently dangerous. The ash production during the magma-

Fig. 2 - Comparison of the material properties of subglacial and subaerial eruption products from the 2010 volcanic eruptions in Iceland. Although the magmatic composition of both eruption products was roughly similar, the scale and properties of the formed materials are clearly different due to the eruption environments. Scoria from the Magni crater (a) illustrates the type of material formed by a subaerial eruption. Ash from the subglacial Eyjafjallajökull eruption (b) shows the end-product of explosive fragmentation and rapid quenching. Scoria samples were collected by the author in 2011 while ash samples were collected by L. Kerstens near Hvosvöller and Mulakot (along the F261 road) four months after the main eruption phase of the Eyjafjallajökull eruption.
ice interactions of the Eyjafjallajökull eruption had detrimental effects on the habitability of the ash-fall affected areas due to the increase in health (Gislason et al., 2011; Gudmundsson, 2011; Carlsen et al., 2012) and environmental hazards (Colette et al., 2011).

2.2 Erosion and redistribution of glass

Throughout the deglaciated Icelandic landscape erosion of subglacially formed landforms and unconsolidated hyaloclastite deposits has led to the modification and redistribution of glassy materials (van Bemmelen and Rutten, 1955; Jones, 1969). Fluvial processes have most frequently been related to the erosion of subglacially formed landforms and can be separated into processes of water-initiated debris flows and landslides (Whalley et al., 1983; Sigurðsson and Williams, 1991; Tuffen et al., 2002a), alluvial fan formation (Schopka et al., 2006) and gully erosion (Hartmann et al., 2003). Catastrophic outburst floods from glaciers (jökulhlaups) are also known for their post-eruptive transport of hyaloclastites into proglacial environments (Bergh and Sigvaldason, 1991; Björnsson, 2002; Carrivick et al., 2004). It may be evident that the environmental conditions in Iceland also drive non-fluvial processes that contribute to the erosion and subsequent redistribution of glassy sediments (Einarsson, 1984). However, studies of the redistribution of hyaloclastites and the postglacial alteration of tuyas and tindars are scarce (Jakobsson and Gudmundsson, 2008). Especially the lack of process studies emphasises the need for research into the post-glacial environmental fate of hyaloclastite materials. Periglacial and aeolian processes involving hyaloclastite sediments have hitherto been neglected, but these may be particularly relevant for understanding the behaviour of similar materials in the unearthly cold and ‘hyperarid’ periglacial surface environment on planet Mars.

3. A glassy soil on planet Mars

It is well-known on Earth that magma-ice interactions can have a significant influence on the material properties of eruption products and the morphology of subglacially formed landforms. Glaciovolcanism is, strictly speaking, a better term for describing magma-ice interactions as it includes all possible interactions of magma with glacial ice, snow, firn as well as ground ice (Smellie, 2006, 2007). Expansion of the definition is especially relevant in the case of planet Mars. Glaciations on Mars, like on Earth, are driven by orbital forcing. The most recent glacial period occurred 2.1-0.4 Myr ago (Head et al., 2003a) when changes in obliquity have led, for example, to substantial variations in climatic conditions, increased polar ice sheets and glaciated parts of subtropical and tropical latitudes (Carr and Head, 2010). Some argue that these periglacial conditions have been persistent at the surface of Mars (e.g. Gaidos and Marion, 2003), yet others argue in favour of a wetter and warmer Mars with an Earth-like hydrological cycle (e.g. Pollack et al., 1987). An important prerequisite is the stability of water at the surface of Mars. Liquid water may have been stable at some point when surface pressures reached approximately 1 bar, yet it is inherently unstable in the present atmospheric pressures that average only 6 mbar, or 10-15 mbar during periods of high obliquity (>30°) (Kieffer and Zent, 1992; Laskar et al., 2004; Phillips et al., 2011). The majority of water-rich deposits on Mars are therefore found in the form of ice. The largest quantity of ice contained in the Martian cryosphere is currently found at the poles (Clifford et al., 2010) and in the subsurface at lower latitudes (Levy et al., 2010). Irrespective of the exact evolution of the cryosphere, there is ample evidence of glacial and volcanic activity to support the idea that an appreciable portion of volcanism on Mars had a glaciovolcanic nature (Chapman et
Outcrops of tholeiitic basalt (rich in silica and iron, poor in aluminium; McSween et al., 2009) at the surface of Mars show that volcanic processes span from the ancient Noachian epochs of >3.5 Gyr ago (Hartmann, 2005; Werner, 2009) to more recent activity in the Early Amazonian epoch, several hundred Myr ago (Neukum et al., 2010). Crater age dating of these volcanic surface features has established that episodic pulses in volcanic activity coincided with periods of increased glacial activity (Neukum et al., 2010). These absolute ages illustrate that conditions for glaciovolcanism have been persistent throughout a significant part of Mars’ geologic history and its surface development. Figure 3 links the formation age of several glaciovolcanic surface features to the geologic history and episodes of coinciding volcanism and glaciation.

3.1 Martian tuyas and tindars

Many putative tuyas on Mars were identified by Allen (1979) in the northern lowlands and near the present-day polar ice cap. Due to instrument limitations it used to be impossible to directly observe diagnostic hyaloclastite beddings and generic topographic evidence has therefore been the foremost tool to identify tuyas on Mars. Similar to their analogues in the Icelandic landscape, morphological properties were primarily used for the identification of clear flat-topped features near the Martian North Pole as sub-ice volcanoes (Head and Wilson, 2007; Hovius et al., 2008; Fagan et al., 2010). Many of the Martian tuyas have similar morphologies as Icelandic tuyas, but their slightly lower flank slopes suggests that the relaxation angles of the hyaloclastites may be influenced by effects of the lower gravitational acceleration on Mars (3.71 m s⁻² vs. 9.81 m s⁻² on Earth; Kleinhans et al., 2011). Summit heights of North Polar tuyas were used by Fagen et al. (2010) to reconstruct the polar palaeo-ice sheets and point to ice thicknesses of 57-610 m. Similar to these features around the North Pole, numerous tuyas have been identified near the Martian South Pole, see appendix A for locations. Features first mapped by Tanaka and Scott (1987) were interpreted as putative subglacial landforms by Ghatan and Head (2002) and a re-evaluation by Fagan et al. (2010) corroborated their

Fig. 3 - Timeline of glaciovolcanism and eruption locations on Mars (locations: Cousins and Crawford, 2011). Magma-ice interactions on Mars are favoured by the coinciding peaks of volcanic and glacial activity (grey vertical bars) at 3.8-3.3 Gyr, 2.5-2.2 Gyr, 2.0-1.8 Gyr, 1.6-1.2 Gyr, 800-300 Myr and 200-100 Myr ago (from: Neukum et al., 2010). Black horizontal bars in the lower part of the figure highlight the estimated periods when glaciovolcanic surface features were formed; they do not reflect the duration of volcanic activity. See appendices B and C for locations on a map.
subglacial formation. The eruptions that formed the south polar tuyas were much more productive compared to the north polar tuyas, and melted through ice sheets of 500-2000 m thick (Fagan et al., 2010). Since then, polar ice margins have retreated to their present-day locations. Numerous studies have shown the relation of such deglaciation with the pulsed release of magma from the lithosphere on Earth (Jull and McKenzie, 1996; Slater et al., 1998; Maclellan et al., 2002). It is not inconceivable that lithospheric unloading of glaciated polar areas has also played a role in the promotion of eruptions on Mars. Similar to the formation of tuyas in Iceland the increased intensity of eruptions during lithospheric unloading may have led to the eruption of sufficient magma volumes for a rapid formation of tuyas (Licciardi et al., 2007). This new and provisional hypothesis provides a better and faster formation mechanism within a plausible regional context compared to the low extrusion rates suggested by Garvin et al. (2000) for the formation of volcanic features at the plains around the North Pole.

While ground resolutions of satellite imagery and topographic measurements have improved drastically to sub-metre scales in recent decades, the substantial modification of the Martian surface impedes the identification of the diagnostic units from tuyas (Keszthelyi et al., 2010). Exceptions are locations in Chryse and Acidalia Planitia, where basic units of tuyas, such as subaerial cap rocks and summit vents, were identified by Martínez-Alonso et al. (2011). In contrast to polar areas, glaciovolcanic eruptions at equatorial latitudes are most probably related to dike intrusions into ice-rich subsurface layers from volcanic activity associated to the proposed mantle plume below the Tharsis volcanic province (Head et al., 2003b; Grott and Breuer, 2010). These glaciovolcanic eruptions have led to landforms that resemble Icelandic tindars and are found in Vallis Marineris, Cavi Angusti, Cerebrus Fossae, Marte Vallis and Juventae Chasma (Wilson and Head, 2002; Chapman et al., 2003; Komatsu et al. 2004; Zealey, 2009). Appendices B and C show the locations of these and other glaciovolcanic surface features on a map. The massive hydrological networks that drain away from these features, with outwash plains at their terminus in the northern lowlands, suggest that these were carved out by catastrophic floods that resemble terrestrial jökulhlaups. (Mouginis-Mark, 1985; Rice and Edgett, 1997; Carr and Head, 2003; Chapman et al., 2003; Burr, 2010). The large-scale outflow features formed by the hydrological activity in the Hesperian and early Amazonian epochs and the associated geomorphological features are currently best explained by a jökulhlaup hypothesis, induced by sub-ice volcanism (Gaidos and Marion, 2003). Catastrophic outburst floods have therefore been an important driver in the redistribution of glaciovolcanic eruption products and other hydrated minerals across the Martian surface.

### 3.2 Abundance of glass-rich deposits and parallels in formation

The strongest evidence for the existence of glaciovolcanic eruption products results from the observations by Horgan and Bell (2012a) who used the OMEGA instrument on the European Mars Express satellite. Their detailed spectral analyses of the dark sand seas around the North Pole and the largest dune field Siton Undae in the northern lowlands suggest that 80-90% of these sand fields consist of volcanic glass formed by explosive volcanism, such as glaciovolcanism (Fig. 4). These ratios of glass and crystalline materials are comparable to the materials formed by basaltic and rhyolitic sub-ice volcanism in Iceland (e.g. Jakobsson and Gudmundsson, 2008; Denton et al., 2009). Granular volcanic glass skirting the proglacial areas of the Martian North Pole is primarily sourced from the basal unit below the present ice cap. Sediments from the cross-bedded basal unit were introduced in the circumpolar environment by catastrophic glacial outburst floods, where they are currently redistributed by polar winds (e.g. Fishbaugh and Head, 2002, 2005; Hovius et al., 2008). Catastrophic floods flowing from
tindar features in Chryse Planitia, Valles Marineris and Juventae Chasma and from tuyas in Southern Acidalia may have deposited substantial amounts of granular glass in parts of the Northern Lowlands such as Siton Undae (Martínez-Alonso et al., 2011, Horgan and Bell, 2012a). While the contribution of jökulhlaups in the (re)distribution of these materials is clearly not new, Horgan and co-workers are now finding the first compositional evidence that these large sand seas are sourced from equatorial glaciovolcanic eruptions that occurred in an ice-rich subsurface (Horgan, personal communication, 2012). Post-depositional chemical weathering was hypothesised by Horgan and Bell (2012a) to have leached low-valence cations from the glass structure. The formed Fe^{2+} rinds were subsequently removed by the abrasive effects of wind-induced saltation and exposed the leached silica-rich, almost obsidian-resembling, glass that now chemically stabilises these deposits and prevents further dissolution and consolidation (Horgan and Bell, 2012a). The absence of post-depositional cementation causes these glassy materials to be commonly found in aeolian landforms such as dune fields where the glass is affected by present-day transportational and erosional processes. These

Fig. 4 - Simplified classification map showing areas where volcanic glass is abundant in the polar sand seas and the dune fields of Siton Undae on Mars. The red areas are a combination of the concavity and the 1.2-1.5 micron spectral regions that were interpreted by Horgan and Bell (2012a) as volcanic glass deposits (>80% glass content). Arrows highlight pathways of possible volcanism-driven glacial outburst (e.g. Hovius et al., 2008) that can have deposited the volcanic glass in the circumpolar area. The possible pathways of the catastrophic floods from the equatorial highlands that deposited sands in Siton Undae fall outside the map’s extent.
processes drive the migration of dunes (Hansen et al., 2011) and include aeolian abrasion from saltation and wind-induced mass-wasting in the form of granular avalanches on dune slip faces (Horgan and Bell, 2012b).

Determining the physico-mechanical properties of glass particles is still problematic, despite the high abundance of glassy sediments at the Martian surface. Mineralogical properties can be derived from Mars-lander instrumentation and satellite observations (Chevrier and Mathé, 2007; Mustard et al., 2008; Horgan and Bell, 2012a), but detailed microscopic observations of Martian particle populations are only limited to incomparable materials at a few lander sites (e.g. Sullivan et al., 2008; Goetz et al., 2010). These observations show that aeolian sediments are well-rounded, which is generally consistent with abrasion from prolonged aeolian transport over geologic time (Keunen, 1960; Greeley and Iversen, 1985). In contrast, glaciovolcanic glasses are characterised by blocky and angular morphologies and have a low degree of vesiculation (Heiken, 1972; Tuffen et al., 2001, 2002a). Scarce field observations (Ayling and McGowan, 2006) and experimental studies (Greeley and Iversen, 1985; Marshall et al., 2012) also show that angular materials such as these glasses are modified at slower rates than other particle types (e.g. Mangold et al., 2011). The discrepancy between the sparse observations of the Martian particle population and known properties of terrestrial glaciovolcanic glasses illustrates the hiatus in our comprehension of glassy materials at the Martian surface. Erosion processes that are involved in the modification of analogue glasses in Iceland can therefore help to increase our understanding of these materials in the environment on Mars. The baseline for such a comparative approach is formed in this dissertation by the parallels in glaciovolcanic eruption environments. These parallels are governed by the ice overburden pressures and the availability of water for the quenching of magma. Both are responsible for controlling the physico-mechanical characteristics of glasses, such as particle size, morphology and degree of vesiculation. Studies of Martian polar ice sheets show that these are mainly composed of water ice with average densities of 1220 kg m⁻³ (Bibring et al., 2004; Zuber et al., 2007; Phillips et al., 2008, 2011). The topographic evidence from Martian polar tuyas establishes that subglacial eruptions occurred under ice thicknesses of 57-2000 m and consequently, based on the known Martian ice properties, confining glaciostatic pressures varied from 0.2-9 MPa. This range in pressure is comparable to the glaciostatic pressure of 2-8 MPa created by 255-960 m thick ice sheets in Iceland, generally composed of a lower-density ice of 850 kg m⁻³. Refer to appendix D for a comparison of these glacial reconstructions. Subglacial eruptions on Mars and in Iceland are therefore controlled by similar pressure regimes and quenching of erupting magmas by water, forming materials with comparable physico-mechanical properties. Terrestrial hyaloclastites are as such suitable analogue materials for Martian glaciovolcanic glasses. The access to these analogue glasses on Earth allows parameters to be quantified that are of relevance for process-based geomorphological studies to understand glass modification, transport and erosion characteristics. This is where the exploration of Mars brings us back to the Icelandic landscape.

4. Objective and research questions

The objective of this dissertation is to study the behaviour and fate of granular glaciovolcanic glass in different planetary environments. The main aims are to fill a gap in the knowledge of physical erosion mechanisms and transport thresholds of high-silica glaciovolcanic glass and to investigate the role of atmospheric pressure and local environmental conditions in these geomorphological processes. These aims will be addressed by investigating the following research questions:
1. How do landforms composed of glaciovolcanic glass physically weather; which environmental processes are dominant in regulating weathering processes?

2. What is the role of the physico-mechanical properties in the physical weathering of glaciovolcanic glass by wind and ice?

3. What mechanisms permit the mobilisation and transportation of non-cohesive glassy sediments by winds in low atmospheric pressures, such as on planet Mars?

4. Is the fabric of aeolian sediment capable of retaining information on local wind flow conditions and the types of particle transport?

4.1 Outline and structure of this dissertation

Based on the research questions, this dissertation is divided into six chapters. In Chapter 1, this chapter, the role of glaciovolcanism in the formation of granular glass has been explored for defining the context, parallels and abundance of this type of material in different planetary environments. Chapter 2 ‘Erosion of a subglacial edifice’ sets-out to study which processes affect the modification of hyaloclastites at landscape scales. The underlying aim of this chapter is to understand how the environmental (meteorological) conditions drive various geomorphological processes that are responsible for eroding an edifice. The chapter combines various field observations inside a gorge composed of glaciovolcanic glass in Iceland. A broad approach is applied to the landscape analysis and involves sampling of scree sediments and their source areas to establish if and how dominant transport and erosion processes are reflected in the sedimentary record. The focus in this chapter is then drawn to the contribution of aeolian processes to the erosion of hillslopes and the formation of sedimentary landforms. In reference of the first research question this chapter answers which processes are constructive in the erosion processes at a local scale.

Chapter 3 ‘Physical weathering of glaciovolcanic glass’ takes the analysis of erosion characteristics a step closer to a particle level. While erosion processes at a landscape scale are discussed in chapter 2, this chapter aims at understanding how these erosion processes physically modify particles that compose the friable glassy breccias. The methodology of this chapter is based on environmental laboratory simulations of the two most influential erosion processes that were observed at the field site. Transport of particles after detachment from the matrix was simulated by tumbling sediment non-stop for several months to assess abrasion and textural changes. Freeze-thaw cycles on the other hand were simulated by subjecting larger pumiceous glass particles to diurnal freeze and thaw cycles. Detailed measurements of pores and fracture strengths of the glass give insight in the scale effects of ice growth and glass fracturing during freezing and thawing. In relation to the second research question, this chapter specifically focusses on the role of the material properties in the destructive modification of glaciovolcanic glass. As chapters 2 and 3 are complementary, they provide a ‘cause and effect’ analysis of the erosion of hyaloclastites at a landscape and particle scale.

In contrast to Iceland, the importance of erosion by flowing water is negligible in the present-day Martian surface environment. Dry erosion processes of hyaloclastites are therefore favoured on Mars and the wind is by far the most shaping geological force, especially when considering that glass-rich sediments are primarily found in dune fields. In order to understand the dependence of aeolian processes in the different planetary conditions, experiments are used to translate these processes to the surface conditions on Mars. The magnitude of atmospheric pressure, the principal ‘planetary variable’ that affects...
these aeolian processes, is therefore used as the variable in the experimental methodology of the 'hypobaric' wind tunnel simulations. In Chapter 4 ‘Wind transport at the fluid threshold’ I will examine how glaciovolcanic glass can be transported by winds in the very thin atmosphere of Mars. This focus on aeolian processes is relevant for several reasons. In Iceland aeolian processes are found to play an important role in the modification of textures and sedimentary processes. On Mars the atmospheric pressures are low and the structure of the atmospheric boundary layer is different if compared to Earth. This affects the thresholds for removal and the physical modification of sediments. At the fluid threshold, where particle mobility is initiated by the wind only, rolling is the lowest threshold at which mobility can occur. Experimentally simulating the removal of volcanic glass is achieved by using a special hypobaric (low-pressure) wind tunnel. The ancient age of the surface and limited knowledge on properties of the glassy particle population on Mars makes a comparative approach seemingly difficult. However, due to the parallels in formation environments of glaciovolcanic glasses on Earth and Mars, it is possible to determine a realistic threshold range for particle mobility of glass-rich sediments on Mars. This chapter will therefore address the third research question and assesses how glassy sediments are initially mobilised, thereby triggering saltation and subsequently driving the physical alteration of particles. Various landers and rovers have shown that aeolian sediments on Mars have been strongly modified by wind transport. Observed particle shapes may represent the 'end state' of particles and the glass detected in dune fields will likely have obtained such well-rounded morphologies due to their aeolian transport over geologic time. In Chapter 5 ‘Orientation of particles to wind flow’ I continue the study of wind-induced particle mobility, yet this time in situ on Mars. Where the preceding chapter addressed the detachment threshold for setting particles in motion by rolling and saltation, this chapter will focus on how these forms of transport create non-random, preferred orientation patterns in the sediment fabric. Using imagery of non-cohesive sand grains as obtained by the Microscope Imager of the Mars Exploration Rover 'Spirit', I will examine how particles orient themselves and how this orientation can be used to infer local wind flow directions. I briefly trade the landscape in Iceland for that of the Brandenburg Ice Marginal valley in Germany. Here, cover sands and inland dunes composed of laminated sands have been deposited by winds in a periglacial environment during the last glaciation of the area. Palaeowind directions that built these dunes have been inferred in the past from dune morphologies and from the long-axis orientation of sand particles in thin-sections. A new method is developed based on object-based image analysis, to segment and reclassify objects in images into polygons that represent the circumferences of individual sand grains. This in turn allows the measurement of sediment statistics such as size distribution and long-axis orientations of individual grains. The method will first be tested and compared to known sediment of the inland dunes and subsequently applied to imagery of sand grains in the Columbia Hills on Mars. In answering the fourth research question, I will show that surficial sediments on Mars have retained patterns that represent the wind flows that formed these aeolian features. This new methodology highlights that mobilisation of sand grains can complement pre-existing aeolian analyses that have relied on the analyses of surface features such as dunes, ripples and ventifacts.

Chapter 6 ‘Synthesis - environmental fate on Earth and Mars’, the final chapter of this thesis integrates the conclusions of these preceding chapters to answer the four research questions. This chapter works towards a coherent vision on the behaviour and fate of glaciovolcanic glass and places glaciovolcanic glass in a broader context at the surface of planet Mars. Finally this outline helps in defining future research directions.
4.2 Selection of an analogue glass in Iceland

The research presented in this PhD dissertation is founded on the premise that hyaloclastites in Iceland can be used as an analogue for glaciovolcanic glasses on Mars, as I outlined in section 3.2. Erosion processes and thresholds that drive the environmental behaviour of hyaloclastites are dependent on the material’s physico-mechanical properties. Unlike comparative studies that use geochemical analogue materials based on remotely sensed surface mineralogy, selection of an analogue material in this dissertation is based on the physico-mechanical properties of amorphous (non-crystalline) materials that are controlled by the subglacial eruption environment (see Appendix D). The properties of the Icelandic glass analogue therefore need to be well-characterised to understand their interrelationship with various processes outlined in the preceding section. The selection of a single particle population is in this sense vital to exclude mixed materials that would possibly bias the characterisation of the material's physico-mechanical properties. These criteria have led to the selection and use of a rhyolitic hyaloclastite that was formed during the isolated subglacial eruption of Bláhnúkur in the Torfajökull caldera complex (Fig. 5, Fig. 6). Particles in these rhyolitic glass breccias are blocky in shape with a low vesicularity of 5-23% (Tuffen et al., 2001, 2002a; Owen et al., 2012). When the physico-mechanical properties of the Bláhnúkur particle population are compared to basaltic hyaloclastites we see that these glasses are characterised by blocky particle morphologies and vesicularities of 5-30% (Heiken, 1972; Furnes, 1978; Schopka et al., 2006). Weathering of these basaltic hyaloclastites involves cementation from palagonisation, filling of vesicles and as such strengthening. In contrast, rhyolitic (silicic) hyaloclastites appear to be more resistant to such chemical weathering and are generally not well-consolidated (Jakobsson and Gudmundsson, 2008). This also appears to be the case for glass deposits on planet Mars, where leaching of basaltic glass created particles with silicic exteriors that are now detected as chemically-resistant, unconsolidated deposits (Horgan and Bell, 2012a). The excellent accessibility to Bláhnúkur’s hyaloclastites has facilitated detailed studies of eruption conditions and hydration properties that are dependent on the subglacial eruption environment (e.g. Tuffen et al., 2001, 2002a; Denton et al., 2009, 2012; Owen et al., 2012). These conditions make the particle population of Bláhnúkur arguably the best-studied example of silicic hyaloclastites. No other basaltic or rhyolitic edifice has been studied to the same extent and provides access to a similar well-characterised material. This is a substantial benefit for the experimental studies presented in this dissertation.

5. Bláhnúkur: a unique field site in Torfajökull, Iceland

5.1 Regional development and subglacial eruptions

The active volcanic zones in Iceland are dated relative to the Brunhes normal magnetic epoch (Sæmundsson, 1979; Jónasson, 2007) and are subdivided into two zonation types: rift zones and flank zones (Sæmundsson, 1974, 1979). Rift zones roughly follow the course of the Mid-Atlantic Ridge through Iceland. Volcanic systems within these zones consist of a central volcano with well-developed fissure-swarms extending several tens of kilometres along the rifts. These systems are frequently composed of tholeiitic basalts (Sæmundsson, 1979). A characteristic property of central volcanoes is that they are often higher in elevation than surrounding terrain. The colder conditions with increasing altitude can nowadays be treacherous for hikers, but it has also led to the development of massive ice sheets during glacial epochs. Their high elevation and exposure enforces an increased likelihood for magma-ice interactions and this contributes to the formation of abundant glaciovolcanic
eruption products in the Icelandic landscape (McGarvie, 2009). In the flank zones however, the volcanic activity is dominated by the >3 cm yr\(^{-1}\) spreading rates of the North American and Eurasian plates (Árnadóttir et al., 2009). Consequently, the central volcanoes in these systems are much larger, fissure swarms are lacking or are only poorly developed and some systems are dominated by rhyolitic compositions. Rhyolitic subglacial eruptions in Iceland are currently linked to 23 (suspected) locations with edifices of varying scales (McGarvie, 2009). One prominent example in the southern central highlands is Torfajökull; an area that is recognised as the largest rhyolitic complex in Iceland (Walker, 1966; Jónasson, 2007; Martin and Sigmarsson, 2007) and as the largest on an oceanic crust (Gunnarsson et al., 1998). It has produced roughly two-third of the total erupted rhyolite in Iceland during the past 0.8 Myr, 225 km\(^3\) of the 350 km\(^3\) (Gunnarsson et al., 1998; McGarvie, 2009). The caldera is located at the point where the Easter Volcanic Zone (EVZ) meets the Southern Flank Zone (SFZ) and has been active since the mid-Quaternary. Torfajökull is still considered volcanically active today, as is evidenced by micro-earthquakes from shallow magma

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**Fig. 5** - Overview map of the Landmannalaugar area (63°59’04” N, 19°3’51” W) where the Veidivotn swarm fissure intersects the magma chamber of Torfajökull. This section of the Torfajökull region in highlighted by the black box (a) in the southern central highlands of Iceland. The gorge for the field studies in this dissertation is situated between the 1477 AD Laugahraun outflow lava and the subglacially formed Bláhnúkur edifice (b). Local eruption fissures of Bláhnúkur were inferred by Tuffen et al. (2001).
intrusions (Soosalu and Einarsson, 2004; Lippitsch et al., 2005; Soosalu et al., 2006) and large geothermal gradients in the subsurface (Pálsson et al., 1970). The circular depression of the complex is not a caldera in the strict sense of the definition as there is no clear evidence that subsidence of the central area took place. The shape of the caldera was more likely caused by confinement of eruption products underneath the ice that increased the vertical growth of the ring wall during subglacial eruptions (McGarvie, 2009). Subsequent eruptions and geothermal alteration of the eruption products have produced a colourful landscape that is now part of the Fjallabak Nature Reserve (Fig. 6, page 26-27).

The Bláhnúkur edifice near the northern edge of the complex is an example of an isolated small-volume eruption that took place during the last glaciation of Torfajökull between 115-11 kyr ago. It is therefore considered to be the youngest glaciovolcanic landform in the area and consists of a 50 m thick layer of rhyolitic hyaloclastite (Tuffen et al., 2001; McGarvie, et al., 2006). The pyramid-shaped edifice (Fig. 6) was formed by the eruption along four WSW-ENE and NW-SE trending fissures and currently rises 350 m above the surrounding rhyolite plateau to a summit altitude of 945 m.a.s.l. (meters above sea level). The emplacement of the Bláhnúkur hyaloclastites during different eruption stages were first described by Furnes et al. (1980) and substantially improved by Tuffen et al. (2001). Detailed field studies by Tuffen et al. (2001) have shown a complex sequence of volcano-ice interaction where the distance between glacier ice and magma increased during the later eruptive stages and gave room for the emplacement and filling of the subglacial eruption cavern with brecciated ash. This glacial recession destabilised already deposited eruption products and triggered avalanches and debris flows inside the subglacial eruption cavern.

Increased subglacial channelization (Tuffen et al., 2002a) reduced the explosivity of the eruption by draining water from the area around the primary vents. Geologic features and sedimentary strata presently exposed around the edifice reflect a dynamic and well-constrained eruption during which the interaction of magma and ice controlled the material properties of the glaciovolcanic glass (also see Box 1). Degassing of magma during the complex magma-ice interactions also fostered a new approach to studying subglacial eruption dynamics in relation to palaeo-ice reconstructions (Tuffen et al., 2010). The volatiles sequestered in the glass at the time of solidification are considered to follow predictable patterns depending on the glaciostatic pressure (e.g. Tuffen et al., 2010; Owen et al., 2012). In an eruption environment where meltwater from magma-ice interactions dominates the rate of quenching, dissolved H$_2$O appears to be a suitable, albeit complex, proxy for inferring palaeo-ice thicknesses from subglacial eruption products (Owen et al., 2012). The decrease in water content with increasing sample altitude along the flanks of the edifice showed that Bláhnúkur erupted underneath an ice sheet of 400 metres thickness. This is in line with the thickness inferred from conventional geological methods (Tuffen et al., 2001) and topographic indications from local tuyas (Tuffen et al., 2002b).

Radiometric dating of three tuyas in Torfajökull using $^{40}$Ar-$^{39}$Ar have provided an accurate age (67-278 kyr) and minimum ice sheet thickness for their eruption during past glaciations of the area (McGarvie et al., 2006). These datings show that in contrast to other tuyas in Iceland (Licciardi et al., 2007), tuya-forming eruptions in Torfajökull are likely dissociated from lithosphere unloading during deglaciation (McGarvie, 2009). The promotion of eruptions in this area of Iceland is in fact a likely consequence of the unique architecture in the subsurface where the basaltic (tholeiitic) Veíðivotn fissure swarm intersects the rhyolitic magma chamber of Torfajökull (McGarvie, 1984; Mork, 1984; Gunnarsson et al., 1998; Jónasson, 2007). The Bláhnúkur breccias have basaltic inclusions of several millimetres
to centimetres in size that are indicative for the break-up and mixing of a basaltic body inside the rhyolitic magma chamber (Blake, 1984; Tuffen et al., 2001, 2002a). The presence of these basaltic inclusions also establishes that the eruption of Bláhnúkur was encouraged by the intrusion of a pre-eruptive basaltic magma body in the Torfajökull magma chamber (McGarvie, 1984; Mork, 1984). The adjacent Laugahraun lava flow underwent a comparable fate and outcrops show similar signs for basaltic intrusions prior to the eruption. Although the eruption products from Bláhnúkur and Laugahraun clearly differ and illustrate the effects of the eruption environment (subglacial vs. subaerial), both can be considered as comparable effusive rhyolitic eruptions.

5.2 Hydrological evolution and development to present-day state

After the subaerial eruption of Laugahraun in 1477 AD, local hydrological networks had to re-establish their flow directions due to the blockade of the Landmannalaugar valley by the lava flow (Fig. 5). The gradual evolution of these drainage networks led to the incision of the Brennisteinsölusvísl stream at the interface between the resistant Laugahraun formation and the less-consolidated Bláhnúkur hyaloclastite. This mainly affected the erosion of the North-western quadrant of the edifice where it caused significant fluvial erosion at the base of Bláhnúkur and undercutting of sections from Laugahraun. The present Grænagil gorge was formed as a consequence of the local hydrological evolution in response to the Laugahraun eruption. Here, green and grey hyaloclastites (see Box 1) are excavated by continuous basal erosion of the stream and by the interaction of local environmental conditions with the exposed slopes. Especially winds are funnelled and aggravated inside the gorge due to the local topographical gradients. The main study area was therefore situated inside the Grænagil gorge (63°59’04” N, 19°3’51” W) due to the occurrence of a large variety of environmental processes that are of interest to this dissertation research. The excellent accessibility and unique geological setting as an isolated subglacial edifice make Bláhnúkur a prime location for studying: (i.) the interaction and effects of local environmental conditions, (ii.) the role of physico-mechanical properties of glaciovolcanic glass in weathering, erosion and transportation processes and (iii.) making the translation of this material’s environmental behaviour to the conditions at surface of planet Mars.

Box 1 50 Shades of green

The Grænagil gorge is known for its bright-green hyaloclastites that intrigue many hikers and scientists alike. So far, a conclusive explanation for the notable colour has been lacking, while the nature of the green glass may give insights in the eruption and formation conditions of these deposits. Conventional measurements using X-ray diffraction (based on scattering of the radiation by crystalline lettuces, also see chapter 4) show that less than 10% of the glass breccia is composed of minerals such as anorthite, huelandite, mordenite and albite (Denton et al., 2009). None of these minerals are known for their vivid green colours and their abundance is too low to have any contribution to the observed colours by intermixing in the breccia matrix. This colour enigma can be solved by a more detailed study of the glass’ geochemical composition and spectral properties. In the production of industrial glasses, colours are created by adding the oxides of transition metals (3d electron shells) or rare-earth metals (4f electron shells) (Shelby, 2005) with ferric and ferrous iron being the most common cause for green hues in glasses. High ferrous-ferric ratios typically produce blue-green colours, while yellow tinges occur in glass mixes with a more ferric ratio. The bulk of such glass fragments may in fact appear black at a greater viewing distance, while still having these green or yellow
tinges on closer inspection (compare Fig. 6 with Fig. 26). These optical properties are also reflected in the names given to the edifice and its features; Bláhnúkur translates from Icelandic to ‘blue peak’, while Grænagil translates to ‘green gorge’. It would thus be logical to attribute the green colour of the glassy breccias to the ferrous-ferric ratios of the various formations. However, other ions can have similar colouring effects and are also known to produce green glass, such as copper (Cu$^{2+}$), and multivalent chromium (Cr$^{2+}$, Cr$^{3+}$, Cr$^{6+}$). Spectral properties of several Bláhnúkur glasses were measured using a Lambda 900 UV/VIS/NIR spectrometer with integrating sphere from Perkin Elmer. Green, grey and black (obsidian) glass samples were milled to a fine powder and measured from 300-2500 nm at a scan speed of 450 nm per minute. The diffuse spectral reflectance was then normalised by removing the continuum with a convex hull fit (the line connecting the peaks on top of the original graph) for a better comparison. A notable absorption feature for the green glass occurs at 700 nm that absorbs red, orange and yellow, giving the glass a green appearance. This broad feature and a smaller feature at 900 nm are most consistent with Cu$^{2+}$. The high Fe$^{2+}$ absorption at 1050 nm seen at the other samples and stronger absorption features of Fe$^{3+}$ around 400 nm for the green glass indicate that the green glass is more oxidised than the other three samples. The higher oxidation of the green glass is most likely the cause of steam activation (e.g. Starokon et al., 2003) associated with hot steam filtering through the glass breccias when the material of the green outcrop avalanched down-slope (see Tuffen et al., 2001). The colour at the entrance of the Grænagil gorge is therefore associated to proposed mass wasting processes inside the hot and steamy subglacial cavern during the formation of Bláhnúkur.

**Fig. B2** - Entrance of the Grænagil gorge in Iceland. Veins in the exposed rock face were proposed by Tuffen et al. (2001) to have formed by filling of cracks with fines mobilised by steam filtering through the breccias during avalanching of these deposits inside the hot subglacial eruption cavern.
Fig. 6 - The Bláhnúkur edifice in Torfajökull (see Fig. 5 for the regional context), viewed from the flank of the Brennisteinsalda towards the northeast. The edifice is roughly pyramidal in shape with a summit altitude of 945 m above sea level (350 m above the valley floor). A 50 m thick layer of silicic hyaloclastite drapes an older pre-existing rhyolite core. Towards the left border of photo, between the Laugahraun lava flow and Bláhnúkur, is the entrance to the Grænagil gorge. Photo courtesy of Daniel Bergmann, used by permission.