Reviewed research article

Stratigraphy, ^{40}Ar–^{39}Ar dating and erosional history of Svínafell, SE-Iceland

Jóhann Helgason[1] and Robert A. Duncan[2,3]
[1]*National Land Survey of Iceland, Stillholti 14–16, 300 Akranes, Iceland*
[2]*College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA*
[3]*Department of Geology and Geophysics, King Saud University, Riyadh, Saudi Arabia*
jhelgason@internet.is, rduncan@coas.oregonstate.edu

Abstract — *The interplay of volcanism and erosion in the Svínafell massif, on the western slope of the Öræfajökull volcanic center, SE-Iceland, is traced with geological mapping, magnetostratigraphy and ^{40}Ar–^{39}Ar age determinations. The volcanic strata are mainly of Quaternary age, i.e., geomagnetic chrons of lower Matuyama to upper Brunhes. The 1832 m thick sequence in Svínafell is composed of 37 discrete lithologic formations, assigned to seven volcano-stratigraphic groups beginning with the onset of volcanism in the Öræfajökull stratovolcano during lower Brunhes magnetic chron (C1n < 781 ka). A regional basin formed shortly before the initiation of volcanism, generating a depocenter for the plant-fossil bearing Svínafell sediments between 0.70 and 1.78 Ma. The Svínafell volcanic strata accumulated during a minimum of eight glacial and inter-glacial stages. We document the Svínafell erosion history and landscape evolution, including 12 erosion surfaces. Erosion has led to extended stratigraphic hiatuses and removal of thick volcanic sequences.*

INTRODUCTION

Volcanoes and glaciers in the Öræfi district have actively shaped the landscape for millions of years. Relief increased and glaciers began to form and persist during inter-glacial intervals. Although glacial erosion occurred during inter-glacials it reached maximum extents during glacial intervals. Key erosion factors include ice thickness, duration of glaciation, lithology, as well as the mass balance between accumulation of new volcanic material versus eroded material and mass wasting. Much of the build up of erupted material during glacial periods occurred subglacially as hyaloclastite deposits, or móberg (Helgason and Duncan, 2001). The interplay, magnitude and timing of the above factors are poorly known. We present data that contribute to an understanding of the erosion history of the Öræfi district, an area that experienced active volcanism and erosion from before the onset of major northern hemisphere glaciations (~2.7 Ma) to the present (Helgason and Duncan, 2001; Eiríksson, 2008).

Active glaciers in the Öræfi district, SE-Iceland, have dissected strata into isolated mountain ranges. One of these is Svínafell, bounded by Svínafellsjökull on the north side and Virkisjökull to the east. The Svínafell massif is located at the western margin of the Öræfajökull volcano. The purpose of this study is threefold, i.e., to 1) provide a basic geological bedrock map of Öræfajökull's volcanic history, 2) determine the stratigraphic age range for the Svínafell lacustrine sediments, and 3) trace Svínafell's erosion history and evolving landscape.

Geological setting

The Svínafell massif, located 8 km southwest of the Öræfajökull stratovolcano's caldera rim, consists mainly of volcanic rocks. The distance to Hrútsfjöll, an extinct Brunhes age (<781 ka) volcano farther north, is about 5 km. The Öræfajökull volcano has erupted twice in historic times, first with a devastating explosive eruption in AD1362 and later with a basaltic eruption in 1727 (Þórarinsson, 1958). Together with centers in Esjufjöll and Snæfell, the Öræfajökull volcano forms a chain of central volcanoes, the Öræfajökull Volcanic Zone (ÖVZ), trending NNE (Figure 1).

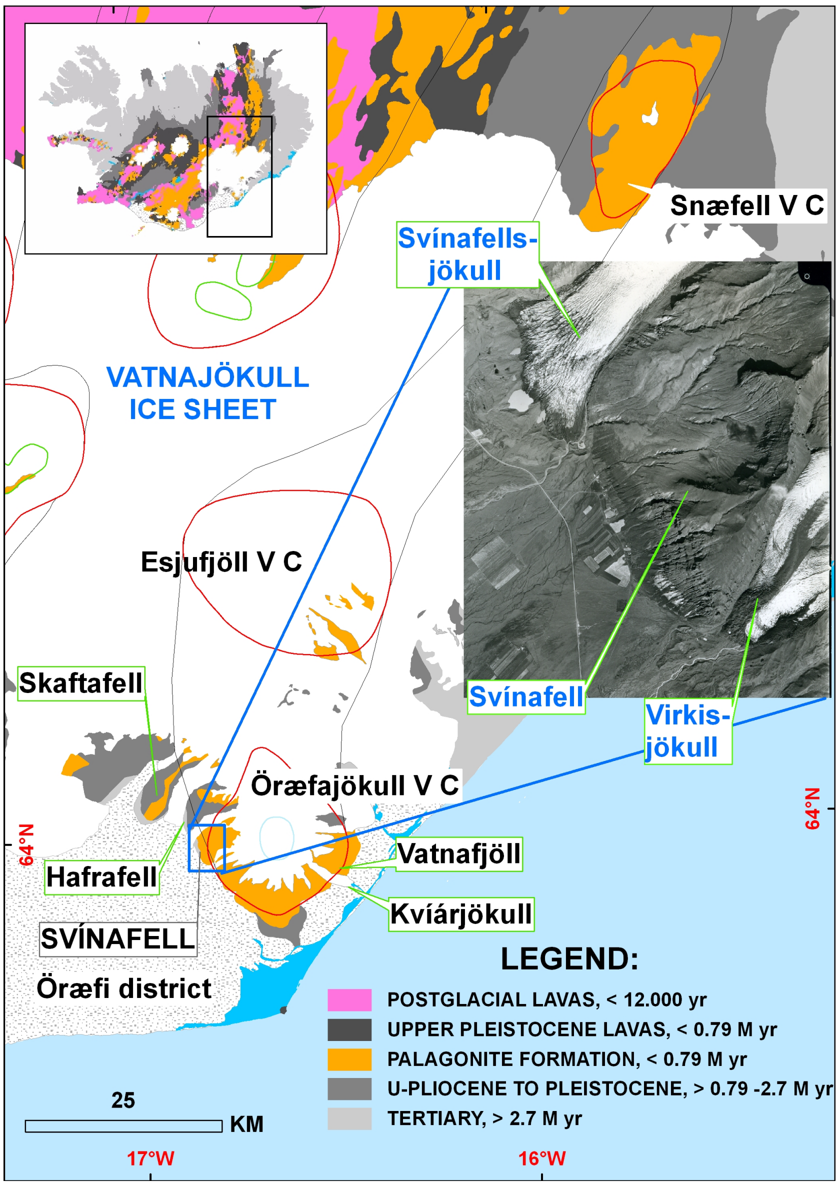

Figure 1. Geological setting, Svínafell research area in relation to Öræfajökull volcano and neighboring volcanic centers and fissure swarms. – *Lega Svínafells með hliðsjón af eldstöðinni í Öræfajökli, nálægum megineldstöðvum og sprungusveimum.*

Öræfajökull is the most active volcano within the ÖVZ. The youngest rocks found in Snæfell have an ^{40}Ar–^{39}Ar age of about 240 ka (Helgason and Duncan, 2005). Rocks in Svínafell, from the Öræfajökull volcano, typically belong to the tholeiitic fractionation series, i.e., tholeiites to rhyolites (e.g., Prestvik, 1979, 1982). More recently, the volcanic products in the ÖVZ are defined as transitional alkalic (Jakobsson *et al.*, 2008).

Previous work

Nielsen and Noe-Nygaard (1936) and Noe-Nygaard (1953) studied indurated moraines in the Svínafell massif and identified several tillites in bedrock outcrops, however, their exact location is unclear. Þórarinsson's (1963) pioneering work on the Svínafell strata outlined the stratigraphic framework for the plant-fossils found in the Svínafell lacustrine sediments, stating that the base of the Svínafell layers, just north of Skjólgil lies about 160 m above the plain with a thickness of about 15 m. The underlying basalts are normally magnetized down to about 100 m and reversed farther down. Einarsson (1977) concluded that normally magnetized volcanic units overlying the Svínafell sediments formed during the Brunhes polarity chron. Þórarinsson (1963) considered the Svínafell sediments to have formed during the second last inter-glacial whereas Einarsson (1968) regarded them as being somewhat older, from the third last inter-glacial, based on Albertsson's (1976) K-Ar age dating, which suggests an age of about 500 ka. Torfason (1985) suggested a Tertiary age (>3.1 Ma) for the lowest part of the Svínafell massif and Brunhes age for the upper sequence. Prestvik (1979) cites Albertsson (1976) on rocks from the upper part of the Svínafell massif suggesting that the Svínafell lacustrine sediments may have an age of "between post-Jaramillo (ca. 890 ka) and the beginning of the Elster glaciations (ca. 600 ka)". Although his main contribution was to Öræfi's petrology, Prestvik (1979) reported three glacial surfaces in Svínafell, one above the Svínafell sediments and two below.

GEOLOGICAL MAPPING AND STRATIGRAPHIC DATA

Stratigraphic classification in the Svínafell area reflects highly diversified lithology, frequent glacial-interglacial transitions, subaerial as well as subglacial volcanism, extensive transgressive erosion and magnetic reversals. During our geological mapping of the Svínafell massif numerous stratigraphic profiles were made through cliff sections from which we observed rock lithology, magnetic polarity and general field relations (Figures 2–4).

We compiled an 1832 m thick stratigraphic master sequence. Initially, strata were mapped and divided into 37 rock formations (Helgason, 2007), mainly emphasizing transitions between glacial and inter-glacial conditions as well as magnetic reversals (Figure 2).

While mapping Quaternary strata in Svínafell we focused on glacial to inter-glacial transitions indicated by abundance of subglacially formed lithologies, and erosion surfaces caused by the numerous glaciations. Mapping in the Öræfi district has revealed a general distinction of "upper" and "lower" strata (e.g., Prestvik, 1979) where the upper strata rest unconformably on the lower strata. The upper strata are predominantly of Brunhes age (<0.781 Ma) whereas the lower strata have an age range of about 5 to 0.781 Ma (Helgason and Duncan, 2001; Eiríksson, 2008). In the field, Walker's rock classification was used to divide lavas into specific lithologic types (Walker, 1959); that is, plagioclase porphyritic lavas, aphyric tholeiites and olivine tholeiites (the last type not found in Svínafell). The aphyric, fine-grained "tholeiites" of Walker tend to have alkali basalt chemistry in Svínafell.

Stratigraphic division: groups S1 to S7

Stratigraphic units, such as lavas or subglacially erupted strata, are numbered for each profile and divided into formations and groups which are correlated based on ^{40}Ar–^{39}Ar age determinations and geomagnetic polarity measurements. Erosion surfaces, that predominantly coincide with subglacial volcanic events, are commonly glacially striated. Based on lithology the stratigraphic sequence is divided into inter-glacial or glacial stages. Amount and

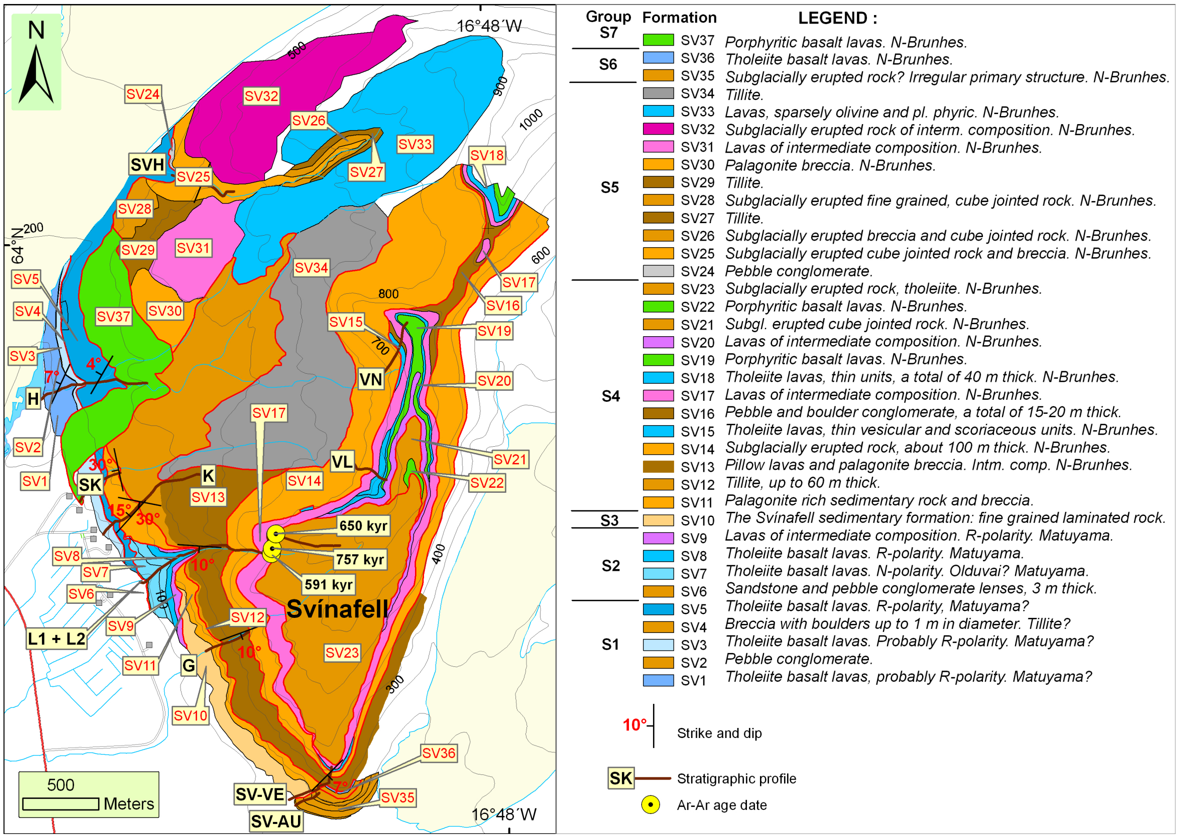

Figure 2. Detailed geological division of Svínafell with formations (*SV1–SV37* and groups (*S1* to *S7*). – *Ítarleg skipting jarðlaga í Svínafelli í myndanir SV1–SV37 og yfirmyndanir S1–S7.*

timing of erosion can be estimated based on missing stratigraphic units. Based on lithology, magnetic polarity and lava field classification (International Stratigraphic Guide, 1976) we have simplified and combined 37 rock formations into a broader subdivision of 7 groups, S1 to S7, from oldest to youngest, and 12 erosion surfaces, SR1–12 (Figures 3 and 4).

Group S1 includes formations *SV1–SV5*, comprising 149 m of basalt lavas. The lowest strata in Svínafell, i.e., Hrútagil, consist mainly of rather thin basalt lavas with thin red sedimentary interbeds of sand to silt size. Massive, subglacially erupted volcanic rocks are not preserved from this time, only subaerially erupted lava flows. The lavas are hydrothermally altered within the mesolite-scolecite zeolite zone and intruded by numerous dykes trending N66°E. Field measurements indicate either reverse or anomalous magnetization for these lavas. The lack of hyaloclastite beds within this group and parallel lava flow surfaces suggests that it predates major glaciations and development of irregular relief in the region. Within this group is, however, a sedimentary horizon with two units, i.e., a lower breccias/tillite?, 3 m thick with boulder size fragments up to 1 m (Figure 5) and an upper unit of sandy dark brown hyaloclastite. In between these two units is erosion surface SR1 that dips 14° toward 75°.

Below the unconformity the lava flows dip 7° toward N60°W (*SV1*), but 4° toward N120°E above. Erosion at surface *SR1* formed minor landscape and created a hiatus. After accumulation of *SV5* lavas substantial glacial erosion began, as indicated by comparison of strata in Svínafell and Hafrafell, 2–3 km north of Svínafell. The Hafrafell lava sequence is 600 m thick and reaches an elevation of about 800 m (Helgason, 2007) whereas in Svínafell comparable lavas extend only to about 250 m above sea level. While lava tilt and/or tectonics could partly explain this difference in elevation, erosion (surface *SR2*) must have removed at least several hundred meters of the lava section.

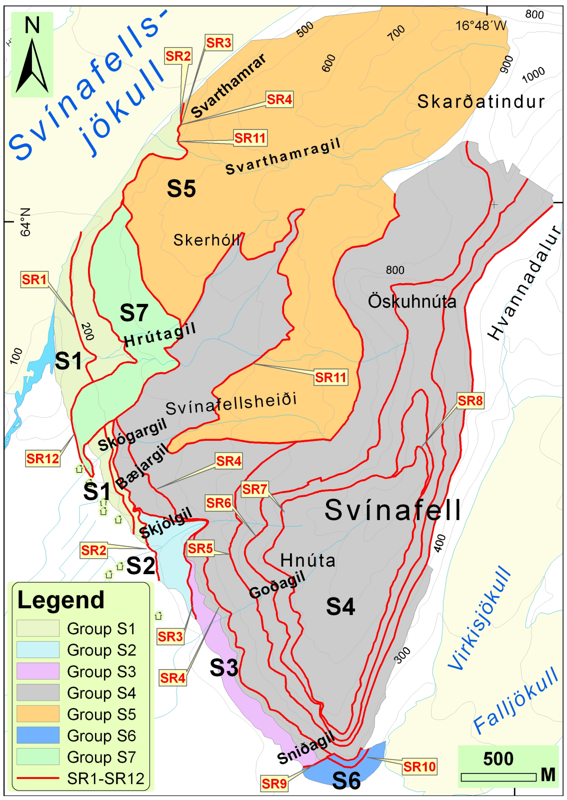

Figure 3. Geological map of Svínafell showing groups *S1–S7* with erosion surfaces SR1–SR12. – *Jarðfræðikort af Svínafelli sem sýnir yfirmyndanir S1 til S7 ásamt rofflötum SR1 til SR12.*

Group S2 consists of four lava formations (*SV6–SV9*), the basal Skjólgil lavas with a total thickness of 104 m (Figures 4, 6 and 7). *S2* lies on top of a poorly exposed, thin, dark brown, reworked hyaloclastite sedimentary unit. The two lowest lavas (*SV6*) are thin reversely magnetized tholeiites which are overlain by three normally magnetized lavas, of which the first (*LK*, Figure 8) is 28 m thick with a 15 m high central colonnade, indicating depositional ponding early within an inter-glacial. The first (unit *LK*) and third (unit *LI*) N-lavas of formation *SV7* in Skjólgil were drilled for paleomagnetic measurements (Figure 7). The second lava (*LJ*) was measured as normal with a handheld magnetometer. Above are four reversely magnetized tholeiite lavas (*SV8*) and four basaltic andesite lavas (*SV9*), also reversely magnetized. Lava flows of group *S2* become gradually thinner upwards. Following deposition of the Skjólgil lavas glaciers eroded this formation, almost to obliteration and shaped *S2* into a small hill with tillites on its western side and a large valley on its eastern side, into which the Svínafell sediments (*S3*) were deposited during an inter-glacial interval.

Group S3 includes formation *SV10*, the 80 m thick Svínafell sediments. The sediments have distinct vertical and lateral variations, with basal silt-sized beds grading upwards to homogenous massive hyaloclastic units, 10–15 m in thickness at the top. With increasing hyaloclastite content massive "walls" with zeolite coatings become more frequent (Figure 9, left). The lower part of the Svínafell sediments consists mostly of fine-grained greyish silt and some light brown palagonite-rich beds, 1 to 3 cm thick, dipping 1–2° southward. Lateral variations are seen in grain size, degree of lamination and dip. From north to south, the sediments can be divided into central-and distal-facies strata. The central facies are seen in Goðagil and farther north but the distal facies strata are found to the south in Sniðagil and surroundings. The lower part of Sniðagil is mostly fine-grained silt in good agreement with a southward deepening of the sediment basin. There, plant-bearing fossils (leaf imprints and pollen) are found. Based on sediment layer thickness, apparent small regional extent and fine grain size we regard these sediments of lacustrine origin. The northern boundary of the sedimentary basin is not exposed but the base of group *S2* extends southward (Figure 4). The Svínafell sediments are exposed over the same interval as group *S2* indicating that they piled up against the Skjólgil lavas.

Group S4 consists of formations *SV11–SV23* that have a total thickness of 862 m. All units above *SV10* in Svínafell are normally magnetized, as measured with

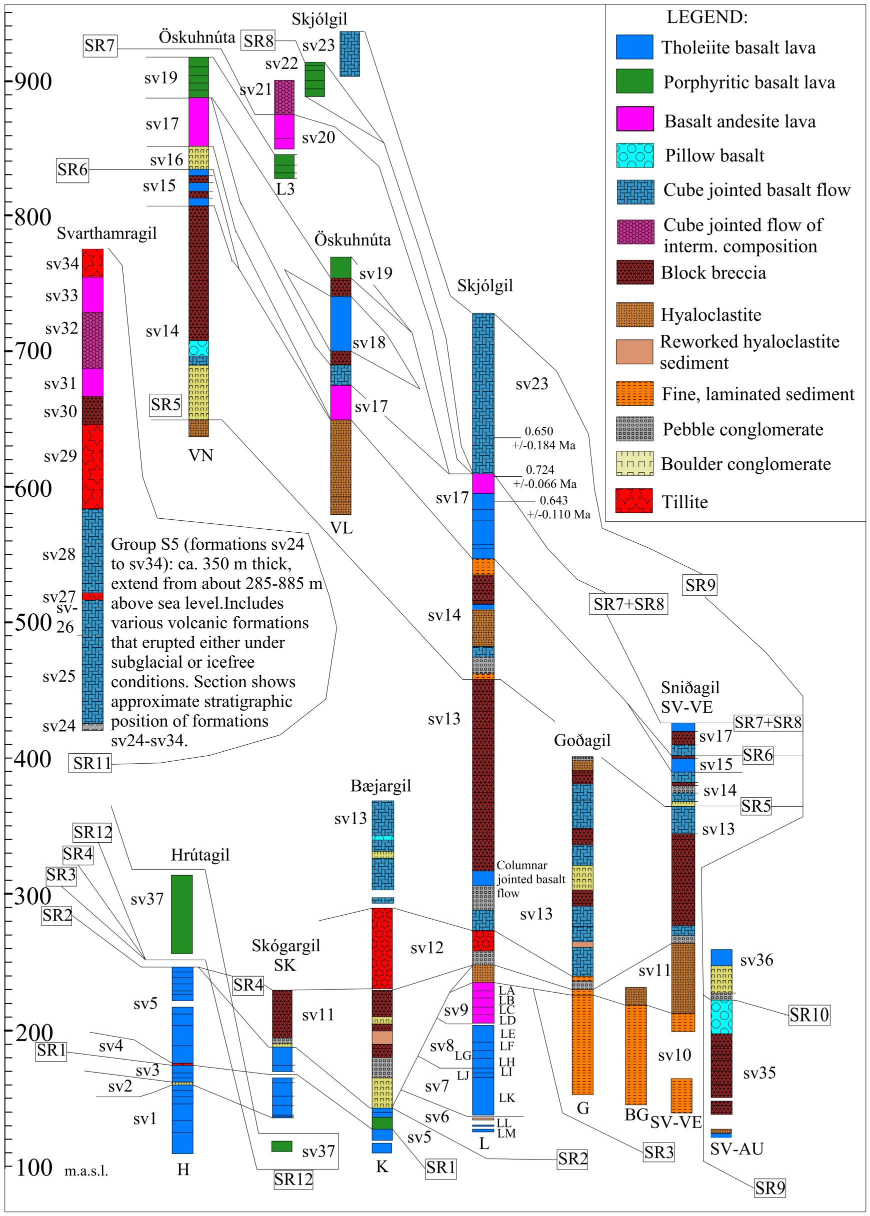

Figure 4. Correlation of stratigraphic profiles in Svínafell. Formation name, e.g., *SV1* to *SV37*, appears by the side of each column, and erosion surfaces, *SR1* to *SR12* are indicated with lines connecting through columns. Profile name, e.g., *H*, *K* or *L*, is provided at the base or top of each stratigraphic column. Age determinations are noted for formations *SV17* and *SV23* in profile *L*. Lava units *LA* to *LM* in profile *L* were drilled for paleomagnetic work. – *Tenging jarðlagasniða í Svínafelli. Nafn hverrar jarðmyndunar (SV1–SV37), er til hliðar við hvert snið. Roffletir SR1 til SR12 eru sýndir með tengilínum milli jarðlagasniða. Heiti jarðlagasniða, t.d. H, K eða L er efst eða neðst fyrir hvert snið. Aldursgreiningar fyrir myndanir SV17 og SV23 eru í sniði L. Hraunlög LA til LM í sniði L (Skjólgili) voru boruð til segulmælinga.*

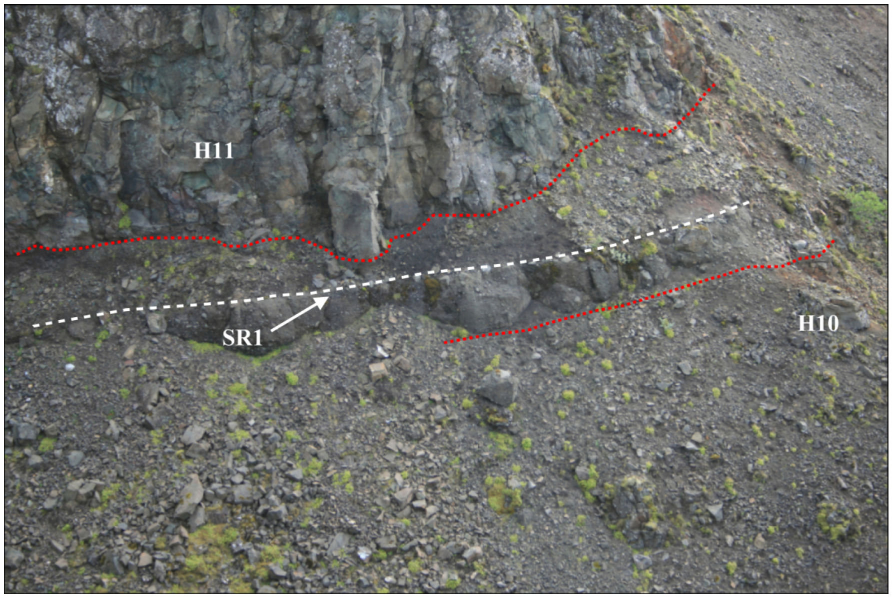

Figure 5. Sedimentary horizon in the Hrútagil gully. Erosion surface *SR1* has an angular unconformity on a breccia/tillite? that dips 14°/75°. The horizon is intercalated between lavas *H10* (formation *SV3*) and *H11* (formation *SV5*). – *Rofflötur SR1 í Hrútagili er á breksíu/jökulbergi. Um hann er mislægi sem hallar 14°/75°.*

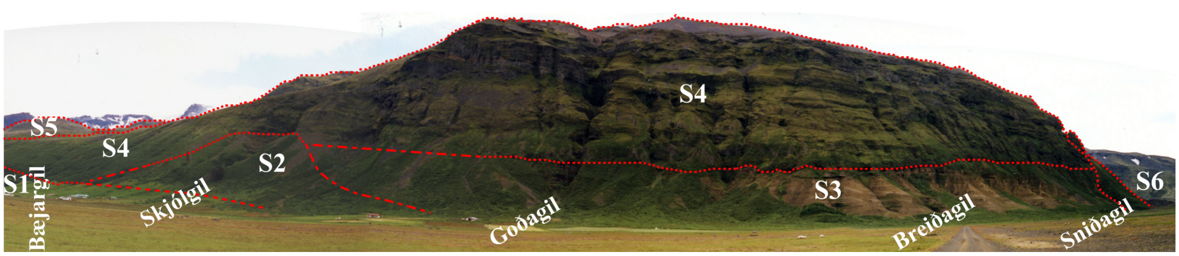

Figure 6. Stratigraphic group division on the western side of the Svínafell massif, view toward east. – *Skipan jarðlaga í vestanverðu Svínafelli, horft til austurs.*

a handheld magnetometer, and therefore assumed to be of Brunhes age, less than about 0.781 Ma. Hyaloclastite deposits form the strata on top of the Svínafell sediments (*SV11*). They are 53 m thick, formed through subglacial volcanic processes and appear to have accumulated within the Svínafell sediment depression, probably as a result of jökulhlaup based on its homogeneity. *SV12* is a thick tillite overlain by subglacial volcanic rocks. Volcanism within the Öræfajökull volcano appears at this stratigraphic level (Figure 10). Formations *SV13–SV23* consist either of lava flows, subglacial volcanics or sedimentary rocks (Figure 4) and are all assumed to be part of the Öræfajökull volcano.

Volcanism led to accumulation of strata under both sub-glacial and inter-glacial conditions. Absent from the early Brunhes age section are acidic tephras and lavas, indicating that during the initial stage of Öræfajökull volcanism, eruptions were only of basaltic composition. This suggests that the Öræfajökull caldera, which presently produces highly acidic compositions, is a relatively recent feature, which is in agreement with work on the base of the Öræfajökull volcanic sequence by Kvíarjökull (Stevenson *et al.*, 2006) as well as work by Prestvik (1979). Accumulation of volcanic rocks within group *S4*, above surface *SR4*, was rapid. *S4* has a dip of 7° toward SE and acts as a thick cap rock that prevented erosion of the soft Svínafell sediments below. During the build-up of group *S4*, accumulation of volcanic strata far exceeded removal by erosion.

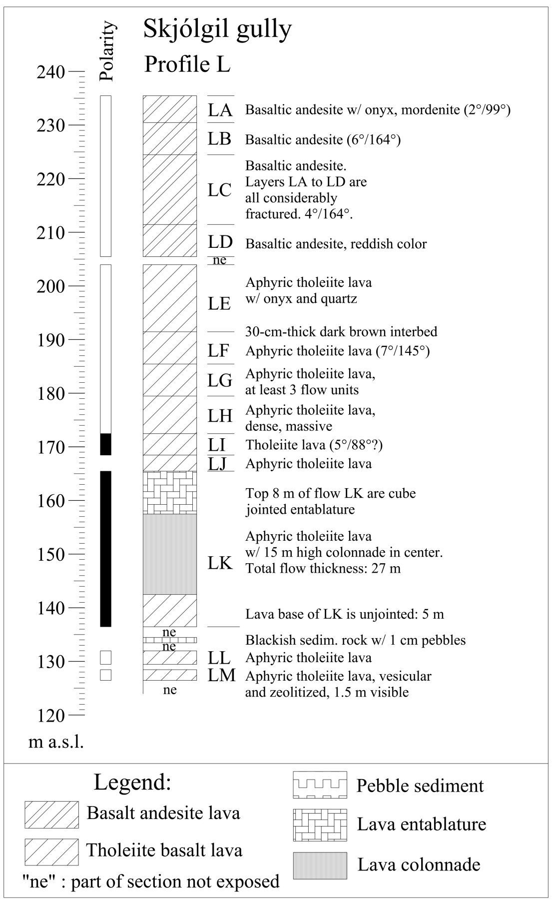

Figure 7. Stratigraphic profile *L* in Skjólgil. – *Jarðlagasnið L í Skjólgili.*

Group S5 consists of miscellaneous rock formations of mafic to intermediate composition which represents late stage volcanism in the Öræfajökull stratovolcano. Formations *SV24–SV34* within group *S5*, have an estimated total thickness of 350 m and are best exposed in the Svarthamragil gully (Figure 11). They include tillites, subaerially erupted lavas, pillow basalt and basalt andesite, that dip up to 40°/292°.

No attempt is made to correlate group *S5* formations within a specific glacial or inter-glacial period. The *S5* formations, which vary 10–50 m in thickness, were deposited on steeply sloping surfaces in a valley on the western side of the Svínafell massif. A major erosional unconformity is present below *S5*. Although glacial erosion removed several hundred meters of strata prior to deposition of group *S5*, the hiatus below *S6* and *S5* may, however, represent only a short time interval, about 0.1 to 0.2 Myr. The erosion period and subsequent formation of *S5* lavas occurred well within the Brunhes magnetic chron.

Group S6 contains volcanic strata, formations *SV35–SV36* with a total thickness of 134 m, on the eastern side of Svínafell. These strata accumulated on an irregular surface and flowed down to the eastern side of Svínafell, banking against the Svínafell sediments, perhaps in a depression between glacier ice and the mountain cliff. Instability of the underlying ice may have contributed to the uneven accumulation in this group. The boundary between groups *S3* and *S6* is nearly vertical, as *S6* lavas are banked up against eroded *S3* lavas. Group *S6* is distinctly younger than *S3*, whereas Þórarinsson (1963) believed *S6* to lie below *S3*. Measurements with a handheld fluxgate magnetometer show *S6* to be normally magnetized and, thus, of upper Brunhes age.

Group S7 consists of highly porphyritic, 153 m thick, pristine section of basalt lava flows, formation *SV37*, which is correlated with formation *HF43* in Hafrafell where it has been dated at 215 (±12) ka (Helgason and Duncan, 2001). *S6* has thus been mapped on both sides of the Svínafellsjökull, where it has accumulated against the steep cliff side, 250–353 m above sea level. Based on K-Ar age determination this interglacial formation was most probably deposited during the third last inter-glacial (Mindel-Riss for the Alps; Holsteinian for N-Europe). The *S7* lavas flowed

Figure 8. Lava flow *LK* in Skjólgil (Lambhagi), with its colonnade center, is a good example of ponding at the beginning of an inter-glacial stage. – *Háar stuðlasúlur hraunlags LK í Skjólgili (Lambhaga) eru gott dæmi um "tjarnarmyndun" sem vænta má í upphafi hlýskeiðs.*

Figure 9. Left: The Svínafell sediments (formation *SV10*). Right: Close up of the lower part of the Svínafell sediments showing fine lamination with alternating beds of brown palagonite and gray silt. Pen height: 8 cm. – *T.v. Ljósleit setlög neðst í Svínafelli (SV10). T.h. Nærmynd af neðri hluta Svínafellslaganna sem sýnir fína lagskiptingu á milli eininga af brúnu, móbergsríku, sandkorna efni og gráleitum silteiningum. Hæð penna: 8 cm.*

Figure 10. Formation *SV13* marks the onset of volcanism in Öræfajökull volcanic center when subglacially erupted strata began to fill in landscape depressions. The two columnar jointed lobe units are about 70 m high. Dip of base: 5°/160°. – *Jarðmyndun SV13 markar upphaf eldvirkni í Öræfajökulseldstöðinni þegar jökulgosberg hóf að byggjast upp og jafna út óreglur í landslagi. Stórstuðluðu einingarnar tvær (frá hægri) eru samtals um 70 m háar. Undirlagi hallar 5°/160°.*

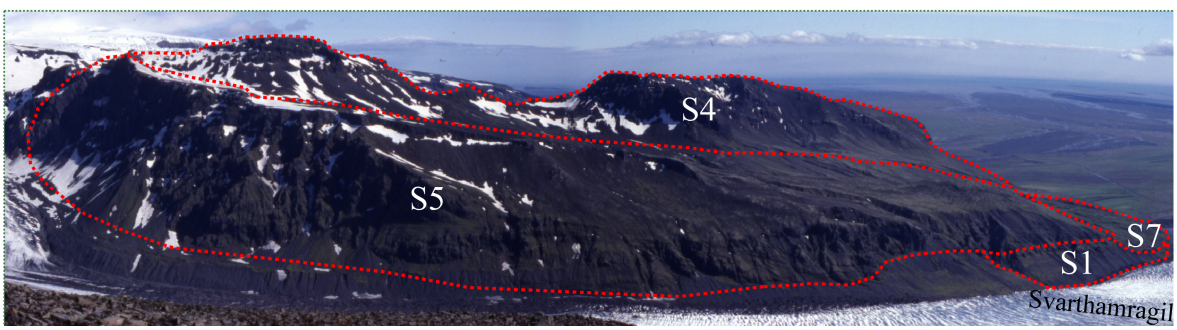

Figure 11. Stratigraphic group division on Svínafell's NW side, view from Hafrafell toward SE. – *Skipan jarðlaga í norðvestanverðu Svínafelli, horft frá Hafrafelli til suðausturs.*

along the north side of Svínafell, across the Hrútagil gully, where they extend from about 250 m above the present sea level to about 340 m. Group *S7* lavas accumulated on Svínafell's west side to 100 m a.s.l. The lower level of *SV37* at about 250 m, both in Svínafell and Hafrafell, suggests that the valley now hosting Svínafellsjökull was some 150 m higher 215 kyr ago and that the glacier has since deepened the valley by this amount.

PALEOMAGNETISM

The Skjólgil lava group (S2) forms a 120 m high hill between two basins; a small basin in Bæjargil to the northwest and a greater basin into which the Svínafell sediments were deposited to the southeast. Sedimentary rocks bank up against the hill on both sides. This hill is the only preserved fragment in Svínafell that can be correlated with the upper Matuyama chron. The Skjólgil lavas are stratigraphically older than the Svínafell sediments (group *S3*) on the east/south side. Although the Skjólgil lavas terminate abruptly toward the east, and do not continue below the Svínafell sediments, their magnetic polarity is highly significant for constraining the age of the sediments. The same comment applies to the volcanic units further up-section; i.e., group *S4*. Cooling units within *S4* are finer grained and fresher in hand sample compared with lavas of group S2 and appear considerably younger. Generally, basaltic rocks of Brunhes age are fresh, have strong remanent magnetic signature, and thus a hand-held magnetometer suffices to determine their magnetic polarity in the field and to map their areal extent.

Sampling for paleomagnetic measurements

We drilled 12 lavas of stratigraphic profile *L* in Skjólgil gully (Figure 7) for paleomagnetic purposes, as these are the cooling units below the Svínafell sediments. Sampling was conducted using a two-stroke Pomeroy drill. Core tube diameter is 2.5 cm and core length about 5 cm. Normally four cores were sampled per cooling unit. The samples were demagnetized in Dr. Leó Kristjánsson's laboratory in the Geophysics Division, Science Institute, University of Iceland, using Molspin AF demagnetizing equipment. The samples were measured after treatment at 0, 10, 15 and 20 mT peak field strength, respectively, and the best results chosen. A correction for tilt, 6°/150°, was made for profile L.

Paleomagnetic results are presented in Table 1. The magnetic polarity in Skjólgil changes from R to N to R. The N-lavas are correlated with the Olduvai magnetic chron based on their lithological similarity with a dated R/N/R-sequence in Hafrafell (Helgason and Duncan, work in progress). The Hafrafell sequence has been defined as "valley filling" and one of the R-units, 40 m above the N-lavas, was dated at 1.69

Table 1. Paleomagnetic results for Svínafell: section *L* in Skjólgil. – *Niðurstöður segulmælinga fyrir Svínafell: snið L í Skjólgili.*

Form.	No	N	D	I	P_{Long}	P_{Lat}	α_{95}	J_{10}	Pol
SV9	LA	2(2)	168.8	–50.3	1.0	–56.3	10.6	2.2	R
SV9	LB	3(1)	200.7	–71.6	280.8	–77.2	5.6	2.3	R
SV9	LC	4	187.4	–65.9	325.7	–73.7	4.1	2.7	R
SV9	LD	4	198.5	–70.0	291.8	–76.2	3.0	4.3	R
SV8	LE	4	255.7	–62.9	241.5	–44.8	12.6	1.3	R
SV8	LF	3(1)	231.9	–61.7	264.2	–54.1	2.0	5.0	R
SV8	LG	4	183.7	–73.9	317.9	–85.7	4.5	4.8	R
SV8	LH	3(1)	188.4	–75.3	272.6	–85.9	9.1	2.0	R
SV7	LI	4	12.5	70.3	124.0	78.5	2.0	6.0	N
SV7	LK	3	16.4	73.0	101.0	80.4	5.4	2.3	N
SV6	LL	3	218.6	–61.4	279.3	–59.3	10.3	1.0	R
SV6	LM	4	211.3	–58.6	291.7	–59.3	2.6	2.2	R

Explanations: Form: stratigraphic formation number. No: Unit number. N: Number of measured samples with number of rejected samples in brackets. D, I: Declination and inclination after tilt correction. PLong: Longitude of virtual geomagnetic pole (VGP). PLat: Latitude of virtual geomagnetic pole (VGP). α_{95}: Mean field 95% confidence radius. J_{10}: Remanence intensity (Amperes/m) after demagnetization in 10 mT AF. N: Normal polarity. R: Reverse polarity.

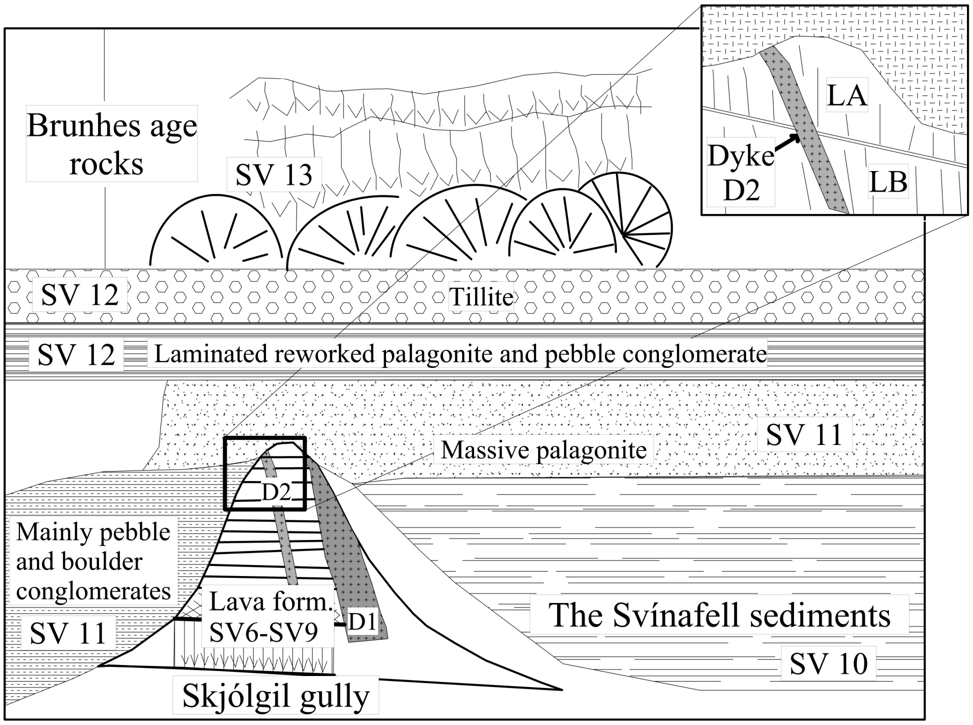

Figure 12. Stratigraphic position of Skjólgil showing conditions where dyke *D2* cuts lavas *LA* and *LB* (inlet). – *Skipan jarðlaga í Skjólgili. Á minni myndinni er sýnt hvar gangur (D2) sker hraunlög LA og LB.*

($\pm$0.29) Ma, thus providing a correlation with the geomagnetic polarity time scale to the normal Olduvai magnetic chron (C2n: 1.78–1.95 Ma). The N-lavas in Skjólgil have a high VGP-latitude.

AGE DETERMINATIONS

Volcanic units above the Svínafell sediments (group *S3*) proved normally magnetized when measured with a handheld magnetometer in the field and were therefore inferred to be of Brunhes age or younger than about 0.781 Ma. As the uppermost volcanic units below the Svínafell sediments are reversely magnetized, i.e., lavas in Skjólgil, it is clear that these could be from the Matuyama reversed chron or older. Therefore, we emphasized sampling units for dating from below as well as above the Svínafell sediments to constrain their age. Geological mapping showed the Skjólgil lavas to be stratigraphically older than the Svínafell sediments (Figure 12).

We collected the freshest samples, based on minimal vein and vug-filling secondary minerals, from the Skjólgil paleomagnetic *L*-section as well as from volcanic units above the Svínafell sediments. Initially, several attempts using ^{40}Ar–^{39}Ar incremental heating experiments revealed that no lava samples from the Skjólgil *L*-section provide reliable crystallization ages due to alteration effects and variable amounts of excess ^{40}Ar. This indicated that the Skjólgil lavas are considerably older and more altered than the Brunhes age rocks above the Svínafell sediments, which provided reliable age determinations. When dating the Skjólgil lavas proved unsuccessful we examined fresher dykes that could provide a minimum age for the strata below the Svínafell sediments (Figure 12, enlarged insert). Two dykes cut lavas *LA* and *LB*, i.e., the two top lavas in formation *SV9*. The dykes are clearly part of the lower strata and do not extend above surface *SR3*. Therefore, their age must be somewhat younger than the host lavas but older than both formations SV10 (i.e., the Svínafell sediments) and SV11 above. Dyke D2, that is reversely magnetized based on measurements with a handheld magnetometer, was sampled and dated by ^{40}Ar-^{39}Ar incremental heating methods.

We prepared whole rocks for age determinations by crushing, sieving to obtain the 0.1–0.5 mm size fraction, ultrasonic washing in distilled water, drying and hand-picking under a binocular microscope to obtain the freshest, phenocryst-free samples possible. From three normal polarity lavas (units *SV17* and *SV23*) lying above the Svínafell sediments, we loaded approximately 500 mg of each sample in quartz vials, evacuated and sealed them, then irradiated these for 6 hr near the central core of the 1 MW Oregon State University TRIGA reactor, along with neutron flux gradient monitor FCT-3 biotite (28.03 Ma; Renne *et al.*, 1998). Samples and monitors were analyzed in single-step, total fusion experiments using an AEI MS-10 mass spectrometer. All gases were extracted by radio-frequency heating of samples in Mo-crucibles under vacuum, followed by removal of active gases via hot metal getters. We made corrections for mass discrimination based on frequent measurements of atmospheric Ar from an on-line reservoir, and for interfering isotopes produced during irradiation (Wijbrans *et al.*, 1995).

From reverse polarity dyke *D2* cutting the Skjólgil lavas lying below the Svínafell sediments, we separated feldspar and, after identical irradiation conditions, incrementally heated the sample in 6 temperature steps from 500°C to fusion using a 10W CO_2 laser. Step heating gas compositions were analyzed using a MAP 215/50 mass spectrometer.

Three samples from lithologic units *SV17* and *SV23* in group *S4*, lying some 300 m above the Svínafell sediments, produced consistent and stratigraphically acceptable age determinations. The measured ages (reported in Table 2) are not statistically distinguishable (at the 2 s.d. level), so we have calculated a mean, weighted by inverse variance, which is 698 (±54) ka. Other samples, from lava flows below the Svínafell sediments, produced ages that were unreasonably old (up to 10 Ma) and imprecise, which we attribute to alteration, with addition of excess ^{40}Ar, possibly trapped with hydrothermal quartz (Seidemann, 1988). However, dating of dyke *D2* that cuts the Skjólgil lavas and terminates at the uppermost lava (unit *LA*), gave a plateau age of 1.67 (±0.15) Ma.

Table 2. ^{40}Ar–^{39}Ar total fusion and incremental heating ages for Svínafell strata. – *Niðurstöður Ar–Ar aldursgreininga fyrir Svínafell.*

Sample no.	coordinates	stratigraphic height (m)	age ± 2s (Ma) total fusion	age ± 2s (Ma) plateau	elevation, m a.s.l.	comment
20–9–93–8	N63°58.94599 W16°49.79781	1038	0.650 ± 0.184		628–765	Subglacially erupted volcanic unit (*SV23*).
20–9–93–7	N63°58.89426 W16°49.83128	880	0.724 ± 0.066		598–613	Tholeiite to basalt andesite lava flow (*SV17*).
20–9–93–6	N63°58.83366 W16°49.91939	870	0.643 ± 0.110		586–598	Tholeiite lava flow (*SV17*).
D2	N63°58.88486 W16°50.60318	253		1.67 ± 0.15	240	Reversely magnetized dyke *D2* cuts lavas of *SV9* in Skjólgil. Strike N18°E, 0.7 m thick.
HV	N64°0.52176 W16°52.47622	1679	0.215 ± 0.012		240–345	Pl–phyric lava formation *HM36* in Hafrafell. K–Ar age; 0.54 % K

Ages calculated with the following decay and abundance constants: γ_ε = 0.580 x 10^{-10} yr^{-1}; γ_β = 5.530 x 10^{-10} yr^{-1}; ^{40}K/K = 1.17 x 10^{-4}.

GLACIAL HISTORY

Glacial–interglacial division

Lava flow units in the Öræfi district that erupted subaerially clearly accumulated during interglacial intervals. Subglacial eruptions typically grade upwards from pillow lavas, block breccias to hyaloclastite (Lescinsky and Fink, 2000; Smellie, 2000; Loughlin, 2002; Stevenson *et al.*, 2006; Smellie, 2007). In this study we have identified such volcanic sequences as glacial. Conglomerates and tillites indicate the action of significant thicknesses of glacial ice. In these cases glaciers covered the area and caused erosion, but without addition of volcanic rocks. Such sedimentary units commonly alternate with hyaloclastites in glacial intervals. Lava flow units in the Öræfi district that erupted subaerially clearly accumulated during interglacial intervals. Subglacial eruptions typically grade upwards from pillow lavas, block breccias to hyaloclastite (Lescinsky and Fink, 2000; Smellie, 2000; Loughlin, 2002; Stevenson *et al.*, 2006; Smellie, 2007). In this study we have identified such volcanic sequences as glacial. Conglomerates and tillites indicate the action of significant thicknesses of glacial ice. In these cases glaciers covered the area and caused erosion, but without addition of volcanic rocks. Such sedimentary units commonly alternate with hyaloclastites in glacial intervals.

Erosional surfaces *SR1* to *SR12* in Svínafell

Erosion events in Svínafell are best represented on surfaces that signal the end of each erosive period.

Table 3. Division of Svínafell's rock formations into glacial and interglacial stages and their proposed correlation with the geomagnetic polarity time scale. – *Skipting jarðlagamyndana Svínafells í jökul- og hlýskeið og tenging þeirra við segultímatal.*

Group	Formation	Field classif. – lithol.	Strike/ dip of strata	Str.gr. thickn.- (m)	Mg. pol.	Mg. chron	Mg. age Ma	^{40}Ar–^{39}Ar total fusion age	Inf. g-ig. stage	ER-surf.	Glac. stri. on ER-surf.
S7	SV37	l, pl.ph	10°/225°	153	N	Brunhes	<0.781	0.215(±0.012)[1]	I	SR12	
S5	SV24–SV34[2]	var. lithol.	40°/292°	ca. 350	N	Brunhes	<0.781		I+G	SR11	
S6	SV36	l, th	–	12	N	Brunhes	<0.781		I–8	SR10	
	SV35	sub	–	122	N	Brunhes	<0.781		G	SR9	
S4	SV23	sub, th	13°/183°	160	N	Brunhes	<0.781	0.650(±0.092)	G–8	SR8	
	SV22	l, pl.ph	–	25	N	Brunhes	<0.781		I–7	–	
	SV21	sub, ba	–	25	N	Brunhes	<0.781		G–7	SR7	
	SV20	l, ba	–	25	N	Brunhes	<0.781		I–6	–	
	SV19	l, pl.ph	5°/158°	25	N	Brunhes	<0.781		I–6	–	
	SV18	l, th	–	40	N	Brunhes	<0.781		I–6	–	
	SV17	l, ba	20°/156°	63	N	Brunhes	<0.781	0.724(±0.033)/ 0.643(±0.055)	I–6	–	
	SV16	s	–	18	N	Brunhes	<0.781		G–6	SR6	186°
	SV15	l, ba	–	18	N	Brunhes	<0.781		I–5	–	
	SV14	s, sub	–	160	N	Brunhes	<0.781		G–4	SR5	
	SV13	sub, ba	7°/135°	190	N	Brunhes	<0.781		G–4	–	
	SV12	s, sub	–	60	N	Brunhes	<0.781		G–4	SR4	
	SV11	s	–	53	N?	Brunhes?	<0.781		G–4	–	
S4	SV10	s	–	80	?	?	0.7–1.1		I–4	–	
S3	SV10	s	–	80	?	?	0.7–1.1		I–4	–	
S2	SV9	l, ba	–	30	R	U-Matuyama	1.072–1.778		I–3+G–3	SR3	213°
	SV8	l, th	–	33	R	U-Matuyama	1.072–1.778		I–3	–	
	SV7	l, th	–	38	N	Olduvai?	1.778–1.945		I–3	–	
	SV6	l,s	–	3	[4]R	L-Matuyama?	1.945–2.581		I + G–2	SR2	
S1	SV5	l, th	4°/120°	71	[4]R	L-Matuyama?	1.945–2.581		I–2	–	
	SV4	s	14°/75°[3]	2	[4]R	L-Matuyama?	1.945–2.581		G–1	SR1	
	SV3	l, th	–	12	[4]R	U-Gilbert?	3.596–4.187		I–1	–	
	SV2	s	–	2	[4]R	U-Gilbert?	3.596–4.187		I–1	–	
	SV1	l, th	7°/300°	62	[4]R	U-Gilbert?	3.596–4.187		I–1	–	

Explanations: l: lava flow; s: sedimentary rock; th: tholeiite; ba: basalt andesite; pl.ph: plagioclase–porphyritic basalt; sub: rock formed under subglacial conditions; I: interglacial stage; G: glacial stage, N: normal magnetic polarity; R: reverse magnetic polarity; SR1 to SR12: erosional stages/surfaces. [1]Age estimate based on correlation with a dated unit. [2]Group *S5* consists of formations *SV24* to *SV34*. Group *S7* has one formation (*SV37*) that is younger than group *S5*. [3]Dip of angular unconformity. [4]R Magnetic polarity as measured with a hand–held fluxgate magnetometer in the field.

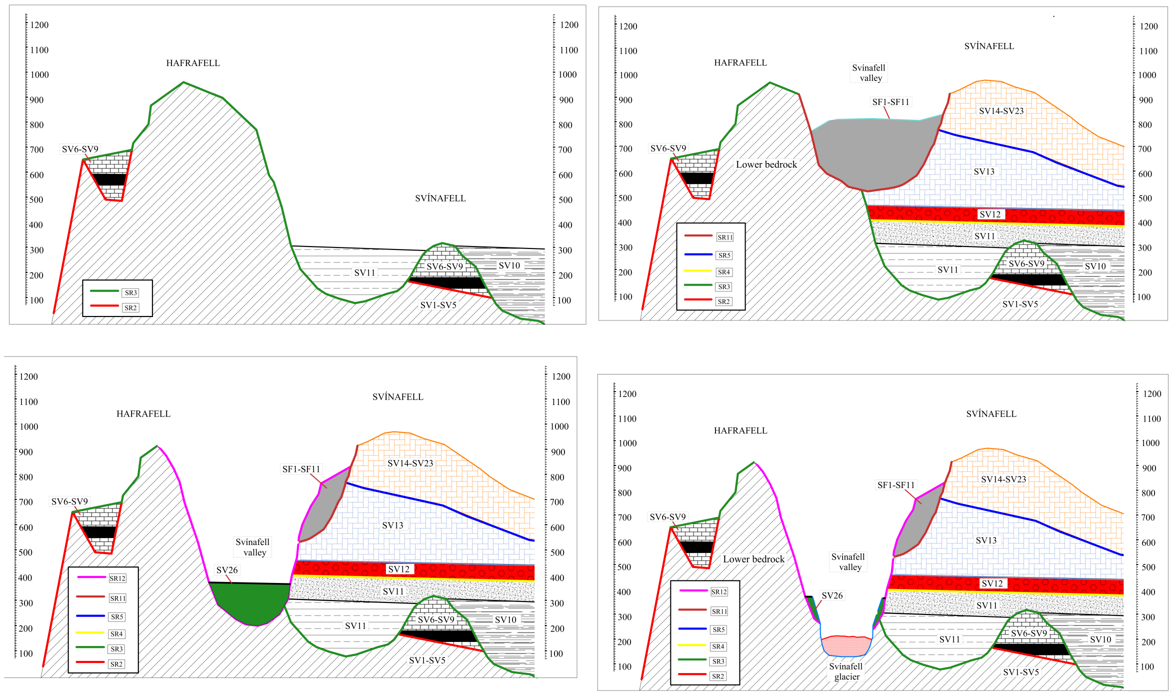

Figure 13. Formation and erosion history of the Svínafell massif. a) Glacial erosion during the Matuyama period carved the lower strata by several hundred meters (*SR2*), followed by a sequence of lavas (formations *SV6* to *SV9*). A few lavas of normal magnetic polarity (black), correlated with Olduvai-chron (C2n: 1.78–1.95 Ma), indicate that at least 250-m-deep valleys had formed in the Hafrafell-Svínafell area prior to 2 Ma. Glaciers eroded most of the N-lava sequence during erosion event *SR3*. The Svínafell sediments (*SV10*) were deposited in lakes formed as the glaciers retreated. Erosion surface *SR4* was formed by readvancing glaciers, followed by a thick tillite deposit (*SV12*). b) A minor erosion surface (*SR5*) divides two major volcanic sequences from the Öræfajökull volcanic center (*SV13* and *SV14–SV23*). c) Subsequent erosion events (*SR11* and *SR12*) eroded the "Svínafell valley", down to about 250 m a.s.l., followed by accumulation of lava flows (*SV37*). d) At present, the Svínafell glacier has carved the Svínafell valley, down to about 100 m a.s.l. – *Myndun Svínafells. a) Jökulrof á Matuyama segultímabilinu nam nokkur hundruð metrum (rofflötur SR2). Síðan runnu hraunlög niður dalinn, jarðmyndanir SV6 til SV9. Nokkur rétt segulmögnuð hraunlög (svört) frá Olduvaisegultíma (C2n: 1.78–1.95 Ma), sýna að 300–400 m djúpir dalir mynduðust á milli Hafrafells og Svínafells fyrir um 2 milljón árum. Svínafellssetlögin mynduðust í stöðuvötnum í dalnum (SV10) í kjölfar jökulhörfunar. b) Þykk bergmyndun frá Öræfajökulseldstöðinni (SV13) hlóðst ofan á jökulbergslagið SV12 við eldgos undir jökli. Síðan varð minniháttar rof (SR5) áður en þykkur stafli af hraunlögum (SV14–SV23) lagðist á Svínafellið. c) Jökullinn gekk síðan aftur fram og gróf sig niður í um 250 m hæð áður en hraunlög runnu yfir dalinn (jarðmyndun SV37). d) Svínafellsjökull hefur grafið sig í 100 m hæð.*

Mapping has revealed a total of 12 erosion surfaces, *SR1* to *SR12*, in the Svínafell massif (Figure 3). The stratigraphic framework for these surfaces is summarized in Table 3 but here each erosion surface is described in more detail within a stepwise schematic representation of Svínafell's erosion history (Figure 13). After that the erosional evolution is summarized into four stages (Table 4).

SR1. This erosion surface cuts through formation *SV4* in Hrútagil (Figure 5). Above and below are tholei-

Table 4. Main characteristics of four erosional stages in Svínafell's stratigraphy. – *Helstu einkenni fjögurra rofskeiða í jarðlagastafla Svínafells.*

Stage	Erosive agent	Degree of volcanism	Environm.	Main lithology on erosive surfaces	Unconformity	Estim. depth erosion (m)	Estim. age (Ma)
1st	river erosion	continuous	subaerial	sediments, e.g., pebble conglom.	minor or absent	< 25	pre-ice age $\sim$ 4 to $\sim$ 2.7
2nd	dominant glacial erosion	no volcanism observed	mainly subglacial	minor tillite or conglom.	clear	> 250?	Early Quat. $\sim$ 2.7–1.95
3rd	dominant glacial erosion	subglacial and subaerial	subaerial and subglacial	extensive sedimentary deposition	erosional unconform.	> 100	Upper-Mat. $\sim$ 1.95–0.781
4th	dominant glacial erosion	extensive subaerial volcanism	subglacial and subglacial	extensive accumul. of volcanics	major valley deepening	>1000	Brunhes chron <0.781

Stage 1. As strata in Svínafell that predate the Matuyama chron (> ca. 2.6 Ma) consist entirely of lavas we assume that erosion was minor (< 25 m) during the Tertiary and that rivers were the dominant erosive agent.
Stage 2. When glacials became frequent, roughly after 2.6 Ma, glaciers began to form and shape the earliest valleys. Into one such lavas of Olduvai age were deposited by Svínafell. When stratigraphic position lavas of this age in Hafrafell and Svínafell is compared we conclude that valleys at this time were at least 250 m deep.
Stage 3. During Upper-Matuyama or from about the Olduvai chron to the onset of Brunhes (about 1.945 to 0.781 Ma) lavas were carved down by over 100 m.
Stage 4. Volcanism from the Öræfajökull volcanic center during Brunhes was extensive by Svínafell as well as erosion and valleys continued to deepen by at least 1000 m.

ite basalt lava formations *SV3* and *SV5*, respectively. A clear unconformity is seen in relation to this surface, i.e., 14°/75°, and lava flow dip is notably greater above it. Formation SV4 has two units, i.e., an upper unit of sandstone and a lower unit of pebble conglomerate. The conglomerate is 3 m thick with boulders up to 1 m in diameter. The conglomerate lacks bedding, has poor sorting and pebbles are angular. Matrix is heterogeneous with grain size mostly less than 1 cm, gray to brown.

SR2. Erosional development through the formation of surfaces *SR2* to *SR4* is shown on Figure 13a. Formation *SV6*, deposited during erosion stage *SR2*, consists of a 3 m thick sandstone and pebble conglomerate. This conglomerate is intercalated between the lower basalt lavas (formations *SV1* to *SV5*) and the Skjólgil lavas (formations *SV7* to *SV9*). The Skjólgil N-lavas are correlated with the Olduvai polarity chron (1.78–1.95 Ma) based on lithologic and magnetic similarity to N-lavas in Hafrafell west of Svínafellsjökull, i.e., formation *HF29* at about 560–580 m elevation. It follows that surface *SR2* is older than approximately 1.95 Ma. Despite only minor sediment deposited on erosion surface SR2 we argue that a major erosional unconformity coincides with this surface. Thus, in Hafrafell, reversely magnetized lavas of lower Matuyama age have a thickness of at least 350 m (Helgason, 2007). There, a second sequence dated and correlated with Olduvai, is found as valley filling lava flows, banking up against the 350 m thick R-lava flow sequence of lower Matuyama age. The abrupt reduction in thickness of R-lavas of lower Matuyama age in Svínafell, over a distance of only 2 km, is interpreted to result from relief amounting to at least 230 m. This erosion presumably took place during lower Matuyama time, approximately 1.95 to 2.58

Ma. Likewise the Skjólgil lavas were deposited into a depression formed during *SR2* and they resemble the Olduvai valley-filling sequence in Hafrafell that grades upwards from R to N to R lavas, where one of the upper R lavas has been dated at 1.69±0.29 Ma (Helgason and Duncan, 2001). East of Hafrafell the "lower strata" are last seen in Svínafell and disappear farther east, at least as far as Vatnafjöll, 18 km to the east where the lowest strata are of Brunhes age (Stevenson *et al.*, 2006). The small outcrop of lower strata in Svínafell and its disappearance to the east suggests a time-transgressive erosion interval.

SR3. The basin into which the Svínafell sediments were deposited formed during this erosion stage. The top of group *S2* (formation *SV9*) in Skjólgil has glacial striations trending 213°. Erosion surface *SR3* is slightly younger than the Olduvai chron that has an upper age of about 1.78 Ma. Presumably, erosion first carved out the depressions on both sides of the Skjólgil hill of group *S2* lava flows. We observe that erosion during *SR3* was extensive, amounting to at least the thickness of the Skjólgil lavas, or in excess of 120 m.

Lacustrine sediments are rarely found in the SE-Iceland bedrock and it is thus likely that rather unique landscape conditions prevailed in the region after formation of surface SR3. Then, an interglacial stage began with the formation of a lake into which the Svínafell sediments were deposited. Upward, lithology of the sediment changed from fine-grained dark grayish silt with thin lamination to coarse-grained brown volcanic sands and more massive hyaloclastite. This upward change in lithology indicates that climate was relatively warm and stable during deposition of the lower part of the sedimentary sequence. Then, increasing influx of hyaloclastite indicates a change to volcanic eruptions under ice, culminating in intense subglacial volcanism that filled the lake. Lithification of the hyaloclastite presumably formed a cap rock that preserved the soft lower part of the sediments.

SR4. A >60 m thick tillite in Bæjargil (profile K), formation *SV12*, was deposited during erosion stage *SR4*. Considerable relief was generated during *SR4* based on steep dipping of the tillite upper surface, i.e., by 24° toward SW (232°) in Skjólgil and substantial ponding of basal cooling units within formation *SV13*. The formation of this tillite preceded the build up of a thick Brunhes age volcanic sequence that presumably erupted from Öræfajökull volcano.

SR5. This is an erosion stage defined by a 40 m thick pebble and boulder conglomerate below the 120 m thick subglacially erupted volcanic formation *SV14*. *SR5* dates from the Brunhes polarity chron (Figure 13b).

SR6. Erosion surface *SR6* in group *S4* is represented by a 15–20 m thick tillite, i.e., formation *SV16* that is intercalated between formations *SV15* and *SV17*.

SR7. Erosion surface *SR7*, within group *S4*, is below formation *SV21*. In Öskuhnúta, at about 880 m elevation, it is located at a sharp boundary between a subglacially erupted volcanic formation (*SV21*) and subaerially erupted lavas of intermediate composition (*SV20*).

SR8. This erosion surface, also within group *S4*, follows formation *SV23* lower surface in Öskuhnúta at about 920 m elevation. Erosion during this stage has clearly been much greater than during stage *SR7*. In Öskuhnúta surface *SR8* is on formation *SV22*. However, farther down in Svínafell, at about 420 m, it is on top of formation *SV17*. There, surfaces *SR7* and *SR8* coincide.

SR9. Erosional stage *SR9* was marked by the contact between groups *S6* and the much older Svínafell sediments, *S3*.

SR10. A 25 m thick tillite formed during this erosion stage. It is intercalated between pillow basalt lavas and a 12 to 14 m thick tholeiite lava flow at the top of section *SV-AU*, both within group *S6*. This surface, within one of the youngest groups, is of upper Brunhes age. Group *S6* must have formed at the valley floor east of Svínafell, very late in its erosion history. The lowest part of formation *SV35* is unusual, in that it is neither a typical subaerial lava flow sequence nor a pillow basalt sequence. It may have formed in the depression between the glacier and the adjoining Svínafell ridge. The lava flows on top of *SR10* (*SV36*), however, presumably formed when the valley of the present Virkisjökull glacier was in part or wholly free of glacial ice.

SR11. In contact with erosion surface *SR11* are 11 volcanic formations (*SV24* to *SV34*) of group *S5*, that bank up against the mountains Skarðatindur, Öskuhnúta and Svínafell ridges (Figure 13c). The strata in these massifs are continuous and assumed to have extended far in an east–west direction. That is, the formations do not peter out toward east or west but are terminated abruptly by an erosion surface. At the end of erosion stage *SR11* a 300 to 400-m-deep valley, here referred to as the "Svínafell valley", had formed on the west side of Skarðatindur and Öskuhnúta where volcanic group *S5* later accumulated. Available dating helps narrow down the time of formation of the valley beneath Svínafellsjökull. During *SR11* glaciers carved out the "Svínafell valley". After that erosion has extended farther west, where Svínafellsjökull is now located. During formation of volcanic group *S5* the floor level of "Svínafell valley" must have been over 300 m above the present sea level. Since deposition of group *S5* erosion has continued into the "Svínafell valley" down to about 250 m above present sea level where group *S7* was deposited, about 215 ka. Subsequently, the base below Svínafellsjökull was eroded down to below 100 m above the present sea level.

SR12. This erosion surface follows the base of group *S7*, or formation *SV37* that is correlated with formation *HF43* in Hafrafell and has a date of 215 ka (Helgason and Duncan, 2001). Group *S7* is stratigraphically the youngest in Svínafell. Formation *SV37*, highly porphyritic basalt lavas, occurs at the same levels both in Svínafell and Hafrafell (Figure 13d). The *SV37* age correlates well with the third last interglacial. A major valley had formed in the current bed of Svínafellsjökull during *SR12*, as formation *SV37* is exposed on both sides of the outlet glacier. It is interesting to trace *SV37* southward in Svínafell as it crosses Hrútagil at 250 m a.s.l. There, it diverts abruptly toward the SW, i.e., down to about 100 m.a.s.l., where it reaches the base of Bæjargil gully. We assume that *SV37* flowed along a glaciated valley formed by Svínafellsjökull. The *SV37* lava flows may have covered the lower level of Svínafellsjökull or the glacier may not have been present in the valley which may have had a base at some 250 m above the present sea level. Once out of the valley the lava could flow down to much lower levels as seen by the outcrop in Bæjargil at about 100 m a.s.l. Continued erosion up to the present has further deepened the "Svínafell valley" to this level (Figure 13d).

Main erosional stages in Svínafell

We now synthesize the temporal and erosion evolution of the Svínafell area and quantify some of the associated geological factors. The activity responsible for erosion surfaces *SR1* to *SR12* grades from minor "smoothing" where glaciers have gently scraped the substrata, to major angular unconformities where several hundreds of meters of volcanic strata were removed with, in cases, clear examples of valley formation. The erosion surfaces can broadly be divided into four stages as presented in Table 4.

INTERPRETATION AND DISCUSSION

Age of the Svínafell lacustrine sediments

No direct dating exists for the Svínafell lacustrine sediments. Therefore, their age can be constrained only by information about the age of strata above and below. Volcanic rock units above the Svínafell sediments (group *S4*) are normally magnetized and sourced from Öræfajökull volcano. Accordingly, these strata formed during Brunhes chron, i.e., <0.78 Ma. This assignment of Brunhes age for volcanic rocks above the sediments is confirmed by our new ^{40}Ar–^{39}Ar age determinations that have provided three independent ages of lower Brunhes lava flows. Their mean age is 698 ka, for lava flows that are stratigraphically some 300 m above the Svínafell sediments. ^{40}Ar–^{39}Ar age determinations for lavas in Skjólgil, below the Svínafell sediments, proved unsuccessful but a dyke that cuts these lavas but which is terminated beneath the Svínafell sediments gives a plateau age of 1.67$\pm$0.15 Ma. It follows that the Skjólgil lavas are somewhat older. Their magnetic signature is, however, important in that they are reversely magnetized, except for three normally magnetized flows near the section base. This brief N-interval is of importance for stratigraphic correlation.

It is most likely that the reversely magnetized Skjólgil lavas can be correlated with the Matuyama chron (0.781–2.581 Ma). Within Matuyama time there are four rather short normal magnetic chrons/subchron, i.e., Jaramillo subchron (84 kyr), Cobb subchron (12 kyr), Olduvai chron (167 kyr) and Reunion subchron (20 kyr) (Gradstein *et al.*, 2004). Of these Cobb and Reunion have never been observed in Iceland, probably due to their short duration. The age of dyke *D2* (1.67 Ma) is significantly older than the Jaramillo subchron (C1r.1n: 0.988–1.072 Ma) but similar in age to Olduvai (C2n: 1.778–1.945 Ma) chron. Therefore, we correlate the N-lavas in Skjólgil with the Olduvai chron rather than Jaramillo subchron. If our correlation of N-Skjólgil lavas with the Olduvai chron is correct it follows that the R-lavas at the top of the Skjólgil section have an age of 0.78–1.78 Myr (C2n). Keeping in mind the mean age for the dated samples above the sediments of 698 kyr, below which are some undated older units within Brunhes, it follows that the Svínafell sediments have an age between 0.70 and 1.78 Myr. This interval should be even smaller considering the period of erosion after 1.78 Ma, i.e., when the depression into which the Svínafell sediments accumulated was formed.

Regional comparison of the Svínafell stratigraphic sequence

Each region in Iceland has its own character with respect to accumulation of volcanic rocks and sediments that form the stratigraphic succession exposed in dissected cliff sections. By this we mean that the stratigraphic characteristics are determined by the volcano–tectonic environment; i.e., dominantly crustal accretion and subsidence, or erosion exceeding accumulation. An example of this regionally variable character, we compare the 1240 m thick sequence in Svínafell to a stratigraphic sequence of the Öræfajökull volcano at Kvíárjökull (Stevenson *et al.*, 2006), some 10 km to the east of Svínafell and Hafrafell (Helgason, 2007).

Each region in Iceland has its own character with respect to accumulation of volcanic rocks and sediments that form the stratigraphic succession exposed in dissected cliff sections. By this we mean that the stratigraphic characteristics are determined by the volcano-tectonic environment; i.e., dominantly crustal accretion and subsidence, or erosion exceeding accumulation. As an example of this regionally variable character, we compare the 1240 m thick sequence in Svínafell to a stratigraphic sequence of the Öræfajökull volcano at Kvíárjökull (Stevenson *et al.*, 2006), some 10 km to the east of Svínafell and Hafrafell (Helgason, 2007).

The oldest strata at Kvíárjökull (Stevenson *et al.*, 2006) are the "laterally continuous basalt lavas and hyaloclastites" (basal basalt succession), exposed between 200–900 m above sea level. They are normally magnetized and of Brunhes age (<0.781 Myr). Prestvik's (1979) "lower strata" are missing here, an indication that prior to the deposition of Kvíárjökull strata, erosion may have removed the "lower strata" to at least the present 200 m level. At Kvíárjökull, the basal basalt succession is intruded by rhyolitic dykes and lavas of rhyolite and trachydacite composition predominate the upper strata. Thus, this section seems to be more central to the Öræfajökull volcano than is the sequence at Svínafell. The distance, however, of both Svínafell and Kvíárjökull areas from the present Öræfajökull caldera is similar, about 8 km. This may indicate that a channel was open from the caldera toward the Kvíárjökull area during Brunhes or that the Öræfajökull volcanic center had a more SE location when the Kvíárjökull section erupted.

In Hafrafell, northwest of Svínafell, there occurs a 350 to 600 m thick sequence of lavas from lower Matuyama time (Helgason and Duncan, 2001) whereas in Svínafell a sequence of this age is at most 120 m thick. In Hafrafell this sequence is exposed at 300 to over 900 m elevation interval whereas in Svínafell it is exposed at about 100 to 250 m elevation, i.e. lava formations *SV6–SV9* in Skjólgil. Lava flow strike and dip in the region show stratigraphic age to increase toward south to southeast. Thus, the older "lower strata" should thicken in that direction. Why then do the "lower strata" almost disappear in Svínafell when compared to Hafrafell, a distance of some 2–3 km? The most probable explanation is that they originally reached the Svínafell but have now been eroded away. This erosion would have taken place in the Svínafell area during erosion stage *SR2*. Our conservative estimate is that erosion removed at least 230 m of section but that it could have been much greater. This seems reasonable keeping in mind that eastward from Hafrafell the "lower strata" disappear and are not exposed again until perhaps in Breiðamerkurfjall, some 20 km farther east. The "laterally continuous basalt lavas and hyaloclastites" in Vatnafjöll (Stevenson *et al.*, 2006) are all normally magnetized and of Brunhes age and thus not part of the "lower strata". This emphasizes the need for detailed fieldwork and mapping of erosion surfaces that may eventually reveal how relief was modified to its present state.

Age, nature and stratigraphic relationship between groups S4–S7

The youngest groups, *S5* to *S7*, rest unconformably on the sides of Svínafell and their age relationship to the dated group *S4* is of interest. The youngest group in Svínafell, *S7*, was not dated but can be correlated with an identical dated group in Hafrafell that has an age of 215 ka. In the present study group *S4* was dated at 698 ($\pm$54) ka. From a stratigraphic point of view group *S5* is considerably younger than group *S4*. Since we have evidence for several glacial–interglacial transitions occurring after its deposition, we estimate group *S5* to have an age of about 300–400 ka. We consider group *S6*, deposited at only 100 m above sea level, to be of upper Brunhes age (ca. 200–300 ka).

Landscape evolution in Iceland during the Matuyama chron

The effect of glacial ice in sculpting landscape in Iceland during the Matuyama (0.781–2.581 Ma) may have been highly variable and dependent on many factors, including the distribution and thickness of ice sheets. The Matuyama lower boundary is close to the onset of the main northern hemisphere glaciations. Recently, the Subcommission on Quaternary Stratigraphy agreed to define the onset of the Quaternary period at 2.58 Ma, a time that almost coincides with the boundary between the Matuyama and Gauss magnetic intervals (Gibbard *et al.*, 2010). Global Stratotype Section and Point (GSSP) for the Quaternary is just 1 m above the Gauss-Matuyama paleomagnetic reversal (Lourens, 2008). For work on glaciations and erosion history in Iceland, this new definition significantly eases the mapping of the main ice age boundary as it is contemporaneous with a magnetic reversal between two relatively long chrons. Clearly, however, Iceland was covered with ice prior to 2.58 Ma (Eiríksson and Geirsdóttir, 1996).

Tertiary landscape in Iceland

We assume that prior to the onset of northern hemisphere glaciations, at roughly 2.7 Ma, Iceland's surface was relatively flat as a result of prolonged lava accumulation under subaerial conditions during the Neogene (roughly 20 to 2.7 Ma). For the last 2.7 Ma Iceland has been shaped by glacial erosion during some 19 glacial intervals (Geirsdóttir *et al.*, 2006) and, at least during Brunhes, these glacials lasted longer than the intervening ice-free inter-glacials. Not only has erosion been much greater during glacials but the amount of volcanic material lost, with either meltwater or explosive activity under sub-ice volcanism, must have been substantial. On the other hand volcanic material lost to sea under ice-free volcanic conditions must have been negligible. Valleys and fjords continued to deepen and grow during this period causing the land eventually to rise isostatically. Therefore, compared to present day conditions, we suppose that Iceland had, say at 10 Ma, a much greater subaerial extent as well as having a highland that was mostly below the snow line, as indicated by rare hyaloclastite sediments of Tertiary age. The erosion stages in Svínafell bear witness to this developing landscape and clearly hiatuses have become greater with time. We observe erosion surfaces in Svínafell's stratigraphy. We expect many of these surfaces to be coeval with similar surfaces found elsewhere in the region (Helgason and Duncan, 2001; Helgason, 2007) and that with additional work these will prove to be regional markers in documenting the glaciation history of Iceland.

SUMMARY AND CONCLUSIONS

The lowest strata in Svínafell are probably some 4 million years old, i.e., reversely magnetized rocks from the Upper-Gilbert magnetic chron (3.60–4.19 Ma). These Neogene rocks belong to the lower strata in Öræfi that formed prior to the beginning of glacial conditions (>2.7 Ma) when the landscape was most likely relatively flat accumulations of basaltic lava flows. The oldest erosion surface in Svínafell is between R-lava sequences of Upper-Gilbert and Lower-Matuyama age and coincides with a considerable hiatus, based on the absence of normally magnetized rocks of Gauss age in Svínafell.

A major erosion phase dominated the area during Lower-Matuyama time (ca. 1.95 Ma) that resulted in complete removal of at least 230 m of strata. At this time a ridge-valley system had already developed that was amplified from then until the present. A small hill-shaped remnant of some 13 lavas, exposed in Skjólgil, includes rocks correlated with the Olduvai normal chron (1.78–1.95 Ma). The uppermost lavas in Skjólgil are inferred to be of Upper-Matuyama age. Glaciers now carved a depression into which the Svínafell sediments were deposited during an interglacial period. Stratigraphic dip then increased, especially within sedimentary units and on erosion surfaces, up to 30° toward SW and SE (formation *SV11*). At this stage deposition of sediments was intensive and followed by volcanism in the Öræfajökull volcano where onset of volcanism occurred after 0.78 Ma. This timing is based on the fact that all units above the Svínafell sediments are normally magnetized from the Brunhes magnetic chron, consistent with three ^{40}Ar–^{39}Ar total fusion age determinations from Svínafell's upper strata.

During Upper Brunhes time the thick volcanic sequence from Öræfajökull, here defined as group *S4*, was deeply eroded and now stands out as an isolated mountain only to be further carved down and have, from time to time, additions in the form of volcanic strata (groups *S5* to *S7*) that reach to the lowland, as low as 100 m above the present sea level. Group *S4* forms the upper half of Svínafell and was deposited during Upper-Brunhes time. After its deposition severe erosion set in that led to the carving out of the Svínafell mountain. Subsequently erupted volcanic groups, i.e., *S5* to *S7*, were therefore deposited at lower levels and added to the mountain sides, as low as 100 m above the present sea level. At this stage the present day "valley network" was fully developed.

Acknowledgements

We extend special thanks to Dr. Leó Kristjánsson, University of Iceland, for use of his paleomagnetic laboratory and assistance in the field with core sampling. We thank the people at Skaftafell, Freysnes and Svínafell for their invaluable help during fieldwork in Öræfi. JH expresses gratitude to Friends of Vatnajökull for financial aid. An early phase of this research was funded by the Science Fund in Iceland through a grant to JH. We thank Dr. John Stevenson and an anonymous reviewer for their constructive criticism.

ÁGRIP

Jarðlagafræði, ^{40}Ar–^{39}Ar aldursgreiningar og rofsaga Svínafells, Suð-Austurlandi.

Þrátt fyrir öra upphleðslu hraunlaga í Öræfasveit hefur rof þar af völdum jökla verið gríðarlegt og orsakað mislægi og mótað mjög landslag. Rakið er samspil eldvirkni og rofs við mótun Svínafells í Öræfum með kortlagningu jarðlaga, seguljarðlagafræði og ^{40}Ar–^{39}Ar aldursgreiningum á bergi. Aðallega er lýst skiptingu gosbergs frá Kvarter, þ.e. frá segulmundum á neðri-Matuyama og efri-Brunhes. Um 1832 m þykkur stafli í Svínafelli er gerður af 37 myndunum jarðlaga (Helgason, 2007), sem við höfum deilt í 7 yfirmyndanir (e. groups). Í Svínafelli sést að upphaf eldvirkni frá megineldstöðinni í Öræfajökli varð á neðri-Brunhes (C1n < 781 k ár), en skömmu áður höfðu Svínafellssetlögin safnast fyrir í lægð á hlýskeiði. Á myndunartíma jarðlaga í Svínafelli urðu að minnsta kosti 8 jökulskeið og hlýskeið. Tólf roffletir marka rofsögu Svínafells og landslagsþróun. Niðurstaða okkar er að aldur Svínafellssetlaganna sé á bilinu 0.70 til 1.78 M ár. Við rof á Brunhes segultíma hefur rof sífellt aukist með áberandi dýpkun dala. Afleiðing eldgosa undir jökli og rofs af völdum jökla er veruleg landlyfting í Öræfum umfram aðra landshluta.

REFERENCES

Albertsson, K. J. 1976. *K/Ar-ages of Pliocene-Pleistocene Glaciations in Iceland.* PhD-dissertation, Cambridge University, England, 268 pp.

Einarsson, Þ. 1968. *Saga bergs og lands* (in Icelandic). Mál og Menning, Reykjavík, 335 pp.

Einarsson, Þ. 1977. Um gróður á ísöld á Íslandi (On vegetation during the ice age in Iceland, in Icelandic). *Skógarmál*, 56–72.

Eiríksson, J. 2008. Glaciation events in the Pliocene – Pleistocene volcanic succession of Iceland. *Jökull* 58, 315–329.

Eiríksson, J. and Á. Geirsdóttir 1996. A review of studies of the earliest glaciation of Iceland. *Terra Nova* 8, 400–414.

Geirsdóttir, Á., G. H. Miller and J. T. Andrews 2007. Glaciation, erosion and landscape evolution of Iceland. *J. Geodynamics* 43, 170–186, doi:10.1016/j.jog.-2006.09.017.

Gibbard, P. L., M. J. Head, M. J. C. Walker and the Subcommission on Quaternary Stratigraphy 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *J. Quaternary Sci.* 25, 96–102.

Gradstein, F., J. Ogg and A. Smith 2004. *A Geologic Time Scale 2004.* Cambridge University Press, 589 pp.

Helgason, J. 2007. *Bedrock geological map of Skaftafell, SE–Iceland, scale 1:25,000.* Ekra Geological Consulting.

Helgason, J. and R. A. Duncan 2001. Glacial–interglacial history of the Skaftafell region, southeast Iceland, 0–5 Ma. *Geology* 29, 179–182.

Helgason, J. and R. A. Duncan 2005. *Kárahnjúkar Hydroelectric Project, Ar–Ar age dating of the Snæfell volcanic center.* Report for the National Power Company, Iceland, 20 pp.

Jakobsson, S. P., K. Jónasson and I. A. Sigurðsson 2008. The three igneous rock series of Iceland. *Jökull* 58, 117–138.

International Stratigraphic Guide 1976. International Subcommission on Stratigraphic Classification, IUGS Commission on Stratigraphy. H. D. Hedberg (ed.), John Wiley and Sons, 200 pp.

Lescinsky, D. and J. Fink 2000. Lava and ice interaction at stratovolcanoes: Use of characteristic features to determine past glacial extents and future volcanic hazards. *J. Geophys. Res.* 105, 23.711–23.726, doi:10.1029/2000JB900214.

Loughlin, S. 2002. Facies analysis of proximal subglacial and proglacial volcaniclastic successions at the Eyjafjallajökull central volcano, southern Iceland. In: J. L. Smellie and M. C. Chapman (eds.). *Volcano–ice Interaction on Earth and Mars. Geol. Soc. London Spec. Publ.* 202, 149–178.

Lourens, L. J. 2008. On the Neogene–Quaternary debate. *Episodes* 31, 239–242.

Nielsen, N. and A. Noe–Nygaard 1936. Om den islandske Palagonitformation's oprindelse. *Geografisk Tidsskrift* 39, 89–122.

Noe–Nygaard, A. 1953. Notes on the nature of some indurated moraines in South Iceland. *Geografisk Tidsskrift* 52, 222–231.

Prestvik, T. 1979. *Geology of the Öræfi district, SE–Iceland.* Nordic Volcanological Institute, research report 7901, Reykjavík, 28 pp.

Prestvik, T. 1982. Petrography, chemical characteristics and nomenclature of Öræfajökull rocks. *Jökull* 32, 69–76.

Renne, P. R., C. C. Swisher, A. L. Deino, D. B. Karner, T. L. Owens and D. J. DePaolo 1998. Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating. *Chem. Geol.* 145, 117–152.

Seidemann, D. E. 1988. The hydrothermal addition of excess ^{40}Ar at the lava flows from the early Jurassic in the Hartford Basin (Northeastern USA): Implications for the time scale. *Chem. Geol.* 72, 37–45.

Smellie, J. L. 2000. Subglacial Eruptions. In: H. Sigurðsson (ed.). *Encyclopedia of Volcanoes.* Academic Press, San Diego, California, 403–418.

Smellie, J. L. 2007. Quaternary vulcanism: subglacial landforms. In: S. Elias (ed.). *Encyclopedia of Quaternary Sciences.* Elsevier, Amsterdam, 784 –798.

Stevenson, J. A., D. W. McGarvie, J. L. Smellie and J. S. Gilbert 2006. Subglacial and ice–contact volcanism at the Öræfajökull stratovolcano, Iceland. *Bull. Volcanol.* 68, 737–752. DOI 10.1007/s00445–005–0047–0.

Torfason, H. 1985. *Geological map of Iceland, sheet 9, scale 1:250,000. SE–Iceland.* Icelandic Museum of Natural History and Iceland Geodetic Survey, Reykjavík.

Walker, G. P. L. 1959. Geology of the Reyðarfjörður area, eastern Iceland. *Quart. J. Geol. Soc. London* 114, 367–391.

Wijbrans, J. R., M. S. Pringle, A. A. P. Koppers and R. Scheevers 1995. Argon geochronology of small samples using the Vulkaan argon laserprobe. *Proc. K. Ned. Akad. Wet. Biol. Chem. Geol. Phys. Med. Sci.* 98, 185–218.

Þórarinsson, S. 1958. The Öræfajökull Eruption of 1362. *Acta Naturalia Islandica* 2, 100 pp.

Þórarinsson, S. 1963. The Svínafell layers, plant–bearing interglacial sediments in Öræfi, southeast Iceland. In: A. Löve and D. Löve (eds.). *North Atlantic Biota and their History.* Pergamon Press, 377–389.