Science

Geology of Tindfjallajökull volcano, Iceland

Jonathan D. Moles[a], Dave McGarvie[a], John A. Stevenson[b] and Sarah C. Sherlock[a]

[a]Faculty of Science, Technology, Engineering & Mathematics, The Open University, Milton Keynes, UK; [b]British Geological Survey, The Lyell Centre, Edinburgh, UK

ABSTRACT

The geology of Tindfjallajökull volcano, southern Iceland, is presented as a 1:50,000 scale map. Field mapping was carried out with a focus on indicators of past environments. A broad stratocone of interbedded fragmental rocks and lavas was constructed during Tindfjallajökull's early development. This stratocone has been dissected by glacial erosion and overlain by a variety of mafic to silicic volcanic landforms. Eruption of silicic magma, which probably occurred subglacially, constructed a thick pile of breccia and lava lobes in the summit area. Mafic to intermediate flank eruptions continued through to the end of the last glacial period, producing lavas, hyaloclastite-dominated units and tuyas that preserve evidence of volcano-ice interactions. The Thórsmörk Ignimbrite, a regionally important chronostratigraphic marker, is present on the SE flank of the volcano. The geological mapping of Tindfjallajökull gives insights into the evolution of stratovolcanoes in glaciated regions and the influence of ice in their development.

1. Introduction

Tindfjallajökull (alternatively known as Tindfjöll) is an $\sim$300 km^2 stratovolcano in the Eastern Volcanic Zone of southern Iceland (63°47′N 19°35′W). Like nearby Eyjafjallajökull, the name 'Tindfjallajökull' strictly refers to the volcano's ice cap, but is commonly used to refer to the volcano as a whole (in this paper, it is used to refer to the whole volcano). The upper flanks of Tindfjallajökull currently host $\sim$13 km^2 of ice, and the ice-free summit rises to 1464 m above mean sea level (Figure 1).

The geology of Tindfjallajökull is largely unknown. A study of gabbro nodules by Larsen (1979) includes the most detailed geological map previously published. Jakobsson (1979) speculated that Tindfjallajökull is the oldest active volcano in the Eastern Volcanic Zone, and that it probably last erupted in late-glacial or post-glacial time.

Tindfjallajökull is best known as a proposed source of the Thórsmörk Ignimbrite (Jørgensen, 1980). This 1.5–2 km^3 (dense-rock equivalent) peralkaline ignimbrite outcrops to the SE of the volcano (Thórarinsson, 1969) and has been correlated with the rhyolitic component of the widespread North Atlantic Ash Zone II (Lacasse, Sigurdsson, Carey, Paterne, & Guichard, 1996; Sigurdsson, 1982; Tomlinson, Thordarson, Müller, Thirlwall, & Menzies, 2010).

A 1:50,000 geological map (Main map) of Tindfjallajökull is presented here with the aim of documenting the volcano's eruptive products and to provide context for further research. The map was produced as part of a research project on the volcanological development of Tindfjallajökull, focussing particularly on the role of ice in the shaping of the volcano. As is common for Icelandic volcanoes, the influence of past ice is evident in the geomorphology of the volcano, in the presence of glacially worked sediments and in the characteristics of the erupted products.

2. Methods

Geological mapping was undertaken at Tindfjallajökull during the summers of 2014, 2015 and 2016. In the field, lithofacies were mapped onto topographic maps (USA Defence Mapping Agency, 1989) and aerial images (Google Earth Pro, 2010).

Geographical data of topography (contours and spot heights), place names, hydrology, buildings and tracks were sourced from the IS 50 V digital map database (Landmælingar Íslands, 2016). These data were supplemented by field mapping of geomorphological features (mass-wasting scarps and subsidence pits) and superficial deposits (mass-wasting deposits and moraines).

To transform the mapped lithofacies data into the classes displayed on the final map, a division was first made according to the volcanic system. Although most of the mapped area consists of the products of Tindfjallajökull volcano, the products of neighbouring

---
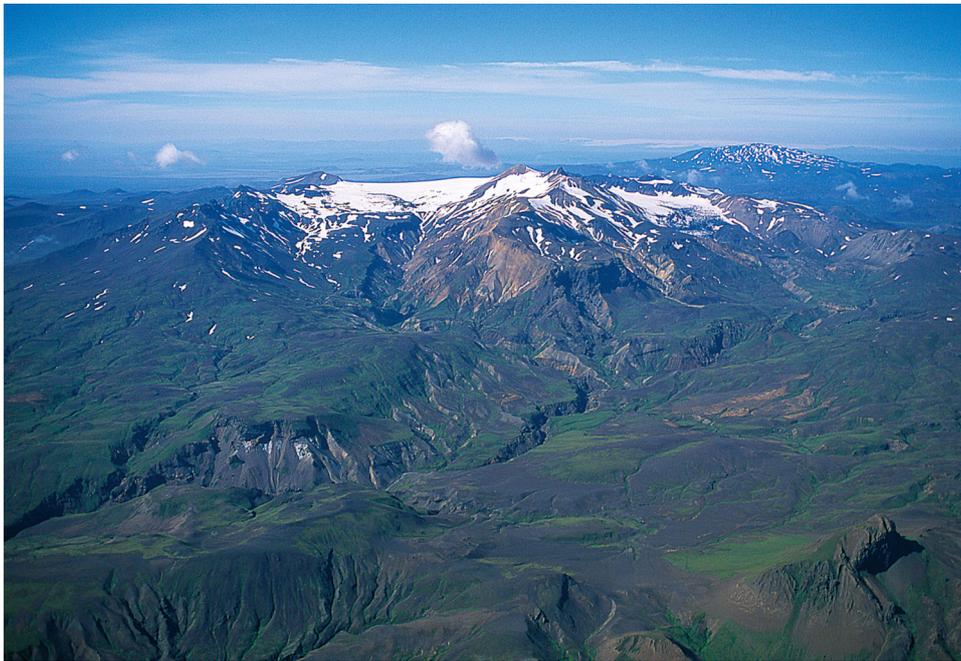
Figure 1. Oblique aerial photograph of Tindfjallajökull from the SE, August 1999. Source: Oddur Sigurðsson. To the right of the glacier-covered shoulder are the orange/brown twin peaks of Ýmir and Ýma, the highest points of the central silicic edifice. The mafic-dominated ridge of Tindfjöll is to the left. The valleys in front contain sediments deposited during the last glacial period.

and older systems are also present. Sediments, which potentially include material from multiple volcanic systems, form a separate category.

Within the categories defined above, divisions were then made based on age. Due to a lack of widespread marker horizons, major stratigraphic discontinuities or radiometric dates, it is only possible to divide Tindfjallajökull into broad stratigraphic groups: Early, Middle and Late Tindfjallajökull (the latter group is subdivided into A and B). The presence of the Thórsmörk Ignimbrite, which has an unpublished ^{40}Ar/^{39}Ar age of 54.5 ± 2 ka (see Sigurdsson, McIntosh, Dunbar, Lacasse, & Carey, 1998), aids the identification of sediments and volcanic units deposited during the last glacial period (i.e. the Weichselian glaciation).

Within the broad stratigraphic groups defined above, volcanic rocks were further subdivided according to composition (i.e. mafic, intermediate or silicic) and lithofacies. Without strict stratigraphic control, these subdivisions group together eruptive units that formed through similar processes and that may have formed in similar environments (Loughlin, 2002). Classification in this way is useful for the study of past glacial environments. However, the constituents of each subdivision are not strictly related in time and will represent a range of ages that are likely to overlap with other subdivisions of the same stratigraphic group (Figure 2). Distinct assemblages of related lithofacies are grouped into lithofacies associations (e.g. hyaloclastite-dominated units, which can also include pillow lavas and lobate or sheet-like intrusions). Note that the term hyaloclastite is used here to encompass fragmental rocks generated through both quench fragmentation (hyaloclastite; Rittman,

1958) and explosive phreatomagmatic fragmentation (hyalotuff; Honnorez & Kirst, 1975) of magma.

Vent locations relating to individual eruptive units were identified at numerous locations and are marked on the map. These vents are all extant scoria cones that are associated with the mafic to intermediate lavas and tuyas of Late Tindfjallajökull B. The vents of the older rocks of Early and Middle Tindfjallajökull have been removed by erosion and their locations could not be determined. Additional ornamentations on the map highlight tuya lava caps and areas of lava delta or highly jointed lava.

Where the position of a geological boundary has an uncertainty of more than ±50 m (due to the presence of overlying superficial deposits and/or soils), it is classed as an approximate geological boundary.

3. Geology and past environments of Tindfjallajökull volcano

In this section, the products of Tindfjallajökull volcanic system are described, from oldest stratigraphic group to youngest, with a focus on indicators of past environments. Mapped units that are associated with other volcanic systems are then described, followed by the sediments and superficial deposits. UTM grid references are abbreviated to four digits representing 1 × 1 km^2, e.g. Sindri: *71 76*.

3.1. Early Tindfjallajökull

3.1.1. Mafic undifferentiated (Emu)
Most of the volume of Tindfjallajökull consists of a succession of interbedded mafic hyaloclastite and lava
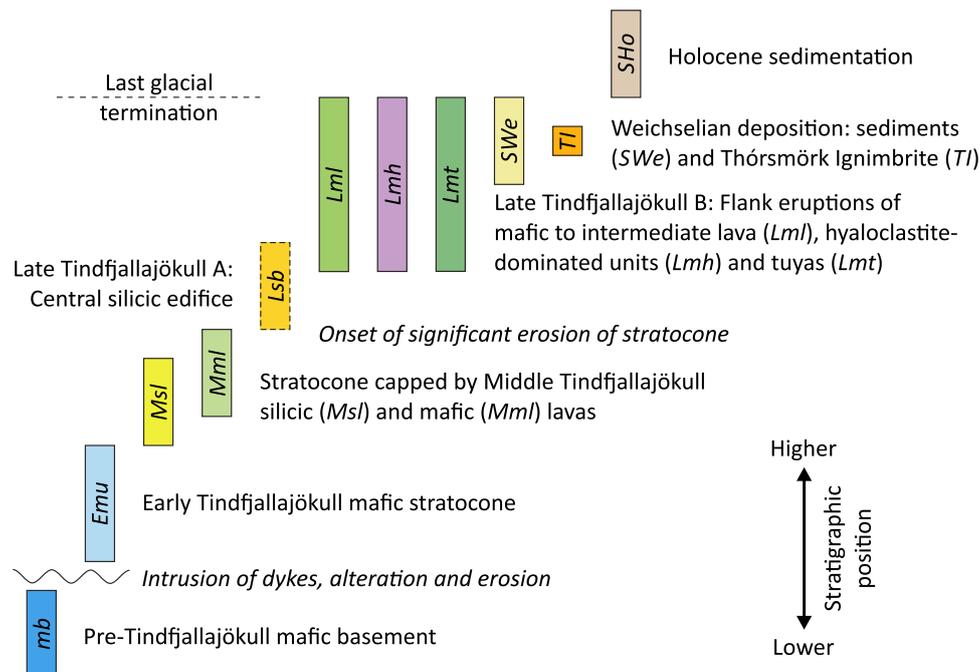
Figure 2. Stratigraphy of the mapped classes on Tindfjallajökull (not drawn to scale). It is not known if there is stratigraphic overlap between Late Tindfjallajökull A and Late Tindfjallajökull B. The eruptive products of Katla volcanic system and the fissure swarm NE of Tindfjallajökull are not included.

sheets, overlying the Pre-Tindfjallajökull basement. The basal contact has not been directly observed. Dykes and alteration in the basement have not been seen to pass into the overlying succession, suggesting that the contact is unconformable. In general, the Early Tindfjallajökull sheets dip gently outward from a central point roughly coincident with the present-day main ice cap. This parallel stratification is occasionally disrupted by minor palaeo-valleys and -gulleys. As a whole, the structure forms a dissected stratocone with an observed vertical extent of 1200 m (present-day maximum elevation: 1299 m above mean sea level, *69 76*).

3.2. Middle Tindfjallajökull

3.2.1. Silicic lava (Msl)
Three main areas of silicic lava are present on Tindfjallajökull, all of which immediately overlie the Early Tindfjallajökull stratocone. Erosion of the lavas has revealed lava lobe thicknesses of 20–60 m. Individual lava lobes have folded glassy margins with some areas of columnar jointing, and microcrystalline interiors which often develop platy structures. Ogives are preserved, or have been exhumed, on the surface of the upper lava lobe at Jökulskarð (~20 m wavelength; *73 76*). The vents of these lavas have not been preserved. A fragmental deposit (0–30 m thick) underlies the lava at Hestur (*72 68*) and is thought to have been emplaced during an initial phase of the same eruption. These silicic lavas are not diagnostic of a particular eruptive environment, though the presence of ogives

suggests that the upper lava lobe at Jökulskarð was emplaced in a subaerial setting.

3.2.2. Mafic lava (Mml)
Much of the west flank of Tindfjallajökull consists of a plateau surfaced with mafic lavas, capping the Early Tindfjallajökull stratocone. Isolated outcrops of capping lava are located on Vestriöxl (*75 75*) and on the NE side of Austurdalur (*66 77*). Individual lavas and vents are not distinct and have not been mapped in these areas. The unconfined nature of the lavas and the lack of evidence of enhanced cooling indicate that the eruptive environment was ice-free.

Since the formation of the Early Tindfjallajökull stratocone and the Middle Tindfjallajökull capping lavas, glacial erosion has cut the major valleys that emanate from the present-day ice cap.

3.3. Late Tindfjallajökull

3.3.1. A: Central silicic edifice
Silicic breccia with coherent lava lobes (Lsb). The summit of Tindfjallajökull (*70 74*) marks the top of a voluminous steep-sided pile of silicic breccia (Figure 3(a)), covering an area of perhaps 10 km² (when overlying volcanic rock and ice is removed). The breccia comprises poorly consolidated angular clasts 1–50 mm across. Coherent lobes of columnar-jointed silicic lava (~100 m wide) are present within the pile, and lava clasts are present within the surrounding breccia. The breccia has been subjected to pervasive hydrothermal alteration, and a hot spring in Hitagil (>60°C,
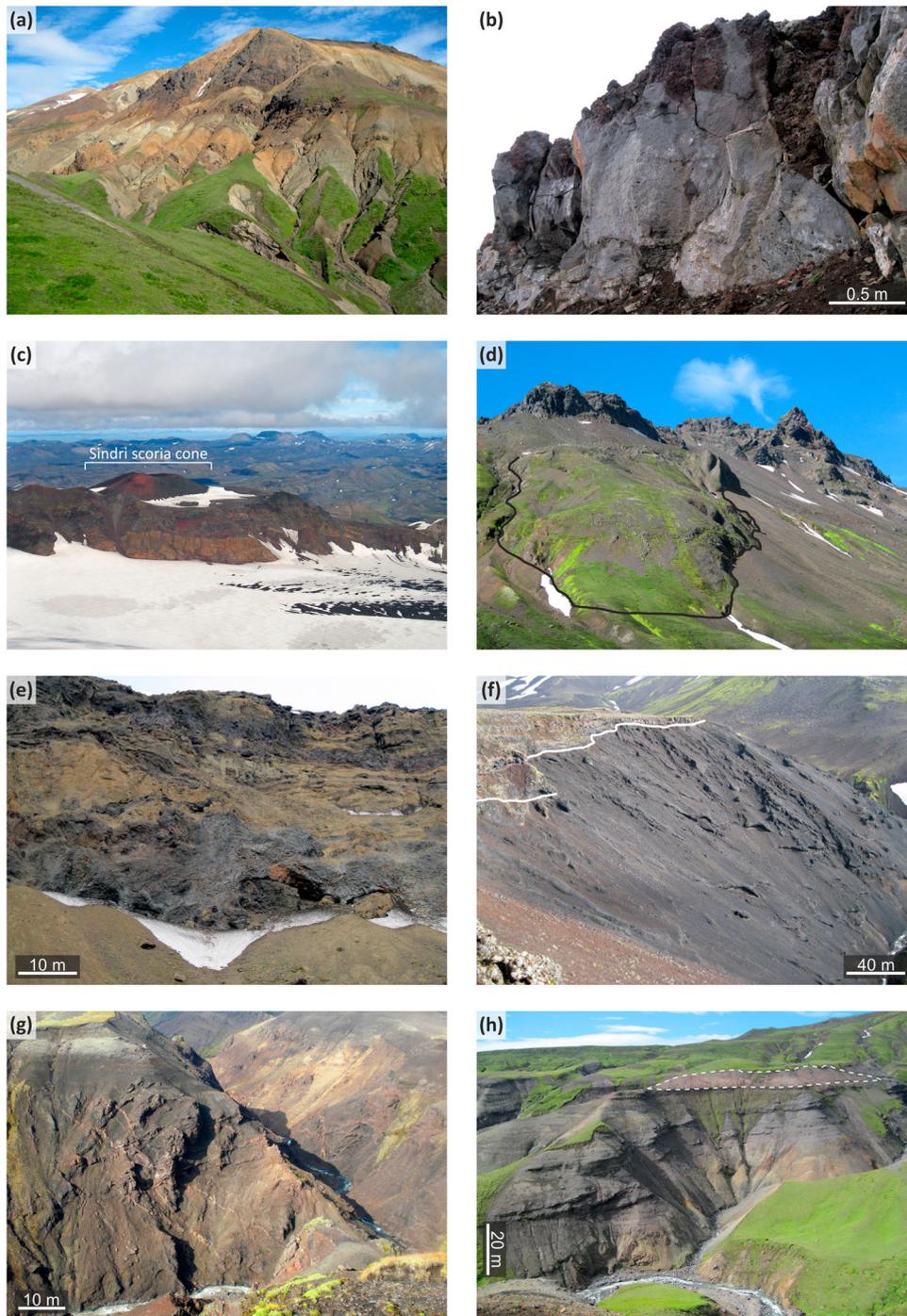
Figure 3. Photographs of selected geological features on Tindfjallajökull. (a) The view north from Botn of the pile of altered silicic breccia and lava lobes (dark) that make up the central silicic edifice of the volcano (Late Tindfjallajökull A). (b) An ~3 m thick mafic a'a lava in Tindfjallajökulsdalur (Late Tindfjallajökull B; *67 72*). This lava flowed into the valley from the Búri scoria cone. (c) Sindri scoria cone (*70 76*) viewed from Ýmir. The 500 m wide scoria cone sits on top of the Early Tindfjallajökull succession. (d) The east side of Tindur (*70 70*) viewed from Botn. A lava of Late Tindfjallajökull B age, outlined in black and ~250 m wide, becomes highly jointed where it has descended into the valley from a vent on the ridge. (e) The interior of a tuff cone has been exposed through mass-wasting at Hitagilsbrún (*72 71*). Mafic sills (grey) intrude bedded hyaloclastite (brown). (f) The lava cap (top left) and lava delta of Bláfell tuya (*66 71*). The white line indicates the passage zone between shallow-dipping a'a lavas and steeply dipping lava lobes and breccia. (g) Pre-Tindfjallajökull mafic basement exposed in a gorge (*73 70*). The lavas and hyaloclastites have been altered and intruded by numerous dykes. (h) The Weichselian depositional succession at Botn (*71 70*) composed of bedded diamictite and the Thórsmörk Ignimbrite (outlined with white dashes).

Ármannsson, 2016; *72 71*) indicates that hydrothermal circulation is still active.

The base of the central silicic edifice was not observed. The lowest outcrop is at ~600 m elevation, over 800 m beneath the highest outcrop. Significant erosion and/or down-faulting of Early and Middle Tindfjallajökull material, which forms ridges up to 1300 m altitude surrounding the central edifice, must have occurred before the breccias were emplaced. It is possible that a caldera formed at Tindfjallajökull

(as marked by Jóhannesson & Sæmundsson, 1989), but no direct evidence for subsidence (e.g. displacement on a fault) has been observed. Syn- or post-eruption subsidence into the top of a magma chamber is necessary for a volcanic structure to be termed a caldera, as defined by Cole, Milner, and Spinks (2005).

Extensive fragmentation of silicic lava and the confinement of a steep-sided pile of erupted material can indicate the presence of ice during an eruption (McGarvie, Stevenson, Burgess, Tuffen, & Tindle, 2007; Stevenson, Gilbert, McGarvie, & Smellie, 2011; Tuffen, Gilbert, & McGarvie, 2001). Angular clasts and jointed lava lobes at all levels of the central silicic edifice suggest that cooling may have been enhanced by a thick body of ice, though further work is needed to reduce ambiguity.

3.3.2. B: Flank volcanism

This category consists of a variety of well-preserved eruptive units that are sourced from dispersed vents and fissures on the flanks of Tindfjallajökull. The preservation of features such as scoria cones and the stratigraphic association of some of the units with the Thórsmörk Ignimbrite suggests that the majority of the units were emplaced during the Weichselian glacial period. There is likely to be chronological overlap between the members of this category (Figure 2), as they are subdivided by lithofacies rather than stratigraphic position.

Mafic to intermediate lava (Lml). Twelve mafic to intermediate lavas that have experienced little erosion have been mapped on Tindfjallajökull's upper flanks. The lavas are typically a'a with autobrecciated bases and tops (where preserved; Figure 3(b)). The remnants of scoria cones are present at the vent of each lava, where not obscured by younger lava or ice. The scoria cone at Sindri (Figure 3(c); *70 76*) is particularly well preserved, suggesting that it has not been subjected to glaciation and probably post-dates the last glacial maximum. Unconfined lavas with no evidence of enhanced cooling are indicative of an ice-free eruptive environment.

Highly jointed lava: In some instances, lavas that have flowed down steep slopes transition from a normal widely spaced jointing pattern to closely spaced pseudopillow fractures and cube-jointing. This occurs on the south side of Sindri (*71 76*), on the southern rim of Austurdalur (*65 74*) and on the east side of Tindur (Figure 3(d); *70 70*). The closely spaced jointing patterns indicate that the lavas were cooled rapidly due to the presence of water (Forbes, Blake, McGarvie, & Tuffen, 2012). Topographic depressions suitable for the ponding of water are not present in these localities, so it is likely that water was instead derived through the melting of ice or snow. The elevation of the transition from subaerial lava to highly jointed lava (marked with

white lines on the map) provides constraints on the upper limits of ice or snow within glaciated valleys at the time of each eruption.

Mafic hyaloclastite-dominated units (Lmh). Hyaloclastite-dominated units on Tindfjallajökull exist as hyaloclastite ridges, tuff cones, breccia mounds and hyaloclastite sheets. Each type can include a variable proportion of pillow lava and/or intrusive dykes, sills or lobes (Figure 3(e)), but capping lavas are not present.

Hyaloclastite ridges on Tindfjallajökull have a range of fissure orientations, with approximate groupings at 040–067° (perpendicular to the regional spreading direction), 104–111° and ~155°. Tuff cones and breccia mounds are sourced from point vents with no linear orientation. Hyaloclastite sheets (2–10 m thick) typically constitute the more distal deposits of tuff cones and are common within a succession of Weichselian sediments on the SE side of Tindfjallajökull (around *73 70*).

Both hyaloclastite and pillow lava lithofacies indicate the presence of water during an eruption. This is commonly an indicator for the presence of ice in this topographical setting (Jones, 1969; Mathews, 1947). The prevalence of water interaction throughout all lithofacies in these units suggests that water or ice was present at the vent for the duration of each eruption.

Mafic tuyas (Lmt). Tuyas are defined here as hyaloclastite-dominated units that are capped with shallow-dipping lavas. Eight tuyas have been mapped on Tindfjallajökull, predominantly on the western upper flank. The footprint area of the tuyas ranges from 0.1 km^2 to the 8 km^2 Þórólfsfell tuya (*66 66*). Scoria cones are preserved at the vents of some of the tuyas, and there are subsidence pits on the a'a lava cap of Bláfell tuya (*66 71*). The five largest tuyas have extensive lava deltas preserved on their flanks, composed of steeply dipping highly jointed lava lobes and lava breccia (Figure 3(f)).

Tuyas are common in Iceland and are interpreted to form when subglacial eruptions breach the upper ice surface (Jones, 1966; Mathews, 1947). When this occurs, the eruption transitions from phreatomagmatic conditions, producing pillow lavas and hyaloclastites, to 'dry' conditions during which a lava cap is emplaced. Meltwater is typically ponded around the growing tuya during the eruption. Where lava flows from the shallow-dipping top into the ice-dammed lake, a lava delta is formed, and the change in lithofacies at this water level is called a passage zone. The level of the passage zone from subaerial to subaqueous lava emplacement can be used to estimate the thickness of the surrounding ice body (Russell, Edwards, Porritt, & Ryane, 2014; Skilling, 2009). The subsidence pits on

Bláfell tuya may have been formed through the draining of subsurface magma or meltwater.

3.4. Other volcanic systems

3.4.1. Pre-Tindfjallajökull (volcanic system unknown)

Mafic basement (mb). The oldest rocks on the map are found on the SE side of Tindfjallajökull (Figure 3(g); *73 70*). These mafic hyaloclastites and lavas have been extensively altered, intruded by dykes, and their pore spaces have been infilled through secondary mineralisation. The extent of alteration and intrusion suggests that these rocks pre-date the unaltered rocks of Tindfjallajökull and most likely constitute part of an older volcanic system that has been largely buried by recent volcanic activity.

3.4.2. Torfajökull volcanic system (speculative)

Mafic hyaloclastite-dominated units in fissure swarm between Tindfjallajökull and Torfajökull (mh). The fissure swarm stretching NE from Tindfjallajökull has been the subject of little study, but is tentatively considered to be part of the Torfajökull volcanic system (Sæmundsson & Larsen, 2016). Mafic eruptions in this area have produced SW-NE oriented parallel hyaloclastite ridges. Pillow lavas are found in the cores of the ridges, where exposed through fluvial erosion. The confinement of material along eruptive fissures and the prevalence of magma-water interaction indicate that these ridges were emplaced subglacially. The ridges show relatively little sign of glacial erosion, suggesting that they were emplaced during the Weichselian glaciation.

Silicic breccia with coherent lava lobes in fissure swarm (sb). Sultarfell is a pale-coloured steep-sided hill (~0.03 km^3; *74 79*) situated in the fissure swarm NE of Tindfjallajökull. It is composed of jointed rhyolitic lava lobes (a few metres across) bounded by unconsolidated breccia of cogenetic fragmented rhyolite. Lobes of fractured lava can be seen in close association with lava fragments that have spalled off the lobes during cooling, which may have been enhanced by the presence of water and/or ice. Like the neighbouring mafic hyaloclastite ridges, the level of preservation of Sultarfell suggests it was emplaced during the Weichselian glaciation.

Thórsmörk Ignimbrite (TI). Most of the preserved volume of the Thórsmörk Ignimbrite outcrops to the south of the Markarfljót, beyond the scope of this map (Jørgensen, 1980). The internal structure of the ignimbrite is complex and both welded and unwelded domains are present. Within the area of the map, the ignimbrite is intercalated within a succession of diamictite (Figures 3(h) and 5) and typically forms a

layer up to 10 m thick, though it is sometimes entirely absent from the stratigraphy. Within 5 km of Tindfjallajökull's summit, lithic clasts make up <5% of the ignimbrite and are <3 mm in diameter. In comparison, exposures south of the Markarfljót have a thickness of ~30 m with ~10% lithic clasts, which are up to 20 cm in diameter (Jørgensen, 1980).

Jørgensen (1980) proposed that Tindfjallajökull is the source of the Thórsmörk Ignimbrite, based on the broad patterns of welding, crystallisation, and outcrop distribution of the deposit. However, geological mapping on Tindfjallajökull has not found evidence to support this. In particular, the relatively low abundance and small size of lithic clasts entrained within the ignimbrite close to Tindfjallajökull and the continuity of diamictite deposition before and after ignimbrite emplacement suggests that Tindfjallajökull is not the source of this major eruption. Further work is being undertaken to trace the source of the ignimbrite. Torfajökull volcano is a possible alternative source, as Grönvold et al. (1995) noted a geochemical similarity between rhyolites at Torfajökull and North Atlantic Ash Zone II (the distal correlative of the Thórsmörk Ignimbrite).

3.4.3. Katla volcanic system

Mafic lava (Kml). A series of Holocene pahoehoe lavas have infilled the Markarfljót valley SE of Tindfjallajökull (*74 66*, SE extremity of map). The source of the lavas is located to the east of the map margin in the Katla volcanic system (Larsen, 2000). The interiors of the lavas have developed an entablature jointing pattern during cooling, and the lavas have subsequently been scoured by jökulhlaups (Smith & Dugmore, 2006). The unconfined nature of the lavas indicates a subaerial eruptive environment, with the entablature interiors indicating enhanced cooling of the lava following the introduction of river water (Lyle, 2000). This indicates that the valley was occupied by an active river at the time of lava emplacement.

3.5. Sediments

3.5.1. Last glacial period (Weichselian; SWe)

A depositional succession (maximum observed thickness of 160 m) extends from the Vestri-Botná valley (*71 71*) to the low-lying Fauskheiði ridge (*71 65*). The dominant lithofacies is diamictite (Figure 4(a)), with occasional water-lain gravels. Clast sizes in the diamictite range from silt to boulders 60 cm across. The clasts are typically faceted and striated, indicating a glacial influence in their transport. Crucially, the 54.5 ± 2 ka Thórsmörk Ignimbrite is present within the succession, dating it to the last glacial period (Sigurdsson et al., 1998). Other pre-Holocene outcrops of glacially worked material are found on the southern flank of Tindfjallajökull (*68 68*) and in the Eystri-Botná valley (*74 73*).

Figure 4. Photographs of sediments deposited (a) during and (b) after the last glacial period. (a) Diamictite exposed in Hitagil (*73 71*). Inset: striated cobble within the diamictite and (b) Rhythmite with alternating laminae of fine sand and silt (*76 74*).

3.5.2. Holocene and last glacial termination (SHo)

Sediments deposited during and after the retreat of the Weichselian Icelandic Ice Sheet infill valleys to the NE and S of Tindfjallajökull. The youngest sediments are conglomerates that are associated with the presently active fluvial systems, such as the braided river plain of the Markarfljót (in the extreme south of the map). Between the hyaloclastite ridges to the NE of Tindfjallajökull, rhythmites are common (Figure 4(b)). These deposits have 3–10 mm thick laminae of alternating fine sands and silts which are characteristic of lacustrine depositional environments, and suggest that lakes (now drained) once occupied the valleys between the parallel ridges.

3.6. Superficial deposits

With the exception of tephra, the present-day ice cap entrains only a small volume of rock debris. This is reflected in the lack of significant deposits of moraine around the margins of the ice. Only one area of hummocky moraine has been mapped, near to the eastern and lowest altitude termination of the present ice cap (*73 74*).

Features produced through the collapse of ice-eroded and ice-confined eruptive units are present on Tindfjallajökull. Mass-wasting has taken place as coherent slumps (e.g. at Bláfell tuya *65 71*) or more chaotic rockslides and falls (e.g. at Hitagilsbrún *73 72*).

4. Geological development of Tindfjallajökull volcano

4.1. Evolution of Tindfjallajökull

Geological mapping of Tindfjallajökull has given insight into the evolution of the volcano over time. Mafic basement rocks were emplaced during a volcanic episode prior to the construction of Tindfjallajökull. Volcanism in this area has been ongoing for perhaps 1–2 million years, building on top of the crust that formed several million years ago (Óskarsson, Steinthórsson, & Sigvaldason, 1985; Sæmundsson, 1974).

The construction of the Early Tindfjallajökull stratocone, a thick succession with consistent radial dip, was a highly productive phase of Tindfjallajökull's initial development. It is likely that the volcano was glaciated during much of this stage and that some erosion took place, but glacial erosion was surpassed by volcanism as the main driver of landscape evolution. Following the construction of the stratocone, all or most of its surface was capped by the subaerially emplaced Middle Tindfjallajökull lavas of mafic and silicic compositions (Figure 5). Glacial erosion has subsequently resulted in extensive modification of the Early-Middle Tindfjallajökull edifice, particularly through the deepening of the valleys that radiate from the centre of the volcano.

At the onset of the Late Tindfjallajökull stage, the eruption of silicic breccia with coherent lava lobes formed the central silicic edifice. It is unclear if the eruption of this material was accompanied by caldera subsidence. Mafic to intermediate flank volcanism has continued through to the end of the last glacial period during various ice-thickness conditions. These eruptions, on the upper west flank in particular, produced a variety of landforms including hyaloclastite ridges, tuyas and lavas.

On the SE side of Tindfjallajökull, a depositional succession records a detailed history of glacially influenced sedimentation and local mafic volcanism during the last glacial period. The Thórsmörk Ignimbrite provides a valuable chronostratigraphic marker within this succession (Figure 5). During and after the retreat of
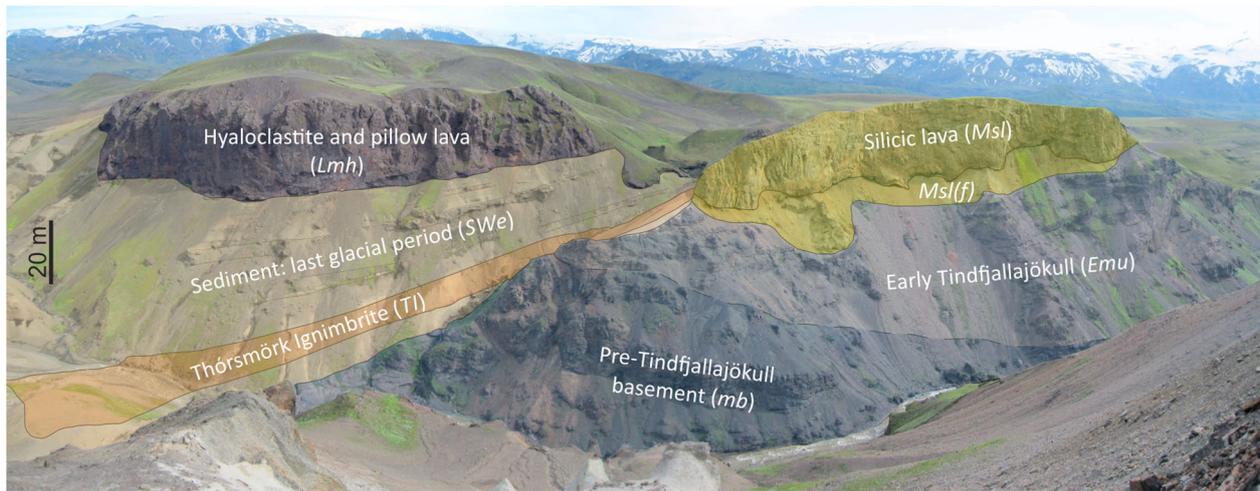
Figure 5. Annotated panorama of the SE side of the Gilsá gorge (*73 68*) viewed from Hestur. Sedimentary and volcanic deposits dating to the last glacial period (left) onlap onto an older succession of volcanic rocks (right).

the Weichselian glaciation, sedimentation has occurred in lacustrine and fluvial settings around the foot of Tindfjallajökull.

4.2. Comparison to neighbouring volcanoes

Several broad characteristics of Tindfjallajökull volcano are comparable to Eyjafjallajökull volcano. The summit of Eyjafjallajökull is only 18 km south of the summit of Tindfjallajökull, and the two volcanoes are of similar size.

The oldest mapped rocks on Eyjafjallajökull are the Laugará Group, exposed on the southern flank of the volcano (Jónsson, 1988). Like the Pre-Tindfjallajökull basement, the Laugará Group is composed of altered basaltic hyaloclastite, pillow breccia and fragmented lava, with numerous intrusive sheets (Loughlin, 1995). The oldest rocks at Eyjafjallajökull were emplaced prior to the Brunhes-Matuyama geomagnetic reversal (∼780 ka), and a K/Ar date of 780 ± 30 ka has been obtained from a lava with reversed polarity (Kristjansson, Johannesson, Eiriksson, & Gudmundsson, 1988).

Like Tindfjallajökull, much of Eyjafjallajökull consists of a thick succession of mafic to intermediate hyaloclastites and lavas (Loughlin, 2002). Furthermore, this succession is capped by lavas that surface much of the upper flanks of both volcanoes (Jónsson, 1988; Loughlin, 1995).

Glacial valleys are thought to have formed in the mid-late period of Eyjafjallajökull's development (Loughlin, 1995). Dissection of Tindfjallajökull's edifice is more advanced than at Eyjafjallajökull. The existence of accommodation space for sedimentary successions within a few kilometres of Tindfjallajökull's summit attests to the greater degree of focussed dissection that has occurred. It is not clear if caldera subsidence is an additional factor that may have contributed to the accommodation of sediment at Tindfjallajökull.

Finally, the mapping of Tindfjallajökull has indicated that it has more extensive deposits of silicic rock in comparison to Eyjafjallajökull (Loughlin, 1995). The presence of a suspected caldera and a high ratio of evolved rock to basalt led Jakobsson (1979) to speculate that Tindfjallajökull is the most mature active volcano in the Eastern Volcanic Zone. However, possible caldera structures and significant volumes of silicic material are also features of the larger nearby volcanoes of Katla and Torfajökull (Jóhannesson & Sæmundsson, 1989).

5. Conclusions

A 1:50,000 scale geological map of Tindfjallajökull provides the first comprehensive survey of this ice-capped stratovolcano. The map enables a reconstruction of the evolution of Tindfjallajökull through time and a comparison to other nearby volcanoes. Much of the volcano is similar to neighbouring Eyjafjallajökull, though Tindfjallajökull has a higher proportion of silicic volcanic rocks and a higher degree of erosion.

Field mapping of volcanic lithofacies and lithofacies associations allows the mapped classes to broadly reflect the environment at the time of each eruption. As is typical in Iceland, ice has had a significant influence on the development of Tindfjallajökull, though the extent of ice has varied widely through time. Lavas, tuyas and hyaloclastite-dominated units have interacted with ice of variable thicknesses. A depositional succession on the SE side of Tindfjallajökull records glacially influenced sedimentation and eruptions dating to the last glacial period. Information on past glacial environments on Tindfjallajökull, if combined with chronological data, could fit into larger scale models of late Pleistocene to Holocene palaeoenvironments in Iceland.

Software

Geological boundaries were digitised using Google Earth Pro and the maps and cross-sections were

produced using ESRI ArcGIS. The map page was constructed and edited using CorelDRAW X6.

References

Ármannsson, H. (2016). The fluid geochemistry of Icelandic high temperature geothermal areas. *Applied Geochemistry*, 66, 14–64. doi:10.1016/j.apgeochem.2015.10.008

Cole, J. W., Milner, D. M., & Spinks, K. D. (2005). Calderas and caldera structures: A review. *Earth-Science Reviews*, 69, 1–26. doi:10.1016/j.earscirev.2004.06.004

Forbes, A. E. S., Blake, S., McGarvie, D. W., & Tuffen, H. (2012). Pseudopillow fracture systems in lavas: Insights into cooling mechanisms and environments from lava flow fractures. *Journal of Volcanology and Geothermal Research*, 245–246, 68–80. doi:10.1016/j.jvolgeores.2012.07.007

Google Earth Pro. (2010). *Tindfjallajökull 63°47′N 19°35′W*. DigitalGlobe 2012.

Grönvold, K., Óskarsson, N., Johnsen, S. J., Clausen, H. B., Hammer, C. U., Bond, G., & Bard, E. (1995). Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. *Earth and Planetary Science Letters*, 135(1–4), 149–155. doi:10.1016/0012-821X(95)00145-3

Honnorez, J., & Kirst, P. (1975). Submarine basaltic volcanism: Morphometric parameters for discriminating hyaloclastites from hyalotuffs. *Bulletin Volcanologique*, 39, 441–465. doi:10.1007/BF02597266

Jakobsson, S. V. (1979). Petrology of recent basalts of the Eastern Volcanic Zone, Iceland. *Acta Naturalia Islandica*, 26. doi:10.1016/0198-0254(81)91274-7

Jóhannesson, H., & Sæmundsson, K. (1989). *Geological map of Iceland, 1:500,000, bedrock geology*. Reykjavik: Icelandic Institute of Natural History.

Jones, J. G. (1966). Intraglacial volcanoes of South-west Iceland and their significance in the interpretation of the form of the marine basaltic volcanoes. *Nature*, 212, 586–588. doi:10.1038/212586a0

Jones, J. G. (1969). Intraglacial volcanoes of the Laugarvatn region, south-west Iceland. *Quarterly Journal of the Geological Society of London*, 124, 197–211. doi:10.1144/gsjgs.124.1.0197

Jónsson, J. (1988). *Geological Map Eyjafjöll, 1:50,000*. Research Institute Neðri Ás Hveragerði.

Jørgensen, K. A. (1980). The Thorsmörk ignimbrite: An unusual comenditic pyroclastic flow in Southern Iceland. *Journal of Volcanology and Geothermal Research*, 8, 7–22. doi:10.1016/0377-0273(80)90004-9

Kristjansson, L., Johannesson, H., Eiriksson, J., & Gudmundsson, A. I. (1988). Brunhes- Matuyama paleomagnetism in three lava sections in Iceland. *Canadian Journal of Earth Sciences*, 25(2), 215–225. doi:10.1139/e88-024

Lacasse, C., Sigurdsson, H., Carey, S., Paterne, M., & Guichard, F. (1996). North Atlantic deep-sea sedimentation of Late Quaternary tephra from the Iceland hotspot. *Marine Geology*, 129(3–4), 207–235. doi:10.1016/0025-3227(96)83346-9

Landmælingar Íslands. (2016). *IS 50V digital map database*. Retrieved from http://www.lmi.is/en/stafraen-gogn/is-50v-nytt/; Licence: http://www.lmi.is/wp-content/uploads/2013/10/licenceNLSI.pdf

Larsen, J. G. (1979). Glass-bearing gabbro inclusions in hyaloclastites from Tindfjallajökull, Iceland. *Lithos*, 12(4), 289–302. doi:10.1016/0024-4937(79)90021-5

Larsen, J. G. (2000). Holocene eruptions within the Katla volcanic system, south Iceland: Characteristics and environmental impact. *Jökull*, 49, 1–28.

Loughlin, S. C. (1995). *The evolution of the Eyjafjöll volcanic system, southern Iceland* (PhD thesis). Durham University.

Loughlin, S. C. (2002). Facies analysis of proximal subglacial and proglacial volcaniclastic successions at the Eyjafjallajökull central volcano, southern Iceland. *Geological Society, London, Special Publications*, 202, 149–178. doi:10.1144/GSL.SP.2002.202.01.08

Lyle, P. (2000). The eruption environment of multi-tiered columnar basalt lava flows. *Journal of the Geological Society*, 157, 715–722. doi:10.1144/jgs.157.4.715

Mathews, W. H. (1947). "Tuyas," flat-topped volcanoes in northern British Columbia. *American Journal of Science*. doi:10.2475/ajs.245.9.560

McGarvie, D. W., Stevenson, J. A., Burgess, R., Tuffen, H., & Tindle, A. G. (2007). Volcano – ice interactions at Prestahnukur, Iceland: rhyolite eruption during the last interglacial – glacial transition. *Annals of Glaciology*, 45, 38–47. doi:10.3189/172756407782282453

Óskarsson, N., Steinthórsson, S., & Sigvaldason, G. E. (1985). Iceland geochemical anomaly: Origin, volcanotectonics, chemical fractionation and isotope evolution of the crust. *Journal of Geophysical Research*, 90(B12), 10011. doi:10.1029/JB090iB12p10011

Rittman, A. (1958). Il meccanismo di formazione delle lave a pillows e dei cosidelti tufi palagonitici. *Atti Acc. Gioenia*, 4, 310–317.

Russell, J. K., Edwards, B. R., Porritt, L., & Ryane, C. (2014). Tuyas: A descriptive genetic classification. *Quaternary Science Reviews*, 87, 70–81. doi:10.1016/j.quascirev.2014.01.001

Sæmundsson, K. (1974). Evolution of the axial rifting zone in Northern Iceland and the Tjörnes fracture. *Geological Society of America Bulletin*, 85, 495–504. doi:10.1130/0016-7606(1974)85<495

Sæmundsson, K., & Larsen, G. (2016). Torfajökull. In E. Ilyinskaya, G. Larsen, & M. T. Gudmundsson (Eds.), *Catalogue of Icelandic volcanoes*. IMO, UI, CPD-NCIP. Retrieved from http://icelandicvolcanoes.is/

Sigurdsson, H. (1982). Útbreiðsla íslenskra gjóskulaga á botni Atlantshafs. In H. Thorarinsdóttir, O. H.

Oskarsson, S. Steinthorsson, & T. Einersson (Eds.), *Eldur er í nordri* (pp. 119–127). Reykjavik: Sögufélag.

Sigurdsson, H., McIntosh, W. C., Dunbar, N., Lacasse, C., & Carey, S. N. (1998). Thorsmork Ignimbrite in Iceland; possible source of North Atlantic ash zone 2? In *AGU 1998 Spring Meeting. Eos (Transactions, American Geophysical Union) 79* (p. 377).

Skilling, I. P. (2009). Subglacial to emergent basaltic volcanism at Hlöðufell, south-west Iceland: A history of ice-confinement. *Journal of Volcanology and Geothermal Research*, *185*(4), 276–289. doi:10.1016/j.jvolgeores.2009.05.023

Smith, K. T., & Dugmore, A. J. (2006). Jökulhlaups circa Landnám: Mid- to late first millennium AD floods in South Iceland and their implications for landscapes of settlement. *Geografiska Annaler*, *88 A*(2), 165–176. doi:10.1111/j.0435-3676.2006.00292.x

Stevenson, J. A., Gilbert, J. S., McGarvie, D. W., & Smellie, J. L. (2011). Explosive rhyolite tuya formation: Classic examples from Kerlingarfjöll, Iceland. *Quaternary Science Reviews*, *30*(1–2), 192–209. doi:10.1016/j.quascirev.2010.10.011

Thórarinsson, S. (1969). Ignimbrít í Þörsmórk. *Náttúrufræðingurinn*, *39*, 139–155.

Tomlinson, E. L., Thordarson, T., Müller, W., Thirlwall, M., & Menzies, M. A. (2010). Microanalysis of tephra by LA-ICP-MS — Strategies, advantages and limitations assessed using the Thorsmörk ignimbrite (Southern Iceland). *Chemical Geology*, *279*(3–4), 73–89. doi:10.1016/j.chemgeo.2010.09.013

Tuffen, H., Gilbert, J., & McGarvie, D. (2001). Products of an effusive subglacial rhyolite eruption: Bláhnúkur, Torfajökull, Iceland. *Bulletin of Volcanology*, *63*(2–3), 179–190. doi:10.1007/s004450100134

USA Defence Mapping Agency. (1989). *Iceland DMA-C761 topographic maps, 1:50,000*. Washington, DC: Defence Mapping Agency. Retrieved from http://www.lmi.is/landupplysingar/kortasafn/