Subglacial volcanism with examples from Iceland

Anne Schöpa

Institute of Geology, TU Bergakademie Freiberg, Bernhard-von-Cotta-Str. 2, 09599 Freiberg, Germany

Abstract. The interplay between glaciation and volcanism leads to the creation of impressive structures like table mountains. Discussion has been continuing about the eruption history of these volcanic edifices whether they are monogenetic volcanoes or not. Furthermore, the eruption environment for many table mountains is still in debate: Facies analysis of volcaniclastic sediments like hyaloclastites makes it possible to distinguish between strictly englacial and lacustrine processes and enables to evaluate ice contact features and traces of possible subaerial stages. This work focuses on the physical processes and environments that control a basaltic volcanic eruption under the ice of a glacier, the evolved rocks in terms of structure and texture and the generated topographic features with a special emphasis on the Icelandic geological setting.

Key words. subglacial volcanism, table mountain, eruptive environment, hyaloclastites, Iceland

Introduction

Table mountains are esteemed to be the subglacial equivalent of shield volcanoes (Stemundsson, 1979), formed monogenetically from a single vent. However, table mountains are constructed of clastic volcanic rocks by a great amount in contrast to shield volcanoes and can therefore be easily compared with seamounts, the product of submarine volcanism, evolving into ocean islands. Whereas direct observation is difficult in a subglacial setting, the development of Surtsey (Fig. 1), a subaquatic volcano that emerged above sea level south of Iceland in 1963, gave an excellent option to investigate submarine to emergent volcanism in situ (cf. Jakobsson et al., 2000). In both settings, subglacial and submarine, the eruption is likely to start with an effusive phase due to high overburden pressure and pillow lavas form. They evolve into pillow breccias and later into hyaloclastites when the pressure decreases, allowing explosive fragmentation processes. In a possibly following subaerial stage the volcanic vent emerges above the water level and effusive eruptions create a lava cap (Thordarson and Höskuldsson, 2006). This similarity in evolitional stages of a submarine and a subglacial eruption is due to the constant presence of external water provided by the ocean or by melting of the glacier.

Although the succession of deposits at submarine and subglacial volcanoes might be the same there are remarkable differences: Firstly, in the constraint of the volcanic edifice. Whereas there is no limitation in the growth of a subaquatic volcano, subglacial volcanoes are restricted in their spatial development by the ice walls leading to steeper slopes (Gudmundsson et al., 1997) and increasing risk of gravitational collapse if the ice retreats (Tuffen et al., 2001). Secondly, subaquatic and subglacial eruptions differ in the water/magma ratio. In the former environmental setting, this proportion is consistently high, while in the latter environment this ratio is more variable. That is due to drainage patterns as pressure changes (positive or negative, leading to meltwater drainage or collection at the vent, see below) are highly dependent on melting rate of the ice and thus on magma temperature and eruption rate. Even sections with little magma/water interaction can be found in subglacial deposits of volcanics (Tuffen et al., 2001) if they intrude into a steam-filled cavity at the glacier base where meltwater was expelled by porous flow into
the underlying substrate (Tuffen et al., 2002b) or flew away at the glacier base. Thirdly, the evolution of the water pressure at the vent, the effective pressure, is dissimilar. In a submarine setting the pressure of the water is only dependent on water depth, hence hydrostatic. Subsequently, it is reduced when the volcanic edifice builds itself up towards the ocean surface (Schopka et al., 2006). On the contrary, the pressure can be less than glaciostatic under an ice cap on account of meltwater drainage and cauldron subsidence. A prerequisite for such conditions to happen is that meltwater flows away from the vent during the eruption. According to Höskuldsson and Sparks (1997) this is possible if a positive pressure change occurs: The combined volume of the volcanic products and of the meltwater needs to be greater than the volume of the melted ice (note 10% difference in volume between ice and water for equivalent masses). If that is not the case and the volume of the melted ice exceeds that of the volcanic products and the water, a negative pressure change would prohibit meltwater to drain away thus accumulate at the vent making catastrophic outburst floods (jökulhlaups) more probable to take place (Höskuldsson and Sparks, 1997). Consequently, the style of subglacial eruptions is likely to be more variable and might change erratically between effusive and explosive (Tuffen et al., 2001) as shown for the table mountain Herdubreið in Iceland (Fig. 1) by Werner and Schmincke (1999).

Table mountains were described in Antarctica (e.g. Wörner and Viereck, 1987; Smellie et al., 1993; Skilling, 1994), British Columbia (e.g. Moore et al., 1995) and Iceland (e.g. Schiellerup, 1995; Werner and Schmincke, 1999). This island with its over 30 active volcanic systems (Fig. 1) (Thordarson and Larsen, 2007) and glaciers recently covering a tenth of the country offers an excellent possibility not only to investigate the resulting landforms of the interaction of fire and ice but also to observe the processes in situ that lead to their construction.

![Fig. 1. Distribution of the active volcanic systems in Iceland. Highlighted with a star are those mentioned in this work.](image)


The large open circle marks the approximate centre of the Iceland mantle plume. Modified after Thordarson and Larsen (2007).
Regional Geology of Iceland

Volcanism

Iceland is a young volcanic island in the North Atlantic that owes its existence to the concurrence of a mantle plume and a mid-oceanic spreading centre. In early Cenozoic spreading was active in the Labrador Strait between Greenland and the North-American continent. In Mid-Cenozoic, the Labrador Strait was abandoned and the North Atlantic ridge between Greenland and Scandinavia (Thordarson and Höskuldsson, 2006) took over the divergent motion of the North American and the Eurasian lithospheric plate. Iceland is situated at their interface (Fig. 2) and experiences the effects of such a constructive plate boundary: Decompressional melting in the astenosphere causes the evolution of a ridge structure with basaltic volcanism at the surface. The northern part of the Mid-Atlantic Ridge is currently spreading 0.9 cm/year in each direction around Iceland (Fig. 2) (Hardarson et al., 1997). Speaking in general, mid-ocean ridges do not reach the sea level. However, Iceland is the only known exception whose incidence is attributed to a mantle plume under the ridge (Jacoby and Gudmundsson, 2007). That term is referred to a body of upwelling heat in the Earth’s mantle transporting eventually also hot and therefore less dense material upward from the lower mantle. The traces of the so-called Iceland mantle plume in the North Atlantic (Fig. 2) range back 65 Ma (Thordarson and Höskuldsson, 2006), recorded by a flood basalt province in West Greenland. Since that time the plume has produced more than 10 Mio km$^3$ of magma (Thordarson and Höskuldsson, 2006) in a region stretching from Greenland over Iceland and the Faeroe Islands to Scotland. Today, the centre of the mantle plume is located under Iceland’s largest glacier Vatnajökull (Fig. 1) (Einarsson et al., 1997). In Iceland, these two phenomena of a divergent plate boundary and a mantle plume coincide and lifted the island above sea level 15 Ma ago (Kristjánsson et al., 2003). Since then, Iceland has been growing constantly in size under subaerial conditions due to its intensive volcanism.

Fig. 2. Geographical position of Iceland in the North Atlantic. Arrows indicate the current spreading direction. Also shown are main rift axis, flood basalt sequences and the location of the Iceland mantle plume through time. Modified after Thordarson and Larsen (2007).
Climate

Iceland is located just south of the Arctic Circle, between 63°N and 67°N. This geographic position and the high moisture supply rates from the Atlantic Ocean enables glaciers to grow. Today, glaciers cover 11% of the island’s surface. But 21 ka ago, during the culmination of the Weichselian Ice Age (Bourgeois et al., 1998) almost the entire country (Andrews et al., 2000) was covered by glacial ice (Fig. 3) up to 1000 m thick (Hubbard et al., 2006) apart from a few coastal nunataks (Bourgeois et al., 1998). The thickness of the ice sheet can be modelled (cf. Hubbard et al., 2006) and reconstructed by the elevation of table mountains and hyaloclastite ridges (cf. Bourgeois et al., 1998).

There is evidence that Iceland saw at least five glacial-interglacial cycles (Bourgeois et al., 1998) during the past 0.7 Ma. And during the last 4 -5 Ma over 20 glaciations are recorded in glacial deposits that can be correlated to the δ18O record of deep-sea sediments (Geirsdóttir et al., 2007).

Fig. 3. Modelled extent of the ice sheet surface in Iceland during the Last Glacial Maximum (LGM) 21 ka ago and its flow regime. Contours show 50 m intervals and the isostatically adjusted bed topography at 0 m LGM sea level (strong blue, lobed line). Modified after Hubbard at al. (2006).

Interaction of volcanism and glaciation

Although 92% of Iceland’s lithology is made up of basalts (Sigmundsson, 2006: 4% accounts for basaltic andesites, 1% for andesites) and only 3% of dacites and rhyolites there are both mafic and felsic examples of subglacial volcanism.

Whereas we can observe the landforms of subglacial basaltic volcanic activity throughout the country, the distribution of rhyolitic subglacial products is limited to central volcanoes (Kerlingarfjöll (Fig. 1)) and fissure zones (Prestahnjúkur (Fig. 1)). The largest silicic complex is Torfajökull (Fig. 1) (Tuffen at al., 2002a). This huge central volcano in the interior of Iceland is made up of obsidian lava flows, airfall tuffs and subglacial rhyolitic lava domes, e.g. Bláhnúkur (Thordarson and Höskuldsson, 2006). These domes are arranged circularly around the central caldera and some of them could melt themselves through the ice to form rhyolitic table mountains like Raudufossafjöll (Tuffen at al., 2002a). In the following, we shall focus on the formation, geometry and depositional processes of basaltic subglacial volcanoes.
Evolution of a subglacial basalt eruption

The general model of a volcanic eruption under a glacier was derived from field observations (for example of the 1996 Gjálp eruption within the Vatnajökull ice cap (Fig. 1) (Gudmundsson et al., 1997) and investigations of subaquatic eruptions and its products (see Jakobsson et al., 2000 about Surtsey (Fig. 1)). Three main phases (Fig. 4) of a subglacial eruption can be classified: An effusive, an explosive and an emergent effusive part.

Effusive stage
When volcanic fissures or single vents become active under a glacier the released heat melts a cavity filled with water into the bottom of the glacier resulting in a caldron-like depression at the surface of the ice. As long as the glacial ice and the water of the lake under the glacier provide enough overburden pressure an effusive eruption occurs with the formation of pillow lavas (Thordarson and Höskuldsson, 2006). Their assemblages can be quite complex as finger-like tongues of lava flow forward and over each other.

If the eruption comes to an end at this stage the resulting landform is entitled as pillow lava ridge when originating from a fissure eruption or pillow lava cone when a circular vent erupts (Fig. 4 (A)). These hillocks are only found in Central Iceland (Höskuldsson et al., 2006) like the ridges in the Kverkfjöll area (Fig. 1) northeast of the glacier Vatnajökull. The pillow ridges at Kverkfjöll are up to 2 km wide, stretch NE-SW for up to 5 km and rise to about 900 m altitude (Höskuldsson et al., 2006).

Explosive stage
When the eruption continues and the volcanic edifice grows the water depth and the ice thickness are reduced and as a result the pressure of the overburden (ice and water) decreases. If the environmental pressure drops below 10 MPa (Höskuldsson et al., 2006) the formation of pillows is not longer possible and the eruption enters an explosive hydromagmatic stage. The lithology changes gradually from pillow breccias into finer-grained hyaloclastites (“móberg” in Icelandic) consisting of fragmented, variably consolidated and palagonitized sideromelane charts in the ash (<2 mm) and lapilli (2-64 mm) size fraction (Werner and Schmincke, 1999).

If the eruption stops at this stage (Fig. 4 (B)), a móberg ridge like Helgafell (a small example, only 2 km long and 0.8 km wide, rising to an elevation of 340 m a.s.l. (Schopka et al., 2006)) or a móberg cone like Keilir (379 m a.s.l.) is built. Both are situated on the Reykjanes Peninsula (Fig. 1), an active rift in the southwest of Iceland.
Emergent effusive stage
If the subglacial volcano grows above the ice sheet or the lake level it may prevent water to enter the vent and the eruption can be characterized as effusive again. Indicators for an eruption under air conditions are bombs, accretionary lapilli, airfall and base surge deposits as well as scarcity of sideromelane fragments and subaerial lava flows (Schopka et al., 2006). These flat-lying lavas cover the hyaloclastites and form lava deltas and a plateau (Fig. 4 (C)). This is typical for table mountains (“stapi” in Icelandic), both ridge like structures like Bláfjall (16 km long and 5 km wide, reaching a maximum elevation of 1222 m a.s.l. with an estimated volume of 13 km³ (Schiellerup, 1995)) and circular structures like Herdubreid (approximately 20 km² in volume and 4 km in diameter (Werner and Schmincke, 1999)), both part of the Northern Volcanic Zone of Iceland (Fig. 1).

During these evolitional stages direct contact features in the volcaniclastic sediments give evidence that the deposits were piled up against ice walls. Bending of initially horizontal beds (Schopka et al., 2006) is caused by the readvance of the glacial ice that tends to heal cavities. In subglacially erupted rhyolitic lavas columnar jointing normal to the steeply inclined sides, the gently inclined base and sometimes also to the top of the lava flow (Tuffen et al, 2001) may indicate contact to the ice, as joints grow normal to cooling surfaces.

Englacial vs. lacustrine origin of hyaloclastites at table mountains
However, when having a closer look at table mountains, they may be more complex as described above and can be the result of several cycles of volcanic activity. Werner and Schmincke (1999) presented a genetic model for the table mountain Herdubreid where they proposed that the lower part of the 1682 m high mountain with lacustrine sediments, including debris flow and turbidite deposits, originated from a depositional regime in huge lakes during warm periods. In contrast, the upper part of the volcanic edifice is made up of englacial deposits in the narrower sense. Therefore, these authors claimed the strict division of hyaloclastite deposits into sub- or englacial sensu stricto (e.g. formation in ice cavities, ice-bound lakes, faults in the ice filled with water) and lacustrine or marine.

Formation in large open lakes: Layered hyaloclastite facies
Description. Layered hyaloclastites made up more than half of the volume of the table mountain Herdubreid (Werner and Schmincke, 1999) and are associated with subaerial sheet lava flows and agglutinates. Armoured lapilli, pumice, scoria clasts and lava clasts are abundant. The sideromelane shards of the slightly altered hyaloclastites are highly vesicular.
The hyaloclastite occurs in the lower part of the edifice in massive and well-bedded layers with sharp contacts (Fig. 5). Grading (both normal and reverse) as well as cross bedding and a finer grained planar lamination with a better sorting is observable in distinct layers of the succession. A systematic change of facies from deep to shallow water and subaerial deposits is obvious.
Interpretation. The large distribution of the layered hyaloclastites and the fact that they are found together with subaerially formed clasts and lavas preclude an eruption in a water-filled ice cavity. That is supported by the high vesicularity of the vitric shards suggesting an explosive eruption and hydroclastic as well as pyroclastic fragmentation processes. Werner and Schmincke (1999) attributed coupled massive and bedded layers to the action of turbidity currents (upper flow regime of the Bouma sequence) and the graded, better sorted massive sections to debris flows (Fig. 5) taking place in large open lakes with a stable water level. The fine-grained layers may have developed during short intervals of quiescence by fallout from a heavily loaded suspension (Schopka et al., 2006). Moreover, the successions of the layered hyaloclastite imply a continuous evolution from deep to shallow water or even subaerial conditions and thus give no evidence for temporary major leakage of these lakes (Werner and Schmincke, 1999).

Englacial deposits: Chaotic hyaloclastite facies
Description. With the term “chaotic” Werner and Schmincke (1999) described massive or poorly bedded hyaloclastic deposits of Herdubreid with irregular shape, diffuse bedding planes and random arrangement (Fig. 6) where no organized change from deep water over shallow water to subaerial deposits can be traced. These hyaloclastites overlie the layered hyaloclastite facies and are associated with subaerial sheet lavas, lava spatter and pillows. The sideromelane shards are blocky with a large maximum grain size (>10 mm), a very poor sorting and a moderate palagonitization. The texture and composition of the hyaloclastites is homogenous compared to the layered hyaloclastite facies.

Fig. 5. Characteristic hyaloclastite of the layered facies at Herdubreid: Small mass flow deposit. Modified after Werner and Schmincke (1999).
Interpretation. Werner and Schmincke (1999) accredited the chaotic hyaloclastite facies having formed englacially sensu stricto in small ice-bordered lakes or chimney-like ice cavities (cf. Gudmundsson et al., 1997). The lack of transportation features in the deposits like good sorting, significant layering and secondary fragmentation emphasizes this theory. The limited space of ice-bound lakes precludes long transportation paths and permits the deposits to be piled up against ice walls. These eruption-fed hyaloclastites are believed to have accumulated near the vent because the moderate alteration suggests a higher temperature.

However, the chaotic and randomly changing structures of the hyaloclastites may not only be a result of the restricted width between the ice walls but also of the repeated build-up and emptying of small lakes in the ice sheet. This instability is possibly caused by the rapid drainage of meltwater from the glacier resulting in catastrophic glacier outburst floods, jökulhlaups. There is consent that releases of water occur episodically in long-lasting or repeated volcanic eruptions under glaciers (Werner and Schmincke, 1999). The triggered change in the eruptive environment is responsible for the development of erratic sections of shallow, deep water and subaerial volcanic deposits linked to unsystematic variation in eruption style between effusive and explosive where hydroclastic and pyroclastic fragmentation processes occur.

Discussion

Although Werner and Schmincke (1999) put forward a coherent theory on the formation of layered hyaloclastite deposits they could not outline the maximum aerial extent of the open lakes besides that they must have exceeded the volcanic edifices studied. That would mean at least 4 km in width for Herdubreid.

In addition, Werner and Schmincke (1999) only speculated about the origin of such ephemeral large open lakes. They disagreed with the scenario of Höskuldsson and Sparks (1997) and Gudmundsson et al. (1997) proposing sustained eruptions melted large quantities of ice because the petrology suggests different sources of magma (Werner et al., 1996) and therefore distinct eruption episodes. In between these eruption stages the glacier ice would have flown into the depression of the lake that would have frozen quickly. Due to this fast healing mechanism of the glacier, a lake formed by volcanic melting of the ice cap can be excluded.

Werner and Schmincke (1999) emphasized the hypothesis that the melting of the glacier is caused by climatic fluctuations. Two facts substantiate this assertion: Many strandlines known in the interior of Iceland are interpreted as lakefronts formed by ice-dammed lakes during warmer intervals of the Weichselian glacial period (Tómasson, 1993). Furthermore, the succession of lithofacies at Herdubreid suggests different water levels for the
formation of distinct subaerial deposits and therefore a thinner ice sheet during the evolution of the underlying lake sediments, the layered hyaloclastites.

Because sedimentary structures and other criteria are missing Werner and Schmincke (1999) were not able to outline a depositional setting for the basal pillow lava complexes at Herdubreid. They just referred to the generally known theory that the pillows are thought to correspond to the effusive stage of subaquatic eruptions and evolved in deep water or ice vaults.

Werner and Schmincke (1999) did also not take into account that even if the features for an eruption under subaerial conditions are absent the eruption might have nevertheless reached a subaerial stage e.g. through a chimney-like cavity. Subsequent aeolian and glacial erosion might have removed all traces of this eruption episode even so it cannot be totally excluded (Schopka et al., 2006). The same might be the case for ice contact features that were eroded by the glacial ice making an interpretation of successions at table mountains even more challenging.

**Conclusions**

Facies analysis may be the key to distinguish eruptive environments of subglacial volcanism. Although the main differences between strictly englacial deposits with no sign of transportation and lacustrine sediments built up by mass flows and gravity currents seem to be obvious they need to be applied more strictly to further subglacial volcanic edifices, not only in Iceland but also in other settings in the world like in British Columbia and Antarctica.

**References**


