Abstract

Dimmuborgir is thought to be a former rootless shield volcano, which was fed with lava from a nearby crater row, 2170 ± 38 calendar years before present. In this study, the orientation of striations on the sides of lava channels, collapse structures and lava pillars were measured to find out how the enigmatic ~2 km by 2 km volcanic structure at Dimmuborgir was drained. During one week of field work 149 striations were found and measured, with respect to their dip angle, dip direction and elevation. Their locations were recorded with a GPS (Global Positioning System) receiver. The orientations of the striations were visualized on Google Earth satellite images and on images from a Digital Terrain Model (DTM) of Dimmuborgir. Resulting visualizations show that Dimmuborgir was drained radially and in multiple stages. It is concluded that Dimmuborgir was drained towards the west, the northeast and the southeast. The drainage towards the west was channeled. The drainage towards the northeast and the southeast was radially inwards, towards the collapsed parts of Dimmuborgir.

Table of contents

1. Introduction

The origin of the Dimmuborgir volcanic structure, northern Iceland, has been the focus of a number of previous studies, because of its unusual morphology. Dimmuborgir is thought to be a former rootless shield volcano, which was fed with lava from a nearby crater row (Skelton et al., 2016). This hypothesis build upon previous models of Dimmuborgir by Rittman (1938), Barth (1942) and van Bemmelen and Rutten (1955).

The remnants of the rootless shield volcano testify to large-scale drainage. Bamlett and Potter (1986) described Dimmuborgir as a slightly domed structure, which was drained of lava through a channel, before all the lava had solidified. Barth (1942) described Dimmuborgir as a former lava lake, which drained back into an underlying reservoir. Skelton et al. (2016) described Dimmuborgir as overlapping rootless shields, which were drained along lava tubes with calculated effusion rates similar to measured effusion rates to the collapse of a rootless shield, during the 2007-2008 Thanksgiving Eve Breakout (TEB) eruptions of Kīlauea Volcano, Hawai'i. In these studies striations on lava pillars and side walls of lava channels at Dimmuborgir were mentioned as evidence of drainage or flow of lava.

This study will contribute to an ongoing assessment of the origin and drainage of the Dimmuborgir volcanic structure. The focus of this study is about drainage of Dimmuborgir. For the first time striations on the remnants of the rootless shield volcano were used to map drainage of the structure. The broader perspective of this study is to gain more insight about the geology and behavior of rootless shield volcanoes in general.

1.1 Aim of the study

The aim of this study is to use striations on the side of lava channels, walls and pillars to study the drainage of the Dimmuborgir volcanic structure.

Hypotheses which will be tested are:

- Whether Dimmuborgir was drained in one direction or radially.
- Whether Dimmuborgir was drained all at the same time or in stages.

The goals of this study are:

- To map striations on lava channels and pillars in the Dimmuborgir area.
- To use the compass orientation of these striations to interpret the direction/s of drainage.
- To use the dip angle of these striations to identify areas of fast and slow drainage.
- To use the elevation of these striations to decide if Dimmuborgir was drained in stages and in different directions.

1.2 Geologic setting

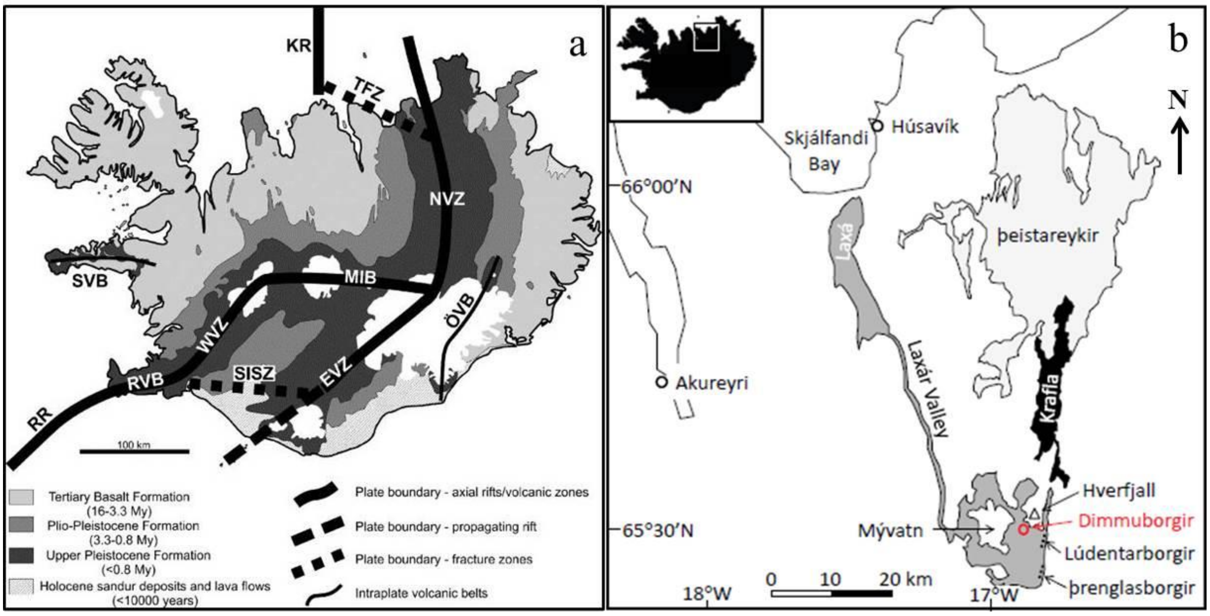

Figure 1a. The plate boundary between the North American plate and the Eurasian plate runs across Iceland where it is divided into segments. The Myvátn area and Dimmuborgir are situated at the North Volcanic Zone (NVZ in the figure). The figure was modified from Thordarson and Larsen (2007). **b.** Location map of northern Iceland illustrates the location of Dimmuborgir and the spreading of the Younger Laxá Lava, which is the dark grey area. The figure was modified from Skelton et al. (2016).

Iceland, the largest volcanic island on the Earth, is situated on the Mid-Atlantic Ridge, which runs through it. This is a divergent plate boundary, where extension of Earth's lithosphere occurs and volcanic material is welling up, forming new crust. Dimmuborgir is a volcanic structure situated between the Lúdentarborgir crater row and the lake Myvátn, northern Iceland (figure 1b). The Myvátn area is part of the North Volcanic Zone (NVZ) of Iceland (figure 1a), which is a zone where extension occur in northern Iceland. Numerous NNE-SSW trending crater rows, faults and eruption fissures, are situated in the Myvátn area, forming narrow horst and graben strips (Thorarinsson, 1979)**.** The lava forming Dimmuborgir is the Younger Laxá Lava (YLL). The postglacial volcanic activity in the Myvátn area is confined mainly to three cycles of which the YLL is part of the most recent cycle. This, the Hverfjall cycle, started about 2500 years ago with the formation of the tuff ring volcano Hverfjall (Thorarinsson, 1979). Radiocarbon dating of charred vegetation beneath the YLL provides an age of the YLL of 2170 ± 38 calendar years before present (Hauptfleisch and Einarsson, 2012). The YLL erupted from the NNE-SSW trending Threngslaborgir and Lúdentarborgir crater rows, which have a combined length of ~10 km and are situated at an elevation of 344-374 meters above sea level (m.a.s.l.) (Skelton et al., 2016). During the eruption of the YLL, the lava flow moved westwards across the Dimmuborgir area further west around the lake Myvátn. The lava continued NNW, following Laxár Valley and finally reached Skjálfandi Bay on the north coast of Iceland, 63 km from Threngslaborgir. The predominantly rubbly pahoehoe type YLL (Skelton et al., 2016) cover an area of about 220 km^2 and the volume is estimated to be at 2.5 km^3 (Thorarinsson, 1979). The geochemical character of the lava is tholeiitic (Jakobsson, 1972).

1.3 The volcanic structure of Dimmuborgir

Dimmuborgir covers an area of approximately 2 × 2 km. Skelton et al. (2016) have described the structure of Dimmuborgir as a shield-like plateau with two central depressions, one circular and the other semicircular (figure 2). These central depressions are rimmed with lava pillars and walls. The summits of the lava pillars and walls can be envisioned to connect and form an upper plateau or surface of Dimmuborgir, which is seen to slope outwards from the centre of each central depression (Skelton et al., 2016).

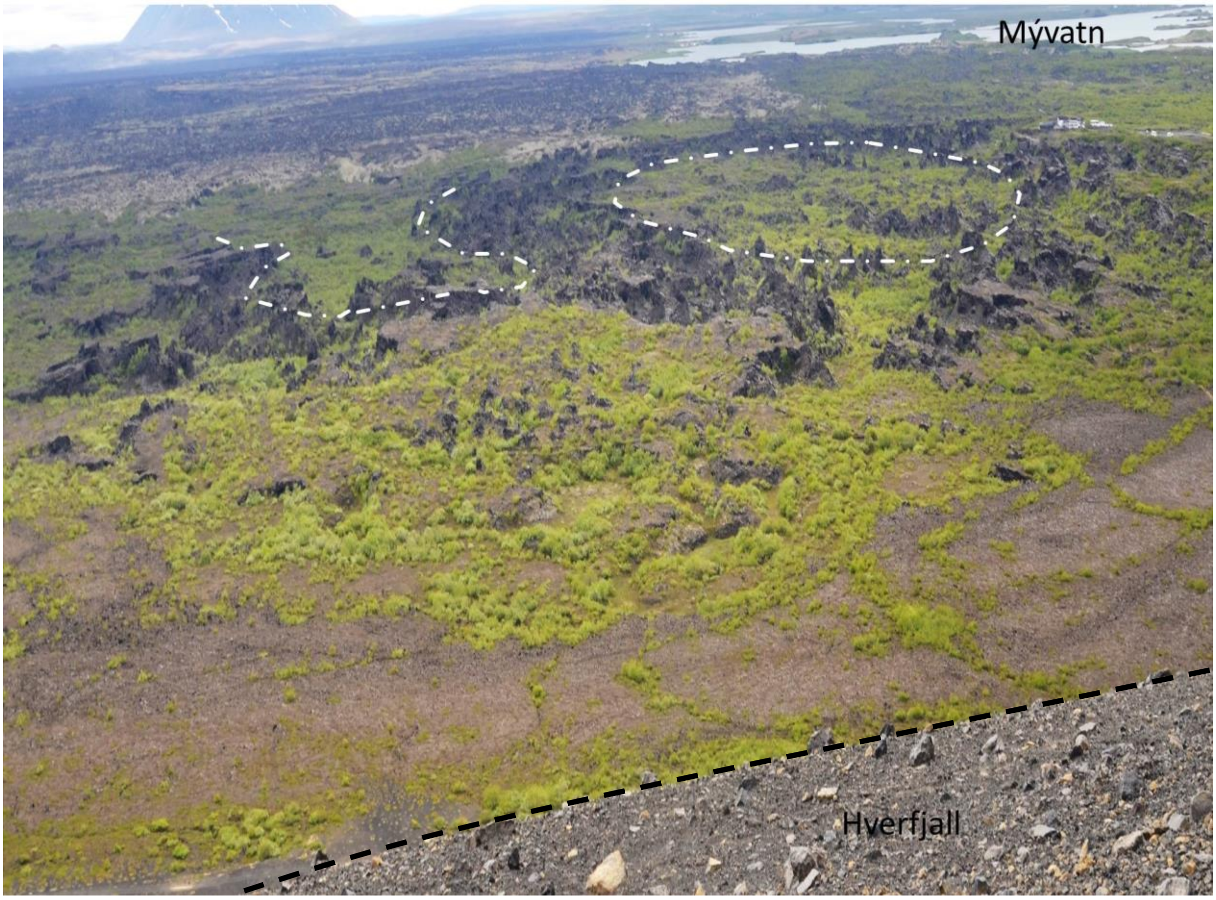

Figure 2. Dimmuborgir viewed southwest from the nearby tuff ring volcano Hverfjall. The picture is modified with two time's vertical exaggeration and was taken from the edge of the southern rim of Hverjfall. The black line delineates the edge of Hverfjall, about 120 m above the Dimmuborgir area. A circular and a semicircular depression are delineated with the white encirclements. The lake Myvátn is visible in the background.

Based on a Digital Terrain Model (DTM), Skelton et al. (2016) have proposed that Dimmuborgir is a shield-like plateau, which may consist of two overlapping shield-like structures, with approximate diameters of 1.0-1.5 km. The central parts of Dimmuborgir are elevated by ~30 m with respect to the surrounding lava flows (Skelton et al., 2016). The slope angle of the overlapping shields is within the range for tholeiitic shield volcanoes on Iceland (0.03-7°: Rossi, 1996). The DTM also revealed that the remnants of the shield-like structures, which rim the central depressions, form multiple semi-circular and circular collapse structures. Some of these collapse structures follow NNE-SSW trending fractures, which run across Dimmuborgir (Skelton et al., 2016).

Various marks from the time when Dimmuborgir was active have been found on lava pillars and walls within the central depressions and at the surrounding rims. Skelton et al. (2016) described multiple laterally extensive lava levels beneath the upper plateau of Dimmuborgir. These are seen to slope out from the centre of the structure. Barth (1942) described that many of the pillars have horizontal lava shelves and also vertical marks, which resemble slickensides. Bamlet and Potter (1986) described the lava shelves as ‘tide marks’. The vertical marks are also known as striations. Skelton et al. (2016) described vertical striations and striations which have dip angles in different directions, recording the flow of lava. Bamlett and Potter (1986) described a lava channel along where they claimed the remaining fluid lava drained out from Dimmuborgir. Skelton et al. (2016) described the same structure as a 30 m wide lava channel, which is descending westwards from Dimmuborgir. This lava channel and a similar one, which is descending southwards, can be seen on the DTM (Figure 3a and b). Skelton et al., (2016) associated these channels with westwards and southwards drainage of Dimmuborgir.

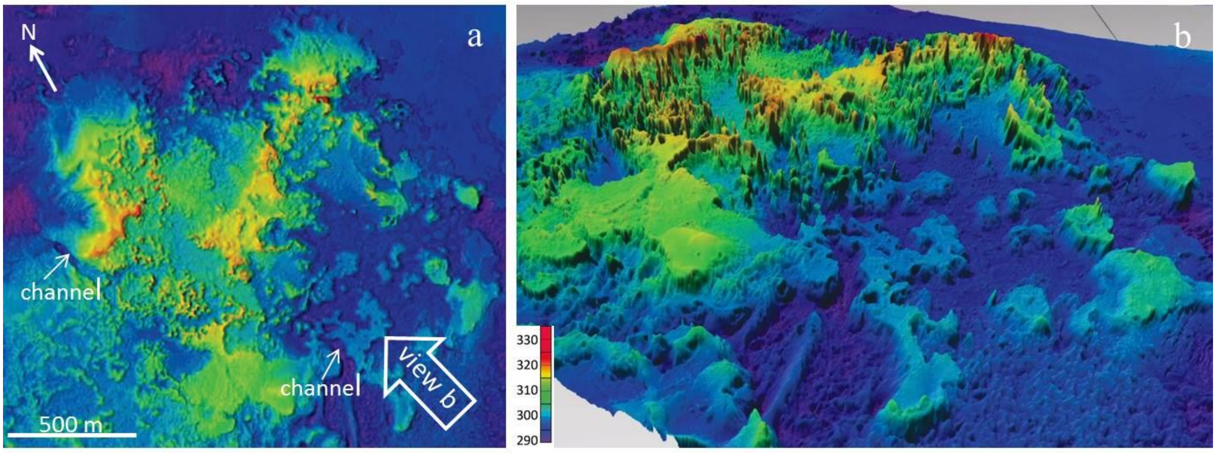

Figure 3a. DTM shows an overview of Dimmuborgir. Two lava channels are marked with arrows. **b.** Dimmuborgir viewed obliquely from ‘view b’ on figure 3a. Colour coded scale denotes elevation in m.a.s.l. Both figures were modified from Skelton et al., (2016).

1.4 Rootless shields

Shield volcanoes are directly linked to a deep-seated magma chamber or vent. Unlike large shield volcanoes, rootless shields are smaller shield-like mounds of lava, which are fed by and built above shallow and active lava tubes just below the Earth’s surface (Poland et al., 2014; USGS, 2008). These features are considered rootless because they are not directly linked to a deep magma chamber. Active rootless shields were first discovered in 1999 and have since then been observed several times (Poland et al., 2014). The largest rootless shields can be about 40 m high (USGS, 2008) and 400-700 m in diameter (Patrick and Orr, 2012). They are unstable features and may rupture or collapse, leaving hollow interiors which were filled with lava before draining (Poland et al., 2014). The 2007-2008 TEB eruptions of Kīlauea Volcano, Hawai'i, have contributed a lot to the knowledge of the geology and behavior of rootless shields (USGS, 2008).

1.5 Striations in volcanic settings

Striations occur in volcanic settings. These types of striations are parallel to the direction of movement of the object that caused them and can be used as an indicator of movement direction. Previous studies have been done where striations have been coupled with the direction of lava flows. Petry et al., (2007) described flow striations in sandstone, which formed in unconsolidated dry sand. The striations were formed from the shear stress at the base of the lava flow. Jerrham and Stollhoffen (2002) described lava-sediment interaction as lava moving over the sand, resulting in striations which were preserved as sub-parallel linear ridge and trough structures, on the top of the sand surface with less than 1 cm of relief. Scherer (2002) described striations in sandstone as lava flow features, printed onto the dune surface and probably caused by a pahoehoe lava flow. Naranjo et al., (1992) described well-developed horizontal striations on the inner wall of a lava channel, where andesitic lava levees took place. Stevenson et al. (2012) described former channels or collapsed tubes that have sub-horizontal striations on the walls, due to scouring by drainage of lava during the prehistoric Nesjaharaun basaltic lava eruption on Iceland.

Gregg and Christle (2013) described vertical striations on lava pillars in Skaelingar, Iceland, where a lava flow in a valley was drained out in the 1700s. The lava pillars here were generated sub aerially by lava-water interaction. When the lava level in the valley subsided, solidified lava crust on the surface of the lava flow is thought to have scratched the still ductile pillar walls and left behind vertical striations. The striations are a few cm to tens of cm long and typically < 10 cm wide. They have a surface texture which feels smooth when rubbing ones fingers from the top to the bottom of vertical striations on a pillar and rough from the base to the top. This textural feature indicates movement of the lava flow from the top of the pillar to the pillar base (Gregg and Christle, 2013).

Calvari and Pinkerton (1999) described vertical grooves along the walls of a lava tube, resulting from the scraping of cool 'a'a clasts against the once plastic tube walls. These grooves indicate withdrawal of the lava in a steady downwards motion. Abrupt changes in the direction of the grooves can record sudden changes in flow direction of the lava (Calvari and Pinkerton, 1999).

2. Methods

2.1 Field work

Between 28/6 and 4/7, in 2015, a field study was conducted at Dimmuborgir, which cover an area of approximately 2 km by 2 km. The field work objectives were to locate striations and measure their orientation on the walls of lava channels and lava pillars in the Dimmuborgir area. The orientation in the field and the localization of the striations was conducted on the basis of printed maps from Google Earth, a GPS (Global Positioning System) receiver (Garmin GPS 12 Personal Navigator) and a compass. The reference system used in the GPS receiver was World Geodetic System 1984 (WGS 84). For each location where striations were found and measured, a waypoint was saved in the GPS receiver. In the evenings during the field study, these waypoints were added to Google Earth, which uses the same geodetic datum as the GPS receiver. Keeping track on the waypoints made it easier to plan the route for the next day. Furthermore, a function in the GPS receiver was used, which showed the bearing and distance to the closest recorded waypoints. A total of 140 waypoints were recorded with the GPS receiver (figure 4).

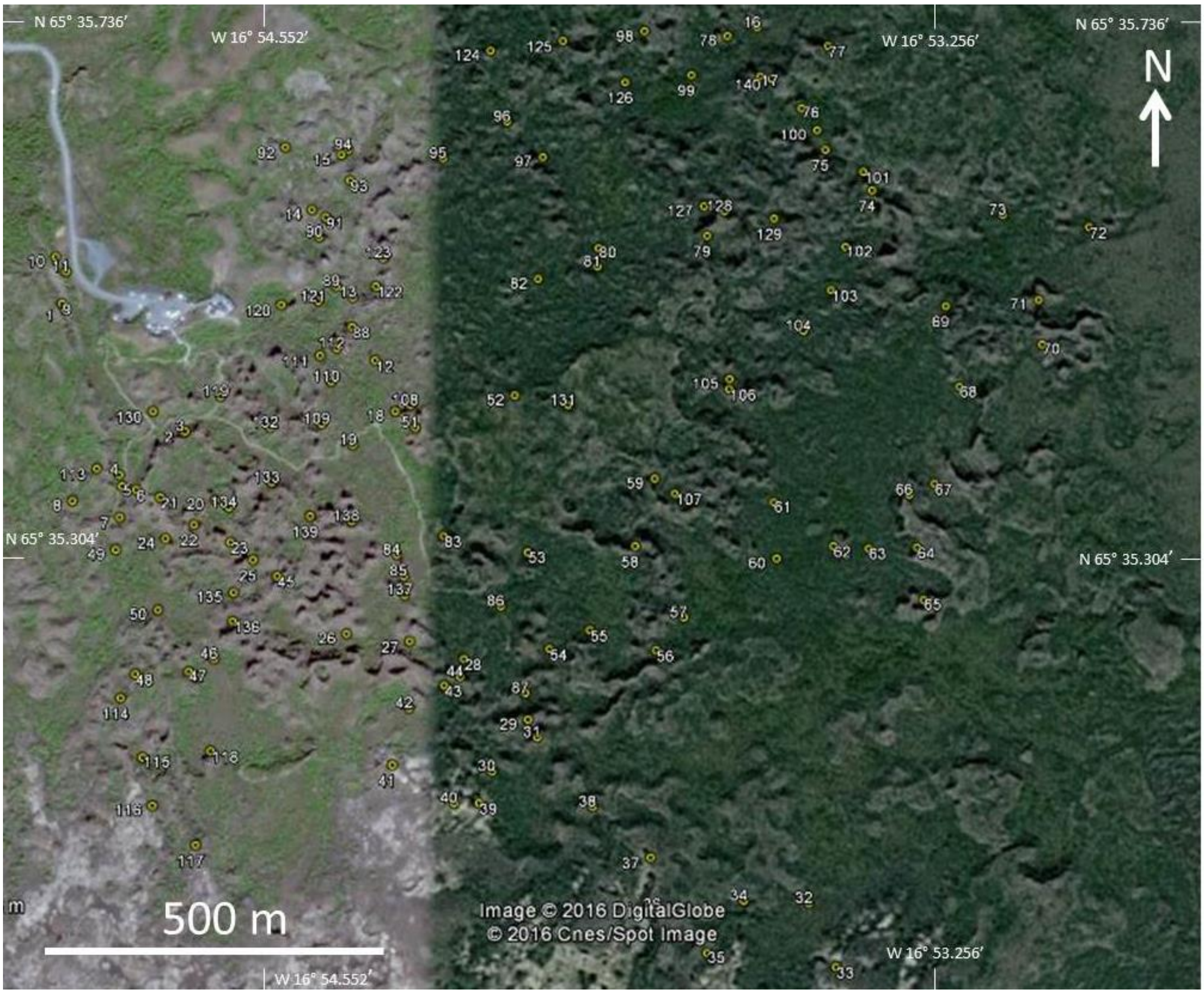

Figure 4. Modified satellite image from Google Earth showing an overview of the Dimmuborgir area and 140 waypoints which mark the positions where striations were found and measured. The position format for latitude and longitude is degrees decimal minutes, based on the reference system WGS84.

The waypoints were taken facing the striations, a few meters out from the striations, preferably on a flat surface. This was done to make it easier for measuring the elevation of the striations. Another reason was that the connection between the GPS receiver and satellites is better a few meters away from big objects, such as lava pillars, rather than close to them. This was experienced during the field work and the connection between satellites and the GPS receiver was better a few meters away from the lava pillar and lava walls. In that sense the margin of error of the GPS receiver was reduced and the waypoints taken were more accurate. The validity of the location of these waypoints relies on the assumption that lava here were flowing in the same direction as the lava that made the striations.

All striations were measured with respect to dip angle and dip direction (figure 5), using a compass clinometer. Dip direction is the compass direction in degrees that the striations are inclined towards. The north corresponds to 0°/360°, the east to 90°, the south to 180° and the west to 270°. Dip angle is the inclination angle of the striations relative to a horizontal plane. Horizontal striations have a dip of 0° and vertical striations have a dip of 90°. Dip direction of the striations was used to interpret the compass direction of lava flow, whereas dip angle of the striations was used to interpret the velocity of lava flow. Pictures were taken of the striations at all waypoints except the last ten, because the battery of a smartphone ran out. The pictures of striations at 51 of the total 140 waypoints were taken during the first three days with a camera (Nikon D7000). Due to weather the rest of the pictures of the striations were taken with a waterproof smartphone (Sony Xperia C6603) during the last four days of the field work.

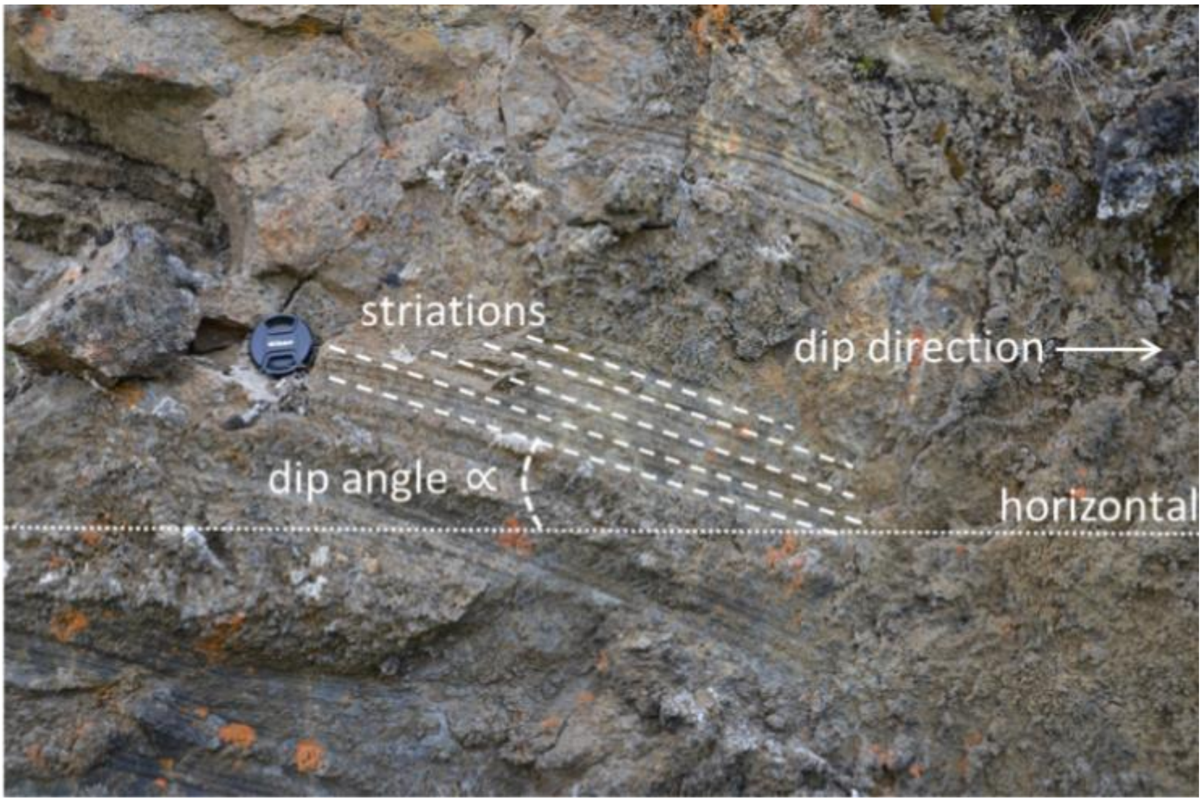

Figure 5. The dip angle is the inclination of the striations with respect to the horizontal. The striations are dipping towards the dip direction. Camera lens cap for scale.

A digital laser inclinometer and rangefinder (Bosch GLM 80 Professional) was used to measure the height of the striations, relative to the place where the waypoints were taken with the GPS receiver (figure 6). The highest visible points of the striations were measured. The instrument measured the height, the angle of elevation and the distance between striations and the place of measurement. The instrument was used from a predefined height above the ground of 1.13 m, which was added to all the measured heights.

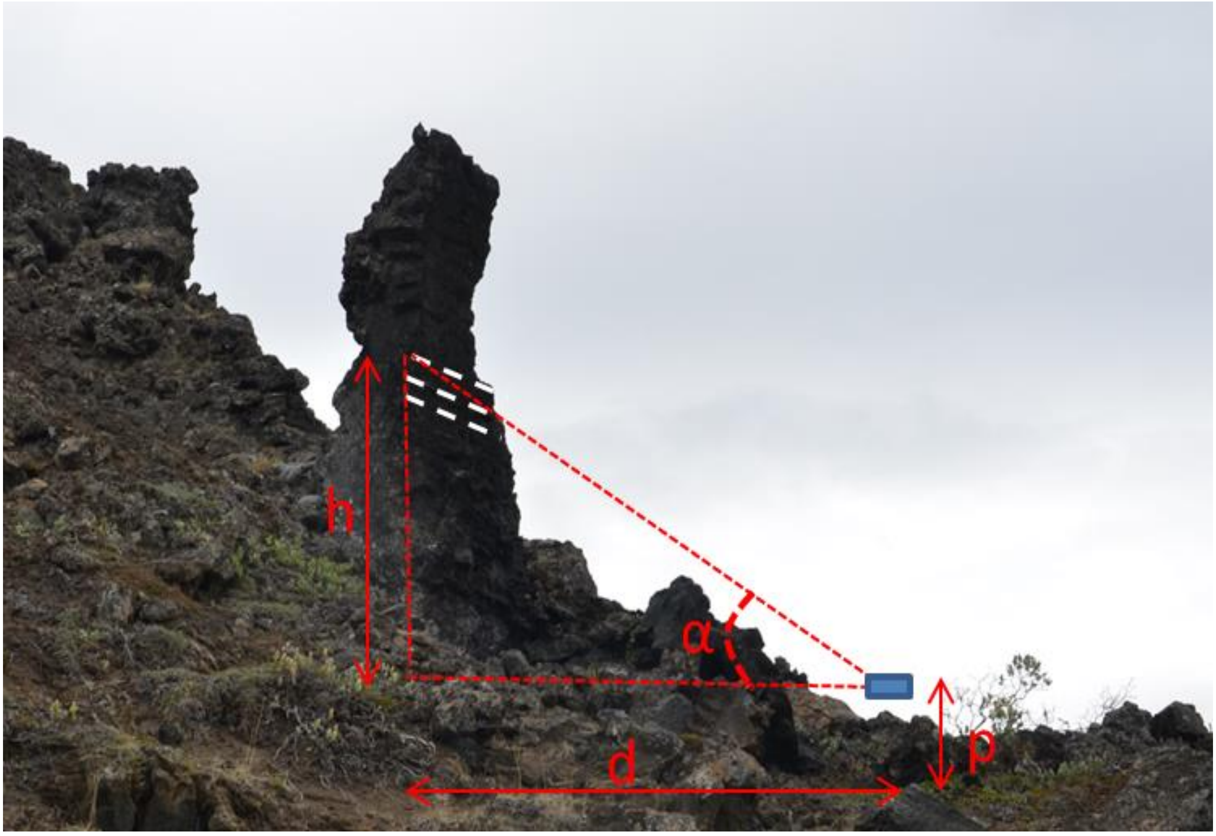

Figure 6. The white stripes represent striations on the lava pillar. The blue rectangle represents the digital inclinometer and rangefinder, which was used to read the height (h) of the striations from a predefined height (p) of 1.13 m from the ground. The angle of elevation (α) and the distance (d) to the striations from the place of measurement and were also measured. The photography was taken at Dimmuborgir.

2.2 Data processing

The waypoint coordinates and the measurements of the striations were written down in a field notebook. The waypoint coordinates were transferred from the GPS receiver to Google Earth and also into a text file. All data were compiled in Microsoft Excel spreadsheets. Data visualization was performed using the software Fledermaus, Google Earth and Microsoft Powerpoint. Fledermaus, which is an interactive 3D data visualization system, was used to retrieve the elevation (m.a.s.l) of the ground were the waypoints were taken. The waypoint coordinates were incorporated in the DTM. The elevation (m.a.s.l) of the ground where the waypoints were taken was then extracted from the DTM into Microsoft Excel spreadsheets. To get the correct elevation (m.a.s.l) of the striations, their measured heights in the field were added to the elevation data that was extracted from the DTM.

Striation data were visualized by arrows superimposed on Google Earth satellite images and images from the DTM of Dimmuborgir. Microsoft Powerpoint was used to superimpose the arrows on these images. The positions of the arrows were synchronized with the waypoint coordinates, which were obtained from Google Earth. The arrows were colour coded based on dip angle, dip direction and elevation of the striations. Four different maps were made. The arrows on all maps were given four different lengths based on the dip angle of the striations, to identify areas of fast and slow drainage in the Dimmuborgir are. The arrows on all maps were also placed so that they are pointing in the same compass direction as the dip directions of the striations.

The first map is focused on dip direction of the striations, to interpret the direction/s of drainage. The arrows were superimposed on a Google Earth image of the Dimmuborgir area. The arrows were given four different colours based on their compass direction which was obtained from the dip direction of the striations.

The second map is focused on dip angle of the striations, to identify areas of fast and slow drainage. The arrows were superimposed on the same Google Earth image used in the first map. The arrows were given four different colours based on the dip angle of the striations.

The third map is focused on elevation of the striations, to interpret possible stages of drainage. The arrows were given eight different colours based on their elevation. The elevation interval for each colour was set to 2.825 m and was calculated based on difference in elevation between the highest (310.1 m.a.s.l.) and the lowest (287.5 m.a.s.l.) situated striations which was measured in the field. One-eight of this difference in elevation equals 2.825 m.

The fourth map is focused on dip angle and dip direction of the striations, relative to the shield morphology of Dimmuborgir. The arrows from the first map were superimposed on an image from the DTM of Dimmuborgir. This map was used to interpret the drainage of Dimmuborgir.

3. Results

3.1 Field results

Figures of the striations at waypoints 1-130 are found in Appendix A.

3.1.1 Waypoints of the striations

A total of 149 striations situated at different locations were observed and measured at Dimmuborgir during the seven days of field work. Their coordinates were marked with 140 waypoints by the GPS receiver. Two different sets of striations, with respect to dip angle, dip direction and elevation, were located at nine of these waypoints. Hence, some of the 149 striations share the same waypoint. Prior to processing the data, a total of 152 waypoints were marked. After the fieldwork all striations were reviewed. Striations at six waypoints were found to be some other structural feature and another six striations were found to be doublets. These twelve waypoints were removed and the total number of waypoints where striations are situated resulted in 140 (figure 4). The 140 waypoints of the observed striations cover almost the entire area of Dimmuborgir, which is about 2 km by 2 km. The striations were found on lava pillars and other lava structures at different elevations.

3.1.2 Structures of the striations

The striations found at Dimmuborgir are sets of thin, parallel and alternating ridge and groove structures, which vary in thickness from several millimeters to a few centimeters. The depth of the grooves and relief of the ridges also vary and are from several millimeters to a few centimeters deep and high. Some striations are a few centimeters wide, while others are a few meters wide. Both curved and linear striations were found (figure 7 a-c). The curved character of the striations indicates that they were formed when the lava pillars and walls were ductile. The dip angle of the curved striations was measured with respect to their mean dip angle. Curved striations which abruptly change dip angle are both situated on rounded corners of lava pillars and on vertical lava walls. At waypoint 34 vertical striations are situated at the bottom of a lava wall, which have a descending lava tube from its base (figure 7 c and d). Waypoint 34 is situated about 110 m east to the southward-trending channel, which was described by Skelton et al. (2016)

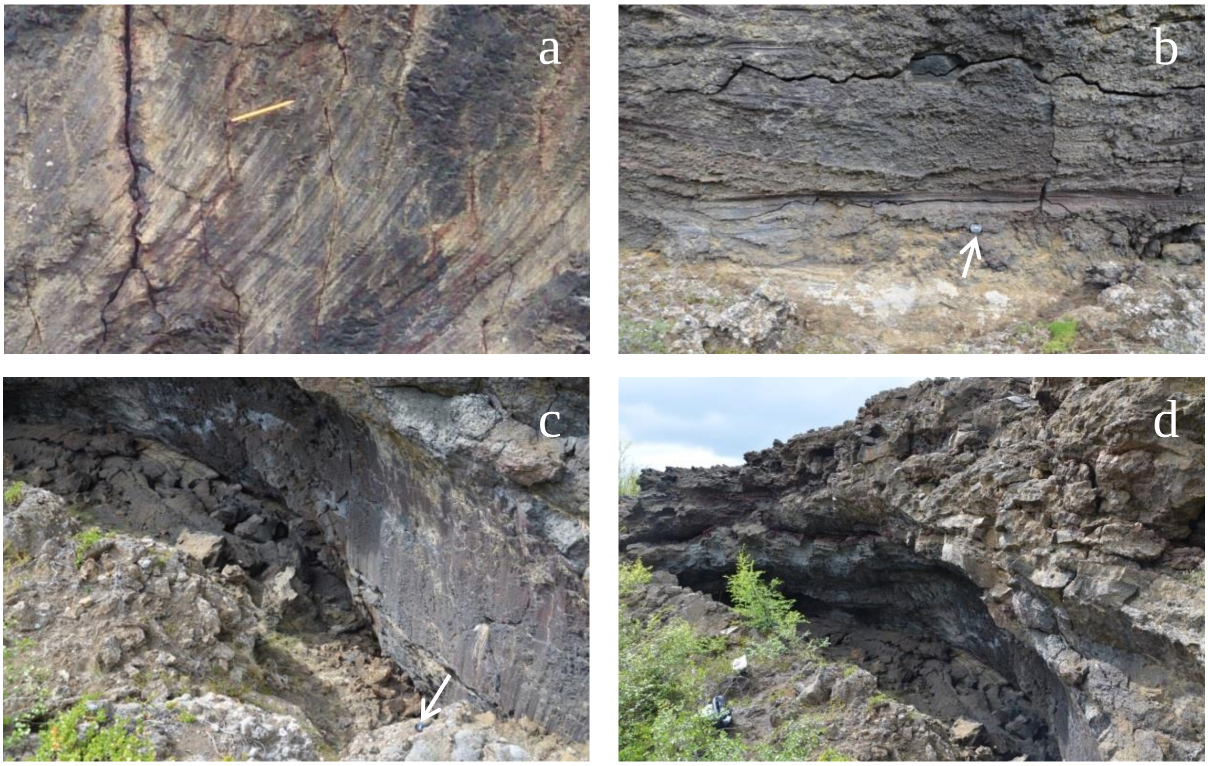

Figure 7. Different types of striations. **a.** Curved striations on a vertical wall. Pen for scale. **b.** Horizontal striations. Highlighted lens cap for scale. **c.** Vertical striations.Highlighted lens cap for scale. **d.** The striations in figure c were found at the base of a lava wall. What could be remnants of a lava tube is descending from the base of the lava wall.

At nine waypoints more than one set of striations are situated at different elevations, with different dip data (figure 8 a-f). Five of them are situated on rounded corners of lava pillars. At waypoint 20, striations with a notable difference in dip direction are situated close to each other, on a rounded corner of a lava pillar. At waypoint 106 two sets of striations have different dip angle and elevation. The highest situated striations are more vertical and merge into the lowest situated striations. Sub horizontal striations, separated from each other, with almost the opposite dip direction were found at waypoint 1, which is in the lava channel which was described by Bamlett and Potter (1986) and Skelton et al. (2016). In the same lava channel at waypoint 10 sub vertical striations are situated directly above sub horizontal striations. At waypoint 63 striations form a crisscross pattern.

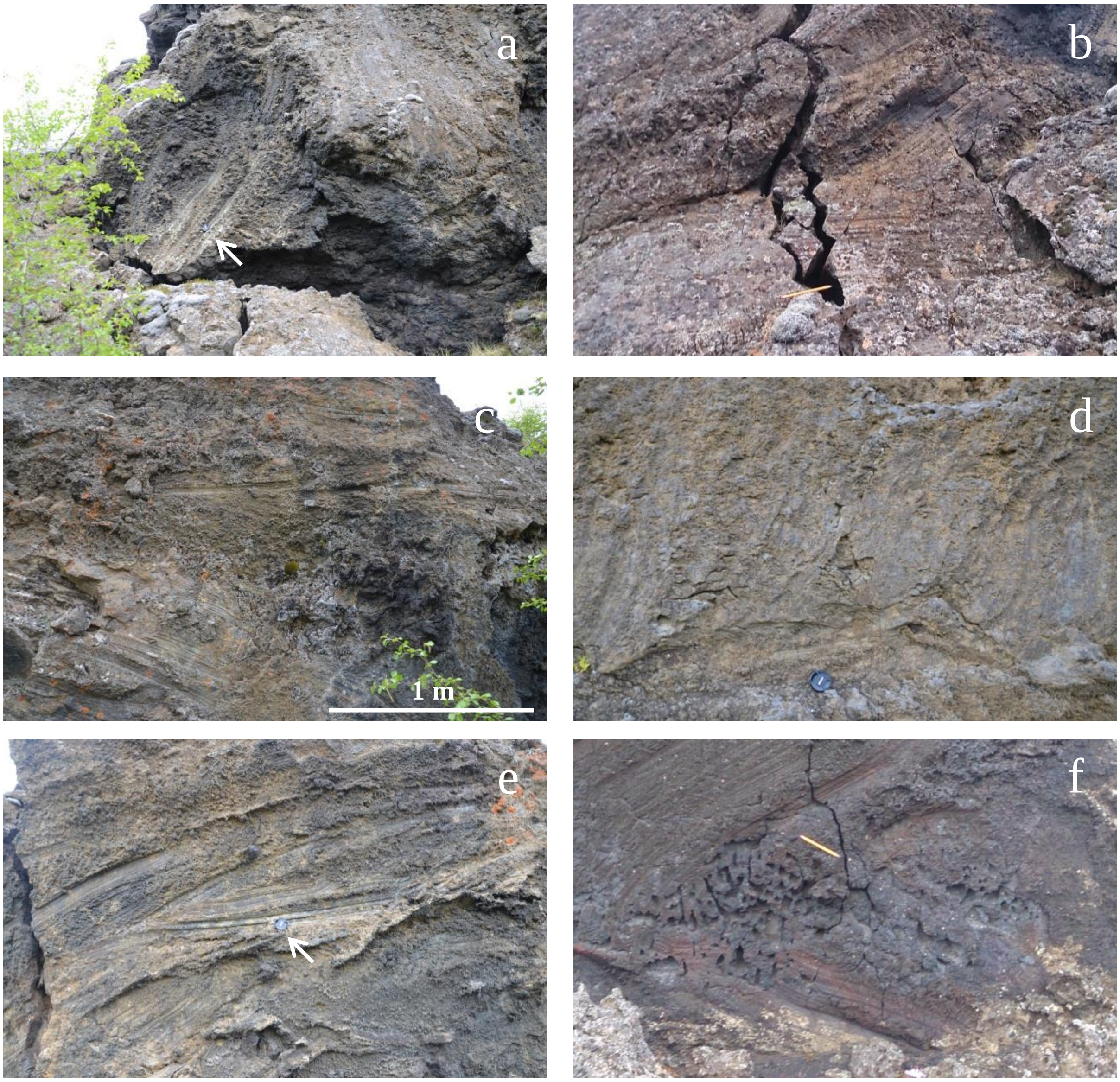

Figure 8. More than one set of striations at the same lava structure, which are situated at different elevations, with different dip data. **a.** Striations at waypoint 20 on the corner of a lava pillar with different dip directions. The arrow highlights a lens cap for scale **b.** At waypoint 106 the uppermost striations are merging in to the same dip angle as the lower striations. **c.** Sub horizontal striations, separated from each other with almost opposite dip direction, were found at waypoint 110. **d.** Sub vertical striations on top of sub horizontal striations at waypoint 10. **e.** At waypoint 12 striations with the same dip direction but different dip angles are forming a v-shaped pattern. **f.** Striations with opposite dip direction situated on top of each other at waypoint 63.

The striations at waypoint 110 are situated at different elevations, separated by a horizontal lava shelf (figure 9). Another horizontal lava shelf is situated on top of the uppermost striations. The dip angle and dip direction of these striations are approximately the same. The elevation of the uppermost striations is 306.2 m.a.s.l., which is the fourteenth highest measured elevation of all measured elevations of the 149 striations.

Figure 9. Striations cover the entire side of a lava pillar at two elevations, separated by a lava shelf.

3.2 Data compilation

Measurements of dip angle, dip direction and elevation of the striations, together with their WGS84 coordinates, are compiled in table 1 (Appendix B).

The mean value of dip angle with respect to the 149 measured striations is 54° The mean value of dip angle for the striations in every 5° dip direction interval is shown in figure 10 a. Broadly, if the Dimmuborgir structure is viewed as one unit, the dip directions of the striations are well spread out (figure 10 b). There is a slightly higher frequency of striations with dip directions 020-025°, 060-065°, 160-165° and 240-245°.

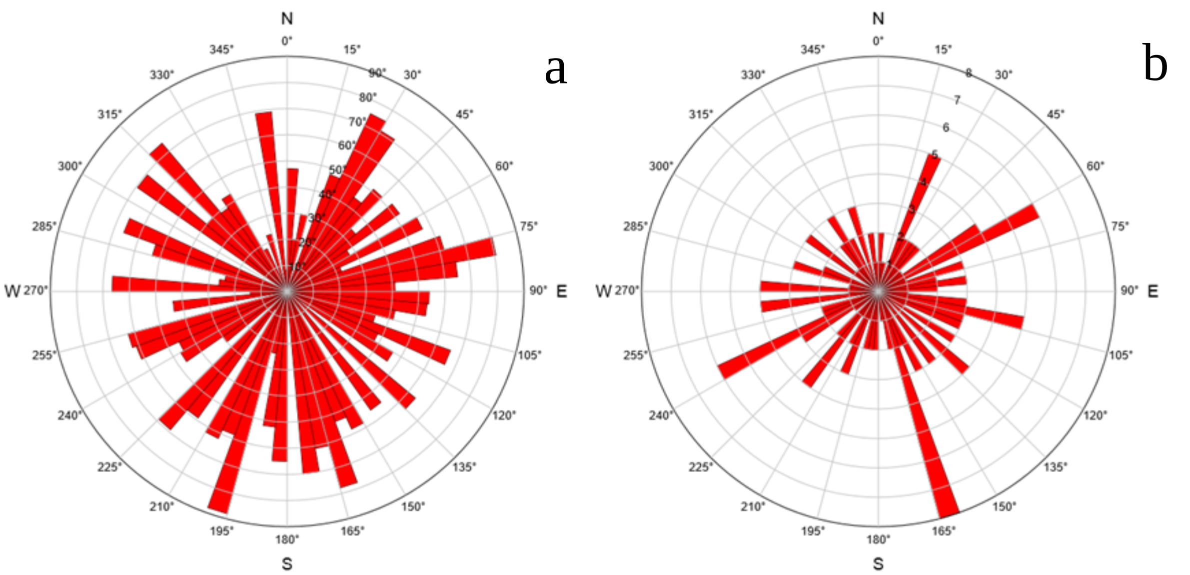

Figure 10. Rose diagram of every 5° compass direction interval relative to the dip data of the striations at Dimmuborgir. The north corresponds to 0°/360°, the east to 90°, the south to 180° and the west to 270°. **a.** Mean dip angle of striations in every 5° dip direction interval. **b.** Number of striations measured in every 5° dip direction interval.

3.3 Data visualization

3.3.1 Dip data of striations relative to their coordinates

Measured striation data were compiled and visualized. The arrows on the map in figure 11 depict dip angle and dip direction of the striations, with respect to their coordinates. This map is focused on dip direction relative to striation coordinates, which can be used to interpret the direction/s of drainage.

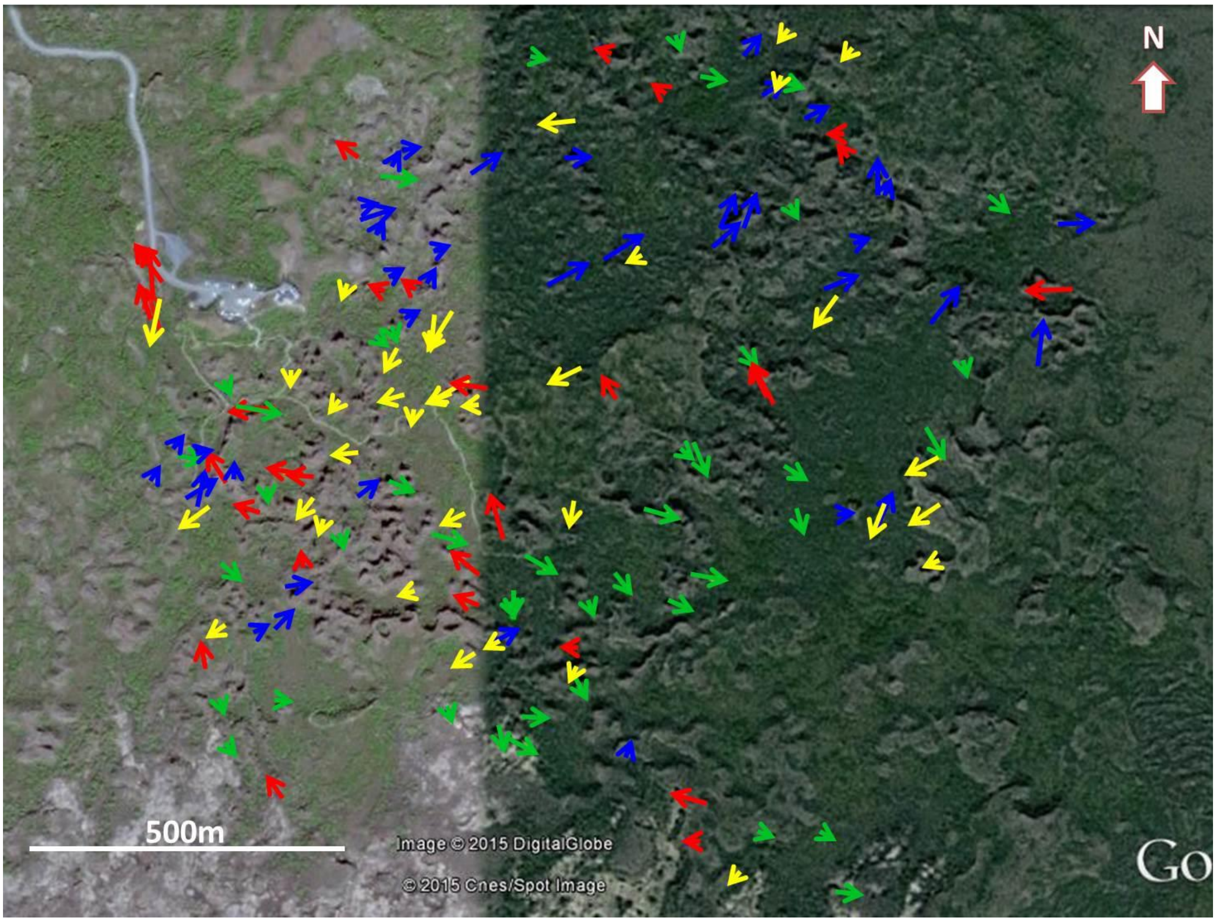

Figure 11. Arrows superimposed on a modified satellite image from Google Earth, depicting dip angle and dip direction of the striations. The arrows are colour coded with respect to dip direction: blue = 0-90°, green = 90-180°, yellow = 180-270° and red = 270-360°. There are four different lengths of the arrows, which represent different dip angle of the striations. From longest to shortest they represent 0-20°, 20-40°, 40-60° and 60-90°.

Blue arrows which indicate lava flow direction between the north and the east constitute ~27% of the total number of arrows. ~65% of these are situated in the northern half of Dimmuborgir. Remaining blue arrows are mainly short, representing steeply dipping striations, predominantly situated at the southwestern part of Dimmuborgir. Green arrows which indicate lava flow direction between the east and the south constitute ~29% of the total number of arrows. ~65 % of these are situated in the southern half of Dimmuborgir. Remaining green arrows are mainly short and well spread out. Yellow arrows which indicate lava flow direction between the south and the west constitute ~24% of the total number of arrows. ~72% of these are a situated in the western half of Dimmuborgir. Remaining yellow arrows are well spread out. Red arrows which indicate lava flow direction between the west and the north constitute ~20% of the total number of arrows. ~67% of these are situated in the western half of Dimmuborgir. Remaining red arrows are mainly short and well spread out. A few long red arrows differ from this pattern. Long arrows represent shallow dipping striations. Arrows with the same length, which represent striations with similar dip angle, are clustered in many places in figure 11. Clusters of arrows are more clear on a map focused on dip angle of the striations (appendix C).

3.3.2 Dip data of striations relative to elevation and shield morphology

The colour coded arrows from figure 11, which can be used to interpret drainage, were projected on a DTM overview of Dimmuborgir (figure 12). Sections of Dimmuborgir differ from each other with respect to elevation and morphology. The focus of the map in figure 12 is the correlation between the dip direction and dip angle of the striations, relative to the morphology of Dimmuborgir. The elevation of the striations is visualized on a map where the arrows are colour coded with respect to elevation (appendix D).

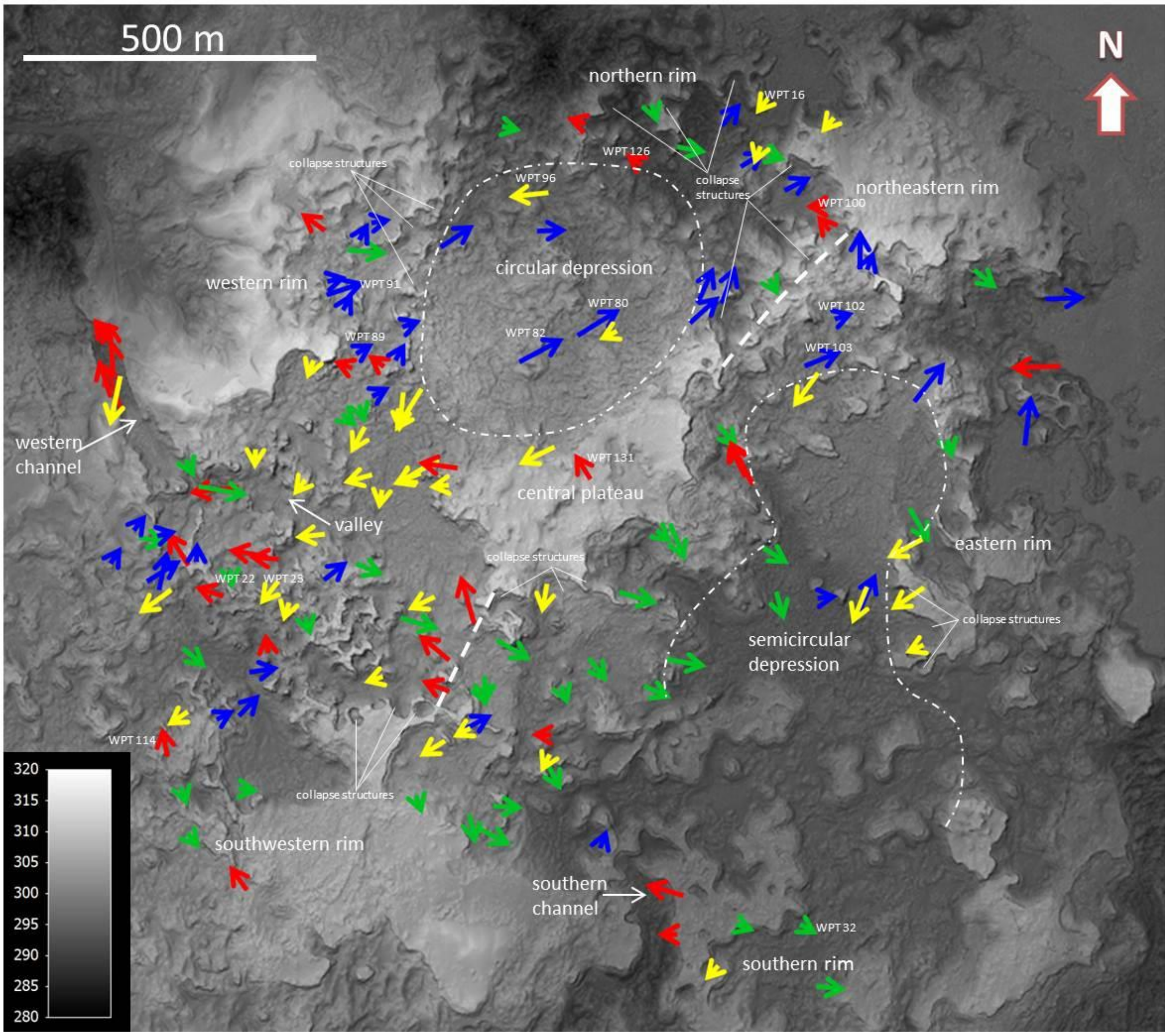

Figure 12. The arrows from figure 11 superimposed on a grayscale DTM overview of Dimmuborgir, depicting dip and dip direction of striations. A circular and a semicircular depression are delineated. The two dashed white lines deliniate relative low-lying areas located southwest and northeast of the central plateau. DTM image is modified after Skelton et al., (2016). Scalebar denotes the range of elevation between 280 and 320 m.a.s.l.

The northern rim of the circular depression is a relatively low-lying area. Striations found on the remnants of the rim have mainly steep dip angles and are some of the lowest situated striations that were found at Dimmuborgir. Multiple semicircular collapse structures are visible here (figure 12). Further evidence of collapse here was observed at waypoints 16, 100 and 126. The striations at these waypoints are situated on partly collapsed lava pillars.The western rim of the circular depression is clustered with steep northeasterly dipping striations. Multiple collapse structures are visible here in figure 12. Further evidence which indicate collapse were observed at waypoints 89 and 91. The striations at these waypoints are situated on partly collapsed lava pillars. Four striations found inside the circular depression are dipping towards the northeast. These are depicted by the blue arrows in figure 12. Three of the striations in the circular depression, at waypoints 80, 82 and 96, are situated on partly collapsed lava pillars.

Striations found southwest of the circular depression and northeast of a valley, which is highlighted in figure 12, are mainly dipping towards the southwest and the valley. These striations are depicted by yellow arrows. The valley is a ~30-50 m wide and is heading towards the lava channel described by Bamlett and Potter (1986) and Skelton et al. (2016). The lava channel is ~30 m wide and clustered with striations which dip towards the northwest. Nearly horizontal dipping striations were found along the valley and lava channel.

Many striations were found on lava structures in southwestern Dimmuborgir, which is the area south of the valley and lava channel and north of the southwestern rim of Dimmuborgir. This area is clustered with peculiar looking lava pillars and lava structures. Several tourist routes are located here. Striations found in the northern half of this area have a tendency to dip towards the lava channel. These striations are depicted by blue and red arrows in figure 12. Dip directions of striations in the southern half of this area are more scattered. The dip angles of these striations are generally steep. Multiple collapse structures are located in this area. Some of these collapse structures are circular. Further evidence which indicate collapse in this area was observed at waypoints 22, 23 and 114. The striations at these waypoints are situated on partly collapsed lava pillars.

The central plateau is an area of relatively high elevation, situated in the central part of Dimmuborgir. This is area is potentially located at the borderland between the two overlapping shield-like structures which were described by Skelton et al., (2016) Few striations were found in this area. The highest situated striations of all 149 specimens were found here at waypoint 131. These striations are situated at an elevation of 310.1 m.a.s.l. and are dipping towards the circular depression (figure 12).

A ~200 m wide area (dashed white line in figure 12) between the southwestern rim of Dimmuborgir and the central plateau is less intact compared the southwestern rim and the central plateau. Three sub horizontal striations are dipping towards the northwest here, depicted by three red arrows in figure 12. Just east of here two striations with relatively shallow dip are dipping towards the southeast, depicted by green arrows in figure 12. Another less intact area (dashed white line in figure 12), which is ~300 m wide, is situated between the central plateau and the northeastern rim of Dimmuborgir. Compared to the central plateau and the northeastern rim of Dimmuborgir this section is less intact and multiple collapse structures are visible here in figure 12. Further evidence of collapse here was found at waypoints 102 and 103, where striations are situated on partly collapsed lava pillars. The striations in this area are mainly dipping towards the northeast. These striations are depicted by blue arrows in figure 12.

The semicircular depression in figure 12 is situated at low elevation relative to the other sections of Dimmuborgir. Remnants of the eastern rim of this depression can be seen in figure 12. Three striations situated at the inner part of the eastern rim are dipping towards the southwest and central part of the semicircular depression. These are depicted by yellow arrows in figure 12. Multiple collapse structures are situated here. The northeastern part of the eastern rim of the semicircular depression is a relatively low-lying area. The striations found here have predominantly shallow dip angles towards the northeast. These are depicted by blue arrows in figure 12.

The western rim of the semicircular depression is clustered with striations which are dipping towards the southeast. These are depicted by green arrows in figure 12. Multiple collapse structures are situated at the western rim of the semicircular depression.

The southern rim of the semicircular depression is a relatively low-lying area and the striations found here are steeply dipping in different dip directions. The southwards lava channel described by Skelton et al., (2016) is located here. Two striations were found in the channel and are dipping steeply towards the west and the northwest, depicted by red arrows in figure 12. The striations at waypoint 32 are located on a partly collapsed lava pillar.

4. Discussion

4.1 Interpretation of the drainage of Dimmuborgir

One of the goals with this thesis was to use the striations to make an interpretation whether Dimmuborgir was drained radially or in one direction. The resulting arrow maps provide an opportunity to interpret the drainage of Dimmuborgir. The arrows depict patterns which depend on dip angle, dip direction and the elevations of the striations. In figure 13 the Dimmuborgir area is subdivided into three zones to interpret these patterns. In figures 14, 15 and 16 single arrows and groups of arrows are encircled to interpret the drainage in each of the three zones. The interpretation of the drainage of Dimmuborgir relies on the assumption that shallow dipping striations are associated with fast drainage, whereas steeply dipping striations are associated with slow drainage. Hence, shallow dipping striations are a better indicator of the direction of drainage than steeply dipping striations, which are a better indicator of collapse and subsidence of the solidified crust of the lava surface.

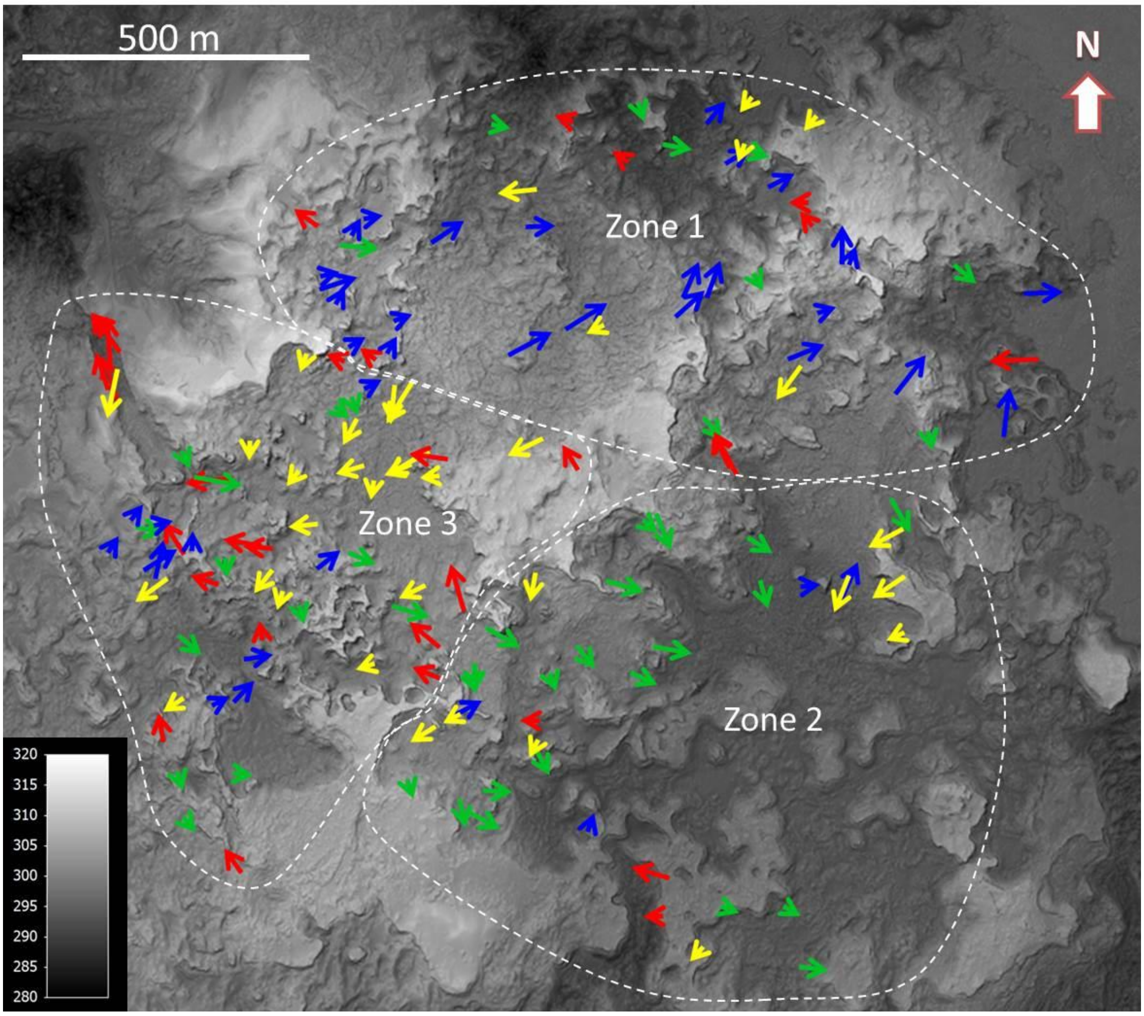

Figure 13. The arrows from figure 11 superimposed on a grayscale DTM overview of Dimmuborgir, depicting dip and dip direction of striations. Three zones are encircled to interpret drainage. The DTM image is modified after Skelton et al., (2016). The arrows are colour coded with respect to dip direction: blue = 0-90°, green = 90-180°, yellow = 180-270° and red = 270-360°. There are four different lengths of the arrows, which represent different dip angle of the striations. From longest to shortest they represent 0-20°, 20-40°, 40-60° and 60-90°. Scalebar denotes the range of elevation between 280 and 320 m.a.s.l.

4.1.1 Drainage in zone 1

~51 % of the arrows in zone 1 (figures 13 and 14) are blue, which indicates that lava here was drained towards the northeast. The arrows in zone 1 are highlighted with eight encirclements in figure 14. The blue arrows in encirclement 1 depict striations which have relatively shallow dip angles. The average dip angle of these striations is ~28° which indicates lava flow of relatively high velocity. These striations are situated inside or adjacent to the earlier described circular depression (figure 12), at elevations between 299.1-302.5 m.a.s.l. The dip directions of these striations are towards the northeast and the northern rim of Dimmuborgir. The arrows in encirclement 2 depict striations at the northern rim which are situated at elevations between 287.5- 301.5 m.a.s.l. These striations are relatively steep and have various dip directions. The striations at the western rim of the circular depression are highlighted in encirclement 3. These striations are relatively steep and have mainly dip directions towards the northeast. The elevation of these striations is between 303.5-308 m.a.s.l. The arrows in encirclement 6 depict striations which have relatively shallow dip angles and are mainly dipping towards the northeast. These striations are situated northeast of the earlier described semicircular depression (figure 12), at elevations between 290.3-301.1 m.a.s.l.

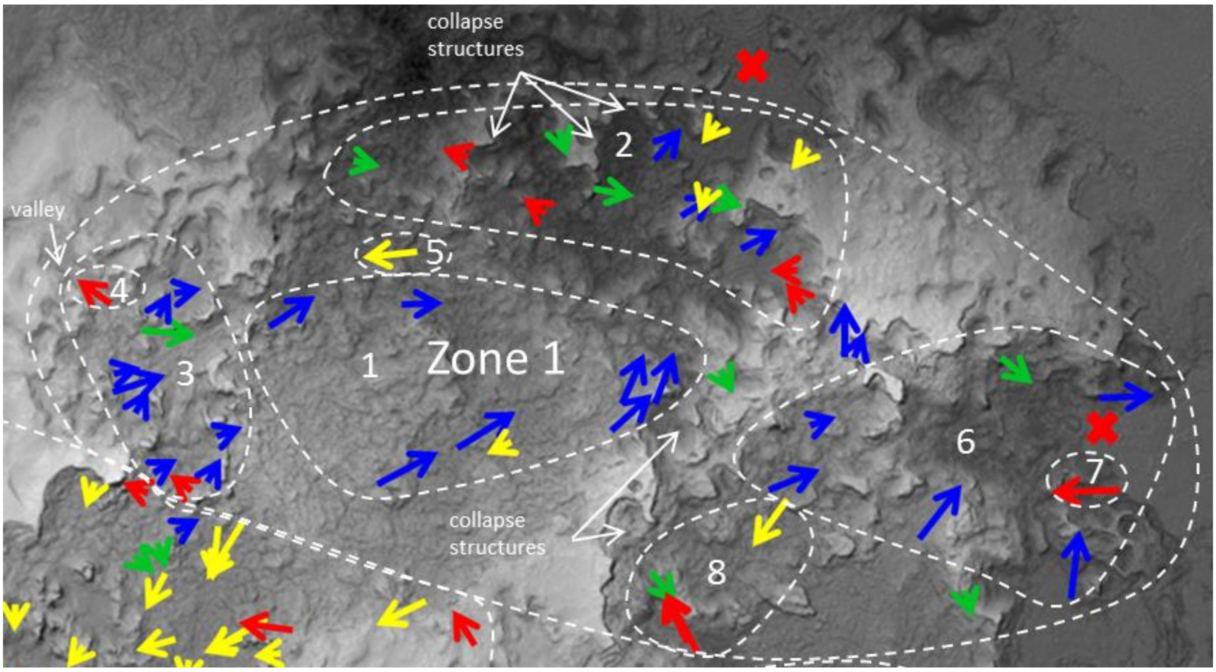

Figure 14. Close-up of Zone 1 from figure 13. Single arrows and groups of arrows are highlighted with eight encirclements to interpret drainage. Red x symbols mark the locations of potential breakouts.

A substantial volume of lava was probably stored within the circular depression before the drainage event started. Subsidence of the solidified upper lava surface is recorded by the steeply dipping striations in encirclement 3, at the western rim of the circular depression. The transport of lava was directed away from the western rim towards the northeast. This could explain why the outer section of the western rim is relatively intact. The outer section of the western rim was potentially overflowed at least at one place in a westerly direction. This overflow is indicated by the red arrow in encirclement 4, which depicts striations dipping towards a ~20 m wide valley (figure 14) of the western rim.

The generally low elevation of the northern rim of Dimmuborgir indicates that a large part of it have collapsed. Evidence of a large-scale collapse of the northern rim is multiple semicircular collapse structures, collapsed lava pillars and steeply dipping striations. Notable is that many of these striations are dipping inwards into the shield, towards the lowermost collapsed areas. The side walls of the semicircular collapse structures are generally located towards the north and northwest, whereas their open side are located into the shield. This indicates inwards collapse. The yellow arrow in encirclement 5 depicts striations which indicate lava flow towards the west. These striations are situated at a relatively low elevation of 295.1 m.a.s.l. and potentially record a local turbulent lava flow, which could have been triggered by inwards collapse of the shield in zone 1. Before drainage started in zone 1, the northern rim was probably intact and reached similar elevations as of the northwestern most and northeastern most rim of Dimmuborgir. Potentially a basal breakout through the former intact wall of the northern rim occurred and lava was drained towards the northeast. The patterns of the striations in encirclement 1, 2 and 3 indicate radially inwards collapse towards the lowermost areas at the northern rim. A potential place of breakout is marked with a red x in figure 14. However, there were no shallow dipping striations found at the northern rim which could be indicators of northeasterly drainage through the northern rim of Dimmuborgir.

The shallow dipping striations, depicted by the arrows in encirclement 6, indicate that lava was drained with high velocity towards the east, through a potential breakout zone in the northeastern rim of Dimmuborgir. Shallow dipping striations, situated at low elevations, are probably good indicators of breakout zones, because drainage of rootless shields occurs through basal breakouts (Patrick and Orr, 2012). The red arrow in encirclement 7 represents nearly horizontal dipping striations towards the west. However, these striations are curved. One end of the striations is dipping towards the east, whereas the other end is dipping towards the west. Based on the trend of the other striations in encirclement 6, the striations in encirclement 7 probably record lava flow towards the east. A big section of the northeastern rim of Dimmuborgir in encirclement 6 is situated at relatively low elevation. A breakout through the former intact wall of the rim potentially unseated portions of the rim here. A location for this potential breakout is marked with a red x in figure 14.

The earlier described area between the central plateau and northeastern most rim of Dimmuborgir is highlighted with a dashed line in figure 14. This area could be located in the borderland between the two overlapping shield-like structures, which were described by Skelton et al. (2016). Multiple semicircular collapse structures are located here. The side walls of these structures are generally located towards the northwest, whereas their open sides are located towards the southeast. This could indicate that the borderland between the two shield-like structures collapsed and ponded lava from the circular depression in zone 1 was drained via this borderland towards the breakout zone in encirclement 6. The arrows in encirclement 8 do not indicate drainage towards the northeast. These striations are situated at elevations between 297.8 and 300.3 m.a.s.l. South of these striations in zone 2, other striations indicate southeasterly drainage, which will be described in the next chapter. The various dip directions of the striations in encirclement 8 could indicate turbulent lava flow caused by drainage in two directions simultaneously.

4.1.2 Drainage in zone 2

~56 % of the arrows in zone 2 (figures 13 and 15) are green and indicate lava drainage towards the southeast. The arrows in zone 2 are highlighted with five encirclements in figure 15. The western part of this zone is clustered with green arrows which represent striations situated at elevations between 293.8 and 307.9 m.a.s.l. These striations are highlighted in encirclement 1 and are dipping towards the centre of the earlier described semicircular depression (figure 12). The average dip angle of these striations is ~51°. Three yellow arrows in encirclement 2 represent striations situated at the inner parts of the eastern rim of the semicircular depression, at elevations between 296.7 and 298.2 m.a.s.l. These striations are also dipping towards the centre of the semicircular depression. The average dip direction of these striations is ~45°. The striations at the southern rim of the semicircular depression are highlighted in encirclement 3. These have predominantly steep dip angles in various dip directions. These are situated at relatively low elevations between 291.1 and 297.3 m.a.s.l. The striations at waypoint 67 are situated in a ~50 m wide valley, which is heading towards the southeast. The striations at waypoint 67 are depicted by the green arrow in encirclement 5 and have dip angle of 40°.

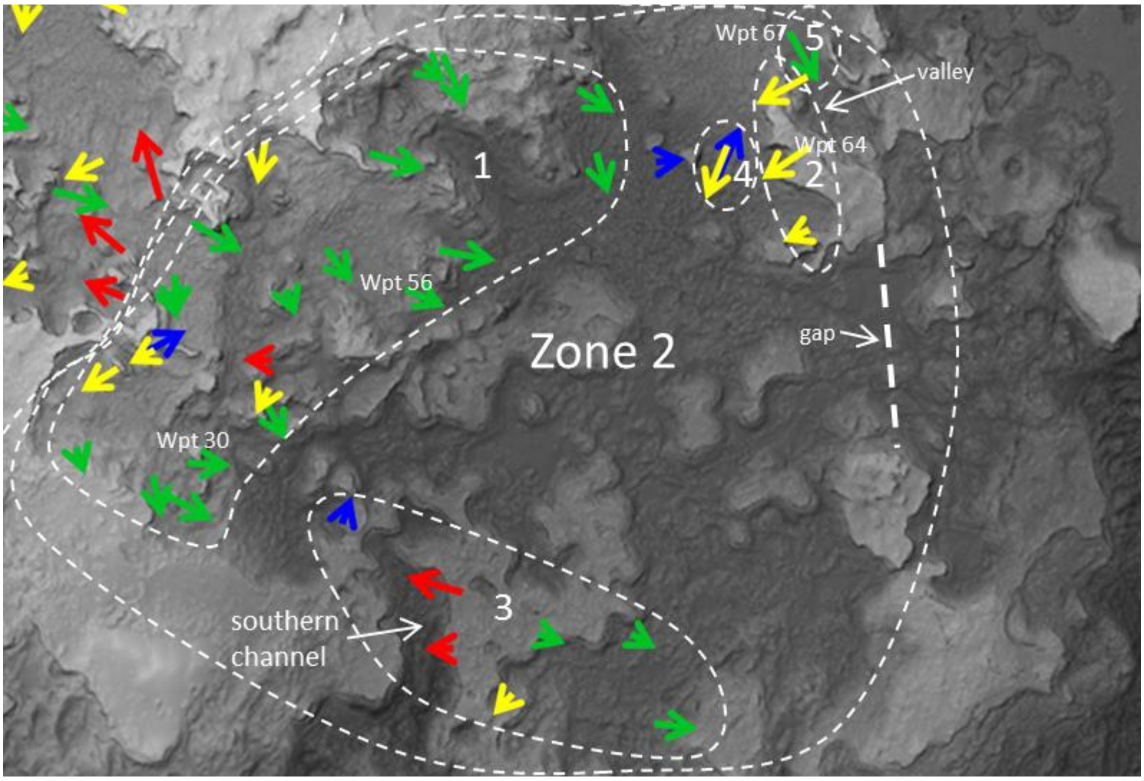

Figure 15. Close-up of Zone 2 from figure 13. Arrows are highlighted with five encirclements to interpret drainage.

An interpretation could be that drainage in zone 2 was directed towards the south and southeast. A substantial volume of lava was probably stored within the semicircular depression before the drainage event started. The green and yellow arrows in encirclement 1 and 2 indicate radial inwards collapse towards the centre of the semicircular depression. What potentially started as basal breakout through the southern channel could have transcended into a combined southerly/southeasterly drainage. Two westerly dipping striations in the southern channel are not indicating lava flow in the same direction as the southwards trend of the channel. High lava pressure in the shield could potentially have triggered a stable basal breakout through the channel, which eventually became overwhelming and led to a large-scale collapse of the southern rim. This could be the explanation of the relatively low elevation of the southern rim and the two westerly dipping striations in the southern channel. Simultaneously, a breakout in the eastern rim could have occurred which created a ~200 wide gap in the eastern rim of Dimmuborgir, marked by a dashed line in figure 15. No field work was done in the southeastern most part of zone 2 which could support this hypothesis. However, the crisscrossed striations at waypoint 63 (figure 8 f) indicate a turbulent flow of lava in two directions. These striations are depicted by the blue and yellow arrows encirclement 4. The uppermost part of these striations indicates southwesterly lava flow. The dip direction of these striations abruptly changes in the lower part, which indicates that the lava flow suddenly changed into a northeasterly direction. This could testify that this part of Dimmuborgir was drained in two directions simultaneously, or first in one direction and then the other. The striations at waypoint 63 are situated at elevations between 291 and 292 m.a.s.l. This relatively low elevation indicates that these striations were formed towards the end of the drainage event. Further evidence in support of radial inward collapse towards the centre of the semicircular depression to was found at waypoints 30, 56 and 64. The striations at these waypoints are curved and their dip angles decrease downwards, which could indicate lava flow of high velocity. Similar striations were found at waypoint 67. These indicate drainage towards southeast.

4.1.3 Drainage in zone 3

~64 % of the arrows in zone 3 (figures 13 and 16) are yellow and red, which indicates drainage direction towards the west. The arrows in zone 3 are highlighted with six white encirclements in figure 16. The yellow arrows in encirclement 1 are generally pointing towards the earlier described valley which is heading towards the western lava channel. These yellow arrows represent both shallow and steeply dipping striations. The red arrows in encirclement 2 are pointing towards the northwest, which indicates lava flow towards the western lava channel which was described by Bamlett and Potter (1986) and Skelton et al. (2016). The blue arrows in encirclement 2 also indicate lava flow towards the western lava channel. A cluster of shallow dipping striations is situated in this lava channel which indicates lava flow with high velocity out from Dimmuborgir in a northwesterly direction along the lava channel. This lava channel runs in a northwesterly direction before veering westwards. The green and yellow arrows in encirclement 3 and 4 represent nearly horizontal dipping striations situated in the valley and lava channel. The dip directions of these striations contradict the interpretation of drainage in a westerly direction. However, both striations have a dip angle of 6°. The low dip angle could indicate that transport of lava was in the opposite direction with respect the dip direction. The validity of this argument relies on the assumption that local geometries of lava channels and high enough effusion rates can force lava to flow upwards. The red arrow in encirclement 5 depicts the highest situated striations measured of all 149 striations in this study. These striations are located at waypoint 131 at an elevation of 310.1 m.a.s.l. and are dipping towards the circular depression in zone 1. This could testify that the northeasterly directed drainage of Dimmuborgir started before drainage in other directions. However, the third highest situated striations at Dimmuborgir are located ~100 m west of the striations at waypoint 131. These striations are situated at an elevation of 309 m.a.s.l. and are dipping towards the southwest. The lava flow recorded by the striations at waypoint 131 could have had a northwesterly direction due to local morphology and eventually changed flow direction towards the southwest. Hence, the lava flow recorded at waypoint 131 could alternatively be connected with drainage in zone 3. The arrows in encirclement 6 depict striations with mainly steep dip angles and dip directions in various compass directions. No clear pattern which indicates direction of drainage has been inferred from these arrows. A semicircular depression, which is ~150 m in diameter, is situated here. This indicates that a substantial volume of lava got drained from this area. The striations at waypoint 26 are sub vertical and situated adjacent to a lava tube which descends into the ground. Some of the striations in encirclement 6 are dipping towards the valley where waypoint 26 is located. A similar lava tunnel was found next to the sub vertical striations at waypoint 21. Potentially lava could have drained via lava tunnels which are descending into the floor of Dimmuborgir. This hypothesis is potentially supported by a circular collapse structure in between the depression and the striations at waypoint 26. Circular collapse structures could indicate that lava drained into the underlying ground into lava tunnels. However, this hypothesis needs more evidence. It has been proposed by Barth (1942) that Dimmuborgir was the site of a former lava pond that drained into an underlying reservoir. Even though this is not supported by this thesis, there could be local areas where lava was drained into underlying lava tunnels or perhaps into fractures. Present day NNE-SSW trending fractures which are younger than Dimmuborgir, transect the area and could follow closely the lines of older fractures that predate Dimmuborgir (Skelton et al., 2016)

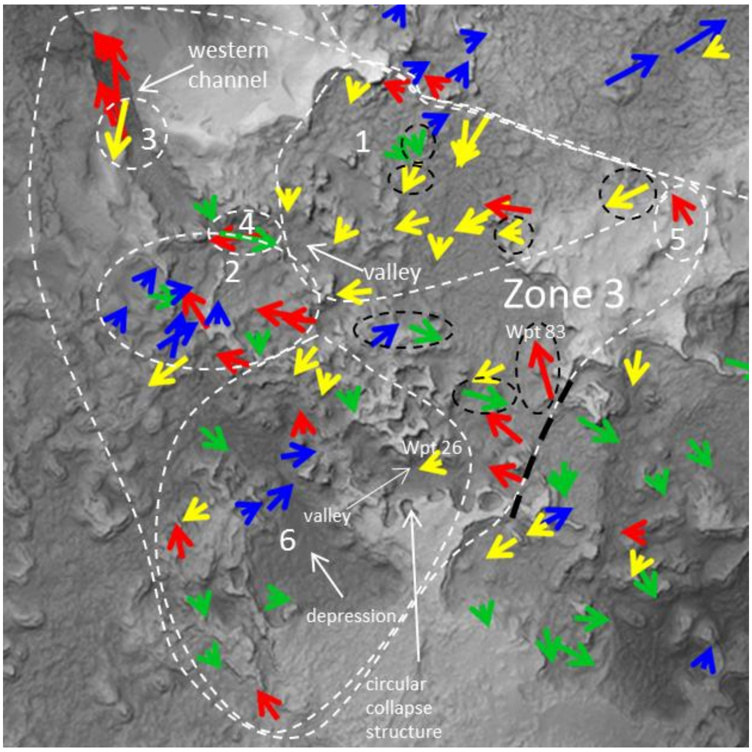

Figure 16. Close-up of Zone 3 from figure 13. Single arrows and groups of arrows are highlighted with six encirclements to interpret drainage. Eight arrows are highlighted with black encirclement. These eight arrows depict striations which indicate drainage across the potential borderland of two shield-like structures. The borderland is marked with the black dashed line.

An interpretation could be that lava in this zone got drained in two stages and towards two compass directions. In the first stage lava was drained towards the southeast across a ~200 m wide area, marked with a dashed black line in figure 16. This area could be located at the borderland between the two overlapping shield-like structures, which were described by Skelton et al. (2016). A potential easterly overflow or breakout from the western shield-like structure into the eastern shield-like structure could have occurred here. In the second stage lava was drained along a basal breakout along the western lava channel (figure 16). The interpretation about the first stage emerged from studying the striations at waypoint 110 (figure 9) where striations at two levels are separated by a lava shelf. This indicates that the solidified crust of the lava surface subsided about two meters and then paused, before it subsided again. The uppermost striations at waypoint 110, together with striations at seven other waypoints, are among the 12th highest situated striations in zone 3. In figure 16 the arrows at these waypoints have black encirclements. These are all situated above 305 m.a.s.l. The striations at waypoint 83, depicted by the encircled red arrow, have a shallow dip of 6° and can potentially record the flow of lava in the opposite direction of the dip direction. The shallow eastwards dipping striations at waypoint 85 support this interpretation. However, some of the eight striations above 305 m.a.s.l. are not dipping towards the borderland. This can potentially be explained with their steep dip angles. Striations with steep dip angles are not as good indicators of drainage direction of lava compared to striations with shallow dip angles. There are multiple lava shelves situated on lava structures in this zone at different levels, which indicates that drainage of Dimmuborgir in zone 3 took place in at least two stages. Lava could also have drained into tunnels beneath the ground in an unknown drainage direction.

4.2 Radial drainage relative to shield morphology

The patterns of the arrows which were described in figures 14, 15 and 16 indicate that Dimmuborgir volcanic structure was drained radially. The inferred drainage directions are towards the west, the northeast and the southeast. Bamlett and Potter (1986) proposed that Dimmuborgir was drained westwards along a lava channel. Skelton et al. (2016) proposed that Dimmuborgir was drained southwards and westwards along lava channels. The interpretation of radial drainage in this study builds upon, rather than directly contradicts these previous models of drainage. The difference is that the patterns of the striations also indicate drainage towards the northeast and the southeast. One could argue that important evidence is missing about these additional directions of drainage, such as drainage channels. However, what starts as a stable basal breakout in rootless shields could eventually become overwhelming and lead to a largescale collapse of the current flank and unseat big portions of it (Patrick and Orr, 2012). This is potentially what happened at northeastern and southeastern Dimmuborgir. The channeled westerly drainage was probably less violent than the drainage in other directions. This could explain the landscape of zone 3, which has more solidified lava structures compared to the other zones.

To understand how Dimmuborgir was drained radially, it is important to interpret the shield morphology of Dimmuborgir and relate it to the patterns of the striations. If Dimmuborgir is viewed as one 2 km by 2 km rootless shield, the radial drainage of the volcanic structure could be hard to explain. Due to gravity it is more likely that one rootless shield is drained in one direction, rather than multiple, especially if it is along a basal breakout. This is because the internal pressure of lava in a rootless shield is higher, the lower the breakout occurs (Patrick and Orr, 2012). The model of Bamlett and Potter (1986), that the entire Dimmuborgir structure was drained through the westwards channel, seems unlikely based on the patterns of the striations and shield morphology. The model of Skelton et al. (2016) that Dimmuborgir may be comprised of two overlapping shield-like structures, which were drained in different directions, is more likely based on the striations and the shield morphology. The visualized patterns of the striations in the three zones indicate that Dimmuborgir was drained in three directions. Assuming Dimmuborgir consists of two overlapping shield-like structures implies that eastern structure was drained in two directions. One potential explanation for this could be that Dimmuborgir is comprised of two so-called elongated composite shields. This kind of rootless shield is formed during combined effusion, when the shield is filled at its inner base, simultaneously as it is drained in a basal breakout of its flank, where a new shield forms (Patrick and Orr, 2012). 'Rootless shield 4' in the TEB was described as an elongated composite shield (Patrick and Orr, 2012. A difference is that 'rootless shield 4' is situated on the flank of Kīlauea Volcano, Hawai'i, whereas Dimmuborgir is situated flatter ground. Assuming that Dimmuborgir is comprised of two or more shield-like structures, radial drainage is not as unlikely as it would be in the TEB, based on the more horizontal land area at Dimmuborgir. In the TEB a series of rootless shields were drained the same direction (Patrick and Orr, 2012).

Skelton et al. (2016) described two shield-like structures at Dimmuborgir with diameters of 1-1.5 km, which had relatively large storage capacity of lava compared to the rootless shield in the TEB. The series of rootless shields in the TEB was between 400-700 m in diameter and had a maximum height of 20-30, before they collapsed (Patrick and Orr, 2012). Because the land-slope was steeper at TEB it seems reasonable to assume that rootless shields at Dimmuborgir could store more lava before a collapse. It would be interesting to find a method to calculate potential threshold values for rootless shield collapses.

4.3 Error sources

During the field work and after the field work the waypoints of six striations were removed, based on the interpretation that these are not striations, which show the direction of the flow of lava. The author could potentially have misinterpreted striations for some other structural feature, or missed striations which are left unmeasured.

The dip angles of curved striations were measured with respect to their estimated mean dip angle. This estimation is a potential source of error. Some of the striations were situated on lava walls which were not perfectly planar, which made it harder to measure dip direction. The dip direction of these striations where measured based on the author's interpretation, which again is a potential source of error.

Gregg and Christle (2013) described a method which indicates the movement direction of lava flow, based on the surface texture on striations. The study of Gregg and Christle (2013) was about drainage of lava in an environment of water-lava interaction. This method was not used in the field work at Dimmuborgir and could potentially have been useful, especially on shallow dipping striations thought to indicate the lava flow opposite to the dip direction. On the contrary, this method could potentially be used for distinguishing striations formed in water-lava interaction from striations formed in a non-aquatic environment.

The GPS receiver is a potential source of error. This was considered during the field work. To reduce this source of error, the coordinates were taken at a short distance, usually a few meters away from lava structures, depending on the size of the object. Also the GPS receiver was held up as high as possible and for a long time in order to get connection with as many satellites as possible. The assumption that the lava flowed in the same way a short distance from the measured striations is also a potential source of error. No corrections were applied for this assumption.

The heights of the striations relative to their waypoints were measured with one measurement at the highest visible point of the striations. Some vertical striations are long and cover an elevation interval of over 1 meter. One measurement at the bottom and another on the top of the striations could potentially have given more useful data.

The last ten striations measured during the field work were not photographed, since the battery of the smartphone ran out. From a positive point of view, these striations were measured during the last day of the field work, when the author had the most experience in identifying and measuring striations.

5. Conclusions

Based upon the field study and the DTM the following is concluded:

- The Dimmuborgir volcanic structure was drained radially. The drainage directions which are inferred in this study are towards the west, the northeast, and the southeast.
- The Dimmuborgir volcanic structure was drained in multiple stages.
- The drainage towards the west was channeled.
- The drainage towards the northeast was radially inwards towards the centre of the collapsed areas at the northern and northeastern rim of Dimmuborgir.
- The drainage towards the southeast was radially inwards towards the centre of the collapsed areas at southeastern Dimmuborgir.

For future research I would like to recommend researching how lava shelves are connected with the drainage of Dimmuborgir. Information about their location and elevation could give more information about the drainage of Dimmuborgir.

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Appendix A. Pictures of striations at waypoints 1-130

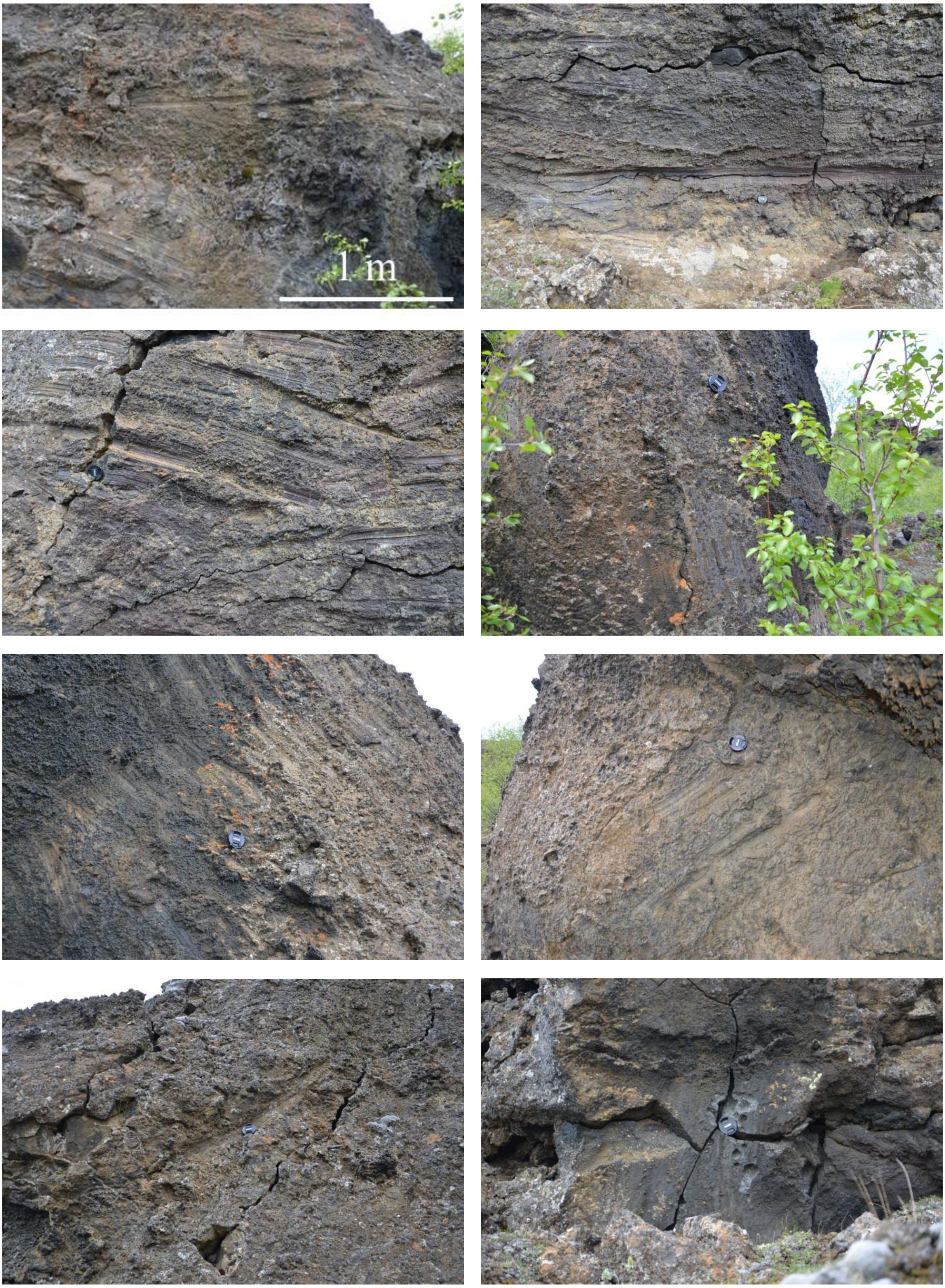

Figure 1. Pictures of striations at waypoints 1 to 8. The pictures are sorted with respect to the waypoints in ascending numerical order from left to right. The uppermost two pictures are from waypoints 1 and 2. Next row have pictures from waypoints 3 and 4 and so forward. Scale bar or camera lens cap for scale.

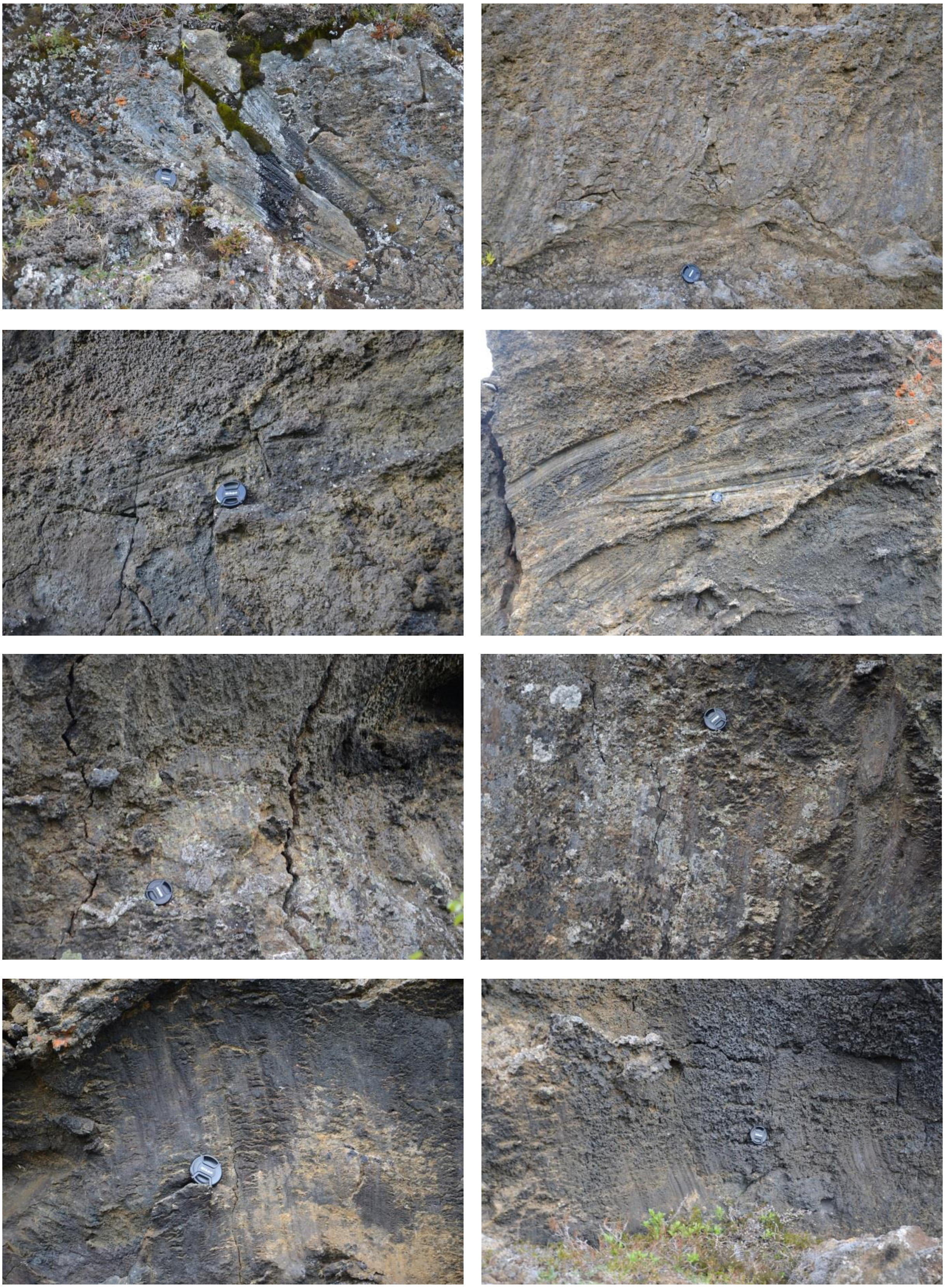

Figure 2. Pictures of striations at waypoints 9 to 16. Camera lens cap for scale.

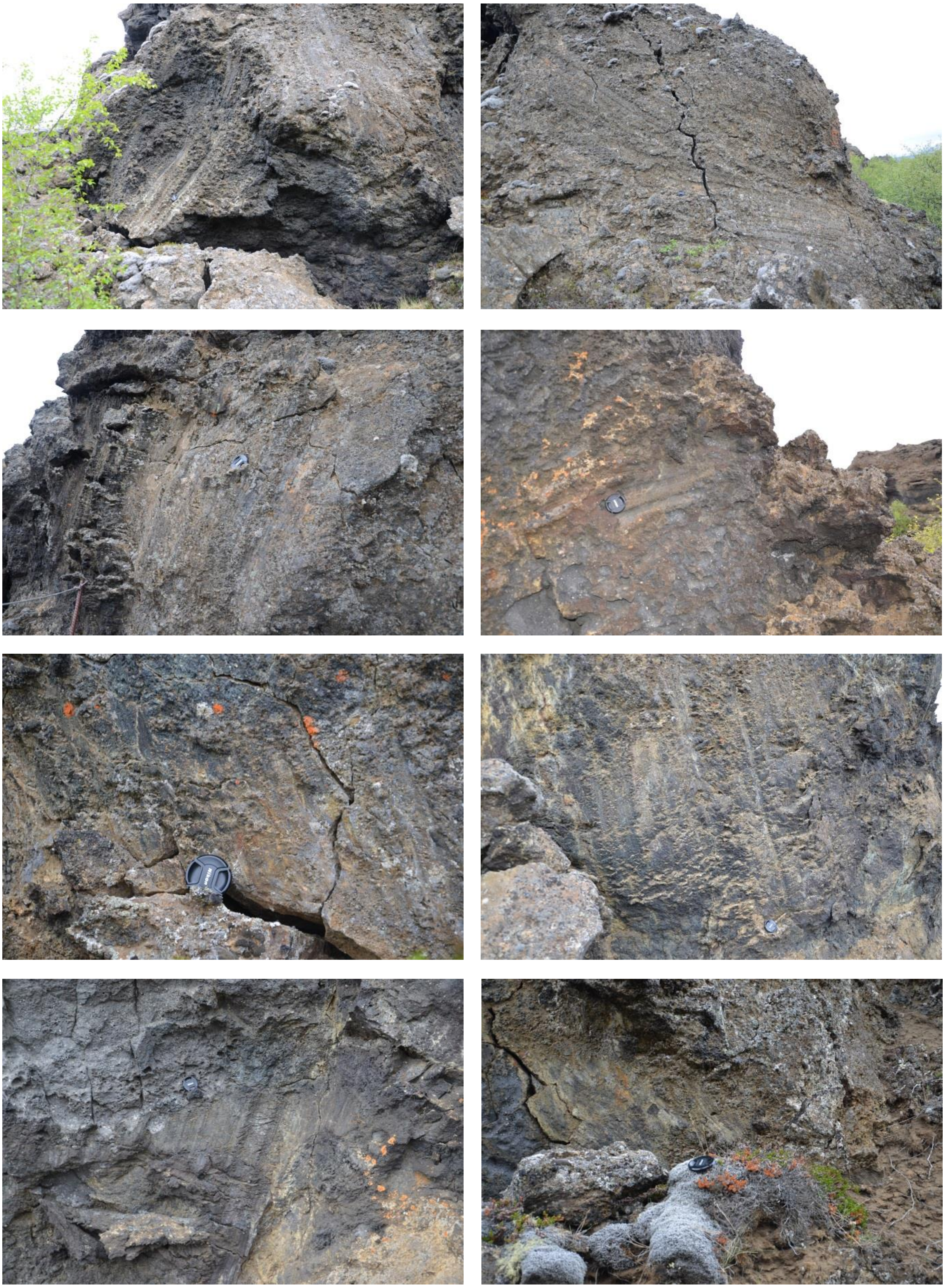

Figure 3. Pictures of striations at waypoints 17 to 24. Camera lens cap for scale.

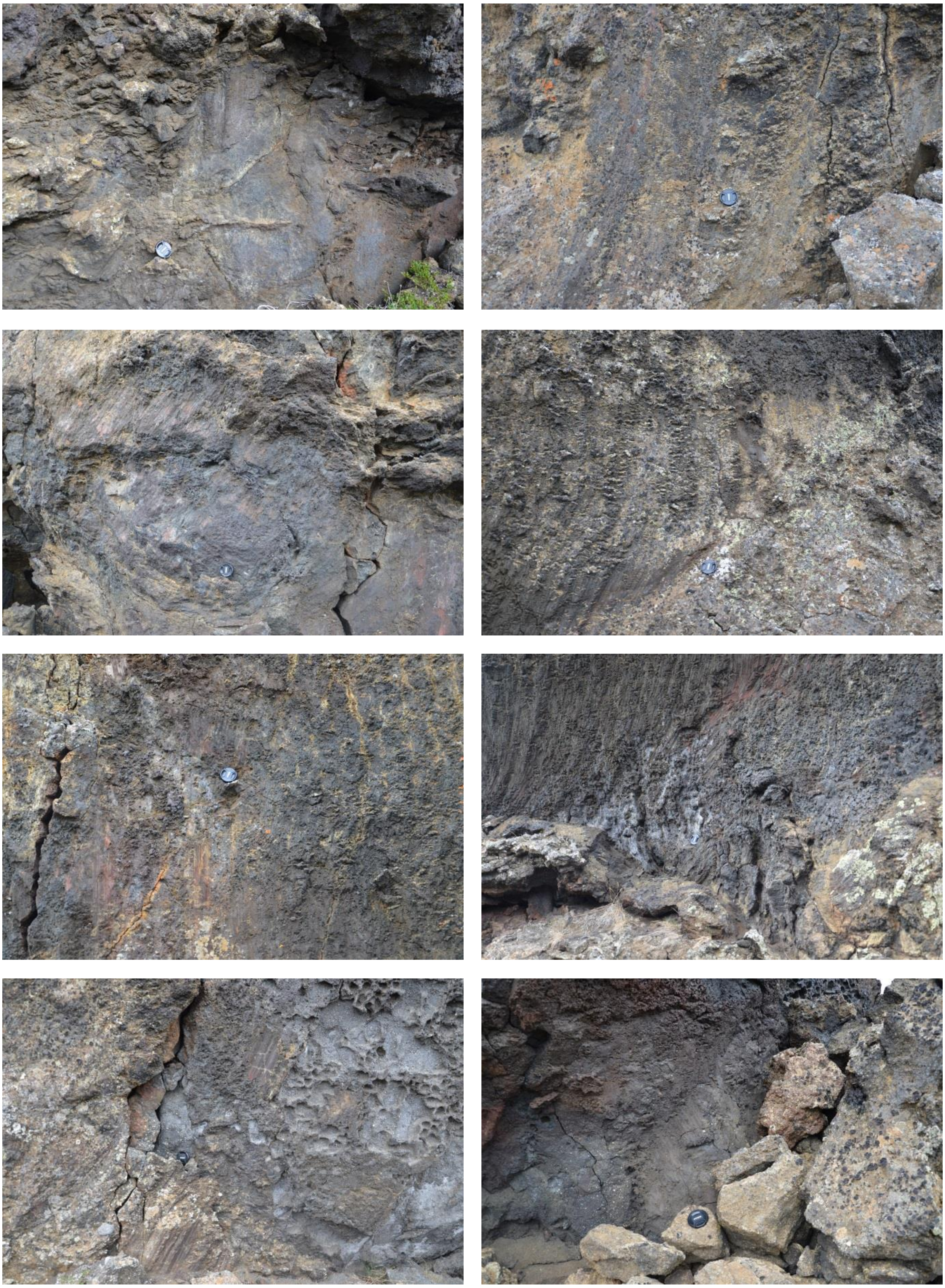

Figure 4. Pictures of striations at waypoints 25 to 32. Camera lens cap for scale.

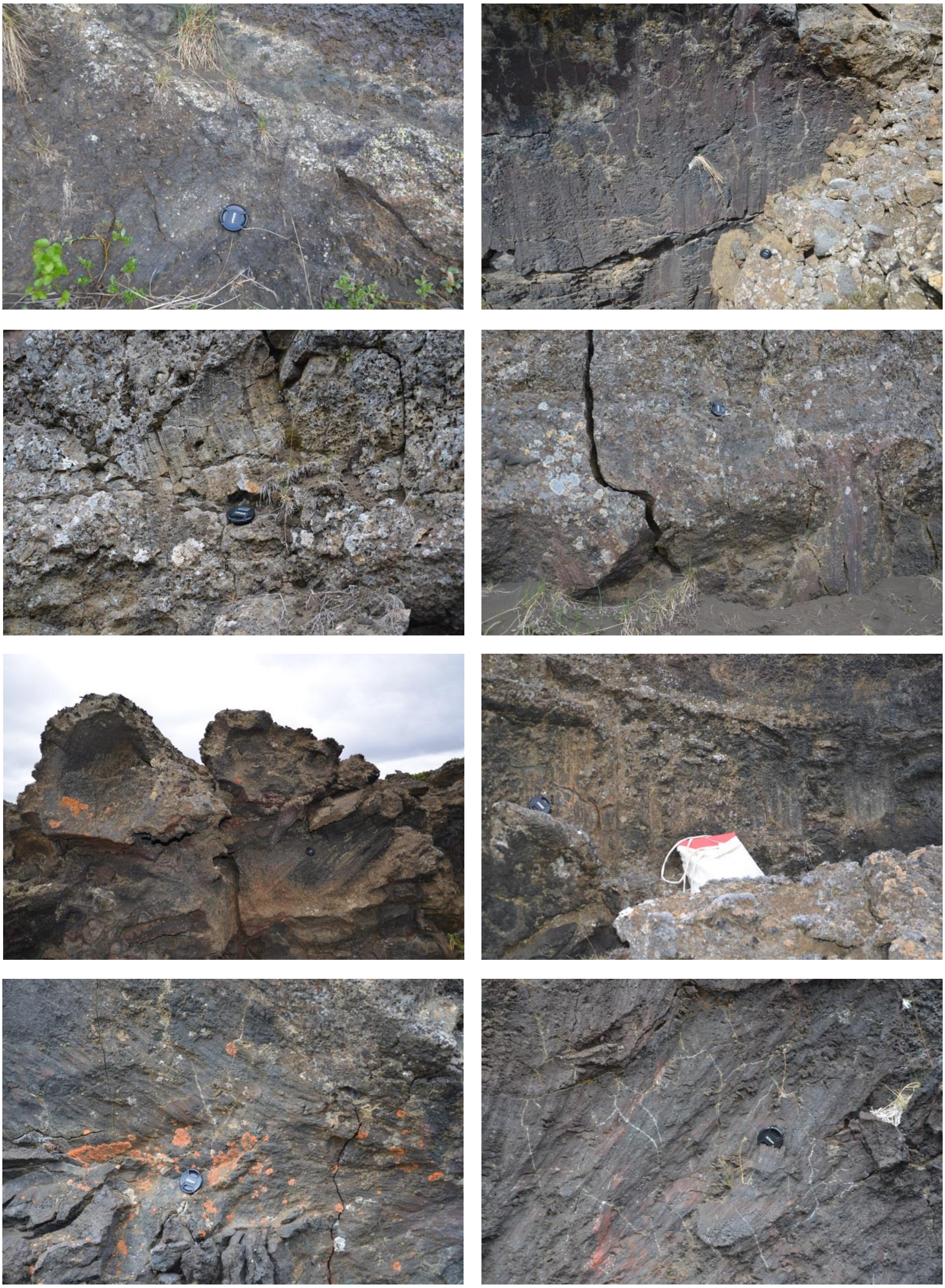

Figure 5. Pictures of striations at waypoints 33 to 40. Camera lens cap for scale.

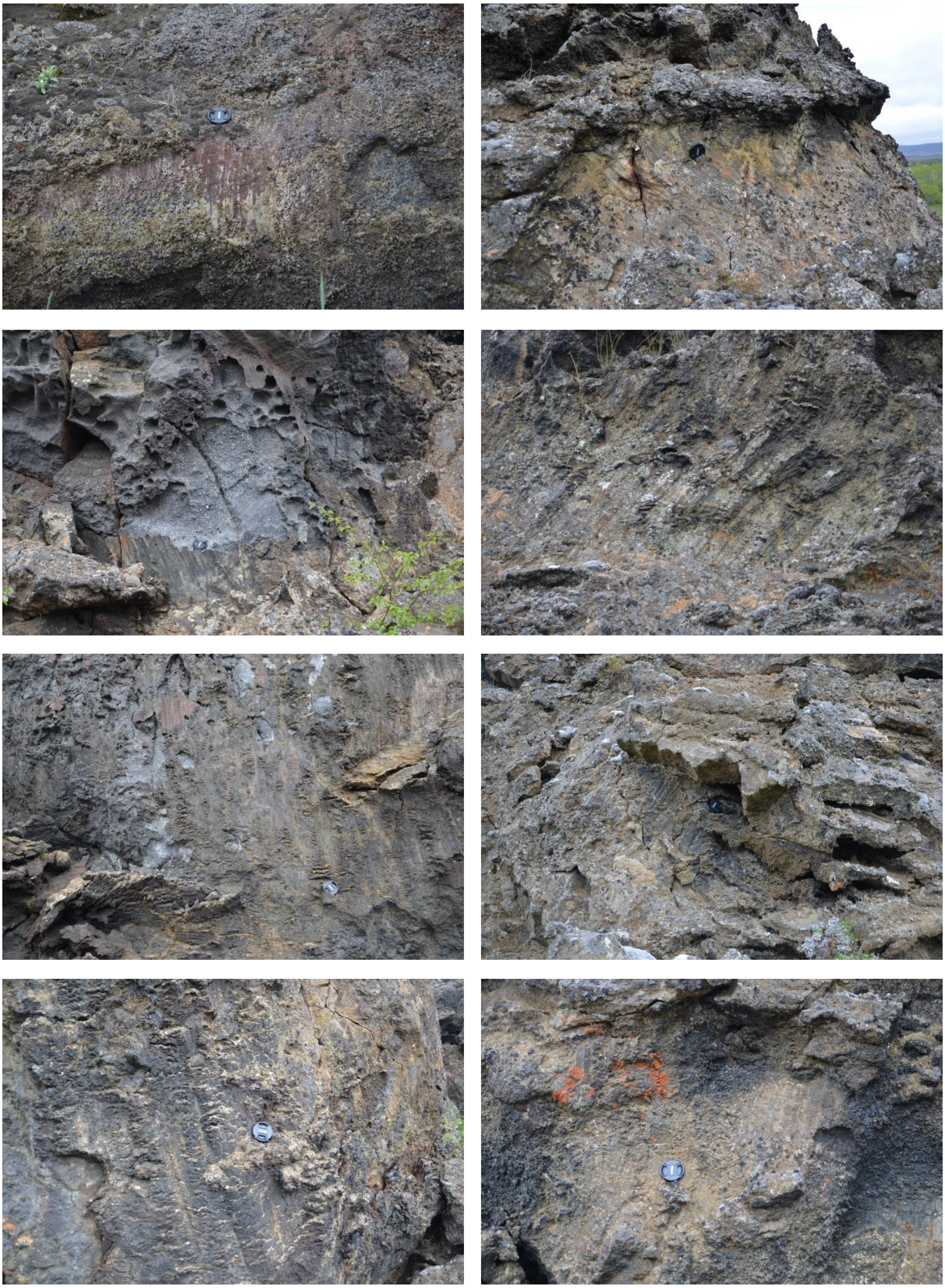

Figure 6. Pictures of striations at waypoints 41 to 48. Camera lens cap for scale.

Figure 7. Pictures of striations at waypoints 49 to 56. Camera lens cap or pen for scale.

Figure 8. Pictures of striations at waypoints 57 to 64. Pen for scale.

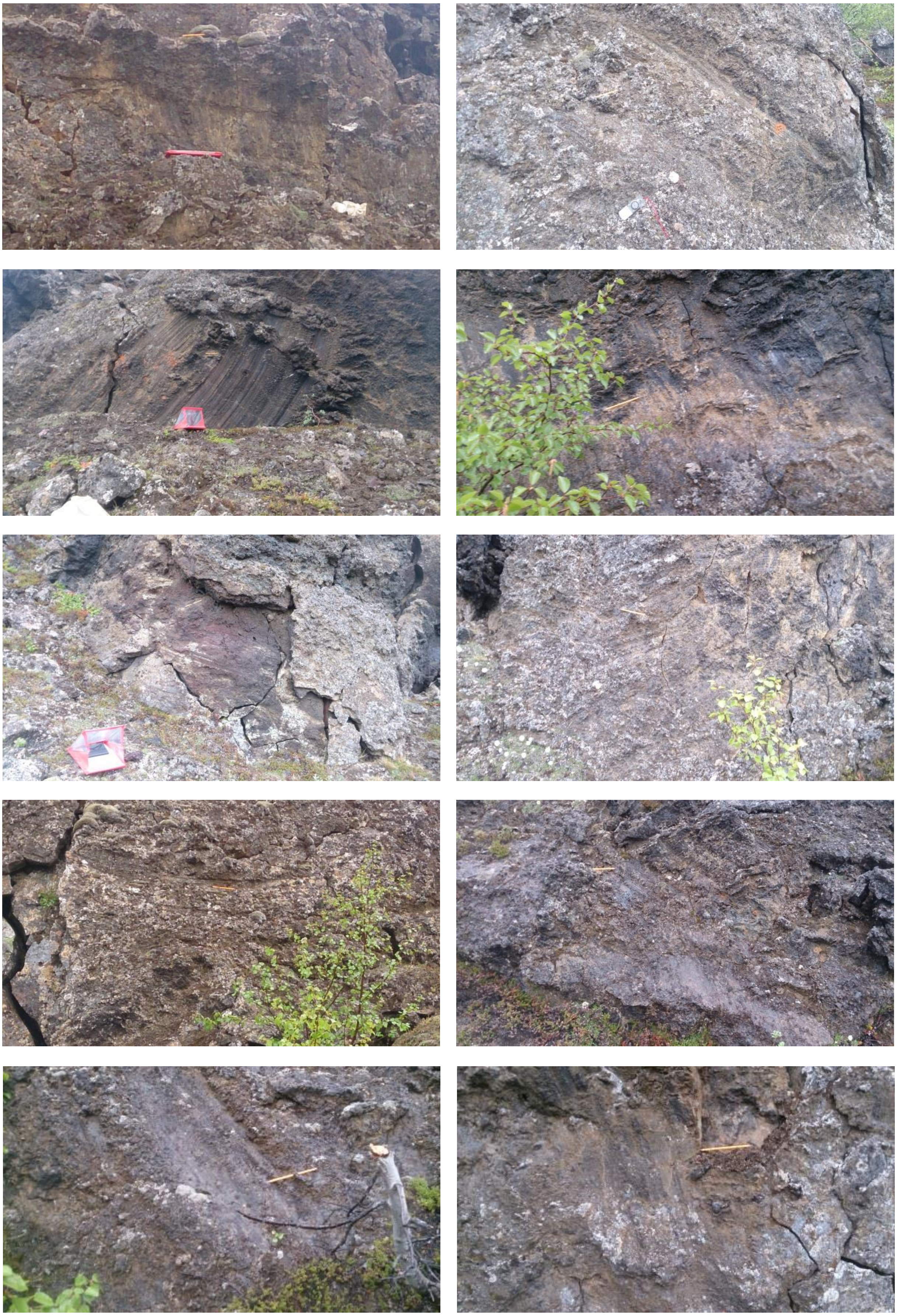

Figure 9. Pictures of striations at waypoints 65 to 74. Pen or weatherboard for scale.

Figure 10. Pictures of striations at waypoints 75 to 84. Pen or weatherboard for scale.

Figure 11. Pictures of striations at waypoints 85 to 94. Pen for scale.

Figure 12. Pictures of striations at waypoints 95 to 104. Pen or compass clinometer for scale.

Figure 13. Pictures of striations at waypoints 105 to 112. Pen or for scale.

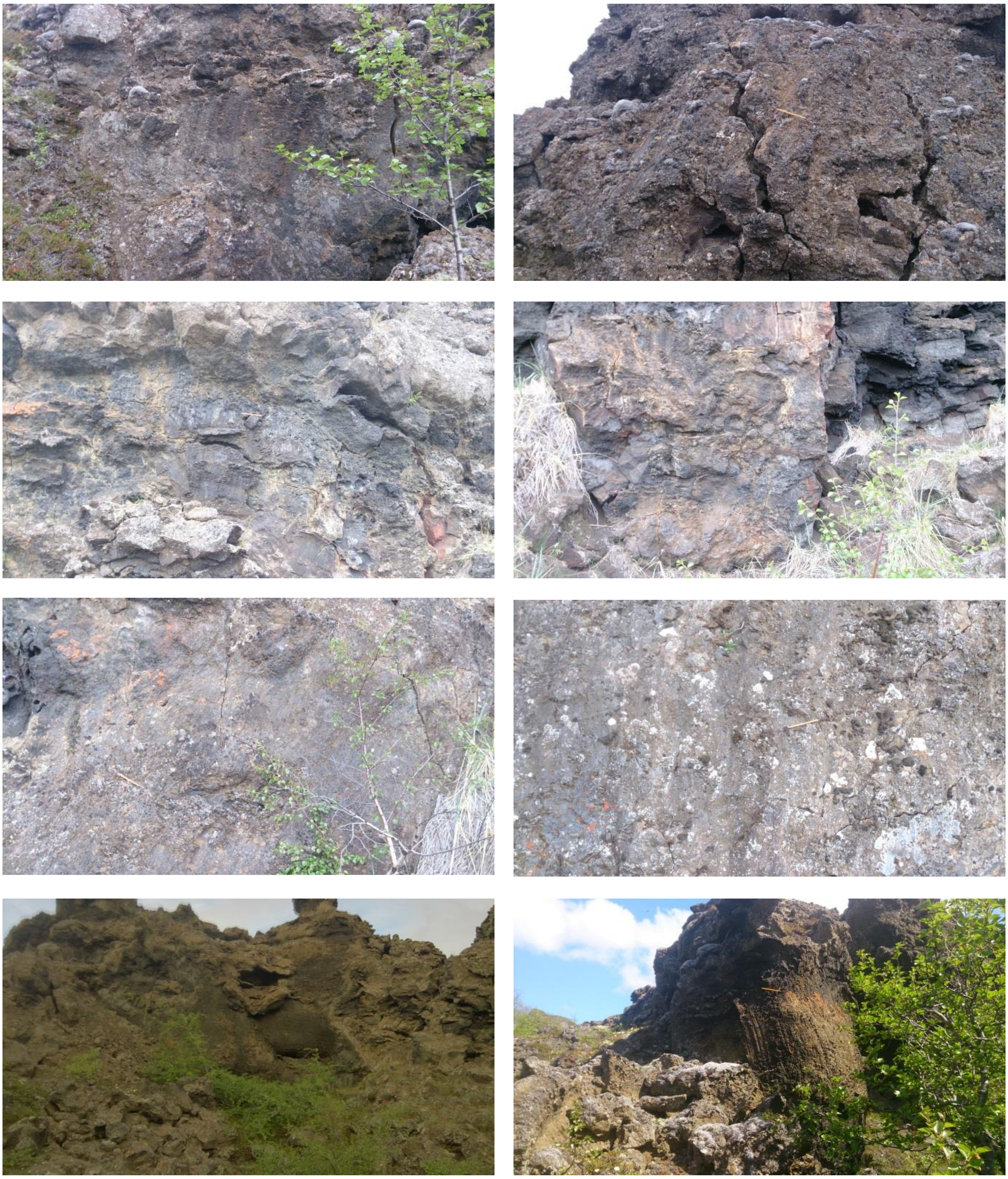

Figure 14. Pictures of striations at waypoints 112 to 120. Pen for scale.

Figure 15. Pictures of striations at waypoints 121 to 124. Pen for scale.

Figure 16. Pictures of striations at waypoints 125 to 130. Camera lens cap or pen for scale.

Appendix B

Table 1. Compilation of data from the field work. The position format for latitude and longitude is degrees decimal minutes (hddd°mm.mmm'), based on the reference system WGS84. The elevation is in m.a.s.l.

Waypoint	Latitude	Longitude	Date	Dip direction	Dip	Elevation
WPT1	N65 35.502	W16 54.964	28/6/2015	342	22	292.1
WPT1	N65 35.502	W16 54.964	28/6/2015	192	6	293.1
WPT2	N65 35.403	W16 54.731	28/6/2015	264	8	298.2
WPT3	N65 35.404	W16 54.728	28/6/2015	100	6	298.2
WPT4	N65 35.369	W16 54.855	28/6/2015	76	85	300.2
WPT5	N65 35.360	W16 54.849	28/6/2015	101	50	298.4
WPT6	N65 35.357	W16 54.822	28/6/2015	328	36	301.5
WPT7	N65 35.346	W16 54.853	28/6/2015	12	30	299.5
WPT7	N65 35.346	W16 54.853	28/6/2015	58	28	298.3
WPT8	N65 35.348	W16 54.945	28/6/2015	33	72	303.6
WPT9	N65 35.507	W16 54.972	28/6/2015	342	40	293.6
WPT10	N65 35.545	W16 54.984	28/6/2015	324	10	294.3
WPT10	N65 35.545	W16 54.984	28/6/2015	317	74	294.8
WPT11	N65 35.533	W16 54.964	28/6/2015	356	8	293.7
WPT12	N65 35.461	W16 54.360	29/6/2015	186	34	302.1
WPT12	N65 35.461	W16 54.360	29/6/2015	212	8	301.7
WPT13	N65 35.512	W16 54.404	29/6/2015	306	84	303.6
WPT14	N65 35.583	W16 54.485	29/6/2015	77	76	303.8
WPT15	N65 35.628	W16 54.428	29/6/2015	28	74	304.3
WPT16	N65 35.732	W16 53.614	29/6/2015	218	70	288.8
WPT17	N65 35.692	W16 53.608	29/6/2015	58	48	291
WPT17	N65 35.692	W16 53.608	29/6/2015	200	76	291.2
WPT18	N65 35.420	W16 54.320	29/6/2015	248	42	301.9
WPT18	N65 35.420	W16 54.320	29/6/2015	240	18	301.6
WPT19	N65 35.393	W16 54.402	29/6/2015	189	70	301
WPT20	N65 35.349	W16 54.669	29/6/2015	280	24	304.3
WPT21	N65 35.351	W16 54.775	29/6/2015	2	72	303.9
WPT22	N65 35.329	W16 54.709	29/6/2015	174	70	298.7
WPT23	N65 35.315	W16 54.638	29/6/2015	218	58	303.4
WPT24	N65 35.318	W16 54.765	30/6/2015	288	48	301.2
WPT25	N65 35.301	W16 54.594	30/6/2015	197	88	302
WPT26	N65 35.242	W16 54.412	30/6/2015	252	65	300.4
WPT27	N65 35.236	W16 54.291	30/6/2015	292	56	300.4
WPT28	N65 35.223	W16 54.185	30/6/2015	180	58	302.5
WPT28	N65 35.223	W16 54.185	30/6/2015	162	82	303
WPT29	N65 35.174	W16 54.061	30/6/2015	206	82	298.7
WPT30	N65 35.133	W16 54.130	30/6/2015	93	54	300.1
WPT31	N65 35.160	W16 54.043	30/6/2015	152	56	298.1
WPT32	N65 35.029	W16 53.521	30/6/2015	120	67	294.4
WPT33	N65 34.979	W16 53.470	30/6/2015	97	44	292.6

WPT34	N65 35.031	W16 53.646	30/6/2015	110	88	297.3
WPT35	N65 34.990	W16 53.717	30/6/2015	222	70	295.6
WPT36	N65 35.024	W16 53.812	30/6/2015	270	70	291.1
WPT37	N65 35.065	W16 53.825	30/6/2015	286	39	293.6
WPT38	N65 35.105	W16 53.936	30/6/2015	20	82	294.8
WPT39	N65 35.108	W16 54.155	30/6/2015	118	38	299.5
WPT40	N65 35.109	W16 54.203	30/6/2015	168	56	300.7
WPT41	N65 35.139	W16 54.322	30/6/2015	162	82	307.2
WPT42	N65 35.183	W16 54.290	30/6/2015	238	42	304
WPT43	N65 35.201	W16 54.223	30/6/2015	242	64	304.9
WPT44	N65 35.208	W16 54.192	30/6/2015	62	52	306.3
WPT45	N65 35.288	W16 54.547	30/6/2015	164	84	305.4
WPT46	N65 35.222	W16 54.667	30/6/2015	44	50	296.7
WPT47	N65 35.212	W16 54.717	30/6/2015	62	74	298.8
WPT48	N65 35.210	W16 54.819	30/6/2015	236	76	303.2
WPT49	N65 35.309	W16 54.860	30/6/2015	234	30	301
WPT50	N65 35.261	W16 54.777	30/6/2015	130	48	297.8
WPT51	N65 35.407	W16 54.281	1/7/2015	264	78	307.7
WPT52	N65 35.433	W16 54.088	1/7/2015	244	30	308.7
WPT53	N65 35.307	W16 54.062	1/7/2015	190	42	304.4
WPT54	N65 35.229	W16 54.020	1/7/2015	160	84	303.9
WPT55	N65 35.245	W16 53.942	1/7/2015	142	44	296.5
WPT56	N65 35.229	W16 53.814	1/7/2015	114	50	294.7
WPT57	N65 35.255	W16 53.760	1/7/2015	100	26	298.4
WPT58	N65 35.312	W16 53.853	1/7/2015	106	34	301.9
WPT59	N65 35.366	W16 53.816	1/7/2015	130	70	301.9
WPT60	N65 35.302	W16 53.580	1/7/2015	164	56	293.8
WPT61	N65 35.347	W16 53.585	1/7/2015	122	42	295.5
WPT62	N65 35.312	W16 53.469	1/7/2015	84	74	290.5
WPT63	N65 35.310	W16 53.402	1/7/2015	202	22	291.7
WPT63	N65 35.310	W16 53.402	1/7/2015	24	20	291.1
WPT64	N65 35.311	W16 53.308	1/7/2015	236	22	296.7
WPT65	N65 35.269	W16 53.295	1/7/2015	246	80	298.1
WPT66	N65 35.353	W16 53.322	1/7/2015	242	34	298.2
WPT67	N65 35.362	W16 53.273	1/7/2015	150	40	299.4
WPT68	N65 35.440	W16 53.223	1/7/2015	166	66	299.9
WPT69	N65 35.505	W16 53.248	1/7/2015	38	18	298.3
WPT70	N65 35.474	W16 53.061	1/7/2015	7	20	293.3
WPT71	N65 35.511	W16 53.067	1/7/2015	268	14	290.4
WPT72	N65 35.569	W16 52.967	1/7/2015	88	34	290.3
WPT73	N65 35.579	W16 53.136	1/7/2015	130	46	292.8
WPT74	N65 35.599	W16 53.391	1/7/2015	20	78	309.5
WPT75	N65 35.631	W16 53.481	1/7/2015	320	68	301.5
WPT76	N65 35.666	W16 53.527	1/7/2015	63	60	296
WPT77	N65 35.717	W16 53.475	1/7/2015	220	68	295.2

WPT78	N65 35.724	W16 53.672	1/7/2015	40	52	287.5
WPT79	N65 35.562	W16 53.713	1/7/2015	48	34	302.5
WPT80	N65 35.552	W16 53.925	1/7/2015	58	4	299.1
WPT81	N65 35.537	W16 53.927	1/7/2015	244	76	301.8
WPT 82	N65 35.527	W16 54.043	1/7/2015	62	20	299.6
WPT 83	N65 35.320	W16 54.225	1/7/2015	344	6	305.9
WPT84	N65 35.305	W16 54.316	1/7/2015	244	50	303.4
WPT85	N65 35.288	W16 54.302	1/7/2015	106	22	305.8
WPT86	N65 35.264	W16 54.114	1/7/2015	120	30	301
WPT87	N65 35.195	W16 54.066	1/7/2015	272	70	299.1
WPT88	N65 35.488	W16 54.405	2/7/2015	62	60	306
WPT89	N65 35.521	W16 54.436	2/7/2015	60	74	304
WPT90	N65 35.562	W16 54.470	2/7/2015	28	76	305.1
WPT91	N65 35.577	W16 54.458	2/7/2015	72	39	303.5
WPT92	N65 35.634	W16 54.537	2/7/2015	306	54	305.8
WPT93	N65 35.607	W16 54.411	2/7/2015	95	32	307.9
WPT94	N65 35.632	W16 54.414	2/7/2015	80	63	303.7
WPT95	N65 35.625	W16 54.229	2/7/2015	56	30	300
WPT96	N65 35.655	W16 54.104	2/7/2015	264	28	295.1
WPT97	N65 35.626	W16 54.034	2/7/2015	88	48	302
WPT98	N65 35.729	W16 53.835	2/7/2015	162	82	293
WPT99	N65 35.693	W16 53.743	2/7/2015	100	44	293.8
WPT100	N65 35.648	W16 53.497	2/7/2015	270	70	294.8
WPT101	N65 35.613	W16 53.407	2/7/2015	0	22	299.7
WPT102	N65 35.553	W16 53.443	2/7/2015	72	70	301.2
WPT103	N65 35.518	W16 53.472	2/7/2015	68	22	300.3
WPT104	N65 35.485	W16 53.526	2/7/2015	216	40	297.8
WPT105	N65 35.445	W16 53.670	2/7/2015	142	54	299.2
WPT106	N65 35.438	W16 53.671	2/7/2015	334	32	300.2
WPT106	N65 35.438	W16 53.671	2/7/2015	332	4	297.9
WPT107	N65 35.354	W16 53.777	2/7/2015	158	30	307.9
WPT108	N65 35.425	W16 54.291	2/7/2015	278	26	303.5
WPT109	N65 35.410	W16 54.463	2/7/2015	254	60	303.9
WPT110	N65 35.444	W16 54.445	2/7/2015	208	42	306.2
WPT111	N65 35.465	W16 54.467	2/7/2015	130	90	303.7
WPT112	N65 35.471	W16 54.435	2/7/2015	162	66	305.5
WPT113	N65 35.374	W16 54.899	3/7/2015	38	70	301.5
WPT114	N65 35.191	W16 54.847	3/7/2015	350	58	302.5
WPT115	N65 35.144	W16 54.803	3/7/2015	162	86	296.4
WPT116	N65 35.106	W16 54.783	3/7/2015	140	68	303.9
WPT117	N65 35.075	W16 54.699	3/7/2015	325	52	302.7
WPT118	N65 35.150	W16 54.672	3/7/2015	96	84	298.8
WPT119	N65 35.433	W16 54.660	3/7/2015	182	72	303.7
WPT120	N65 35.506	W16 54.543	4/7/2016	200	77	304.1
WPT121	N65 35.509	W16 54.471	4/7/2016	292	76	303.8

WPT122	N65 35.521	W16 54.359	4/7/2016	30	70	304.5
WPT123	N65 35.544	W16 54.345	4/7/2016	70	76	308.1
WPT124	N65 35.713	W16 54.137	4/7/2016	102	82	290.4
WPT125	N65 35.721	W16 53.995	4/7/2016	288	72	295
WPT126	N65 35.687	W16 53.873	4/7/2016	306	70	298.3
WPT127	N65 35.586	W16 53.719	4/7/2016	24	28	300.9
WPT128	N65 35.582	W16 53.679	4/7/2016	20	30	301.3
WPT129	N65 35.576	W16 53.582	4/7/2016	150	78	307.8
WPT130	N65 35.421	W16 54.792	4/7/2016	155	76	297.1
WPT131	N65 35.425	W16 53.984	4/7/2016	328	41	310.1
WPT132	N65 35.407	W16 54.563	4/7/2016	218	68	307.4
WPT133	N65 35.363	W16 54.559	4/7/2016	264	60	301.5
WPT134	N65 35.343	W16 54.642	4/7/2016	274	56	306.1
WPT135	N65 35.275	W16 54.631	4/7/2016	352	80	298.2
WPT136	N65 35.253	W16 54.633	4/7/2016	81	58	295.8
WPT137	N65 35.273	W16 54.300	4/7/2016	310	40	305
WPT138	N65 35.332	W16 54.404	4/7/2016	113	60	307.5
WPT139	N65 35.336	W16 54.484	4/7/2016	52	52	309
WPT140	N65 35.691	W16 53.586	4/7/2016	108	48	297.4

Appendix C

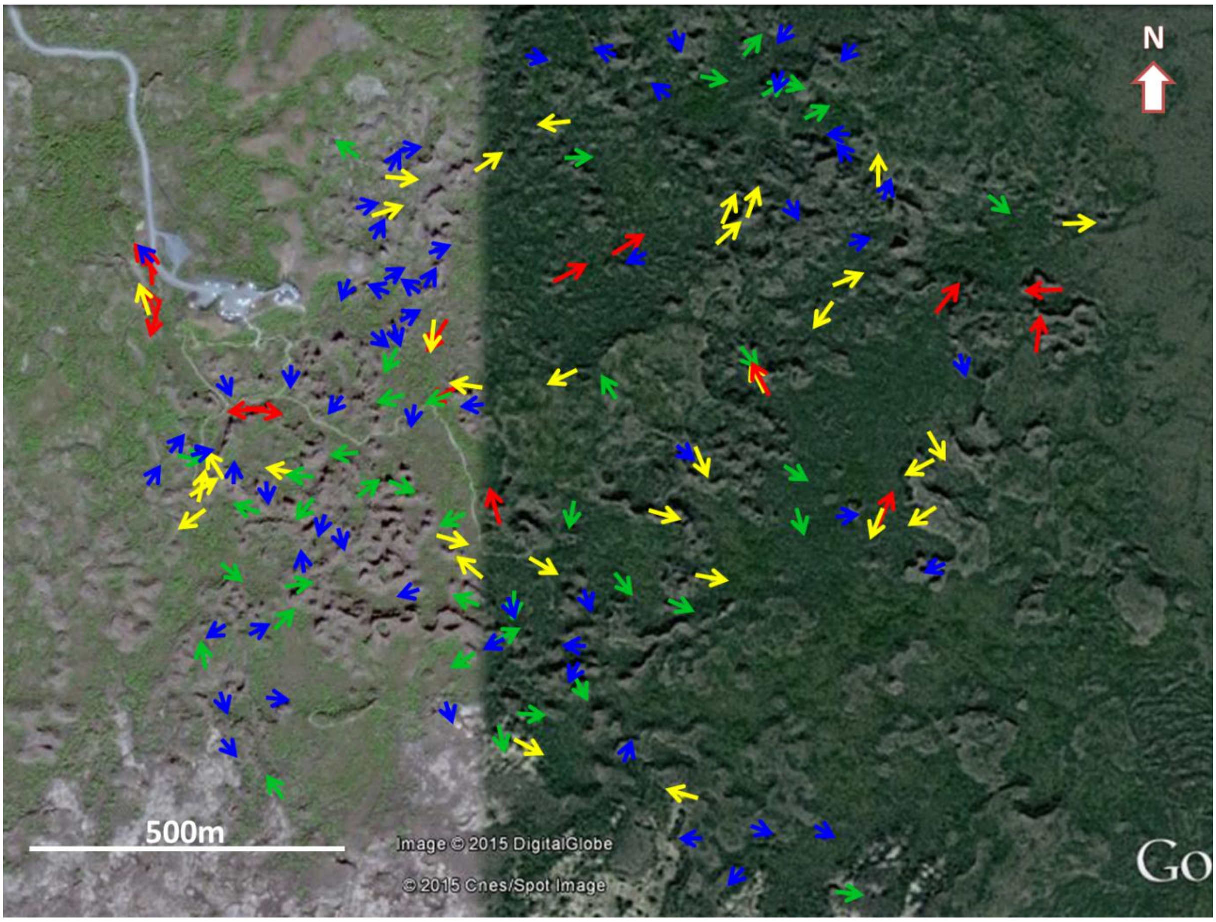

Figure 1. Arrows superimposed on a satellite image modified from Google Earth, depicting dip angle and dip direction of the striations. The arrows are colour coded with respect to represent dip angles: red: 0-20°, yellow: 20-40°, green: 40-60° and blue: 60-90°. There are four different lengths of the arrows, which also represent different dip angle of the striations. From longest to shortest they represent 0-20°, 20-40°, 40-60° and 60-90°. The arrows are pointing in compass directions based on the dip direction of the striations.

Appendix D

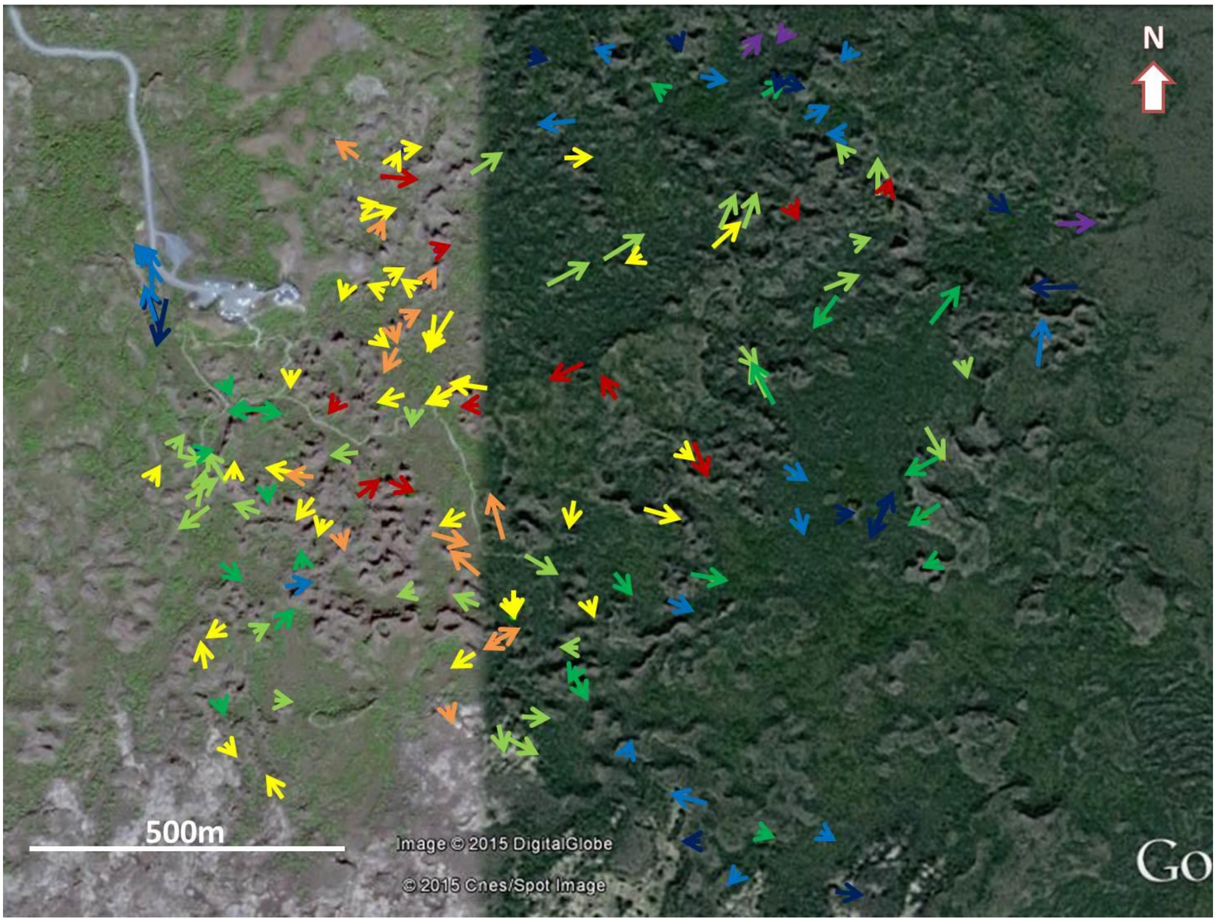

Figure 1. Arrows superimposed on a satellite image modified from Google Earth, depicting dip angle, dip direction and elevation of the striations. The arrows are colour coded with respect to elevation (m.a.s.l.): purple: 287.5-290.3, dark blue: 290.3-293.2, blue: 293.2-296, dark green: 296-298.8, light green: 298.8-301.6, yellow: 301.6-304.5, orange: 304.5-307.3 and red: 307.3-310.1. There are four different lengths of the arrows, which represent different dip angle of the striations. From longest to shortest they represent 0-20°, 20-40°, 40-60° and 60-90°. The arrows are pointing in compass directions based on the dip direction of the striations.