Human (boot) tracks preserved in volcanic deposits of Surtsey Island, Iceland

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ABSTRACT

Several human boot tracks and trackways are preserved in palagonitized tuff in Surtsey Island, south Iceland. The underlying palagonitized substrate is made of reworked tephra debris talus and slump material that lies partly on top of lava flows erupted in 1964–1965 in Surtungur tuff crater and 1966–1967 in Surtur tuff crater. This stratigraphic information along with other evidence from the nature of the sediments, alteration history of the deposits and the record of human presence on the island indicate the tracks were formed in the years between 1967 and 1970. The exquisite preservation and consolidation of the tracks coincide with a period of rapid geomorphic changes in the early stages of development of the island, when the newly formed tephra was still unconsolidated and easily mobilized by mass movements, wind and runoff. Furthermore, cooling magmatic intrusions generated hydrothermal activity on the island speeding up diagenesis of the tephra and the cementation of the boot tracks in the substrate. Expulsion rims preserved in some of the boot tracks suggests the tracks were formed in moderately cohesive substrate, followed by rapid burial of the prints in heavy wind and/or storm. Three boot sizes were identified suggesting the tracks were made by at least three persons, and documentation of the boot anatomy, measurements on angle of gait, stride and pace reveal the direction of movement for each trackway. Intense erosion of the tuff cones has exhumed the tracks to the surface that stand today as a testimony to impressively rapid geological cycles for preservation and exhumation and the role of unstable and rapidly changing environments, the aftermath of high-energy events, in capturing and preserving ichnites. These boot tracks are the first fossil tracks described for Iceland and the first record in the world of boot tracks preserved in sedimentary rocks.

INTRODUCTION

Surtsey is a recently formed volcanic island south of Iceland (Fig. 1). The eruption started visibly on November 14th, 1963, and Surtseyan type explosive activity generated tephra, lapilli and bombs, that accumulated weightily and rapidly building the island that grew to cover an area of 1.05 km^2 with height of 175 m above sea level toward the end of March 1964. From the beginning of April 1964, the eruption transitioned to effusive volcanism that continued intermittently until June 1967, expanding the surface of the island on top of a lava delta to 2.65 km^2, the total volume of the volcano reaching 1.1 km^3 (70% tephra and 30% lava), with subaerial volume of 0.1 km^3 (Thorarinsson 1965a, 1968b). During the eruption and after, intense weathering mobilized the tephra by mass wasting, aeolian activity and runoff, but decreased significantly after 1974 with consolidation and palagonitization of the tephra by hydrothermal alteration (Jakobsson 1978). Intense coastal erosion had also removed about 53% of the area of the island by 2019 (Óskarsson et al. 2020).

During the course of the volcanic activity Sigurður Þórarinsson of the Museum of Natural History of Reykjavík, Iceland (today the Icelandic Institute of Natural History), documented thoroughly the volcanic activity along with the physical changes in the island, but also registered all the early visits to the island (Thorarinsson 1965a, 1967a, b, 1968a, Helgadottir 2021). Þórarinsson states that he "arrived on the scene together with other geologists" on November 14th, 1963 (1967b, p. 15), although this visit was aboard a boat. According to his records, during the explosive

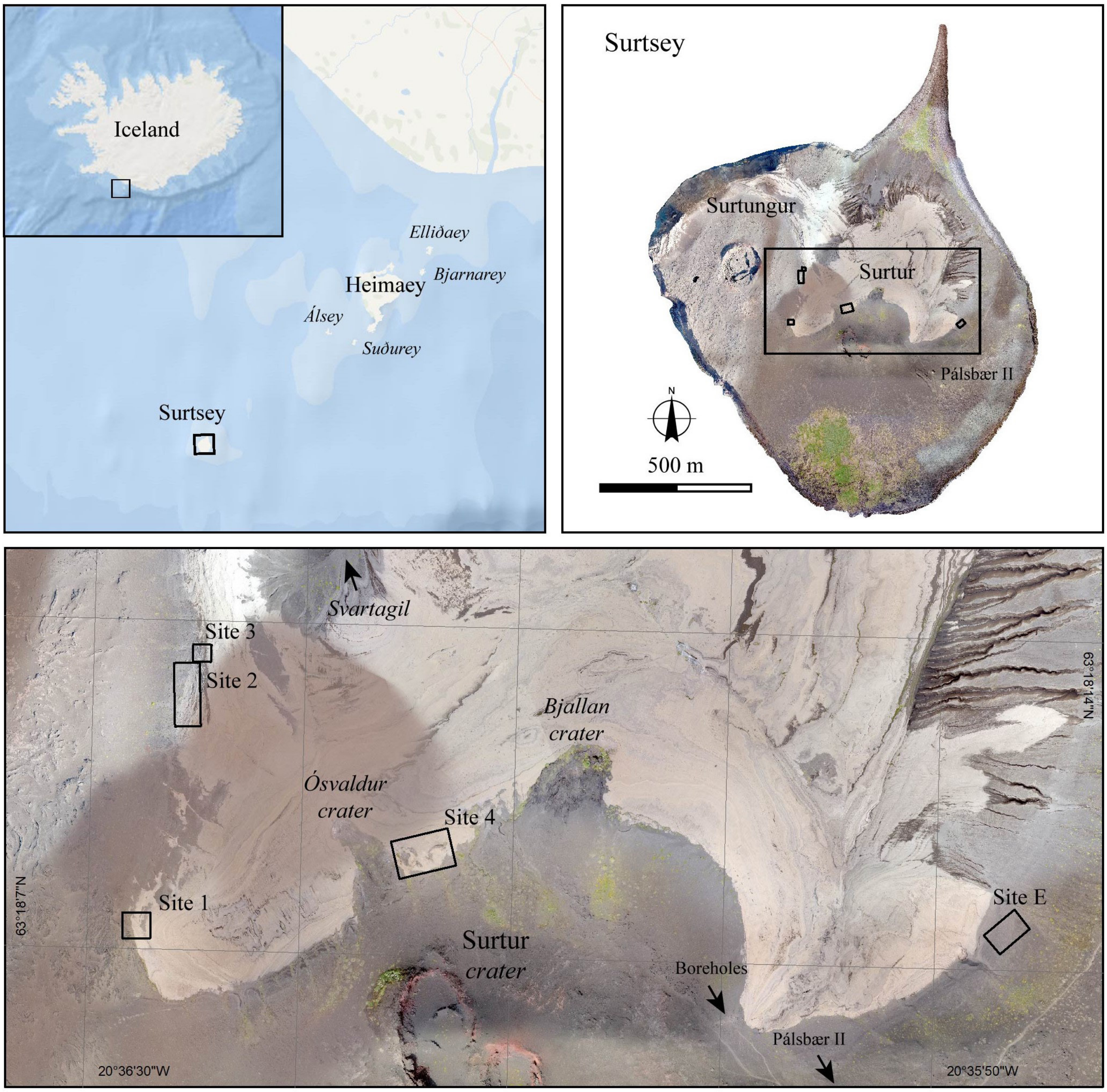

Figure 1. Geographic location of the Island of Surtsey and specific location of study sites on the island. Credit (upper left): Esri, Garmin, GEBCO, NOAA NGDC and other contributors. Credit (upper right and lower) Orthoimage from 2019 (Óskarsson et al. 2020).

phreatomagmatic phase the island was visited only four times mainly due to hazards associated with the phreatomagmatic explosions (Thorarinsson 1967b p.30). The first landing on Surtsey took place on December 6th, 1963, made by three French visitors but lasted ashore only a quarter of an hour before they had to depart as the volcanic eruption resumed intensity. A second very brief landing occurred on December 13th, 1963, when seven Vestmann Islanders went ashore Surtsey to vindicate naming the island as Vesturey (e.g. Lárusdóttir 2017, Friðriksson 2022). Because of the intense volcanic activity during those first weeks, early visitors did not venture far from shore. The third documented landing occurred on December 16th, 1963, when Icelandic geologists Sigurður Þórarinsson and Þorbjörn Sigurgeirsson went ashore to collected samples and walked on the slope of the volcanic cone that had been formed (e.g. Helgadóttir 2021). On February 19th, 1964, a group of seven scientists, journalists and "eruption enthusiasts" went ashore but apparently only stood on the sandy beach on the northeastern side and had to retreat in hurry due to the fall of ash and bombs (e.g. Pálmadóttir 2003, Helgadóttir 2021).

Table 1. Geological history of Surtsey Island from 1963 to 1980 and early visits onshore as recorded in the work of Thorarinsson (1965b and 1968b).

Date	Events, size and elevation of the island	Type of activity	Visits
1963			
14 Nov, 7:15 am	First signs of submarine eruption in Surtsey. Beginning of eruption that would form Surtur crater.	Phreatomagmatic	
1 Dec	First break, 4 hours.		Seaguls sat on the island for the first time.
6 Dec	Short break in eruption. 7 Dec. Lenght of island 1020 m and elevation of highest point about 112 m (elevation measured on Dec. 5).		Three French journalists sponsored by weekly Paris Match landed on the beach and placed a flag on the island. Residence about 45 min.
13 Dec	11 Dec. Length of island 1000 m and elevation of heighest point 106 m.		Seven Icelanders from Vestman Islands landed on the beach and placed a sign with the name Vesturey. Had to flee in hurry due to bomb shower and ash fall.
16 Dec	Break in eruption of 17 hrs. Longest break of all that year. Lengh of island 800 m and elevation of highest point 87 m. According to "Morgunblaðið" news on Dec. 22, 1963, additional 20 m of tephra were deposited on top of the island the day after the visit of Sigurður and Þorbjörn. 17 Dec. Elevation of island 106 m.		Two scientists Sigurður Þórarinsson and Þorbjörn Sigurgeirsson went on land from the vessel Óðinn to collect samples. Walked on the island but with short residence.
28 Dec	Beginning of Surtla submarine eruption 2 km ENE of Surtsey. Small fissure, did not emerge above sea.	Phreatomagmatic	
1964			
6 Jan	Surtla eruption over.		
End January	Activity ceased altogether in Surtsey and snow capped the highes poit for a few days.		
2 Feb, 11 pm	New vent NW of flank of Surtur. Beginning of eruption that would form Surtungur crater.	Phreatomagmatic	
19 Feb	17 Feb. Length 1350 m and area 102 ha.		Seven persons (5 men and 2 women) includsing S. Þórarinsson went on shore from vessel Haraldur but had to flee in hurry due to bomb shower and ash fall. No further attempts were made to go ashore on Surtsey while the explosive phase was still active. Residence of visitors was one hour and half and only on the beach.
4 Apr	Effusive phase began at noon.	Effusive	
15 Apr	11 Apr. Area 133 ha and highest point 173 m.		Three persons land on the island with a Cessna aircraft. Pilot Stéfan Þór Jónsson.
16 Apr			Scientists and filmakers land on Surtsey.
29 Apr	Break in eruption of Surtungur.		
9 Jul	Resumption of effusive activity in Surtungur.	Effusive	
19 Aug	25 Aug. Area 182 ha.		Helicopter from the Coast Guards lands first time on the island.
1965			
18 Jan			Aircraft Prestwick Twin Pioneer (Lóan) lands first time on Surtsey. Pilot Björn Pálsson. The aircraft made dozens of trips to the island.
20 Feb	Feb. Area 234 ha.		Aircraft from Civil Aviation Authority lands on Surtsey.
29 Apr			Last landing of aircraft Lóan.

17 May	Eruption ceased in Surtungur.		1965 to present. Surtsey declared a Nature reserve and from 2008 UNESCO World Heritage Site. Visits only allowed with special authorization.
22 May	Beginning of Syrtlingur submarine eruption 600 m ENE of Surtsey. According to isopach map in Thorarinsson 1967, about 5–10 cm of tephra from Syrtlingur was deposited over the sites in Surtsey Island. 24 Aug. Elevation of highest point 169 m and area 245 ha.	Phreatomagmatic	5 Jun. Páll Helgason, from the Westman islands adventured to the island of Syrtlingur during a short break in the explosive activity (Eyjafréttir Dec. 1995, Friðriksson 2022). 23 Jun. Páll Helgason, Viktor Sigurjónsson and Guðjón Sigurjónsson set up a tent in Surtsey and stamped 4500 envelopes with a newly released Surtsey stamp. They faced a charge for travelling to Surtsey without permission but were later acquitted of the charge (Morgunblaðið 27 Jun. 1965, Eyjafréttir Dec. 1995).
17 Oct	End of Syrtlingur eruption. Syrtlingur Island washed away by Oct. 24.		
26 Dec	Beginning of Jólnir submarine eruption 800 m SV of Surtsey. According to isopach map in Thorarinsson 1967, about 1–3 cm of tephra from Jólnir was deposited over the sites in Surtsey Island.	Phreatomagmatic	
1966	First signs of consolidation of the tephra.		
10 Aug	End of Jólnir eruption. Jólnir Island washed away by Oct. 31.		20 May. Páll Helgason, Hjálmar Guðnason, Hlöðver Pálsson and Ólafur Gräntz are first to adventure onshore the island of Jólnir (Eyjafréttir Dec. 1995).
19 Aug	Beginning of effusive activity at Surtur crater.	Effusive	
12–17 Dec	Minor lava flow from vent on inner NW wall of Surtur crater.	Effusive	
1967			
1–4 Jan	Lava flow from vent on outer north slope of Surtur cone.	Effusive	
1–8 Jan	Another lava flow from vent on inner wall of Surtur crater.	Effusive	
2 Jan	Lava flow from vent on outer NE slope of Surtur cone.	Effusive	
2–7 Jan	Minor lava flow from fault in wall of inner Surtur crater.	Effusive	
5 Jun	End of effusive activity in Surtur crater. Area 2.65 km^2 and highest point at 175 m.	Effusive	
1968	First signs of hydrothermal activity in the tephra.		
1969	First signs of palagonitization in the tephra east of Surtur.		
1977	Sites with tracks fully palagonitized.		
1980	Sites with tracks exhumed near the surface.		

After the explosive phase ceased and the effusive phase began on April 4th, 1964, many people visited the island to see the lava fountains and flows. Þórarinsson reports that from 1963–1964 he had landed there either by boat or aircraft eleven times, then eleven times in 1965, nine times in 1966 and eight times in 1967, each visit lasting for a few hours with a longer stay of four days (Thorarinsson 1965a, 1966, 1967, 1968a). In May 1965 the island was declared a Natural reserve and visits were restricted to authorized scientists and thus decreased significantly in number. Some of these visits are listed on Table 1 in the context of the geological events that occurred during the formation of the island.

Surtsey explorers did not envisage that one or several of these visits would leave permanent traces of its residence. Human (boot) tracks fossilized within the palagonitized tuff layers in Surtsey and exhumed at the surface with erosion were first reported by geologist Sveinn Jakobsson in the 1980s or 90s, while conducting geological research in Surtsey at the time. Sveinn introduced the tracks to geologist Lovísa Ásbjörnsdóttir in 2006 as man-made tracks; nevertheless, Sveinn was not entirely convinced of their authenticity. The first sites to be reported as holding man-made boot tracks were Site 4 (Fig. 1), photographed by geologists Hallgrímur D. Indriðason and Sigurður Sveinn Jónsson in 2001, and Site 1 photographed by geologist Kristján

Jónasson in 2011. The boot tracks in S1 were later documented photogrammetrically by geologist Birgir V. Óskarsson that mapped systematically the prints in collaboration with paleontologist Raúl Esperante in July 2021, which in addition discovered Site 2. In the same trip Þorgerður Ólafsdóttir discovered Site 3. The significance of the finding was remarkable as it posed a unique opportunity for studying the formation of ichnites in modern environments. The stages in the development of Surtsey from the beginning are well documented and the post-eruption changes by weathering and alteration are also well known. Thus, the aim of this study is to describe the tracks within the stratigraphy and environment they are found and to discuss their authenticity and the process of fossilization and preservation. Although others have mentioned the boot tracks in Surtsey before and taken photos, this study describes them for the first time in a scientific way.

THE RECORD OF FOSSIL HUMAN TRACKS IN VOLCANIC ROCKS

Fossil human tracks are very rare in the rock record, and even more rare those associated with volcaniclastic substrates (Lockley et al. 2008), with sites in Italy, Kenya, Turkey, United Kingdom and Tanzania. In Italy, the Middle Pleistocene (Chibanian age) 'Devil's Trails ichnosite outside the town of Foresta, on the northeastern slope of the Roccamonfina volcano, consists of 81 identified tracks in four trackways preserved on a zeolite-rich deposit formed by a pyroclastic flow. The human and some animal tracks are preserved in a zeolithified volcanic ash covered by coarser, granular material (Mietto et al. 2003, Avanzini et al. 2008, Avanzini et al. 2020). Late Pleistocene human footprints, hand tracks, knee and body impressions have been found in the cave named Grotta della Bàsura, about 1 km north of Toirano, at the foot of Mount Carmo of Loano. These traces are preserved on clay sediment and represent a complex set of motions on a difficult path of a group of adults followed by adolescents and children during both stance and progression phases while exploring the cave (Avanzini et al. 2020). Thousands of human and animal tracks are preserved in Afragola, Nola and Palma Campania in several stratigraphic levels of a pyroclastic flow deposit dated to 3780 yrs BP by ^{14}C (Avanzini et al. 2020). Casts of three human footprints were found in Moregine, about 600 m south of the walls of the ancient city of Pompei dated 79 AD (Avanzini et al. 2020). A series of adult and children footprints have been reported in the Aosta area (Armirotti et al. 2017).

In Turkey, a set of human footprints were found in 1969 on the surface of a tuff on the western flank of Çakallar Hill (a volcanic cone) west of the Manisa-Salihli-Demirkprü Dam, with diastemas (significant separation between the toes) and clear erectus bipedalism characteristics (Ozansoy 1969). The relative age of these footprints has not been reported.

More than 400 human footprints have been found in Holocene deposits south of Lake Natron, Tanzania preserved on the surface of a volcaniclastic tuff consisting of moderately sorted fine ash to fine lapilli particles. These footprints are remarkably well preserved with prominent expulsion rims resulting from the deformation of the soft sediment under the weight of the pedestrians (Balashova et al. 2016). Various ages have been assessed for the ash ranging between 5760 ±30 yrs BP and 19.1 ±3.1 kyr BP based on ^{40}Ar/^{39}Ar analysis and ^{14}C dating techniques (Balashova et al. 2016, Liutkus-Pierce et al. 2016, Hatala et al. 2020).

Human footprints and animal tracks have been found in Pleistocene deposits with several layers of coarse basaltic volcanic ash in the Valsequillo Basin, south of Puebla, Central Mexico. Several short human trackways are recognized but incomplete due to poor preservation (González et al. 2006). The age of the ash and even the authenticity of the prints is controversial were Gonzalez et al. (2006) dated the ash layer to at least 40 kyr BP by OSL dating, wheile Renne et al. (2005) dated the layer as old as 1.3 myr based on ^{40}Ar/^{39}Ar dating and claimed that the footprints could not be human but the result of quarrying operations.

Hundreds of exceptionally preserved human footprints in twelve trackways and a trampled path are preserved in two small exposures of a surface of a Holocene volcanic ash in the site Acahualinca near the shores of Lake Managua, Nicaragua. Also present are tracks of deer, opossum and bird tracks. The estimated dates for the tracks range from 2120 to 6500 yrs BP (Lockley et al. 2009, Schmincke et al. 2009, Schmincke et al. 2010).

Véliz (1978) reported the finding of "fragmentary tracks of four feet, and thus dubious" tracks and "indisputable tracks of three human feet" in a rhyolitic layer in the hill named El Portillo de la Crucita, Guaimaca, Honduras. No dates have been estimated for these tracks.

THE RECORD OF BOOT TRACKS

The only reported boot tracks is from military structures in Trentino-Alto Adige Region in Northern Italy left by First World War soldiers (Avanzini et al. 2011). In Valmorbiaweerk (Forte Pozzacchio) the boot tracks are preserved in 2–3 mm on a thin layer of pure cement, and thus man-made and of less significance to this study. In the fortified complex of Monte Celva east of the city of Trento several human and small mammal tracks are preserved on the concrete floor. In both places the tracks record the imprint of boots with soles covered by rows of nails, leaving conical depressions outlining the contour of the shoe (see Avanzini et al. 2020, Figs. 9, 10).

METHODOLOGY

Surtsey Island was visited on July 16th to 19th, 2021 as part of an expedition led by the Icelandic Institute of Natural History. The accessible areas of the island were surveyed for preserved human tracks. Measurements were made with a tape measure and photogrammetrically and consisted of: 1) total length of trackway, 2) compass direction of trackway, 3) length of each track from the middle point of the heel rim to the middle point of the frontal (toe) end, 4) width of each track measured at half the length of the print, 5) pace as distance between individual tracks measured from the middle point of one print to the middle point of the following print, 6) stride measured as distance from the middle point of one print to the middle point of the next consecutive print of the same foot, 7) anatomical right and left identity of tracks in the trackways was determined by the shape and relative position to one another and the angle of gait which is the angle relative to the midline of the track. In this study we differentiate the left out-toeing by assigning a negative number and right out-toeing a positive number (see Table S in supplementary files).

High-resolution photographs were taken with digital cameras Olympus Tough TG-6, Canon 6D and with a Phantom 4 Pro drone. Photogrammetry processing of the drone images (20 MP camera FC6310, focal length 8.8 mm, image resolution 4864x3648 px) was made for each footprint site (images from 90 to 137 for each site) at the Icelandic Institute of Natural History (IINH) with software Agisoft Metashape (version 1.7.3). The resulting products were high-resolution georeferenced orthoimages (~ 2 mm/pix), digital elevations models (DEMs, ~8 mm/pix) and mesh models for three sites (Site 1, 2 and experiment). For scaling the orthoimages and models we used coded targets (12 bits from Agisoft Metashape) with known dimensions and for georeferencing ground control points that were measured with a high-precision GNSS instrument (Trimble R10) by the National Land Survey of Iceland. The methodology of the photogrammetry survey in Surtsey followed the 2019 survey described in Óskarsson et al. (2020). Photogrammetric methods for documenting the trackways were based on studies on hominid footprints (e.g. Masao et al. 2016).

Geological information of the island was extracted from aerial imagery of Surtsey from 1964 available at the National Land Survey of Iceland (www.lmi.is) and geological maps from the IINH (Lýsigagnagátt: NI_J5v Surtsey Jarðfræðikort jarðsaga 1963–2006 – 1:5.000, https://gatt.lmi.is/). A georeferenced 3D model of the island was available for additional observations on the geology of Surtsey and measurements, through the web platform V3GEO (Surtsey Island July 2021, Birgir Vilhelm Óskarsson; Guðmundur Valsson; Lovísa Ásbjörnsdóttir, https://v3geo.com/model/347) and through the software LIME (Buckley et al. 2019).

Orientation and dip of the trackways were measured with an iPhone 8S; for orientation we used the Compass application developed by Apple and for dip we used the Bubble Level application version 3.05 developed by Lemondo LLC. Angles could also be measured from a GIS based software.

In this study we used the following nomenclature to designate sites, trackways and tracks: Study sites are numbered S1, S2, S3 and S4. Site 4 is a single trackway with four tracks that was reported to the authors after field work was completed in July 2021 and thus details of the track could not be obtained. Trackways are named T1, T2 and T3 at each site. Individual tracks are named "t", followed by a consecutive number beginning with 1 for the first occurrence and the letter "r" for right foot or "l" for left foot. As an example, the first track of trackway T1 in Site 1 is S1T1t1r.

EXPERIMENT

An experiment was conducted in a dry tephra debris fan east of the hut Pálsbær II (Site E in Fig. 1), where three trackways were made at different slopes, uphill 14°, subhorizontal 1°, and downhill 11° (Table 2). The trackways were photographed and processed photogrammetrically using coded targets for reference. The height of the person was 190 cm and boot size 32.5 cm in length and 11 cm width (46 EUR, foot length 27.5 cm). Measurements included boot track length and width, pace, stride, and angle of gait. The boot tracks in the experiment site were measured from the orthoimage only. Results are shown in Table 2 and in Table S in the Supplementary files.

GEOLOGICAL SETTING

Surtseyan geology

The eruption of Surtsey Island is divided into two main phases, the explosive Surtseyan phase that characterized the months from November 14th, 1963, to end of March 1964 and the effusive phase, that characterized the months from April 4th, 1964, to June 5th, 1967 (Table 1, Thorarinsson 1965a, 1967a, b, 1968a). During the eruption the activity migrated within Surtsey Island, but also to three other submarine eruptions located nearby Surtsey; Surtla, Syrtlingur and Jólnir, that formed ephemeral islands that were washed away within few months after their formation (see Table 1) and today exist as seamounts. The activity in Surtsey Island began forming the eastern tephra cone, Surtur. The almost unlimited availability of water in the submarine setting of the eruption led to powerful and explosive magma-coolant interactions generating fine-grained tephra and lapilli deposited in finely-bedded layers by air fall, pyroclastic density currents and by base-surge flows (Lorenz 1974). On February 2nd the activity migrated NW and established a new vent forming the western tephra cone, Surtungur. After the tephra closed the access of sea water into the vent beginning of April 1964, the eruption transitioned to effusive beginning first in the Surtungur cone that eventually formed a lava shield building out to the south from the tephra cone. On May 17th, 1965 the eruption ceased at Surtungur and on August 19th, 1966, effusive activity was reestablished in Surtur crater forming a second lava shield, and with five minor eruptions breakouts in the inner and outer cone of Surtur in late December 1966 and early January 1967. The effusive activity in Surtsey Island was terminated altogether on June 5th, 1967.

About one third of the exposed part of Surtsey was made up of basaltic (alkaline) tephra (Jakobsson 1972). The analysis by Jakobsson (1978) indicates that the tephra is very poorly sorted, with about 19% of the particles being fine ash (<0.06 mm), 67% as coarse ash (0.06–2 mm), about 14% as lapilli (2–64 mm), and less than 0.5% of blocks and bombs (>64 mm), according to the classification of Fisher (1961). Microscopic examination of the tephra shortly after deposition (Summer 1964) indicated that 82–88% volume consisted of unaltered and unpalagonitized basaltic glass, the rest consisting of fragments of autogenic hyalobasalt and phenocrystals of plagioclase, olivine and Cr-spinel, with initial porosity of the tephra at surface as high as 45–50% (Jakobsson 1972). Glass, when under hydrothermal alteration, is subject to palagonitization, a post-eruptional hydrolytic alteration process occurring at relatively low temperatures whereby basaltic glass is dissolved producing various authigenic minerals including palagonite, zeolites and smectites (Fisher & Schmincke 1984). Palagonite, the main product of this process, is a vitreous, transparent, but usually yellow to brown authigenic mineral that results in the compaction of the loose tephra (Jakobsson & Moore 1986).

During the build-up of the tephra cones, the steepening of the crater margins and outer slopes resulted in tephra slip, slumps and landslides forming a debris apron at the base and later top of the lava shields which partially filled the craters. Post-eruption degradation of the tephra cones with mass wasting continued to erode the cones and in Surtsey this process was intensive until consolidation with compaction and later palagonitization decreased the rates of surface erosion significantly. In the process, parts of the aeolian and talus sediments got palagonitized leaving only the outermost shell of reworked tephra unconsolidated. Since the termination of the volcanic activity, destructive forces have prevailed causing severe geomorphic changes. Coastal wave erosion is extreme, and the island had decreased by over 53% in 2019 (Óskarsson et al. 2020). Moreover, extreme weather conditions in Surtsey have removed over 4 m of palagonitized tuff from the cones at certain locations exposing the inner layering and sediments have accumulated at the base of the cones (Óskarsson et al. 2020).

LOCATION OF TRACKS IN THE TUFF CONES

Five boot trackways and two single tracks have been documented on palagonitized tuff on the SE slope of the island in four separate sites, Site 1, Site 2, Site 3, and Site 4 (Fig. 1, 2 and 3). Site 1 has two trackways (Fig. 2), Site 2 has three trackways, S2T1 and S2T2

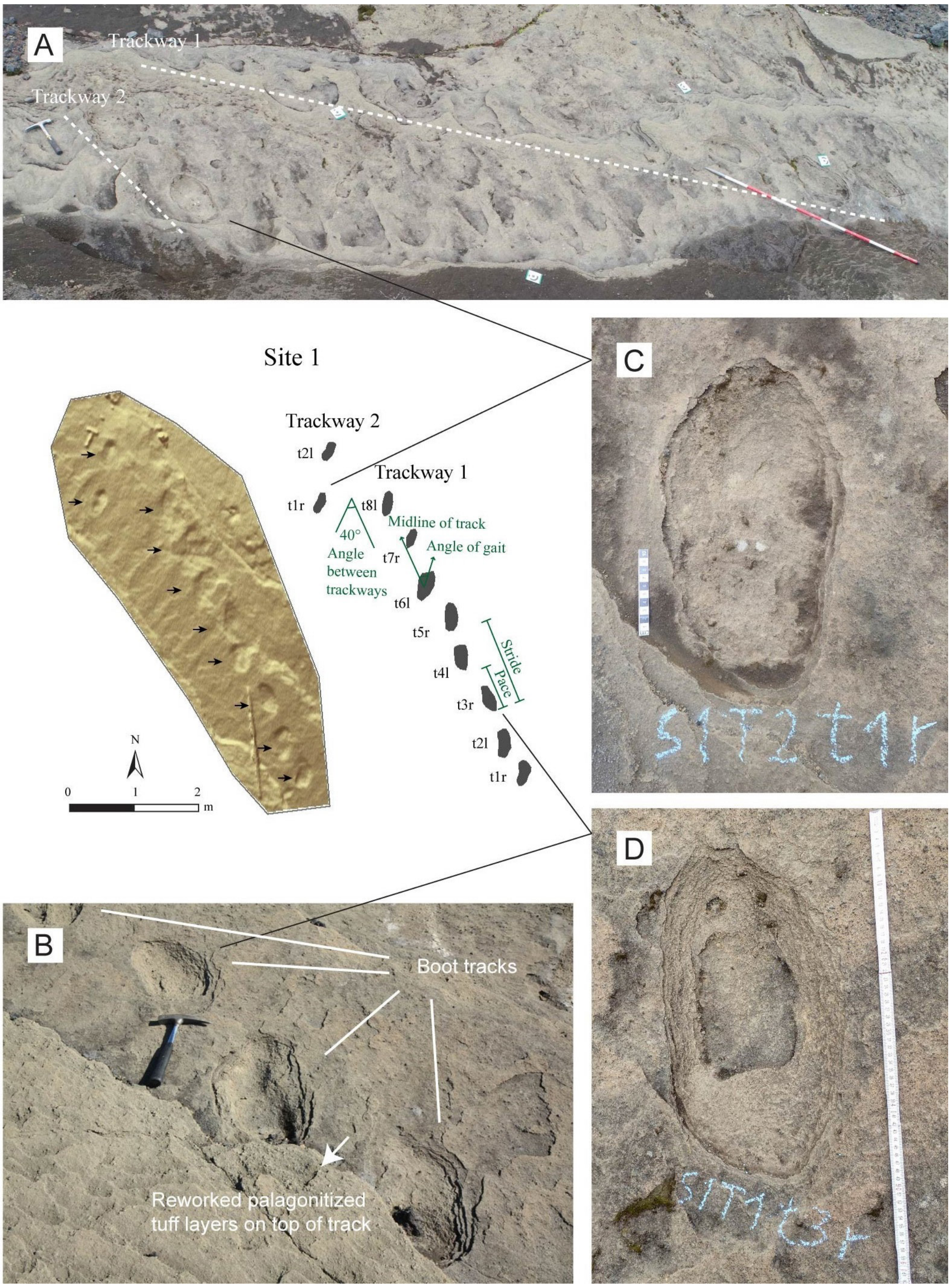

Figure 2. General view and details of Site 1 with trackways S1T1 and S1T2. Centered in the figure is a digital elevation model of the site with the trackways. Arrows point the location of the tracks. A) View of S1T1 in the foreground and S1T2 near the upper left corner. Notice the variation in orientation of the individuals tracks as the trackmaker walked to stay in a straight path while walking on soft ground. Notice other structures similar to tracks that resulted from the erosion of the track layer and both overlying and underlying layers. These pseudo tracks are easily distinguishable from true tracks because they do not show a pattern of alignment as tracks in trackways do. Some tracks show approximately 35° rotation with respect to the trackway midline. B) Four tracks of S1T1. C) Track S1T2t1r. Scale bar 10 cm. D) Track S1T1t3r. Scale bar 30 cm.

being well defined while S2T3 is inferred from the position of three tracks (Fig. 3), Site 3 has one single boot track and Site 4 was reported to have four tracks, but only one was documented (Fig. 4).

The tracks of all sites are positioned at seemingly the same stratigraphic level in the tuff cones within the uppermost (youngest) layers of palagonitized tuff cones (Fig. 5A). Site 1 (63.302081°, –20.607695°) is found at about 90 m.a.s.l. on an 18° slope along the crest of the ridge between Surtur and Surtungur tuff cones. Site 2 (63.303419°, –20.607159°) is found at about 106 m.a.s.l. along a 2° slope inside the eastern flanks of the Surtungur tuff cone. Site 3 (63.30371°, –20.60694°) is in straight northward continuation of Site 2 but slightly above, and Site 4 (see Fig 1 for approximate location) is located on a 20° slope at 75 m.a.s.l. in between two small craters within the inner walls of the Surtur tuff cone (Ósvaldur and Bjallan, Fig. 1) but the exact location of the boot tracks that are likely eroded today, is not known to the authors. The layer with the boot tracks of Site 1 is partially overlaid by 40 cm of palagonitized tuff (Fig. 5B) but 20 m below, the same layer is covered by about 1.2 m of palagonitized tuff beds (Fig. 5C and D). The overlying tuff includes numerous thin and discontinuous 1–5 cm beds of alternating fine ash and lapilli, sometimes with grading and cross bedding. The beds below and on top of Site 1 lack lithics and evidence of impact sags (Figs. 5 and 6). On Site 2 the layer with boot tracks is partially covered by 10–20 cm thick palagonitized tuff beds of lapilli and fine grained tephra (Fig. 5E) but within blocks of slumped material (Fig. 5A).

THE SURTSEY BOOT TRACKS

All the boot tracks studied are true tracks or surface tracks *sensu* Romano and Whyte (2003, Fig. 2 and 3), preserved as concave epichnia and epirelif, not underprints or subsurface tracks. Two main traits indicate that they are boot tracks and not footprints: the absence of toe marks and the occurrence of the mark of the waist or shank, which is the break in the outsole that separates the heel from the toe sections of the shoe.

All tracks in Site 1 have been modified by erosion but nevertheless remained relatively well preserved at the time of study (Figs. 2 and 3). Despite the best exposed tracks occur in Site 2 (Fig. 3). The tracks lack features observed in some vertebrate fossil and modern tracks, including stria, tension fractures,

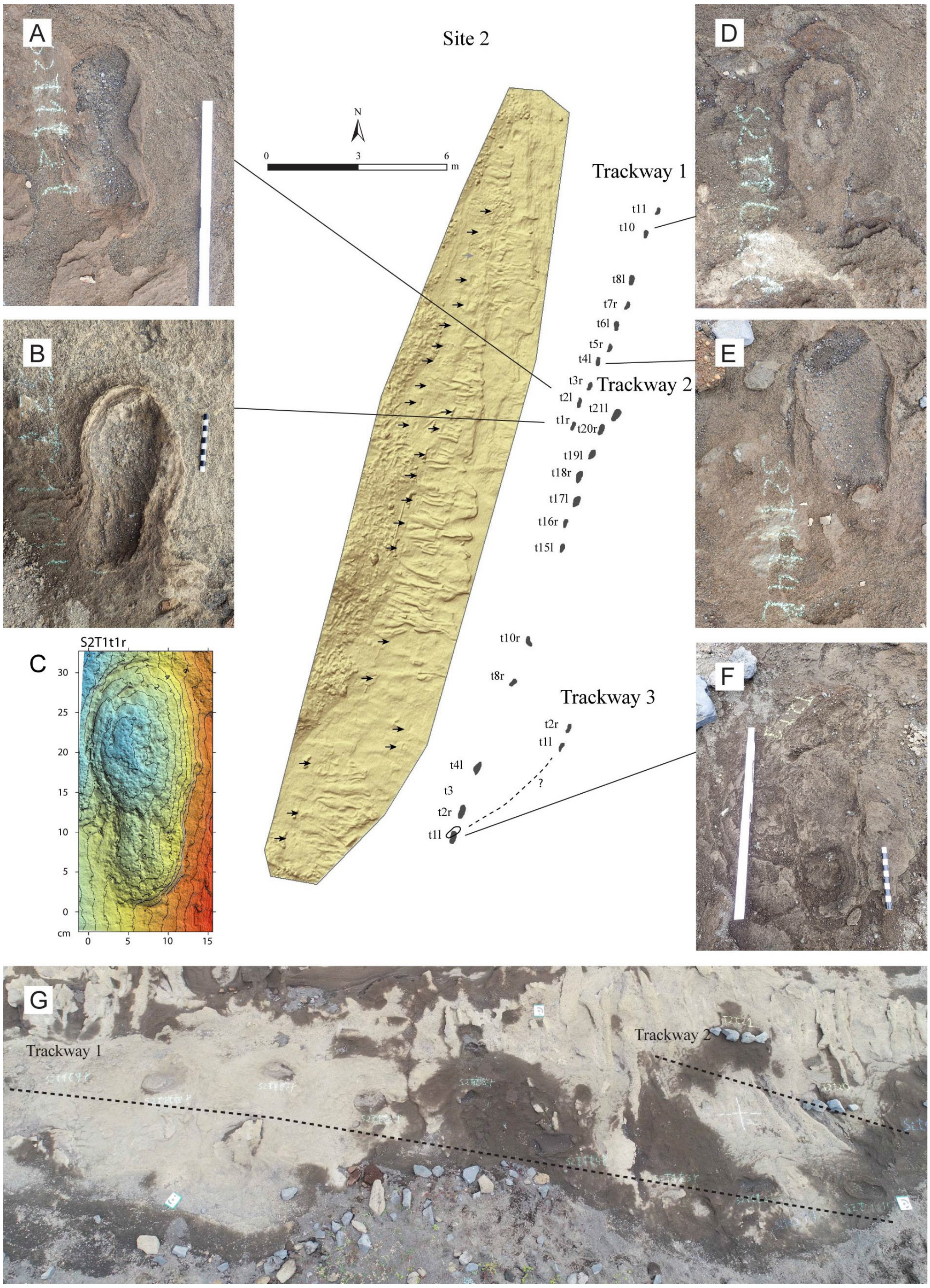

Figure 3. General view of Site 2. Centered a digital elevation model of the tracks in Site 2. Arrows point the location of the tracks. The different tracks show various degrees of preservation, spanning from well-preserved t1r (B) and t2l (A) to poorly preserved t10 (D) and t4l (E). C) A digital elevation model of boot track S2T1t1r. Black contour lines at 5 mm intervals. Notice the well-preserved expulsion rims of the track. F). Beginning of trackway S2T2 showing isolated S2T3 partially overlapping track t1l of S2T2. White scale bar is 42 cm, small scale bar 10 cm. G) Image showing parts of Trackways 1 and 2.

Table 2. Trackways, stride, gait and boot track measurements.

Site	Site 1	Site 1	Site 2	Site 2	Site 2	Experiment	Site E	Site E	Site E
Trackway	Trackway 1	Trackway 2	Trackway 1	Trackway 2	Trackway 3	**Trackway**	Trackway 1	Trackway 2	Trackway 3
Nr. of tracks	8	2	15	21	2	**Nr. of tracks**	17	23	13
Avg. length (cm)[1]	(3) 41±8.2	(2) 34.4±2.7	(4) 32.3±1.5	(5) 38.7±5.3	(2) 30.7±0.3	**Avg. length (cm)**	(8) 37.7±1.5	(7) 38.2±2.4	(10) 42±3.4
Avg. width (cm)	19.7±4.0	15.5±0.2	17±1.7	16.9±3.2	11.2±1.1	**Avg. width (cm)**	17.5±1.5	20.6±2.5	22.3±3.4
Trackway length (m)	5	1,2	8.1 (10.6)	14,3	1	**Trackway length (m)**	12,5	19,4	12,5
Trackway azimuth (degrees)[2]	333	28	21	23	22	**Trackway azimuth**[2]	2	221	77
Slope of trackway (degrees)	18	14	2	2	2	**Slope of track (degrees)**	14	1	11
Avg. angle of gait (degree)[3]	30.4±16.2	0.8±1.01	-2.2±9.14	-1.7±4.5	-0.2±0.4	**Avg. angle of gait (degree)**[3]	18.3±13.3	-6.5±14.2	-0.08±17.5
Avg. stride (m)	1.36±0.1		1.5±0.12	1.6±0.11		**Avg. stride (m)**	1.38±0.08	1.56±0.16	1.79±0.09
Avg. pace (m)	0.67±0.1	0,82	0.79±0.05	0.83±0.05	0,67	**Avg. pace (m)**	0.70±0.09	0.77±0.13	0.90±0.08
Estimated movement	uphill	uphill	uphill	uphill	uphill	**Movement**	uphill	horizontal	downhill
Estimated boot size[4]	45-46 (EUR)	40-42 (EUR)	40-42 (EUR)	45-46 (EUR)	~40 (EUR)	**Boot size**	32.5 cm (46 EUR)	32.5 cm (46 EUR)	32.5 cm (46 EUR)
Estimated stature (cm)[5]	177-190	167-175	167-175	177-190		**Stature (cm)**	190	190	190

[1] Number of tracks used in calculation in parenthesis.
[2] Azimuth direction of trackway.
[3] The angle between the trackway midline and the long axis of the track. Negative values are left out-toeing and positive right out-toeing.
[4] Boot length x boot width divided by 2. Factor is derived from comparison with the boot track in experiment and the actual bootsize that is 32.5 cm in length and 11 cm max width.
[5] Derived from simple foot length x height correlation charts.

marginal thrusts, and ejecta (Melchor 2015). The associated sediment lacks ripple marks, raindrop marks, desiccation cracks, rhyzoliths (traces of plant roots), insect trails, traces left by other vertebrates, and markings made by wind-blown vegetation.

Site 1

Site 1 has two preserved trackways, S1T1 and S1T2, both highly modified by erosion but still well recognizable (Fig. 2). S1T1 dips 18°SW, is oriented 333°N and has nine tracks, the first three with the contour well marked and the other six with the contour of the heel poorly preserved. The first track is a right print S1T1t1r.

S1T2 dips 14°SW, is oriented 28°NE and has two exposed tracks. An oval depression after the second print may be inferred as the third track in the sequence but it is poorly preserved and it could also be a structure resulting from erosion or the empty depression left after the impact of a lithic block, as other such structures are common on the slopes of Surtsey Island. This trackway starts with a left print (S1T2t1l).

Site 2

Three trackways, S2T1, S2T2, and S2T3 occur on this site (Fig. 3). S2T1 and S2T2 have direction about 21°W. The total length of the two trackways combined is 22.4 m as they are currently exposed. Table 2 shows dimensions, pace and stride of the tracks.

The orientation of both the two trackways and individual tracks is unambiguous because of their asymmetry, which show both the prints of the heel and the toe end of the boot track.

Trackway S2T1 is 8.11 m long and consists of eleven exposed tracks. The shape of each track determines whether they are left or right sides. Trackway S2T2 is 14.29 m long and consists of twenty-one exposed tracks with the first track corresponding to the left foot. The trackway occurs behind S2T1, and it distinguishes from S2T2 because the last two tracks of S2T2 (t20r and t21l) occur parallel and at a few tens of centimeters distanced to the right side of the first two tracks of S2T1 (t1r and t2l).

Tracks in trackway S2T2 occur in three different degrees of preservation: 1) as true prints, 2) as prints filled with sediment (t1l, t2r, t4r, t8r, t10r), and 3) as partially filled with sediment (t15l, t17l, t19l, t20r, t21l). Missing tracks in the trackway are t3l, t5l, t6r, t7l, t9l, t12r, t13l, and t14r.

The southernmost track of S2T3 is partially overlapping the heel impression of track t1l of trackway S2T2 (Fig. 3F). The orientation of this single track is 22°N (Fig. 3F). The track is well impressed with a sharp outline and the mark of the shank, clearly distinguishing the heel and toe sections of the boot. The impression on the right side of the track (toward the slope) is 3.5 cm deeper than on the left side (away from the slope). Based on the orientation of the track and the difference in depth within the track, we infer that the trackmaker was walking downhill at an approximate 30° angle with respect to the strike of the slope.

Site 3

About 25 m north of the last exposed track of S2T2 a single, well-preserved boot track, here named S3T1,

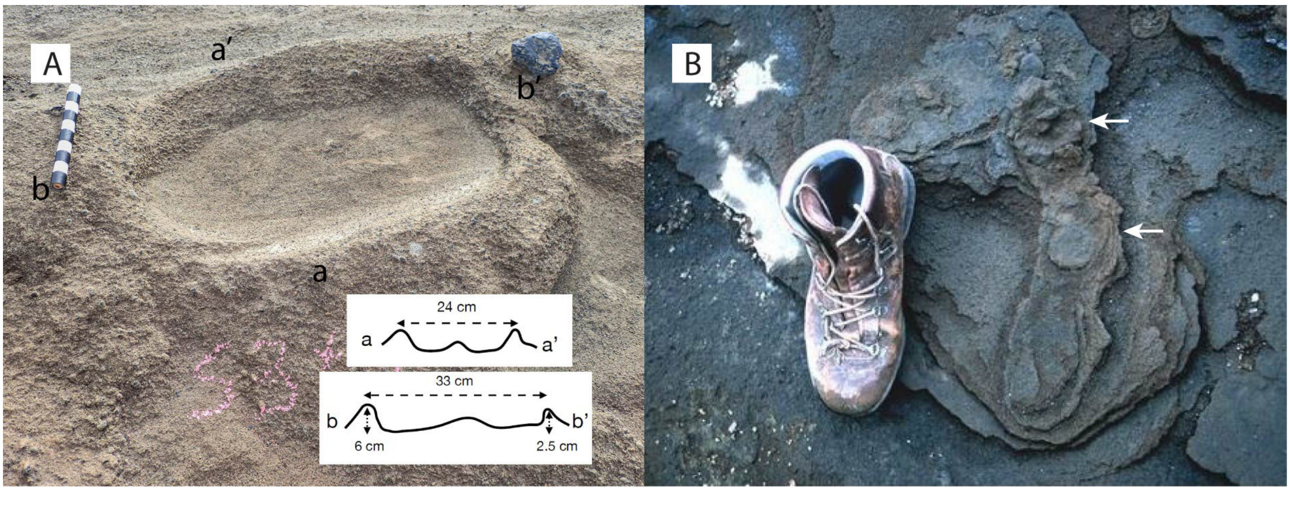

Figure 4. A) Single track in Site 3 with two cross sections. Scale bar is 10 cm. B) Site 4. Arrows point to the position of the heel of two overlapping tracks. Boot for scale size 45 (EUR), comparable in size to the track. Photo credit Hallgrímur D. Indriðason 2001.

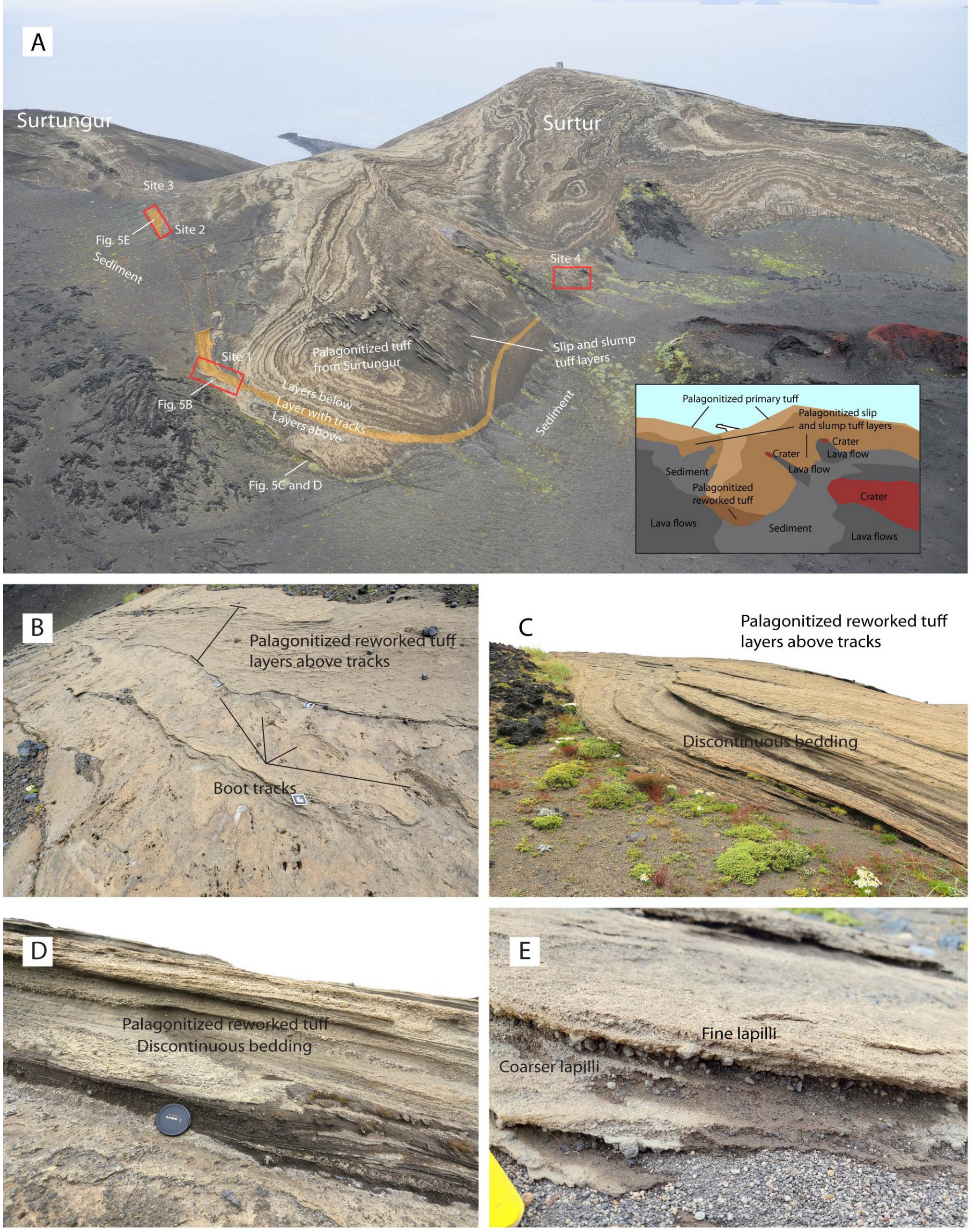

Figure 5. A) Stratigraphic location of the tuff layers with the tracks of this study and sketch showing the main lithologies. B) Trackway 1 in Site 1 showing the palagonitized reworked tuff layers above the track. The layer is about 40 cm thick at this location but 20 m below it thickens to about 1.2 m (C). D) The bedding is discontinuous, and the layers lack lithic clast and blocks and bombs unlike the primary tephra of Fig. 6. E) A close-up of the palagonitized tephra beds within slump layers above site 2.

occurs roughly in the opposite direction to S2T1 and S2T2 trackways (Fig. 4A). The track is fully exposed with a deep track wall surrounding the shaft, a well-formed marginal rim, uniform depth, and absence of sediment filling.

Site 4

Four boot tracks were preserved on this site, whose occurrence was made known to us after we left the island and thus was not studied (see one track in Fig. 4B with estimated boot size of 45–46 EUR). The tracks were seen in the site with a downhill direction towards the south (Hallgrímur D. Indriðason, pers. comm.).

STRIDE AND GAIT MEASUREMENTS

The results from these measurements were useful for determining the direction of the walk and if the walk was uphill or downhill (Table 2 and Table S in Supplementary files). When a line is placed centered in the trackway a left and right out-toeing can be observed. A slender out-toeing is more common in human bipedalism than in-toeing (Morton 1932) and thus we infer the orientation from the out-toeing indicates the direction of the trackways of Site 2 was northwards and uphill. This direction is also observed from the shape of t1r of Trackway 1 in Site 2 (Fig. 3). A clear difference is seen in the angle of gait from the shallow slope of Site 2 and the steep slope of Site 1, the same pattern observed in the trackways of the experiment site. The

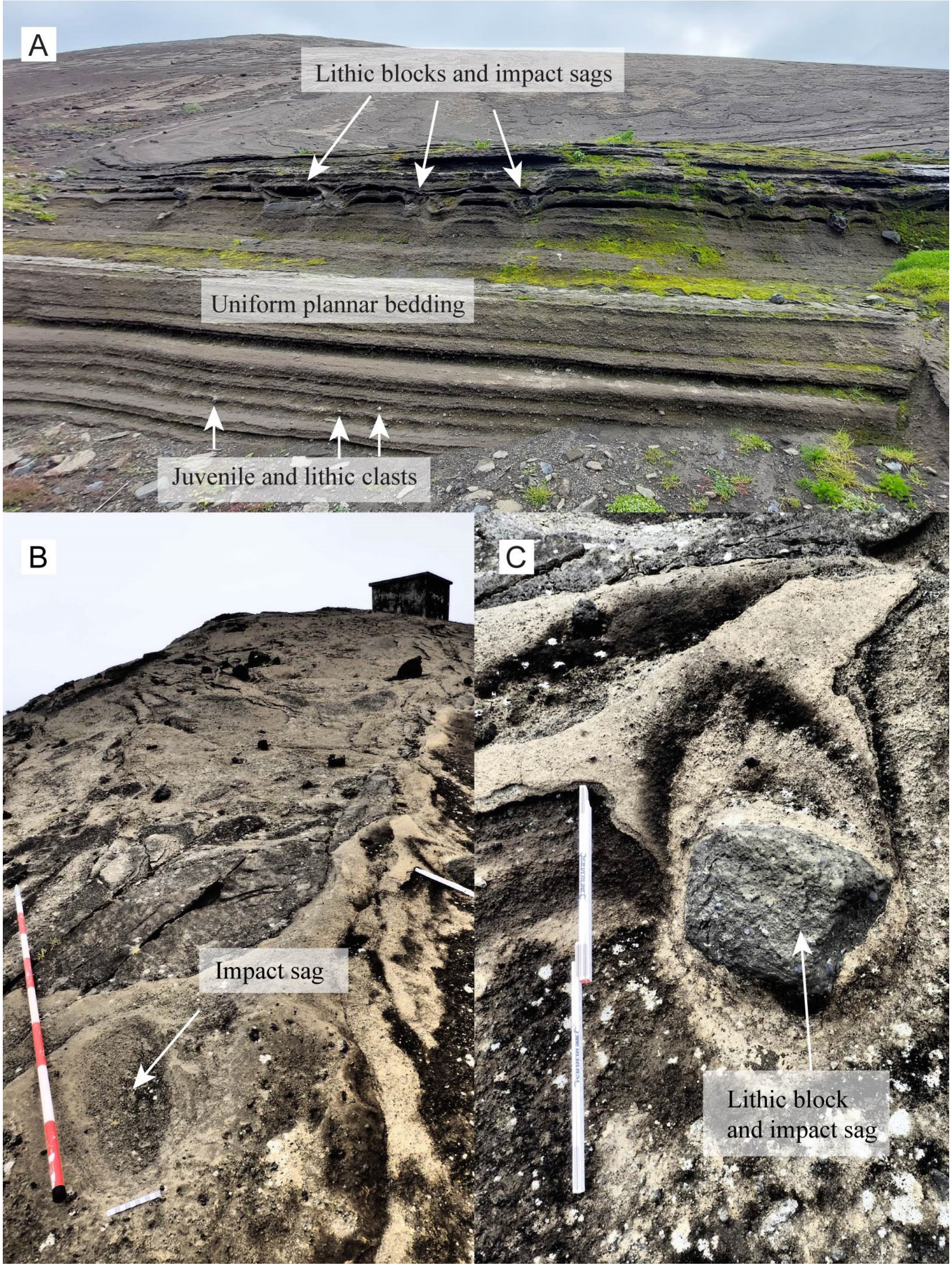

Figure 6. A) Uniform bedding of primary tephra with lithic and impact sags in the gully Svartagil north of Surtsey. Notice the irregular distribution of lithics in the tuff. B) Sags formed by lithic blocks colliding into uncemented tuff. The figure shows a sag left after a bomb was eroded away. Small scale bar 10 cm. C) In-situ lithic block and adjacent sag of another lithic block that was eroded. Scale bar 42 cm.

average angle of gait is low and near zero (from the midline of the track) in shallow slopes while the angle is greater and the rotation unidirectional in the steeper slopes. In Trackway 1 of Site 1 and Trackway 1 of the experiment Site E the angle of gait is unidirectional to the NE, and pace and stride shorter, thus suggesting an uphill motion for the walk of Trackway 1 of Site 1. The estimated boot size, stride and pace length of Trackway 1 were also compared to the boot size (size 46), stride and pace measurements of the experiment, likely indicating a person with similar stature as the person of the experiment (190 cm). The stride and pace length of the downhill walk of Trackway 3 in the experiment Site E was longer, and perhaps a longer stride would be observed in the sites studied if the person had been walking downhill.

DISCUSSION

The boot tracks in Surtsey Island offer an exceptional opportunity for studying ichnites within geological formations formed in recent, well-documented events. The following points were investigated: the nature of the boot tracks and trackways, the stage in the construction of Surtsey Island relative to the elevation of the location and trackways, the lithology of the tephra and timing of fossilization, the nature of the tuff/sediments on top of the layers with the boot trackways, the location of the sites as sediment traps, the location of the sites relative to alteration and palagonitization history of the tuff, the history of visits to the island and potential persons involved in the making of the boot trackways.

The nature of the tracks: boot tracks versus impact structures

Numerous bombs and lithic blocks are seen exposed on the surface of the tephra layers, many of which have been eroded and rolled down the slope (Fig. 6A - C). Some of those bombs and blocks do not show impact sags in the underlying beds and others show deformation of the underlying beds, indicating that they landed ballistically, and the tephra layer was wet, cohesive, and plastically deformable (Fig. 6B - C). The sags are commonly elongated with the long axis orientally radially to center of the crater Surtur I (Lorenz 1974).

In the places where the tephra layer has just been eroded, some blocks and bombs are still attached to the surface, encircled by a rim of the ash layer in which the ejecta impacted. Some of those blocks and bombs are still attached to the ground surrounded by an expulsion rim. The pattern of shapes, structure and preservation of the impact structures differ significantly from the boot tracks. The undulated shape, the preservation of the impression of the shank, and their alignment of the tracks forming a trackway

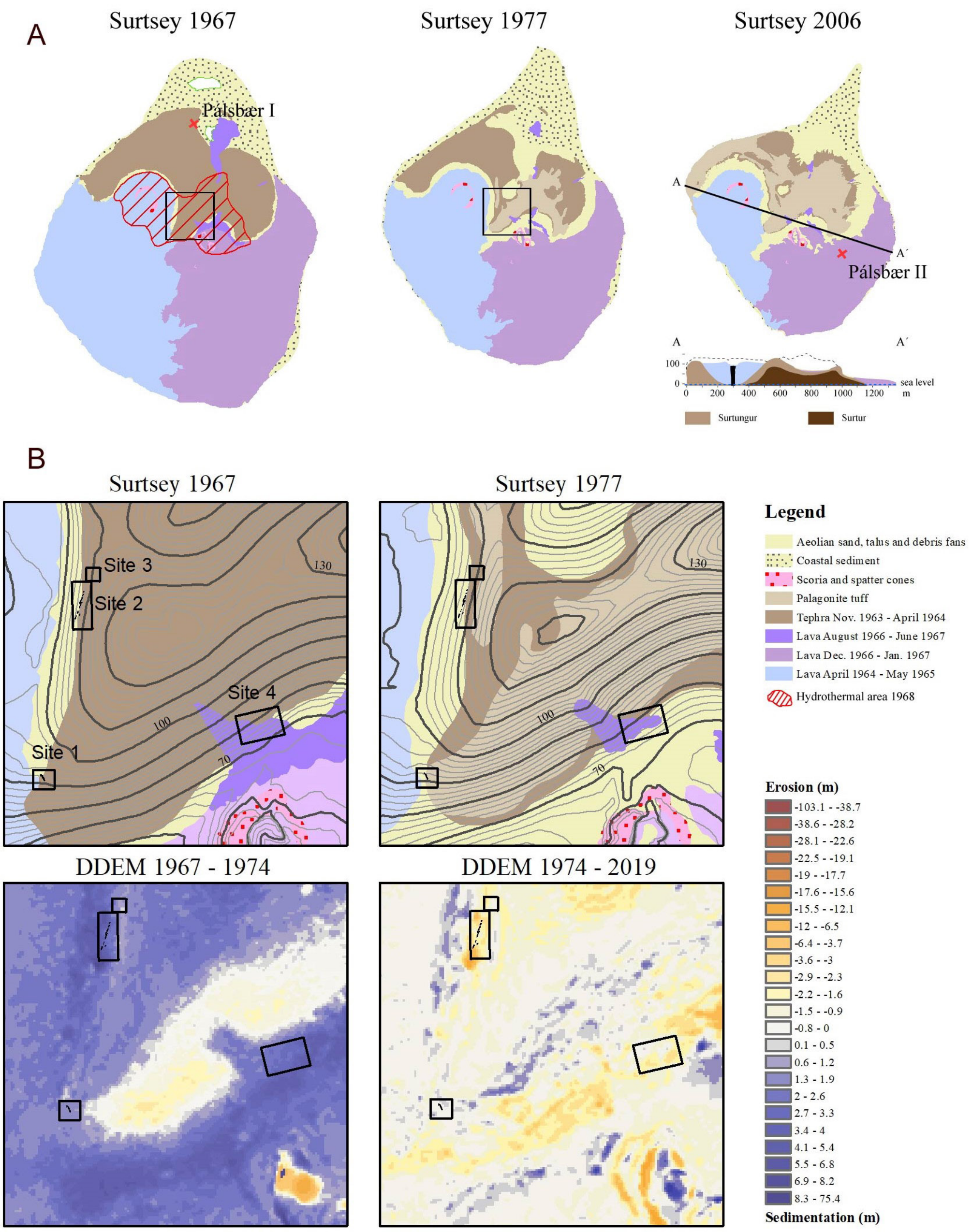

Figure 7. Geological maps of Surtsey from 1967, 1977 and 2006. Note the different palagonitization stages in the maps. Location of Pálsbær I and Pálsbær II shown for reference. Hydrothermal area from 1968 mapped with red lines. Cross sections of the island show how the tephra of Surtungur covers the older Surtur cone. B) (Above) Maps showing a close-up of the sites at different stages of palagonitization. (Below) DEM differencing from Óskarsson et al. (2020) showing the amount of erosion and sedimentation at each site at two periods, 1967–1974 and 1974–2019.

strongly indicate that the studied structures were the result of humans walking and leaving boot tracks and not fortuitous alignment of volcanic bombs.

The stratigraphic position of the boot tracks

As mentioned above the tracks are found seemingly at the same stratigraphic position (Fig. 5A). Their position lies within palagonitized tuff layers that cover the western side of Surtur tuff cone and eastern side of Surtungur tuff cone. The final phreatomagmatic activity of Surtsey was in Surtungur depositing tephra radially away from the vent and burying the older Surtur cone (see cross section in Fig. 7A), meaning that the tephra forming the substrate of the sites is from Surtungur. The thickness of the tuff from Surtungur draping the Surtur cone is unclear near the vent but has been estimated to be about 10 meters in the boreholes east in Surtur tuff cone (Fig. 1, Jackson et al. 2019). The boot tracks are thus posterior to the phreatomagmatic phase of Surtungur. The tracks could have formed towards the end of the Surtungur phreatomagmatic phase; however, the nature of the underlying and overlying tuff beds is reworked as discussed below and no visit to the island is recorded at this time (around March of 1964). The tracks are also found lying on top of the lava shields inside both cones meaning that they formed after the formation of the lava shields and the formation of the reworked tuff beds.

The elevation of the boot track sites relative to the stage of development of the island

We can infer from the location and elevation of the sites with the boot tracks at what stage of development Surtsey Island was when the boot tracks were formed. From Fig. 8 a comparison of maps is shown between the stages of February 17th 1964, late August 1964, July 1967, and the actual position of the boot tracks in July 2019. Around February 17th the location of the boot tracks does not match the current locations as they are 30 meters below current elevations at Sites 1 and 4, and about 10 meters below at Sites 2 and 3. On February 17th the eruption was phreatomagmatic, and the tephra cones were still under construction. Visits to the island were only four during the phreatomagmatic phase and none seem to have reached the elevation of the sites as discussed below. Moreover, it is unlikely that any visitor would have taken the risk of walking on the steep crater walls. On 25th of August 1964 the eruption had transitioned to effusive in the Surtungur vent and the tephra cones had largely been eroded to current form, and the location of the sites match to

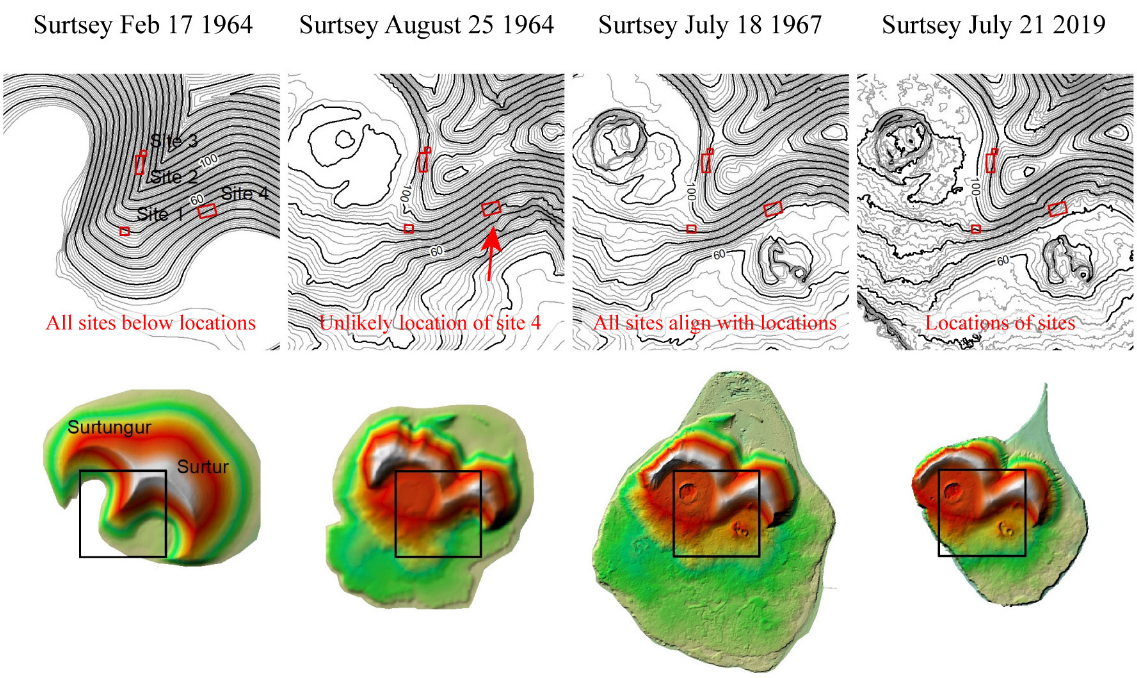

Figure 8. The location of sites placed on top of three different stages of development of Surtsey. The map from 2019 shows the true location of the sites. The stages from Feb 1964 and August 1964 are unlikely whereas the tracks do not align with the true location. The DEMs of 1964 were generated from 2 m contour maps provided by the Icelandic Institute of Natural History. The DEMs of 1967 and 2019 were generated from vertical images (Óskarsson et al. 2020).

some extent the current location. Nevertheless Site 1 was slightly off likely lacking the reworked tuff that would accumulate later at that location, and Site 4 was high up in the inner wall of Surtur tephra cone. If someone walked at Site 4 in late August 1964, the sediment would not accumulate easily to cover the boot tracks for preservation. Nevertheless, in July 1967 the lava shield of Surtur was completely formed and all sites align with current location. Sediment began to accumulate at the sites, and all were easily accessible by pedestrians including Site 4.

Thus, judging from these maps, the stage in which the sites were correctly positioned relative to their present-day elevation and accessible to pedestrians that walked along the margins of the lava shields, is after the formation of the Surtur shield in July 1967. The trackways are found on a route that was common in the early years due to accessibility and led to the hut Pálsbær I (Fig 7A and 9A), build in the north part of Surtsey in 1967. It is common that visitors in Surtsey prefer to walk on top of the sediments instead of walking on the fragile rough lava, and today the palagonite ridge with Site 1 is still the most accessible route up to the top of both Surtur and Surtungur tuff cones.

The physical condition of tephra at the time of track formation and the timing of fossilization

The formation of the Surtsey tracks would have involved the following sequence of events (modified from Thulborn 1990): 1) initial deposition of tephra sediments, 2) halt of the deposition of tephra, 3) surface of the sediment trodden by humans, 4) track molds consolidated, and 5) influx of sediment that covers the tracks.

The formation and successful preservation of tracks depends on multiple factors including the geography of the area, the type and stage of geological events forming the substrate and burying the tracks, the physical conditions of the substrate, the depth of the tracks, the behavior of the trackmaker and the climatic conditions. In the fossil record tracks were commonly preserved in environments that experienced rapid and/or periodic accumulation of sediments (Thulborn 1990).

The physical conditions of the substrate determined whether the tracks were formed at first. If the substrate had been too hard and dry, humans would not have left tracks on the surface. On the other extreme, if substrate had been excessively soft or wet, sediment would have collapsed, and tracks would not have been preserved with well-defined shafts, outline, and expulsion rims. The existence of the Surtsey tracks attest to a substrate of medium consistency and cohesiveness.

If the sediment had been highly cohesive, the humans walking on its surface would have disfigured their tracks as they tried to pull out their boots. Sticky sediment most likely would have recorded large and shapeless tracks and ejecta on the outside of the tracks.

The fossil record of vertebrate tracks shows that the best-preserved tracks occur in fine-grained sediments such as mudstones, siltstones, very fine sandstones, and fine volcanic ash. Tracks may form and be preserved in coarser sediments, but they are rare and of moderately or poor quality (Thulborn 1990). The Surtsey boot tracks are preserved in tephra sediment of medium to very coarse grain size, in which grains have a higher degree of mobility than in finer sediments. The fact that the Surtsey boot tracks are well formed and most of them with clear outlines (except for Site 1, which are modified by erosion), indicates that the substrate had adequate physical conditions for track formation despite having been formed in coarse grained sediments.

As indicated above, many tracks show well-preserved features, including a relatively deep shaft (e.g. track S3T1, Fig. 4), and a well-defined contour line. These traits indicate that the tracks remained mostly morphologically unaltered for the span of time between their formation and their consolidation. However, tracks in unconsolidated sediment do not last a long time, as observed in modern unconsolidated sediments where tracks have a short life span because they are subject to rapid modification or utter destruction by the growth of vegetation, wind, rain, and gravitational processes like grain creeping and slumping, which are likely to be more intense in coarse-grained sediments such as tephra. Sedimentary structures like desiccation cracks and raindrop impressions indicative of a relatively long permanence on the substrate prior to hardening of the substrate are absent in the Surtsey boot tracks.

Slump structures are generally associated with rapid sedimentation (Reineck & Singh 1975), a fact consistent with their occurrence in tephra layers on the slopes of Surtsey Island. Slumping was observed in the tephra layer immediately below the layer with boot tracks on site 2 but not above. Both the relatively high degree of preservation and the lack of slump structures associated with the boot tracks indicate an excellent degree of cohesiveness and a short time between track formation and consolidation.

The tephra/sediment layers above and below the boot tracks

The palagonitized tuff layers on top and below the boot tracks tell us that the tracks were buried by tephra/sediment after they were formed, deposits that were later palagonitized. The nature of the tuff on top is interpreted as twofold: 1) the layers on top and below the boot tracks of Site 1 and 4 is reworked tuff/sediment, that lack lithic and juvenile bombs, and have discontinuous bedding that reflects transport and deposition of tephra grains with slip, aeolian and runoff processes (Fig. 5C and D). 2) The layers below and on the sides of boot tracks of Sites 2 and 3 appear primary tuff layers but within slump deposits that had stabilized on top of the lava field (Fig. 5E).

The reworked tuffs below the boot tracks classify here as sedimentary and were formed after the lava shields were emplaced, because they are located at higher elevations in the craters and needed to have been trapped above the lava flows to be preserved at their present position. These sediments began accumulating on top of the lava flows quickly after their emplacement in Surtungur in May 1965 and December 1966 in Surtur.

Judging from the thickness of the sediments still preserved on top of the layer with the boot track on Site 1 we know that over 0.4 m of sediments overlaid the tracks at this location and 1.2 m slightly below. Extracting thickness change values from the DDEM of Fig. 7B (Óskarsson et al. 2020) we see that during the period of 1967–1974 about 1.6 m of sediment was deposited on top of Site 1, about 3–5 m of sediment deposited on top of Site 2 and 3, and 2–4 m on Site 4. The same figure shows that during the period of 1974–2019, about 0.4 m was removed from Site 1, 2–3 m from Site 2 and 3, and 1–3 m from Site 4. Subtracting these values and comparing them to the present thickness of the sediment on top of these sites, we get about 1 m of remaining sediment that would have accumulated sometime after 1967 but underlying the boot tracks.

Sediment accumulation at the base of the tephra cones and margins of lava shields was high during the first years prior to the consolidation and palagonitization of the cones. This is vividly seen in Fig. 9A that shows sediment over one meter in thickness deposited in one winter season, blocking the entrance of the hut Pálsbær I sometime around 1967–1970. Over 60% of the cones were palagonitized in 1974 meaning sedimentation rates decreased significantly after 1974. From these observations, within this time window of 1967 and 1974, we think the boot tracks formed shortly after 1967 and before 1970 due to the little amount of accumulated sediments.

The location of the sites and the alteration and palagonitization history of the tephra

Jakobsson (1972) reports that the first signs of consolidation in the tephra were seen in 1966, affecting the 10–15 cm of the exposed tephra layers and the first observed palagonitization was observed in September 1969, a process he attributes to local heating of the tephra. Jakobsson (1978) indicated that elevated temperatures were first noticed in April 1968 in areas north of the Surtur lava shield, which had been cool in July 1967. Temperatures in this thermal field, within which the two current study sites occur, were 48–84°C at approximately 5 cm depth in the hottest areas, and 40–60°C at 20 cm depth, with a very steep gradient temperature in the uppermost 40 cm but with a flattening out curve at 100°C temperature. The heating of the tephra was explained as a result of steam at 100°C originating from either precipitated water that subsequently vaporized after seeping down to the 100°C level or vaporized seawater which mixes with meteoric water near the surface (Moore and Jackson 2020). The area north of the saddle near Site 2 is called "Svartagil" which means the black gully, because it was humid and black all year around due to steam and elevated temperatures. This area was malleable and could retain imprints for longer periods (Erling Ólafsson, pers.comm).

Consolidation of tephra continued through 1971 with common precipitation of opal and zeolite in the resulting tuff and in 1976 most of the tephra within the thermal area was palagonitized (Jakobsson 1978). By 1979 the surface temperature at 20 cm depth exceeded 20°C in areas north of both Surtur and Surtungur lava fields. Deposits within this warm zone became lithified as glassy tephra underwent palagonitization. After palagonitization tephra is more evenly resistant to wind and marine erosion (Jakobsson 1978) and studies on the other islands of the Vestmannaeyjar archipelago have shown that the palagonitized tephra (tuff) is more resistant to marine abrasion than the lavas (Jakobsson 1968).

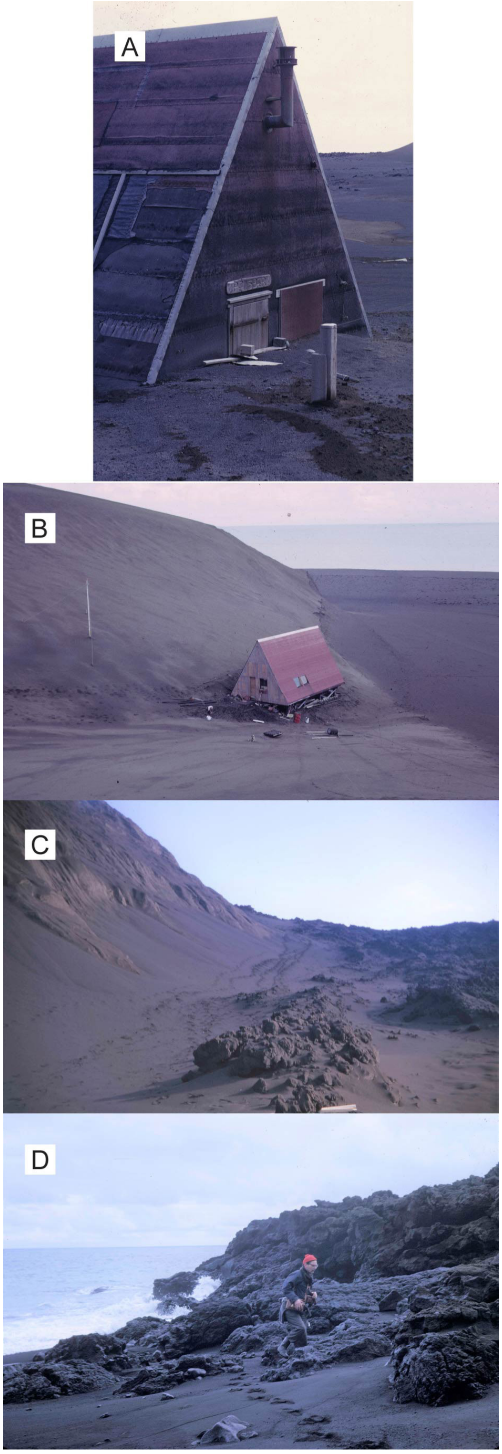

Figure 9. A) Hut Pálsbær I partially buried by remobilized tephra sometime between 1967 and 1970. This hut was dismantled and a new one was built on the SE slope of the island (Photo: Sturla Friðriksson). B) A distant view of hut Pálsbær I (Photo: Sturla Friðriksson). C) Many trackways were formed on the slopes of the volcanic cone during the early visits. The trackways in this photo occur in lose, unconsolidated tephra nearshore and were rapidly modified and destroyed by wind (Photo: Sturla Friðriksson). D) Icelandic geologist Sigurður Þórarinsson wearing water boots onshore in one of the early visits to the island (Photo: Sturla Friðriksson).

The geological maps with the boot track sites of Fig. 7A show the sites were unconsolidated in 1967 while partly or entirely palagonitized in 1977. Thus, palagonitization of the boot track sites is believed to have begun earlier than 1977, underneath 1–4 m (depending on the site) of unconsolidated sediments.

Visits to the island and the makers of the boot tracks

As summarized in Table 1 visits to the island were many and frequent after the termination of the explosive phreatomagmatic phase end of March 1964, and thus it is difficult to identify the makers of the boot tracks. In terms of preservation potential, the explosive phreatomagmatic phase was the most ideal for burying tracks quickly. However, only four visits were made to the island at this stage, three of them with short residence on the coast of Surtsey, and one with longer residence following a 17 hr eruption break in the explosive activity (Table 1). The one with longer residence, on December 16th, 1963, was made by geologists Sigurður Þórarinsson and Þorbjörn Sigurgeirsson, that had been waiting in the coast guard vessel Óðinn and adventured into the island for sample collection landing at 2:00 pm when they saw the eruption had entered a break. With them were two coast guard crew, steersman Kristinn Árnason and seaman Jónas Ragnarsson. Judging from photographs from this date, they landed on the northern coast and only Sigurður and Þorbjörn walked on the island, the other two waited by the boat. It is not known how far into the island they went but the residence was short due to the eminent danger of renewed explosive activity. This visit potentially left boot tracks that were preserved in the Surtur tuff cone because renewed explosive activity on the next day deposited 20 m of tephra on top of the Surtur tephra cone as reported by Sigurður (in Morgunblaðið newspaper, December 22nd, 1963). Images from this day also show the weather was humid and the tephra well consistent for capturing the prints. The height of the cone was about 86 m when they walked on the island, meaning their tracks would be located at this elevation if they reached the top of the island and at lower elevations at the sides of the cones. These height measurements were conducted from the vessel of the Coast Guard on a regular basis with good precision. Thus, the elevation of the tracks from the 16th of December are to be found at lower stratigraphic levels of the tuff cones than the tracks of this study.

Following the explosive phase in the end of March

1964, visits to the island were frequent both from sea and by small aircraft although after 1965, visits were controlled to minimize the impact of humans on the natural development of the island. (Table 1). The size of the boot tracks has been estimated and gives two sizes, 41–42 and 46 (EUR) and the third seems in the range of 40 but is unclear. Both Sites 1 and 2 have two trackways with boot sizes 42 and 46, and boot size of Site 4 is 45–46, which could suggest that the same two people walked on the sites. The stature of the person with shoe size 41–42 is in the range 167–175 cm in height and of the person of shoe size 46 is 177–190 cm in height according to simple height x foot length correlation charts (Giles & Vallandigham 1991). One potential owner of Trackway 1 in Site 2 and Trackway 2 in Site 1 is Sigurður Þórarinsson. Sigurður visited the island eight times in 1967 (Thorarinsson 1968a) and used 41–42 (EUR) in shoe size (Sven Þórarinn Sigurðsson, pers. comm.), which is 25.4–26.3 cm in length that matches the size found in this track. He was about 170 cm tall and wore Wellington boots in his visits (Fig. 9D). He was often accompanied by other scientists, journalists, filmmakers, photographers, and others (Helgadóttir 2021). Figure 9 shows Sigurður Þórarinsson walking on the recently deposited volcanic sediment and several trackways formed by the early visitors to the island.

The tracks in Sites 2 and 3 are relatively well-preserved so that it is possible to determine the direction of movement both from the anatomy of the boots and the angle of gait (Fig. 4–8). From the analyses of the angle of gait, the out-toeing gives a northerly direction for Trackways 1 and 2 in Site 2 in agreement with the anatomy of the best-preserved boot. The two trackways in Site 2 run parallel to one another, indicating that two people walked in the same direction very likely at the same time. Two additional boot tracks above in Trackway 3 indicate a third person. This trackway is possibly connected to a print that intersects Trackway 2 (Fig. 3F) which appears from its anatomy to have an orientation westward. Thus Trackway 3 in Site 2 could be of a person walking in a counter direction to Trackways 1 and 2 and then trending west. In Site 1, despite the high degree of erosion of the tracks, the angle of gait is unidirectional with a relatively short pace and stride. The length x width of the weathered boot tracks divided by a factor of 2 to account for deformation of the sand, a factor derived from the experiment site, indicates a boot size about 46 (EUR). The results are strikingly similar to the result of the experiment indicating the same size person and the short stride would support uphill movement as in the uphill experiment. The two trackways occur at a 42° angle, indicating that there was some intersection in their routes. All tracks are found within common hiking routes within the island, either along the sediment talus at the break of slope between the lava fields and the steeper tuff cones or walking up the ridge between the tuff cones and up to the saddle and possibly towards the hut Pálsbær I (Fig. 9B) at the north shore or hiking up to the top of the cones. In Site 4, the person might have been visiting the newly formed crater on the inner side of Surtur named Ósvaldur (Fig. 1).

Were the tracks of all sites made on the same day?

It is difficult to assert if the tracks in all sites formed on the same day despite that they seemingly form at the same stratigraphic level in the tuff cones. Nevertheless, the environmental conditions for preservation that involve deformation of humid sediments followed by rapid sedimentation triggered potentially by a storm, that coincide with human activity, are less common and would have been restricted to a few days a year. Most boot tracks are made in dry sand and are quickly erased by wind. Thus, it is not unlikely that the boot tracks formed during one visit where the ideal conditions for capture and preservation were met.

Synthesis and broader application

In synthesis, the evidence presented suggests the human boot tracks in Surtsey are authentic and their formation coincides with a period of rapid geomorphic changes following the volcanic event, sometime in between 1967 and 1970. Ideal conditions for capture and preservation of ichnites are rare as most ichnites are obliterated shortly after formation. Preservation of tracks require a soft, deformable substrate wherein an imprint is made and an environment in which minimal erosion of the imprinted surface occurs. However, the capture of the ichnites is best achieved with rapid burial for preservation as well as rapid consolidation of the substrate.

In Surtsey, the early years post-eruption met all these conditions. According to Sigurður Þórarinsson extreme rates of erosion and sedimentation characterized the first years syn- and post-eruption with rapid erosion of the uncompacted and unconsolidated tephra as well as rapid erosion of the lava margins by wave loading (e.g. Norrman 1978, Ingólfsson 1982). Óskarsson et al. (2020) estimated that about 300.000

m^3 of tephra was mobilized from the tephra cones by mass movement, aeolian and runoff in between 1967 and 1974 deposited in taluses at the margins of the cones. These conditions decreased dramatically after the tephra cones palagonitized. As shown vividly in Fig. 9A, the hut Pálsbær I, was often found partly buried in sediment after the winter months and had to be dug out (Fig. 9B, Erling Ólafsson, pers. comm.). This implies that the likelihood of ichnites being rapidly buried after formation was greater under these unstable initial conditions of the young island.

Hydrothermal activity in the early years was also imperative in the preservation and later cementation and consolidation of the sites. The initial steam-saturated tephra of large areas within the cones including the sites is likely to have contributed to the cohesiveness of the tephra that facilitated the preservation of the imprints in the substrate. These conditions deteriorated as the tephra cones consolidated with palagonitization and the hydrothermal activity focused into open fissures, yet on the other hand the boot tracks already captured in the substrate were permanently cemented in the cones.

The observations in Surtsey show that the conditions favorable for capturing and preserving the ichnites were those associated with high-energy events, or those following the aftermath of those events in the form of unstable environments, but with the ichnites somehow protected from being destroyed by those same processes. In this context, volcanic intrusions affected the local hydrological system and hydrothermal venting and steaming formed cohesive substrates and prompted rapid alteration and lithification of the substrate. Imprints susceptible to alteration consolidated rapidly increasing their resistance to erosive processes.

CONCLUSION

The boot tracks preserved in reworked palagonitized tuff layers in Surtsey Island are a case of exceptional occurrence of ichnites. As they date back to the years between 1967 and 1970, they may be the most recent fossils known to exist to this date. Their human origin is unmistakably attributed by their morphological traits and their occurrence forming a linear succession of tracks that is highly unlikely to have had a non-biological origin. Those characteristics and their particular shape make them clearly distinct from the circular and elongate deformations derived from the impact of volcanic bombs and lithic blocks in the soft tuff. They are identified as boot tracks because of their clear anatomical boot-like shape and/or the sediment filling show the outline of the boot outsole and the mark of the waist or shank.

The boot tracks occur in four different sites: Site 1 with two trackways, Site 2 with three trackways, Site 3 with one track and Site 4 four tracks. Because they have been partially affected by erosion, the boot tracks show various degrees of preservation, ranging from well-preserved tracks, to tracks that show a faint outline.

Formation of tracks of any kind requires a relatively soft and humid sediment susceptible to deformation by the trackmaker and an appropriate degree of cohesiveness to maintain the shape of the deformation after the print is formed. Also, fresh tracks are susceptible to rapid destruction due to wind, rain, gravity processes and biological alteration. The occurrence of boot tracks in tuff layers in Surtsey Island and the lack of evidence of deformation or desiccation cracks strongly suggest that the tuff layers in which they occur consolidated relatively rapidly soon after the tracks were formed. The early stages of Surtsey tephra cones underwent rapid erosion due to the uncompacted and unconsolidated nature of the tephra prior to palagonitization, that was imperative in capturing the boot tracks burying them rapidly within reworked tuff sediments. Moreover, steaming, and hydrothermal activity within the tephra prompted cohesiveness to the tephra allowing the preservation of the imprints and rapid consolidation increasing the resistance of the hosting substrate to erosion. These conditions were met in the years following the volcanic event and underline the role of high-energy events and their post-stabilization aftermath creating the suitable conditions for capturing and preserving ichnites.

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Supplementary files

Table S. Measurements of stride, gait and boot track measurements.