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Application of the Handysurf E-35B electronic profilometer for the study of weathering micro-relief in glacier forelands in SE Iceland

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ABSTRACT:

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This article presents the results of weathering micro-roughness measurements performed with the use of a Handysurf E-35B electronic profilometer, a new tool in geomorphological studies. Measurements were performed on glacially abraded basaltic surfaces within the Little Ice Age (LIA) glacial forelands of Hoffelsjökull, Fláajökull, Skálafellsjökull and Virkisjökull in Iceland. Results show a statistical increase in micro-roughness in a direction from the glacial termini to LIA moraines. However, a major change in the micro-roughness of basaltic surfaces only occurs during the first 80 to 100 years since the onset of subaerial weathering. Increase in rock surface micro-roughness is accompanied by an increase in weathering rind thickness and a decrease in Schmidt hammer R-values. Micro-roughness measurements with the use of the Handysurf E-35B can provide insights into initial rates of rock surface micro-relief development. The use of this instrument as a relative dating technique is limited to fine-grained rocks and decadal time-scales of weathering because of the limited range of measureable micro-relief amplitude.

Key words: Rock surface micro-roughness; Electronic profilometer; Schmidt hammer; Weathering rinds; Weathering micro-relief; Basalts; Iceland.

INTRODUCTION

Upon deglaciation a rock surface undergoes subaerial weathering and the resulting relief (or micro-relief) can sometimes be used as an indicator of the relative age of landforms (Hubbard and Glasser 2005). Measuring weathering pits (Dahl 1966; Ives 1978; Nesje and Dahl 1990; Landvik 1994; Dominguez-Villar 2006) or relative heights of protruding rock fragments (André 2002; Nicholson 2009) can provide information about the relative age of the rock surface, however these methods were used for coarse-grained rocks and relatively long time-scales spanning the entire Holocene. Measuring rock surface roughness, rather than single elements of weathering micro-relief, was performed by McCarroll (1992) and McCarroll and Nesje (1996) working on gneiss in the Storbreen marginal zone and Oldedalen in Norway. They used a micro-meter and a profile gauge, capable of measuring a micro-relief amplitude of a few millimetres and detected significant differences in rock surface roughness between landforms created in the Little Ice Age (LIA) and those from the onset of the Holocene. However, it was recently shown by Dąbski (2012, 2014) and Dąbski and Tittenbrun (2013), that even much shorter, decadal time-scales allow for the differentiation of rock surface roughness (later addressed as

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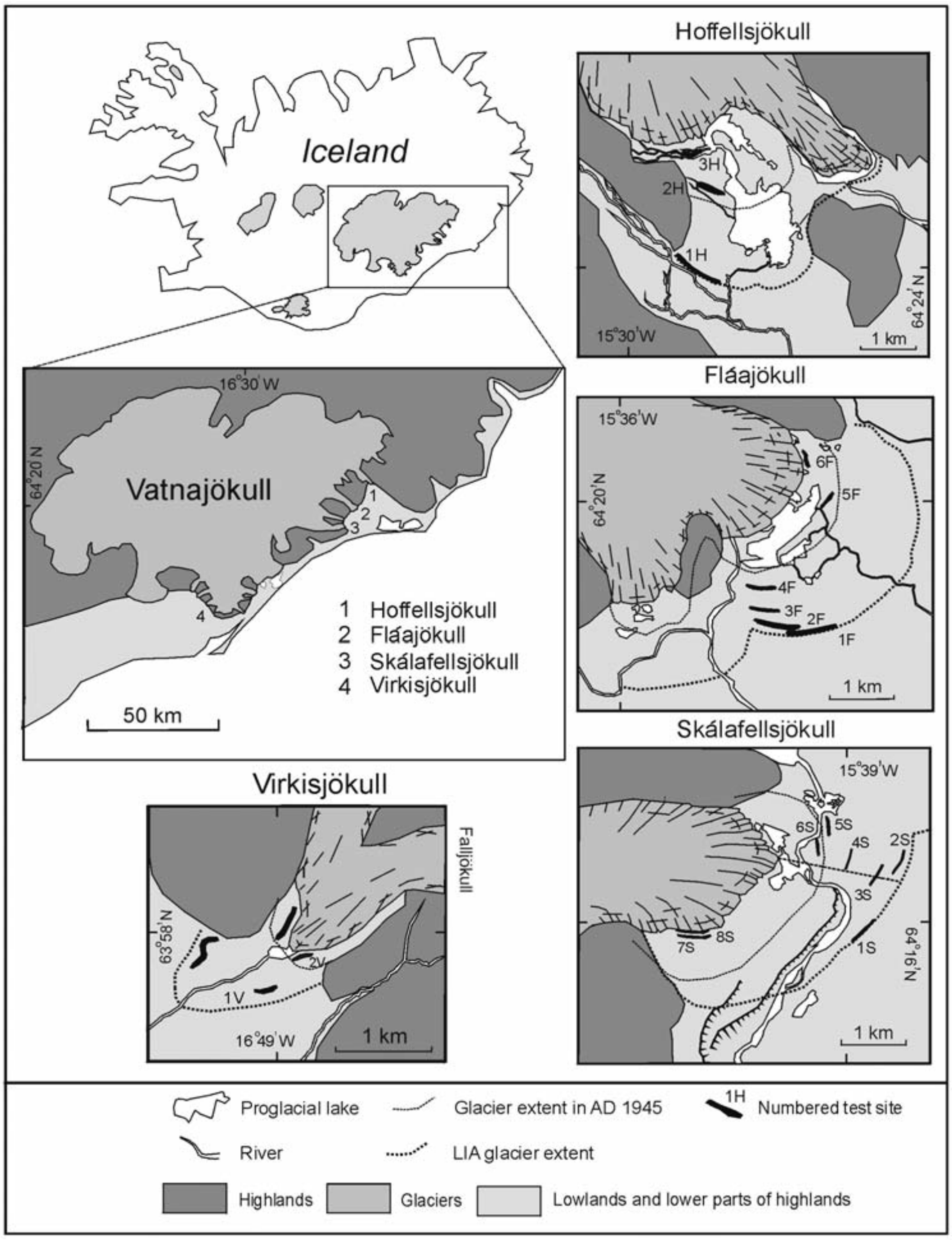
micro-roughness), resulting from paraglacial subaerial weathering of basalts in Iceland.

In geomorphology, the use of the prefix “micro” is controversial. It has been applied in weathering studies to describe rock features measured in millimetres or centimetres (Viles 2001), whereas the prefix “nano” (for example “nanomorphologies”) to describe features measured in micrometres (Viles and Moses, 1998). However, in the International System of Units (SI), the prefix “micro” denotes a factor of 10^{-6} (μm), therefore, the amplitude of rock surface relief at an order of dozens of micrometers is called “micro-roughness” in this paper.

The aim of this article is to compare and evaluate the results of rock surface micro-roughness measurements performed with a use of a Handysurf E-35B electronic profilometer within four LIA glacial forelands in Iceland. The study is a continuation and further elaboration of previous research performed by Dąbski (2012, 2014) and Dąbski and Tittenbrun (2013) who worked on the forelands of Fláajökull and Skálafellsjökull (Iceland) and the Biferten Glacier (Switzerland). In this paper, the study was broadened to include the Icelandic marginal zones of Hoffellsjökull and Virkisjökull and the results were further evaluated.



Text-fig. 1. Location of the study sites

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The results are additionally compared with with Schmidt hammer rebound values and measurements of the weathering rind thickness performed on the forelands of Hoffelsjökull, Fláajökull, and Skálafellsjökull. This is done in order to compare micro-roughness readings with other, widely used indices of rock surface deterioration in proglacial environments (Hubbard and Glasser 2005).

REGIONAL SETTING

The study was performed within the glacial marginal zones developed by Hoffelsjökull, Fláajökull, Skálafellsjökull, and Virkisjökull, the latter sometimes referred to as Virkisjökull-Falljökull (Bradwell *et al*. 2013), flowing south of the Vatnajökull ice cap in Iceland (Text-fig. 1). All of these localities enable access to a full sequence of moraines or abraded bedrock spanning from the LIA glacier maxima to contemporary glacier termini.

The forelands of Hoffelsjökull, Fláajökull and Skálafellsjökull lie within the Tertiary Basal Formation zone dominated by basic and intermediate extrusive rocks older than 3.3 my, while the Virkisjökull foreland is within the Móberg Formation comprised of basic and intermediate lavas, younger than 0.8 my (Jóhannesson and Saemundsson 2009). The studied basalts were dark-grey, fine-grained, hypocrystalline in places, sometimes with a fluidal texture.

Climatic conditions

The Icelandic forelands lie within 20 km from the south-eastern coast of Iceland where mean annual air temperature (MAAT) is about 4.5°C and mean annual precipitation, predominantly rain, is between 1400 mm and 1800 mm, based on data from the nearest meteorological stations of Hólar í Hornafirði and Fagurhólsmýri (Icelandic Meteorological Office 2012). Snow cover is relatively thin and often fragmented, allowing for frequent but shallow freeze-thaw cycles and development of sorted patterned ground on glacial tills deposited in the 20th century (Dąbski 2005). The cooling effect of the glaciers and katabatic winds decrease air temperature and influence duration of a snow cover. Frequent rains and strong winds facilitate wetting and drying of rock surfaces.

Glacial forelands and location of test sites

The test sites were located on glacier forelands spanning from the LIA glacial maximum to the youngest moraines or abraded bedrock. The number and sizes of the test sites were determined by site-specific conditions, such as accessibility and availability of suitable rock surfaces, most importantly: similar petrography and history (abraded rock surfaces facing glaciers).

The foreland of Hoffelsjökull is divided into an eastern lobe and a western one, sometimes referred to as Svínafellsjökull. Both lobes, divided by a narrow bedrock ridge, deposited moraines at an altitude of up to 50 m a.s.l. Recession of the glacier since the LIA glacial maximum was significant only in the western lobe, where terminal moraines are followed by a large sheet of ground moraine and a large proglacial lake. The eastern lobe has receded little since the LIA. Test sites 1H, 2H and 3H were located in the western part of the foreland (Text-fig. 1).

The terminal part of Fláajökull is divided into eastern and western lobes, separated by a large bedrock hill. The eastern lobe developed a sequence of several moraine ridges at an altitude of 55–80 m a.s.l., including terminal moraines and ground moraine overlying pre-LIA terminal ridges (Snorrason 1984). Six test sites (1F–6F) were located in this part of the foreland (Text-fig. 1).

Skálafellsjökull developed its marginal zone at an altitude of 40 m to 100 m a.s.l. In the eastern part, at a low altitude, six study sites were located (Text-fig. 1, sites 1S–6S). In the southern part of the foreland (sites 7S and 8S), the glacier deposited moraines against the northern side of a gently sloping bedrock surface, behind which a 50-metre-high glacially abraded escarpment falls to a glacial river. The moraines of Skálafellsjökull were in contact with the moraines of Heinabergsjökull and Fláajökull (Text-fig. 1) and the three glaciers created a single piedmont lobe in AD 1860–1870 according to Evans *et al.* (1999).

Virkisjökull creates one common marginal zone with Falljökull between 90 m and 160 m a.s.l. The two glacier tongues are separated by the bedrock hill, but their termini are still in contact, despite very rapid recession since AD 2005–2007 (Bradwell *et al*. 2013). The glaciers flow west from Öraefajökull, an active volcano and the highest mountain in Iceland. The oldest LIA moraines are lichenometrically dated by Chenet *at al*. (2010) to AD 1740 (1733–1749). Theses moraines are almost completely overgrown by thick vegetation, including mosses and dwarfed trees such as *Betula pubescens*. Therefore, the study was performed on younger moraines, deposited probably at the turn of the 19th and 20th centuries and at the youngest sites, adjacent to the glacier ice. Due to the small size of the marginal zone, each test site was split into two parts to cover both sides of the glacial river (Text-fig. 1, sites 1V and 2V).

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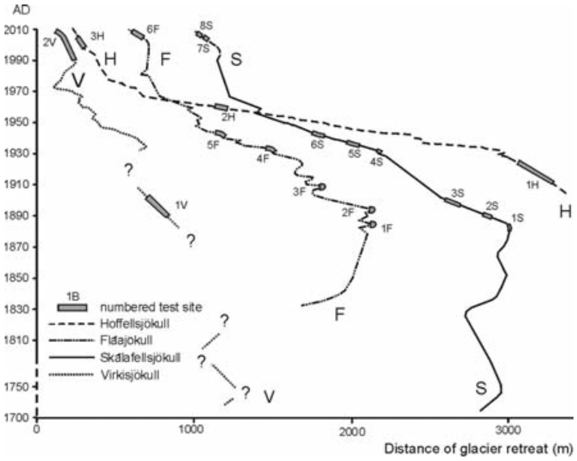

Text-fig. 2. Retreat of glaciers and age of test sites

The test sites at the Icelandic forelands were dated using different sources of information, including: i) historical data (Ahlmann and Thorarinsson 1937; Thorarinsson 1943), ii) measurements of glacier front fluctuations performed by the Iceland Glaciological Society since AD 1930–1932 (Sigurðsson 1998), and iii) lichenometrical dating performed by the author (Dąbski 2002, 2007, 2014; Dąbski and Tittenbrun 2013). However, there is some uncertainty about the oldest moraine ridges in S Iceland (Kirkbridge and Dugmore 2001; Bradwell 2001, 2004; McKinzey *et al*. 2004; Bradwell *et al*. 2006; Chenet *et al*. 2010, 2011; Dąbski 2010), and the oldest moraines could have been created in the 18th or even 17th centuries, or could have been eroded (Kirkbridge and Winkler 2012). The recession rate, as well as the age of test sites, is shown on Text-fig. 2.

METHODS

Rock micro-roughness was measured on smooth, striated surfaces facing the glaciers with only a few exceptions of horizontal surfaces. From this, it was inferred that the starting point of subaerial weathering was the moment of release from glacier ice. Measurements of micro-roughness were taken from the three smoothest lichen- and debris-free places on each boulder, parallel to visible striation in order to omit micro-erosional features on the run of the profilometer (Text-fig. 3). This allowed an inference to be made that a weathering micro-relief was measured, not an erosional one. In the two youngest test sites in the southern part of the Skálafellsjökull foreland (7S and 8S) micro-roughness was measured on whaleback surfaces due to their predominance in the vicinity of the glacier. Calibration of the profilometer was checked at every test site using the reference roughness specimen provided by the manufacturer. There were ten rock surfaces selected in each test site, except for the Fláajökull moraines, where the abundance of suitable rocks allowed sampling of fifteen rock surfaces per test site. This resulted in thirty or forty-five measurements per test site (Table 1). The length of the micro-roughness profile (evaluation length) was set at 4 mm, which is the default setting of the instrument (Text-fig. 4).

Text-fig. 3. Measuring rock surface micro-roughness of glacially-abraded boulder (A); Handysurf E35-B profilometer (B). Phot. A.Tittenbrun

In the forelands of Hoffelsjökull, Fláajökull and Skálafellsjökull, the rock surfaces previously subject to micro-roughness measurement were additionally checked for Schmidt hammer (N-type) rebound and weathering rind thickness. Ten blows of the Schmidt hammer per each rock surface were performed on ten different embedded boulders or whalebacks, giving one hundred blows per each test site. Weathering rind thickness was measured with a micrometer and magnifying glass in the three most representative areas of chipped-off fragments of ten rock surfaces, providing thirty measurements per test site. Samples of rocks were analysed under optical and scanning electron microscopy (SEM) in order to check rock texture and rock surface characteristics, and to determine the dominant type of weathering.

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	Rougness parameters	Onset of weathering (AD)	N	mean	median	min	max	SD
Hoffelsjökull	Ra	2005 -2010	30	3.06	3.10	2.0	4.6	0.72
		1911 -1925	30	5.52	5.05	2.4	12.9	2.51
	Rz	2005 -2010	30	17.25	16.6	12.0	25.5	3.80
		1911 -1925	30	29.24	27.4	15.3	60.6	11.41
	Rsm	2005 -2010	30	233.90	230.8	119.0	365.8	57.34
		1911 -1925	30	289.42	271.4	157.1	611.6	98.62
Fláajökull	Ra	2000 -2010	45	4.03	3.90	2.2	6.8	0.62
		1872 -1898	45	5.44	5.30	3.1	9.5	0.89
	Rz	2000 -2010	45	21.75	19.70	12.7	37.5	0.85
		1872 -1898	45	28.97	28.14	17.8	48.9	0.83
	Rsm	2000 -2010	45	258.67	251.5	137.7	428.0	67.24
		1872 -1898	45	274.13	272.9	167.6	409.1	65.83
Skálafellsjökull	Ra	2011 -2012	30	2.99	2.93	2.0	4.7	0.59
		1884	30	4.08	4.00	1.8	8.1	1.47
	Rz	2011 -2012	30	17.37	16.81	12.1	29.5	3.72
		1884	30	21.47	21.15	11.3	35.6	6.07
	Rsm	2011 -2012	30	200.92	185.60	127.7	313.1	49.22
		1884	30	285.27	281.15	133.5	472.6	86.77
Virkisjökull	Ra	1990 -2010	30	2.51	2.51	0.8	4.6	0.85
		1890 -1900	30	4.12	4.25	2.3	6.0	0.90
	Rz	1990 -2010	30	13.99	13.83	7.0	24.9	4.07
		1890 -1900	30	22.62	22.94	12.7	32.0	4.75
	Rsm	1990 -2010	30	243.96	226.30	140.7	419.8	69.14
		1890 -1900	30	259.28	244.45	170.8	443.6	66.29

Table 1. Values of roughness parameters (in μm) for youngest and oldest test sites

Statistical tests using Statistica 10.0 software were applied in order to check the normality of distributions (Shapiro-Wilk test) and significant differences between populations of readings. One-third of the populations did not have normal distributions, therefore the non-parametric Kruskal-Wallis and multiple comparison post-hoc tests were employed. The U Mann-Whitney test was used if only two populations were compared (the case of the Virkisjökull foreland). All tests were performed assuming a significance level of $\alpha = 0.05$.

Handysurf E-35B electronic profilometer

The Handysurf E-35B electronic profilometer consists of two units: i) an amplification indicator with a micro-processor and LCD display, and ii) a driver unit with a pickup, both units being connected with a signal cable (Text-fig. 3). A built-in stylus is within the pickup, registering rock surface micro-roughness with a vertical resolution of 0.01μm by automatically dragging a diamond tip with a tracing speed of 0.6 mm^{-s} against the measured surface. The cone of the tip makes a 90˚ angle with a 5 μm radius of an inscribed circle. The tip is installed within a sapphire skid and pressed against the rock with a force of 4 mN or less (Text-fig. 4A). The range of measurements is ±160 μm (maximum measurable micro-relief amplitude is 320 μm). A steel hood installed on the pickup allows the device to be pressed against the rock surface, and therefore to obtain better stability of the stylus during a measurement. An optional light, portable printer enables quick printouts of roughness profiles to be made in the field. The Handysurf E-35B electronic profilometer weights about 400 g therefore it is easy to be carried in the field. Batteries must be recharged after about 3h of continuous work depending on environmental conditions (Handysurf E-35B Instruction Manual).

The stylus deformation and noise is filtered out in order to obtain the primary profile (Text-fig. 4B). The waviness of the primary profile (the long wave component) is then suppressed (Text-fig. 4C) using a cut-off value and a roughness profile (or roughness curve) is obtained. The cut-off values can be adjusted between 0.08 mm and 2.5 mm. In this study, the cut-off value was 0.8 mm, serving as the default setting. The travel length of the diamond tip can be adjusted between 0.48 mm and 13 mm, including the evaluation length and

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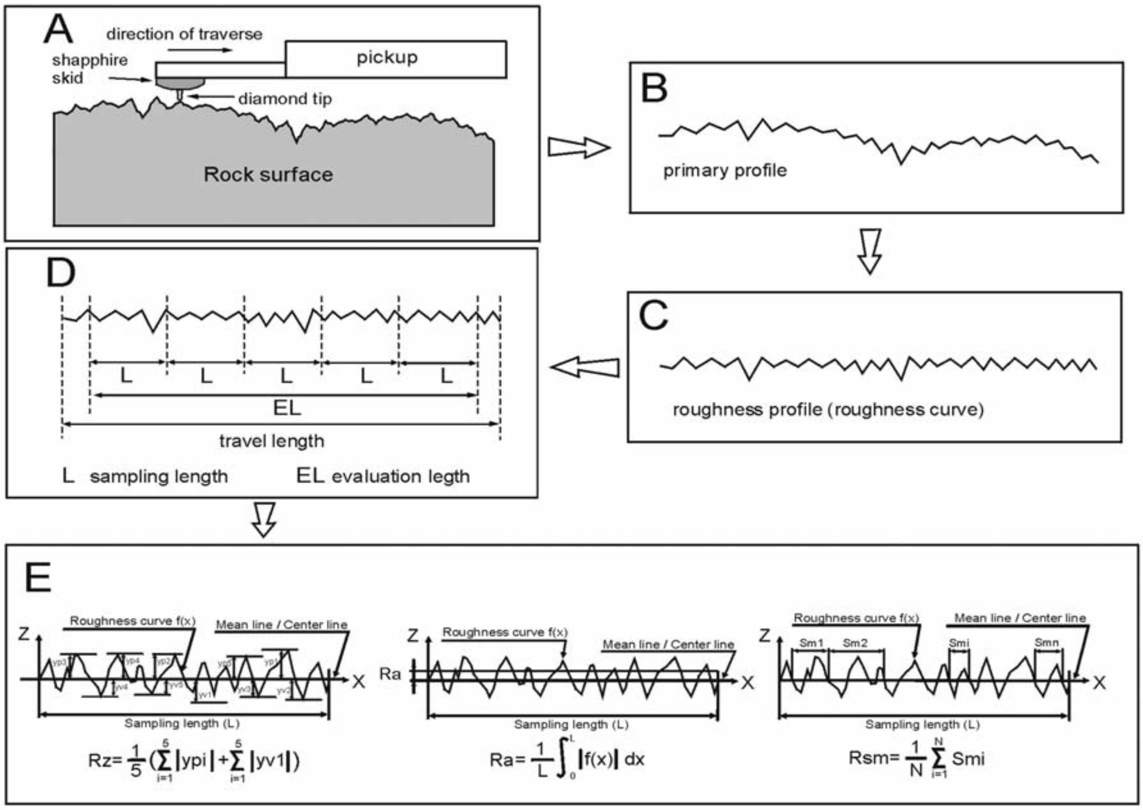

Text-fig. 4. Micro-roughness measurement scheme and calculation of roughness parameters; based on Handysurf E35-B manual

pre- and post-travel distances. The evaluation length of the roughness profile (4 mm in this study) consists of five sampling lengths each equal to the cut-off value (Text-fig. 4D). Roughness parameters (Text-fig. 4E) are calculated separately for each of the five sampling lengths and then averaged for the whole evaluation length. The roughness profile can be printed-out with the portable printer after adjusting the horizontal and vertical scales (Handysurf E-35B Instruction Manual).

Roughness parameters (Text-fig. 4E) are expressed in micrometres and include: Ra – integral value of the roughness profile (mean deviation from the centre line); Rz – average amplitude of roughness profile (average vertical distance between peaks and lows); Rzmax – maximum height of irregularities; Rsm – average wave length or horizontal distance between peaks or lows (Handysurf E-35B Instruction Manual). Former studies of Dąbski (2012, 2014) and Dąbski and Tittenbrun (2013) proved that values of Rz are closely mirrored by Rzmax, therefore only Rz is considered in this article as more objective, because it shows the average amplitude of a micro-relief, not the maximum.

RESULTS

There is a noticeable and statistically significant increase in the majority of roughness parameters in the direction from youngest to oldest moraines (Text-figs 5, 6, 7, Table 1). The average wave length of the roughness profile (Rsm) reveals the smallest change, statistically insignificant, in the cases of the Hoffelsjökull, Fláajökull and Virkisjökull forelands.

It is striking that test sites located close to the glacier margin, such as 3H, 6F, 7-8S, 2V (Text-fig. 1), subject to subaerial weathering for only a few years, possess rock surfaces of statistically significantly lesser micro-roughness than the older sites. Furthermore, there is a visible difference, although not statistically significant, between sites 7S and 8S, which differ by only about four years in terms of weathering duration. The values of roughness parameters seem to stabilize on basaltic surfaces older than 80 to 100 years, and in the Skálafellsjökull foreland, a reverse pattern can be observed within the older sites (Text-fig. 6).

Overall, there is a clear pattern of a time-dependent increase in mean, median as well as maxima and minima of roughness parameters in all of the studied glacier fore-

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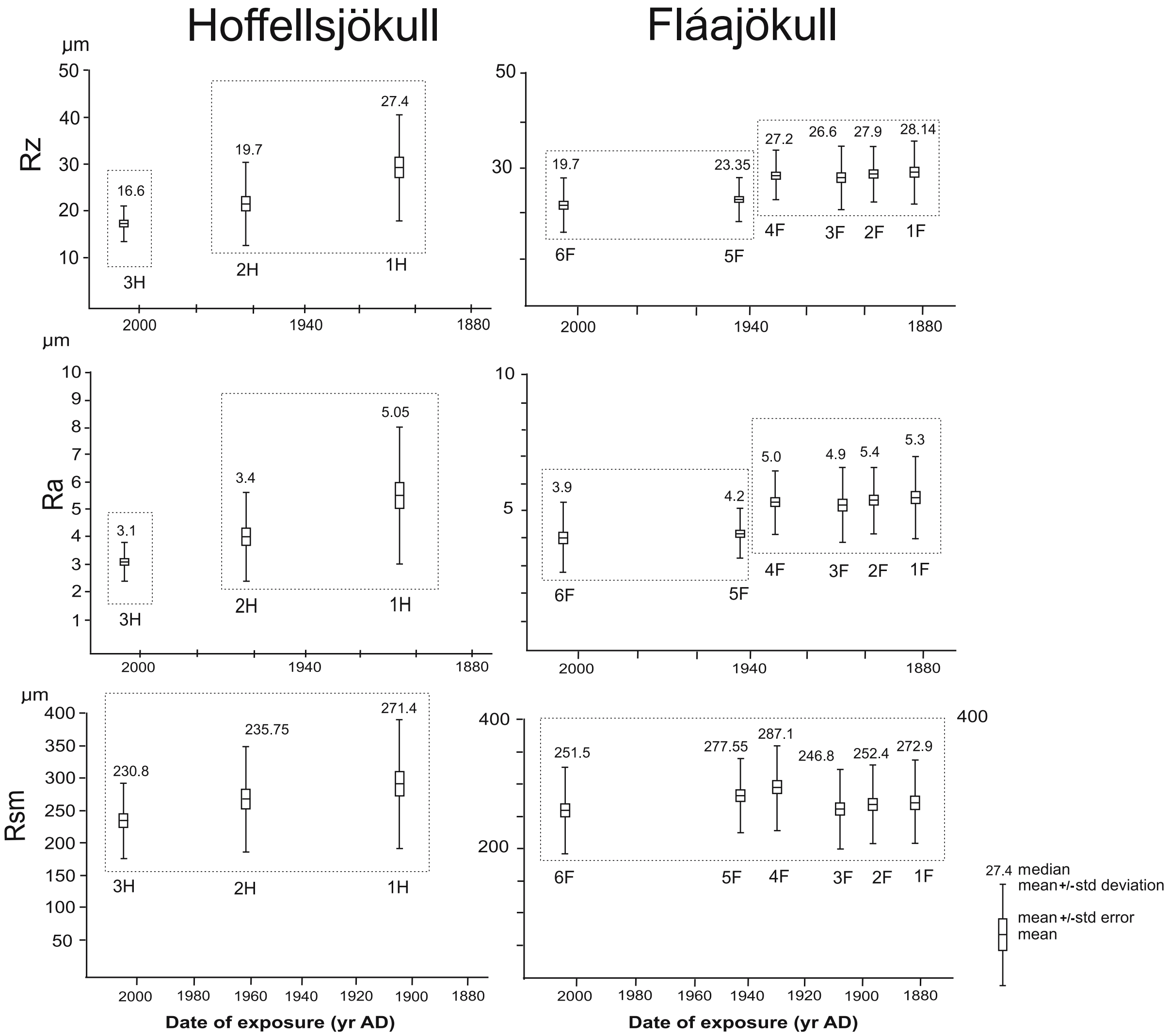

Text-fig. 5. Micro-roughness change on test sites within forelands of Hoffelsjökull and Fláajökull; large dotted rectangles include populations of readings which do not significantly differ from each other according to Kruskal-Wallis and multiple comparison post-hoc tests

lands. Furthermore, this trend is accompanied by an increase in the standard deviation of the readings (Table 1), showing greater variability of rock surfaces on older sites.

The weathering rind thickness was determined based on a visible change in colour. Greyish red (2.5YR4/2 in the Munsell scale) or orange (5YR6/6) results from the oxidation of iron compounds, which is a common process in basalts (Yoshida *et al*. 2011). However, in the foreland of Fláajökull, light-grey coloured (10YR 6/1) basaltic surfaces were analysed due to their abundance. The weathering rinds of these boulders possessed numerous micro-fissures and exhibited no signs of chemical weathering, such as oxidation of ferrous compounds or dissolution (Text-fig. 8). This allows an inference to be made that frost weathering was the dominant process. However, despite differences in observed traces of weathering processes, the average rate of Rz and Ra increase, calculated for the whole range of moraines (from youngest to oldest), is fairly similar, with the exception of the Hoffellsjökull foreland, where the rate is significantly greater (compare trend lines on Text-fig. 7, Table 2). The rate of increase in the average wave length of the roughness profile (Rsm) behaves less consistently.

An increase in micro-roughness is accompanied by an increase in weathering rind thickness and a decrease in Schmidt hammer rebound values (Text-fig. 9). Moreover, the values of theses indices of weathering seem to stabilize or level-off at test sites older than 80-100 years.

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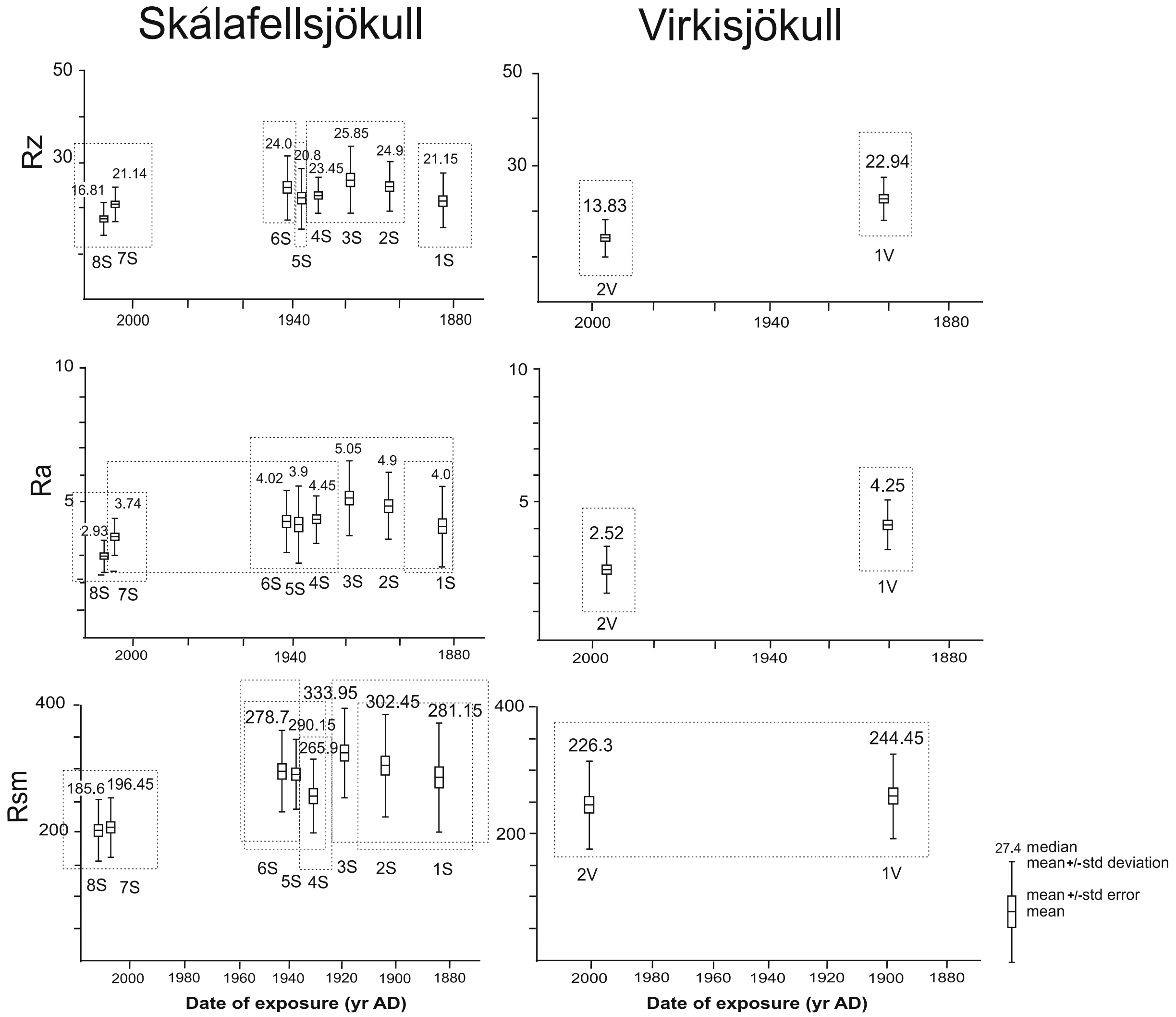
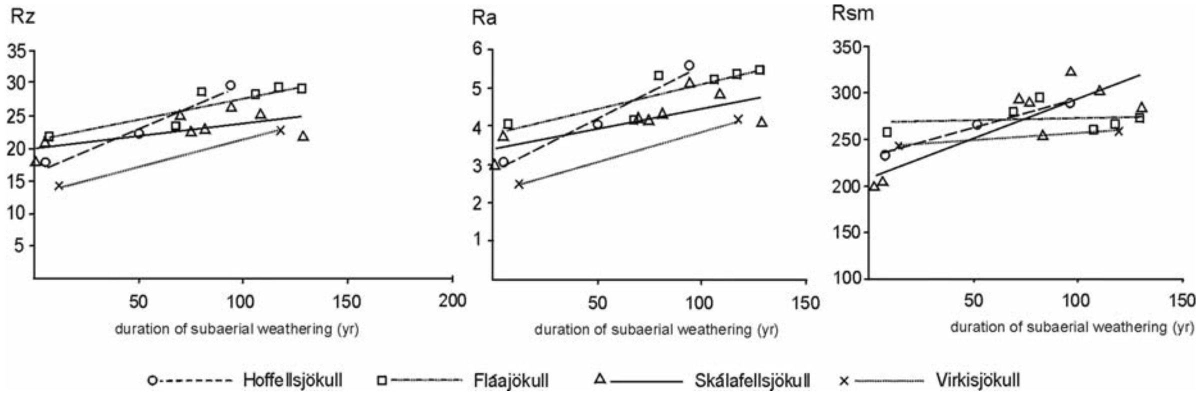


Text-fig. 6. Micro-roughness change on test sites within forelands of Skálafellsjökull and Virkisjökull; large dotted rectangles include populations of readings which do not significantly differ from each other according to Kruskal-Wallis and multiple comparison post-hoc tests



Text-fig. 7. Mean values of roughness parameters versus duration of subaerial weathering

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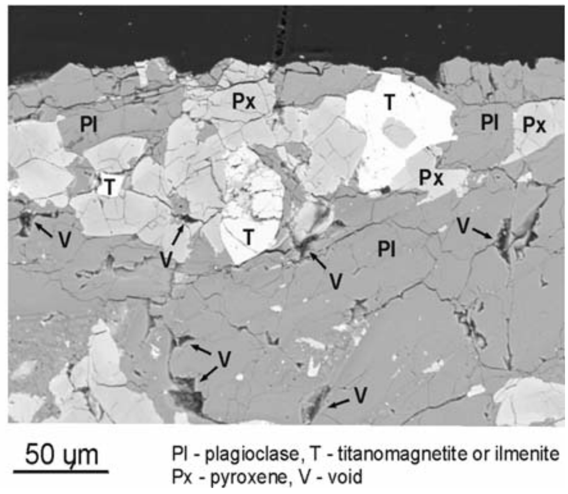
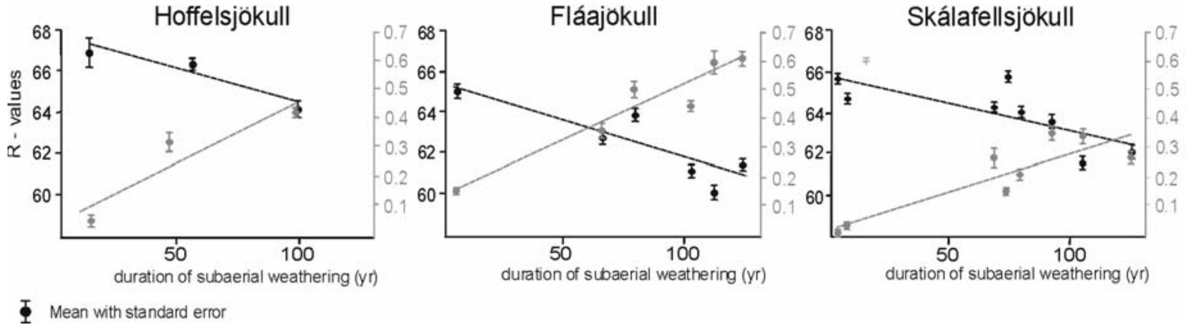


Text-fig. 8. A micro-photography (SEM) of a glacially-abraded basaltic surface subject to weathering since AD 1907 in the marginal zone of Fláajökull

DISCUSSION

Diversification of the values of roughness parameters between rock surfaces in a single test site (Text-fig. 5, 6, Table 1) can be explained by the nature of the rock surface resulting from complex weathering processes, as well as by the textural inhomogeneities of the rocks. Furthermore, it was impossible to exclude hardly visible striations or very small percussion marks or gouges during measurements with the profilometer. These features of the rock surface may influence overall values of the roughness parameters.

Magnitude of micro-roughness increase between the youngest and the oldest moraines in the studied Icelandic glacier forelands (Table 1) is similar to that of the limestone surfaces in the marginal zone of the Biferten Glacier in the Swiss Alps (Dąbski 2012). Table 3 shows the roughness parameters measured on the youngest and the oldest test sites of the Biferten Glacier.



Text-fig. 9. Change in Schmidt hammer R-values and weathering rind thickness versus duration of weathering on forelands of Hoffelsjökull, Fláajökull and Skálafellsjökull

Foreland	Petrography	Type of dominant weathering	Rz	Ra	Rsm
			μm per 100 yr		
Hoffellsjökull	Neogene basalts	oxidation of iron	13.4	2.7	62.1
Fláajökull	Neogene basalts	frost weathering	6.5	1.3	5.0
Skálafellsjökull	Neogene basalts	oxidation of iron	4.0	1.1	84.8
Virkisjökull	Quaternary basalts	oxidation of iron	8.2	1.5	14.6

Table 2. Change in roughness parameters per 100 years

Rougness parameters	Onset of weathering (AD)	N	mean	median	min	max	SD
Ra	2005 -2012	30	3.08	2.93	1.1	5.9	1.18
	1850	30	7.33	7.05	5.1	14.1	1.69
Rz	2005 -2012	30	17.57	16.40	7.4	35.6	6.41
	1850	30	39.69	38.95	30.2	66.3	7.32
Rsm	2005 -2012	30	170.42	159.95	96.5	335.1	55.06
	1850	30	256.86	252.35	160.9	474.6	64.57

Table 3. Values of roughness parameters (in μm) for youngest and oldest test sites in the Biferten Glacier foreland developed in limestones (Swiss Alps)

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The Handysurf E-35B profilometer allows roughness profiles to be quickly obtained due to the automatic filtering out of the waviness of primary profiles. The resulting roughness parameters (Rz, Ra, Rsm) are therefore easier to visualize and interpret in comparison with the indices of rock surface roughness elaborated by McCarrol (1992), including: i) standard deviation of the slope between the two adjacent measured points on the rock surface (index A), and ii) mean absolute difference between adjacent slope values (index B). However, elimination of the waviness of the primary profile results in a loss of some information about variation of the micro-topography. Furthermore, Handysurf E-35B is suitable only for fine-grained rocks and smooth surfaces with a maximum distance between peaks and lows of the roughness profile of 0.32 mm. Therefore, its use in determining the relative age of LIA moraines or older landforms is very limited, as rocks constituting old landforms are usually very weathered and their surfaces are too rough.

Use of the default setting of the cut-off value (0.8 mm) determines the way how the primary profile is transformed into the roughness profile based on which the roughness parameters are calculated (Text-fig. 4). Increase in the cut-off value would possibly make the waviness of the primary profile more influential upon the values of the roughness parameters. This, in turn, might provide more information about differences in micro-topography within older rock surfaces. The issue of different settings of the profilometer (cut-off value and sampling length) calls for further research.

A good picture of a measured micro-topography is a SEM photography of the glacially-abraded basaltic surface (Text-fig. 8) sampled from a moraine deposited by Fláajökull and subject to weathering since 1907 AD (Dąbski and Tittenbrun 2013). The thin section was cut parallel to measured profiles. The rock surface micro-topography is a result of

intra-crystalline fissuring developed in plagioclases, pyroxenes, titanomagnetites and ilmenites. Larger irregularities in the rock surface result from openings of subsurface voids. Visible amplitude of micro-relief, translated into Rz or Rzmax roughness parameters by the Handysurf E-35B, is about 17 μm. Waviness of the primary profile is invisible due to the small field of view, thus this picture shows very well micro-topographic details measured by the profilometer.

Increased surface micro-roughness, as well as the thickness of the weathering rind result in a decrease of Schmidt hammer R-values. This correlation is in accordance with abundant previous research focusing on the Schmidt hammer or weathering rinds developed on deglaciated terrains in millennial time-scales (Carroll 1974; Porter 1975; Chinn 1981; Matthew and Shakesby 1984; McCarroll 1989, 1991; McCarroll and Nesje 1993, 1996; Aa and Sjåstad 2000; Kotarba *et al*. 2002; Winkler 2005; Shakesby *et al*. 2006; Owen *et al*. 2007; Nicholson 2009; Matthew and Owen 2011), as well as with rather limited studies performed within LIA forelands (Evant *et al*.1999; Etienne 2002; Matthews and Owen 2008; Dąbski 2009, 2012, 2014; Dąbski and Tittenbrun 2013).

This study shows that paraglacial subaerial weathering rapidly increases the amplitude of the roughness profiles, but in 80–100 years, this process is somewhat suspended. This may be explained using a model elaborated by Etienne (2002) for basalts of the Solheimajökull foreland in Iceland, which assumes flacking (exfoliation) after c. 120 years since deglaciation. This would inhibit further growth of the weathering rind and possibly make the surface of the rock smoother. Dąbski and Tittenbrun (2013) analysed several samples of basalts from Fláajökull using SEM and found microfractures parallel to the rock surface (partially seen on Text-fig. 8) which would favour exfoliation and possible rejuvenation of the rock surface micro-relief. The stabilisation of micro-roughness as well as Schmidt hammer rebound values and weathering rind thickness on rock subject to chemical weathering could be also explained by case hardening (Dorn 2004). Due to frequent wetting and drying, minerals can precipitate on the rock surface in its micro-depressions decreasing overall micro-roughness and increasing surface strength. This can apply to studied basalts in forelands of Hoffelsjökull, Skálafellsjökull and Virkisjökull which undergo chemical weathering (Table 2). Moreover, rock surface micro-roughness as well as rock strength resulting from weathering rind development are probably influenced by communities of endolithic microorganisms (Etenne 2002; Chlebicki 2007; Viles 2012), however, this issue was not studied here.

Rapid but relatively short–term (30-50 years since deglaciation) proglacial rock surface (gneiss) weathering was measured by Matthews and Owen (2008) with a use of Schmidt hammer in the LIA foreland of Storbreen in Norway. However, this was only proven on rock surfaces overgrown by *Lecidea auriculata* lichens, not on lichen-free surfaces, as in case of this study.

The mean rate of increase in the average vertical distance between peaks and lows of the roughness profile (Rz) ranges between 13.4 μm 100 yr^{-1} to 4.0 μm

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100 yr $^{-1}$ (Table 2). These values can be carefully compared with findings from the Abisko region in Sweden (André 2002) or the Hardangervidda Plateau in Norway (Nicholson 2009), where glacially-abraded coarse-grained igneous and metamorphic rocks have been lowering their surfaces since the end of the Pleistocene at an average rate of 50-55 μm 100 yr $^{-1}$. Other studies on gneiss surface lowering rate in pro-glacial environments of Norway show even faster rates, from 160 μm 100 yr $^{-1}$ (Owen *et al*. 2007) to 480 μm 100 yr $^{-1}$ (Matthews and Owen 2011). This comparison must be made with caution because micro-roughness can also result from the build-up of precipitated minerals on the rock surface. Finally, there is a problem with upscaling – inferring about larger features based on microscopic observations (Viles 2001). This is a very important issue if fractions of micrometres and only decadal time-scales are taken into consideration. In the forelands under study, the weathering system seems to operate in a non-linear, dynamic fashion and more detailed studies are needed to explain it. Other factors may become important as the glaciers retreat, paraglacial processes continue to operate and vegetation cover develops.

This study sheds some light on very initial stages of weathering micro-relief development and the findings cannot serve to infer about proglacial development of weathering relief in millennial time-scales.

CONCLUSIONS

The Handysurf E-35B electronic profilometer proved useful in determining the rate of initial rock surface deterioration and development of micro-relief in the proglacial environments of LIA glacier forelands. Results indicate that the roughness of basaltic surfaces subject to subaerial weathering in the paraglacial environments of S Iceland develops in the first 80–100 years. Afterwards, it stabilises at an elevated level, probably due to complex weathering processes, including micro-cracking, exfoliation, chemical weathering or the action of microorganisms.

Roughness parameters Rz and Ra obtained at the youngest test sites have statistically smaller values than those from LIA moraines. The mean rate of the overall increase in micro-roughness is fairly similar in all of the studied forelands despite differences in the dominant type of weathering.

An increase in rock surface micro-roughness is accompanied by an increase in weathering rind and a decrease in Schmidt hammer R-values, which is in accordance with expectations.

The results of this study indicate that the profilometer can provide interesting insights into the initial rates of rock surface micro-relief development and be used as a relative dating technique, but only in a decadal time-scale from the onset of subaerial weathering, given the used setting of the instrument (e.g. the cut-off value or the sampling length). There is a need for further experiments with different settings of the instrument and other geomorphic situations.

The roughness parameters calculated automatically by the Handysurf E35-B profilometer can be easily visualised and interpreted, while the quick and easy use of the instrument calls for further tests in different geomophological situations and different settings of the instrument.

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