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Geomorphology xx (2006) xxx–xxx

GEOMORPHOLOGY

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Surface displacements and surface age estimates for creeping slope landforms in Northern and Eastern Iceland using digital photogrammetry

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Accepted 27 January 2006

Abstract

In this study three areas of different active, coarse-debris, slope processes are investigated in Northern and Eastern Iceland. Surface displacement of some glacier-derived rock glaciers and a debris-covered glacier in the Hólar area, a moving debris accumulation close to Siglufjörður and a debris layer in Seyðisfjörður are measured. The displacement fields are obtained by cross-correlation matching of multi-temporal orthophotos. Orthophotos are generated using a Z/I-Imaging digital photogrammetric workstation and various series of air photos from 1964 to 1994. Cross-correlation matching is done with the CIAS software. The results are analyzed and used for rough surface age estimates. In addition, type and cause of movement are discussed. The velocity of the debris-covered glacier and the rock glaciers in the Hólar area averages from 0.14 to 0.67 m a^{-1}. The debris accumulation at Almenningsnöf close to Siglufjörður shows an average displacement of 0.19 m a^{-1} with a maximum value of 0.84 m a^{-1}. The displacements at Almenningsnöf agree well with displacements surveyed by GPS by the Icelandic road authorities. The measured velocities in Seyðisfjörður, although using air photos taken 30 years apart, turned out not to be significant, but the homogenous direction of the displacement vectors suggests that the debris is currently creeping. Based on the surface age results all the landforms in Hólar are suggested to have developed during the late-Holocene cooling period, with ages from around 1500 and 3000 to around 5000 years for the different landforms. These surface age estimates coincide with data from moraine datings nearby and Holocene climatic development in the North Atlantic region.

Keywords: Surface displacement; Digital photogrammetry; Rock glaciers; Ice-cored moraines; Surface age estimates; Iceland

1. Introduction

In Tröllaskagi, the high mountain areas of northern Iceland, small cirque glaciers, ice-cored moraines and talus-derived slope accumulation landforms (rock glaciers) are frequent in the periglacial zone above 800 m a.s.l., and comprise an important part of the

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doi:10.1016/j.geomorph.2006.01.034

Holocene sediment flux system of the landscape. Martin and Whalley (1987) and Whalley and Martin (1994) have described and analyzed some of the features, showing in those cases that they consisted of sedimentary ice, covered by coarse debris, creeping some tens of centimetres per year. Those authors defined all these landforms as rock glaciers. Furthermore, they stated that these areas lack permafrost conditions and that the landforms are mostly related to what they assumed to be temperate glacier ice. Thus, they argued against the concept of Barsch and Haeberli (Barsch, 1992; Barsch, 1996; Haeberli, 2000) that rock glaciers are normally an expression of creeping permafrost. Recently, these features were systematically mapped by Guðmundsson (2000), showing a high abundance of active, rock glacier-like forms in certain parts of northern and eastern Iceland. Such slope processes are linked to climatic conditions, and knowledge of these processes can therefore aid interpretations of climatic change through the Holocene and its impact in these environments.

Large coarse-grained slope accumulation landforms are also common throughout northern and eastern Iceland at lower altitudes along the major valleys and coastal slopes. Many of these forms display characteristics of movement and creep as transversal ridges and furrows. Roads and buildings situated on or below such landforms experience damage from soil creep or debris flows. At lower altitudes these landforms are prominent features in the landscape. Þorarinsson et al. (1959) describe them as large landslides, probably formed early after deglaciation due to valley wall stress release. The explanation is commonly accepted among geoscientists in Iceland. However, recently Guðmundsson (2000) proposed the hypothesis that these slope features may be related to a periglacial climate in association with permafrost conditions during their development, and classified them as “fossil rock glaciers”.

With respect to the systems defined by Caine (1974) in models of geomorphic activity in alpine environments, the high mountain areas (Hóladalur) in this study fall within the slope system. In addition Caine (1974) also defines a stream channel system for such environments. The slope system is subdivided into input, transfer and storage, and the processes investigated in this study are within the transfer or mass wasting subsystem. For the two other sites the investigations also concentrate on mass wasting in the slope system, while another classification is needed especially at Almenningsnöf, since no stream channel system is present but rather a geomorphic system involving coastal processes.

The objective of the study is to map the displacement field of selected creeping slope landforms and in thick sediment-covered slopes in northern and eastern Iceland by means of digital photogrammetry. The main goal is to quantify the magnitude and investigate the nature of the displacements, and to use these results for surface age estimates of the landforms. At present, there are very limited data available on the nature and rate of slow slope movements in Iceland. This results in a limited basis for interpretations of the types of processes present, and for estimating the current and Holocene average denudation rates. In this study we have selected three sites, each of them representing different kinds of slope landforms and processes. The first site near Hólar represents a series of active slope landforms at an altitude of 850 to 1000 m a.s.l. The second site, Almenningsnöf close to Siglufjörður, is a huge debris accumulation covering altitudes between sea level and 260 m a.s.l. The third site is close to the village of Seyðisfjörður, covering a debris-mantled slope of up to 70 m thick sediments, which creeps slowly (Fig. 1).

2. Nomenclature used in this paper

The high-mountain landforms investigated in this paper are highly debated, both in Iceland and internationally. According to the concept of Barsch (1992, 1996) and Haeberli (2000) most of the debris bodies defined as rock glaciers by Whalley and Martin (1994), would be creeping ice-cored moraines since glacier or sedimentary ice probably form the core of the debris bodies. Barsch and Haeberli use the term rockglacier (in one word) solely for perennially frozen debris supersaturated with interstitial ice and ice lenses that endure creep due to deformation of ice. This includes the cohesive flow of talus rockglaciers and debris rockglaciers, but excludes features originating from sedimentary glacier ice. Humlum (1982) distinguish between talus- and glacier-derived rock glaciers (in two words), independent of ice origin, but with the precondition of permafrost existence. In our paper we follow the discussion by Humlum, defining the slope features in Hóladalur and Fremri-Grjótárdalur as rock glaciers if they are more or less totally covered by debris. One of the landforms is clearly not totally debris-covered and the term debris-covered glacier is therefore used. By using the term rock glacier, we assume that the landforms are situated in a permafrost area. The assumption of permafrost will be discussed later.

The large debris bodies at lower altitudes are defined as large landslides in the scientific literature, indicating a singular or episodic formation (Þorarinsson et al., 1959). However, many of them are still in a state of creep according to measurements done by the Icelandic road

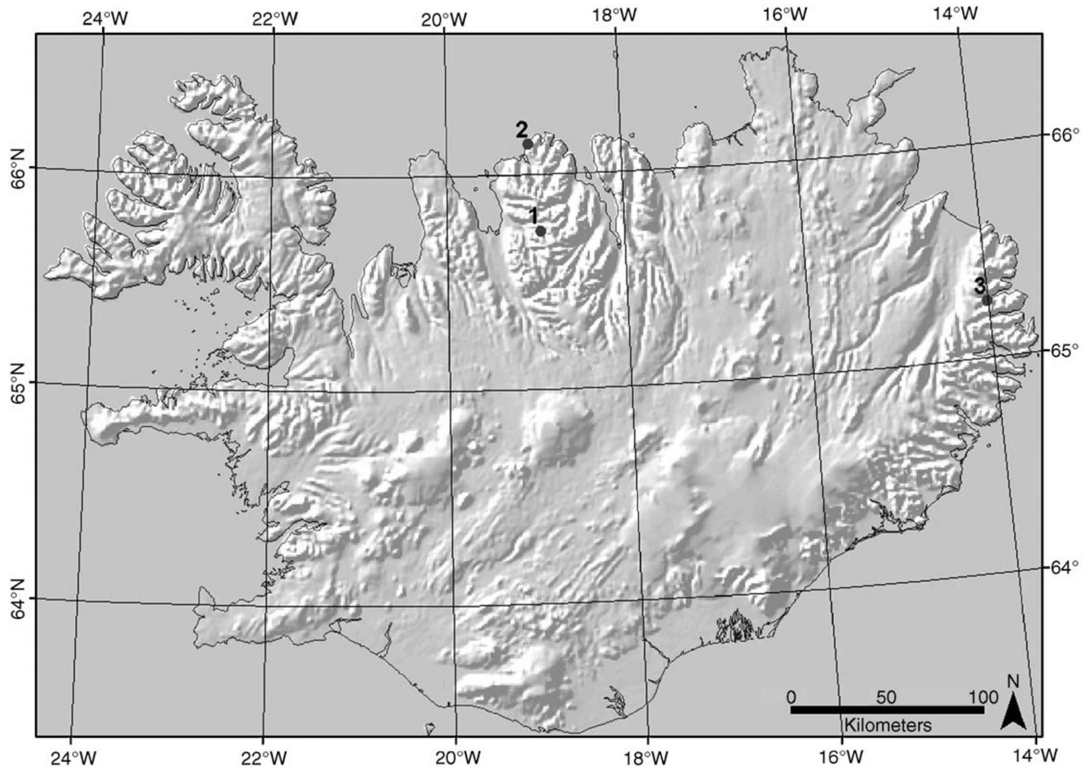

Fig. 1. The location of the three investigated sites; Hóladalur and Fremri-Grjótárdalur (1), Almenningsnöf (2) and Seyðisfjörður (3).

authorities (Sæmundsson, 2004). This paper does not aim to discuss the initial conditions of the landform development, but aims to assess the present movement pattern in the light of displacement rates, and possible surface ages inferred from that. In this paper we therefore use the descriptive term debris accumulation for these landforms, inferring that in an earlier periglacial environment, creep, in addition to slide events, could have contributed to the present-day landform.

3. Setting

3.1. Hóladalur

Hóladalur and Fremri-Grjótárdalur are located close to Hólar on the central part of the Tröllaskagi peninsula (65°40′N, 19°W) (Fig. 1). The Tröllaskagi peninsula is situated in northern Iceland between Skagafjörður in the west and Eyafjörður in the east and made up of land ranging from 600 to 1400 m in altitude having basalts of Upper Tertiary age as its main bedrock component (Þordarson and Hoskuldsson, 2002). Deep glacial valleys and fjords cut into the mountainous peninsula. At least 165 rock glacier-like forms and ice-cored moraines are found to be active on this 4800 km^2 peninsula (Guðmundsson, 2000).

The studied landforms fill the valley ends of Hóladalur and Fremri-Grjótárdalur (see Fig. 2). A big (~4 km^2) debris-covered glacier dominates the upper valley of Hóladalur (Fig. 3A). Adjacent is a glacier-derived rock glacier. In the side valley, Fremri-Grjótárdalur, a complex of glacier-derived rock glaciers fills the inner part of the valley (Fig. 3B). All these landforms are situated between 900 and 1200 m a.s.l. within two cirques, surrounded by mountains and mountain plateaus reaching 1300 m a.s.l. The age of the basalt in this area is about 7 million years (Þordarson and Hoskuldsson, 2002).

The debris-covered glacier (nr. 1 in Fig. 2) has a debris layer which covers 2/3 of the glacier area in the 1964 photos, reaching a thickness of several metres. A debris layer will protect the glacier surface from melting (Østrem, 1959) and in this case the glacier extends far below what would have been the case under debris free conditions. The debris cover consists of unsorted en- and supraglacially transported angular material that probably has reached the glacier as rock falls from the

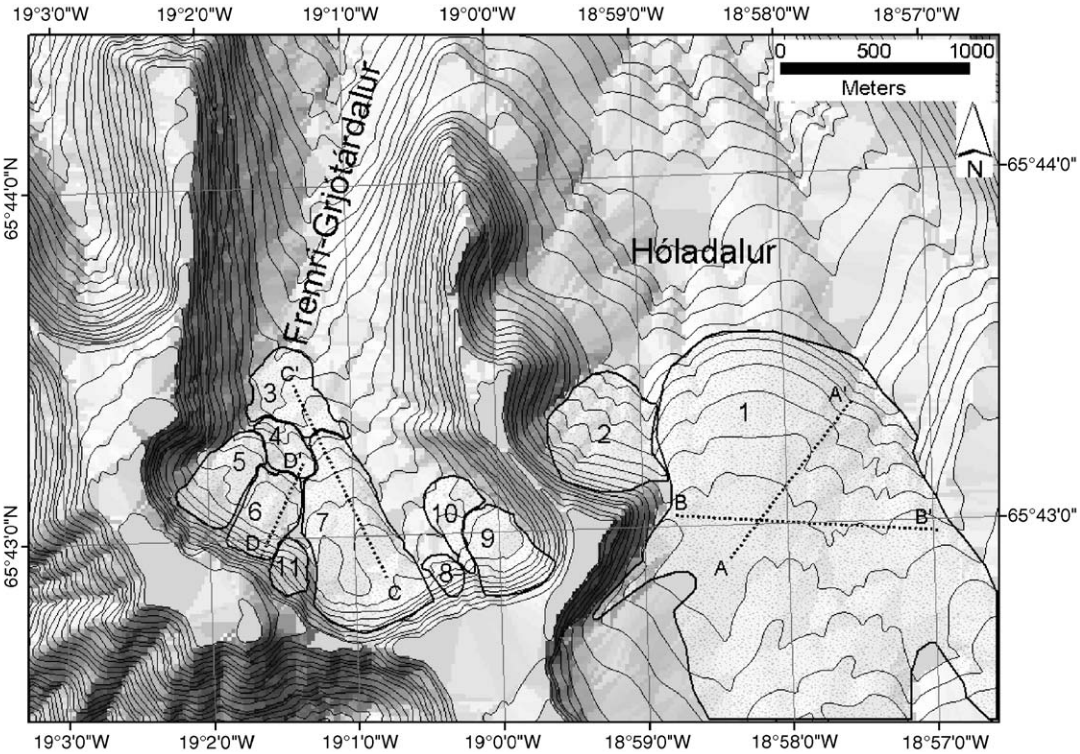

Fig. 2. Overview of the investigated landforms in Hóladalur and Fremri-Grjótárdalur. The numbers refer to the areas in Table 3.

headwall of the cirque. The debris-covered glacier has an area of about 4.3 km^2 of which 3.4 km^2 is covered by the orthophotos used.

The rock glacier adjacent to the debris-covered glacier (nr. 2 in Fig. 2) is rather small and hummocky, and believed to originate from a partly melted ice-cored

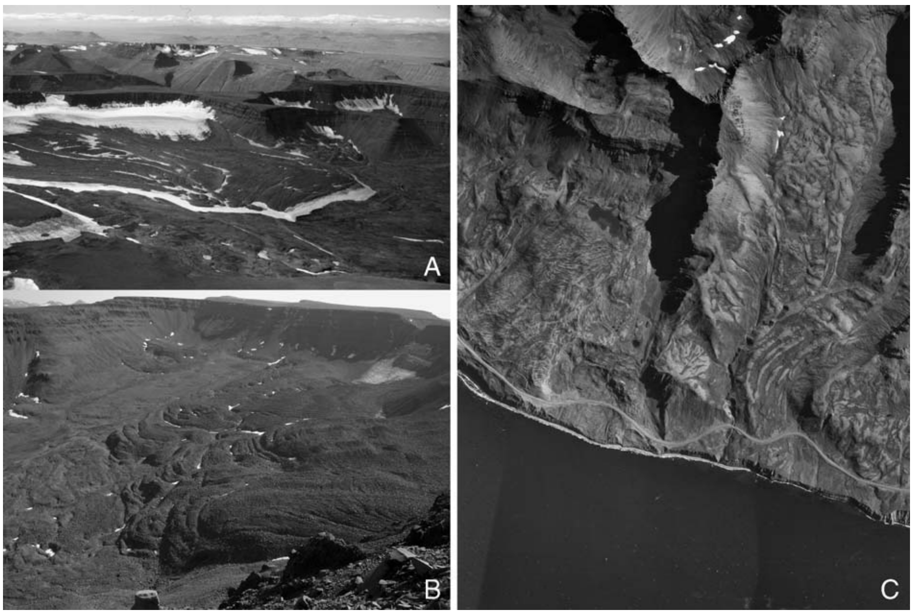

Fig. 3. A) Debris-covered glacier in Hóladalur (photo: Ágúst Guðmundsson), B) active rock glacier complex in Fremri-Grjótárdalur (photo: Herman Farbrot) and C) debris accumulation at Almenningsnöf (air photo: Landmælingar Islands).

moraine. The size is 0.29 km^2 and it is situated between 900 and 1000 m a.s.l.

The rock glacier complex in the neighbouring cirque in Fremri-Grjótárdalur (Fig. 3B) only shows glacier ice in small patches along the headwall. However, the whole landform is probably underlain by ice of unknown origin, indicated by DC resistivity measurements (Farbrot, unpublished data). These landforms also depict what may be several rock glacier generations, and like the neighbouring debris-covered glacier, rock falls from the headwalls of the cirque are the probable main source of material input. The eight identified landforms in this rock glacier complex are numbered 3 to 10 in Fig. 2 and vary in area from 0.031 to 0.435 km^2, with altitudes ranging from 900 to 1160 m a.s.l. What appears to be a small talus-derived rock glacier located centrally below the headwall of the same cirque is numbered 11 in Fig. 2 and has an area of 0.047 km^2. All the landforms described exist due to relative high weathering rates under periglacial conditions. The basalt bedrock is very susceptible to both frost weathering and chemical weathering (see e.g. Beylich, 2000).

There are no temperature measurements in Hóladalur and Fremri-Grjótárdalur, but MAAT is probably around −3.0 °C at the front (900 m a.s.l.) of the investigated landforms at this site. This temperature is extrapolated from a MAAT of 2.4 °C in Hólar at 140 m a.s.l. (The Icelandic Meteorological Office), some 4–6 km away, using the temperature gradient of −0.71 °C/100 m suggested by Gylfadóttir (2003).

3.2. Almenningsnöf

The second location is the moving debris accumulation at Almenningsnöf between Kvígildi and Skriðnavik on the coast road to Siglufjörður at the northern tip of the Tröllaskagi peninsula (66°10′N, 19°W) (Fig. 1). The bedrock of this area is the same basalt of Upper Tertiary age that is found in Hólar, but slightly older with an age of about 12 million years (Þordarson and Hoskuldsson, 2002). However, the relief of the northern tip of the peninsula is more alpine than at Hólar. Geodetic displacement measurements along the road that crosses the moving debris accumulation have been undertaken since 1977 by the Icelandic road authorities. They revealed yearly displacements of up to more than 1 m (Sæmundsson, 2004). These measurements were initiated due to observed damage to the road, and are used as a reference for the displacements derived from photogrammetry in this study. The debris accumulation is situated below north- and west-facing rock walls, between sea level and 260 m a.s.l. (Fig. 3C). It comprises a coast of 2 km in length and has an area of 1.9 km^2. The greatest changes in elevation are found close to the sea with the 100 m a.s.l. contour line 200–450 m inland. The distance from the headwall to the sea is 1.7 km (Fig. 4). The origin of the debris accumulation is uncertain, and different hypotheses exist. Sæmundsson (2004) treats the landform as a result of repetitive rock slides connected to the isostatic rebound after the last glaciation. In contrast, Guðmundsson (2000) argues that the landform is a result of local glaciation and permafrost conditions after or during the last glaciation of Iceland, and also implies that there might be buried ice within the debris accumulation. Guðmundsson (2000) reports on debris thicknesses in the range 15 to 65 m from core drillings along the road, with an average value of 42 m. Sæmundsson (2004) assumes a mean debris thickness of 50 m and a total volume of 110,000,000 m^3 for the whole accumulation.

3.3. Seyðisfjörður

The third location is the debris-mantled slope above the Seyðisfjörður community (Fig. 1). Here, the layer of moving debris does not show any specific landform connected to surface movement in contrast to the two other investigated areas. Heavy rainfall from time to time triggers debris flows from this slope, threatening the infrastructure of the village. The investigated area covers around 1 km^2 of the northeast-heading slope above the Seyðisfjörður community and ranges from 30 to 340 m in altitude. Between 80 and 120 m a.s.l. there is a bedrock threshold with cliffs. The upper part of the slope is also inclined with a gradient around 6%. Elsewhere, the slope is gentler with a gradient between 1 and 3%. Drilling has revealed debris thicknesses of 16–71 m (Guðmundsson et al., 2003). The drillings are all done above the steep bedrock threshold. The bedrock is exposed in steeper areas. The mountains around the glacially deeply eroded Seyðisfjörður reach more than 1000 m a.s.l. The bedrock in Seyðisfjörður is also basalt of Upper Tertiary age (Þordarson and Hoskuldsson, 2002).

4. Technique

Cross-correlation matching has been used for mapping glacier velocities in satellite imagery since the early 1990s (Bindschadler and Scambos, 1991) and in aerial orthophotos since 1995 (Rolstad, 1995). Aerial photogrammetry has been used as a tool for velocity and geometry change measurements of glaciers, landslides

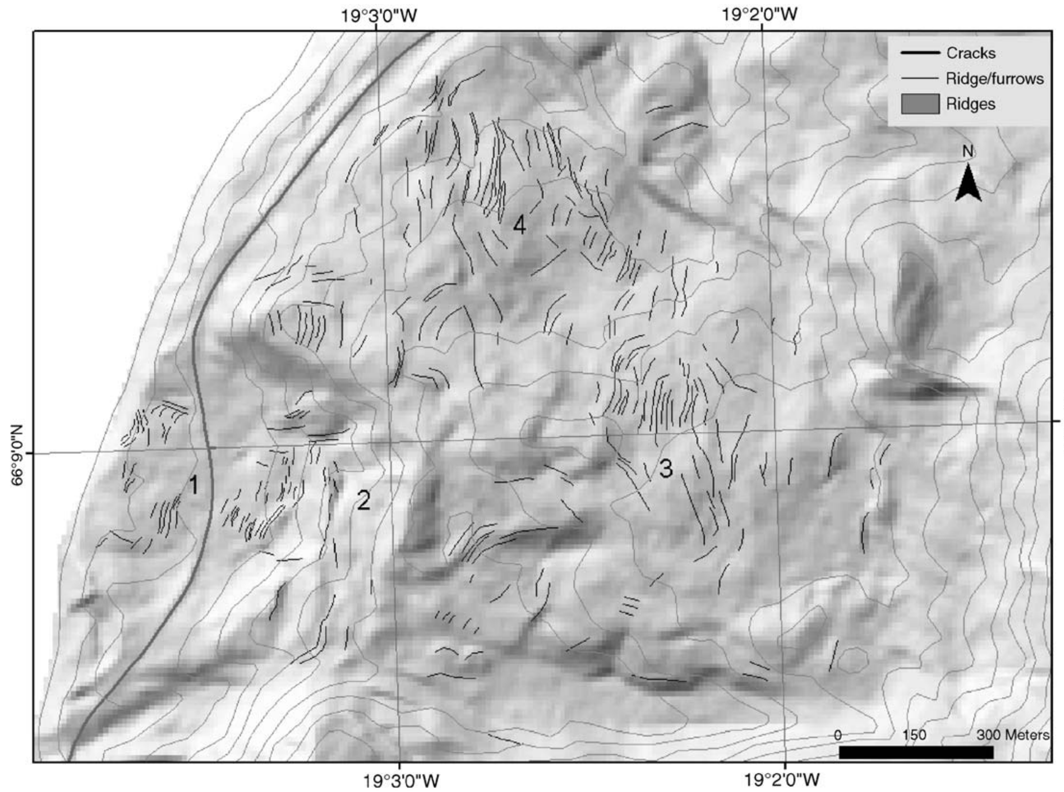

Fig. 4. A geomorphologic sketch of the investigated area at Almenningsnöf. The numbers refer to the areas in Table 3.

and creeping permafrost landforms like rock glaciers for several decades, and since the advent of digital photogrammetry cross-correlation matching of orthophotos has also been widely used (Baltsavias, 1996; Kääb and Vollmer, 2000; Kaufmann and Ladstädter, 2003; Delacourt et al., 2004; Roer et al., 2005).

In this study orthophotos are generated using a Z/I-Imaging digital photogrammetric workstation (DPW) with aerial photography obtained from Landmælingar Islands (National Land Survey of Iceland) (Table 1). Orthophotos are aerial photos transformed to orthogonal projection (i.e. map projection) by the use of air photos and a digital terrain model (DTM) within a DPW (Kasser and Egels, 2002). Since we had no DTM available, the first step in creating the orthophotos was to generate stereo models from the overlapping air photos of each location and year. Ground control points (GCP) used for the absolute orientation of the stereo model were collected during a field campaign in August 2003 using differential GPS. To increase the accuracy between the stereo models of different years homologous tie points and the same GCPs are used for all

Table 1
Data on the aerial photos used, and the generated orthophotos and DTMs

Location	Air photo date	Air photo scale (approximately)	Air photo resolution (m)	Orthophoto resolution (m)	DTM resolution (m)
Hóladalur	06 Aug 1985	1:29,000	0.37	0.5	5 and 20
Hóladalur	07 Aug 1994	1:29,000	0.37	0.5	5 and 20
Almenningsnöf	13 Aug 1977	1:16,000	0.21	0.5	9
Almenningsnöf	06 Aug 1985	1:35,000	0.45	0.5	9
Almenningsnöf	07 Aug 1994	1:35,000	0.44	0.5	9
Seyðisfjörður	09 Sep 1964	1:13,500	0.17	0.3	5
Seyðisfjörður	09 Aug 1994	1:15,500	0.24	0.3	5

At Hòlar 20 m resolution DTMs were used for the debris-covered glacier, while 5 m DTMs were used for the rock glacier complex.

models for the same area. Having a stereo model it is possible to automatically generate a DTM. Z/I-Imaging uses the Match-T algorithm for this purpose (Krzystek, 1991). An orthophoto is then generated for each year at each location using orientation parameters and the corresponding DTM. The orthophotos are generated with 0.3 and 0.5 m resolution with DTMs having a resolution between 5 and 20 m (see Table 1). Coarser models are used at the locations with small variability in topography. The residuals from the relative orientation, including the co-registering of the orthophotos, are between 0.36 and 0.54 m.

The cross-correlation matching of orthophotos is done with the CIAS software (Kääb and Vollmer, 2000). This software matches homologous points in two geo- and co-referenced orthophotos of the same area taken at different times. The points are either selected manually in the orthophoto of time 1 or as points of a regular grid with a specified grid size in the orthophoto of time 1. A reference block, a small window, is extracted from the orthophoto of time 1 around each selected point and the homolog of this small window is searched for in a larger test area around the corresponding coordinate in the orthophoto of time 2. A cross-correlation factor is calculated for each possible location of the reference block within this test area. The location that yields the highest correlation factor is taken to be the new position in orthophoto 2 of the point selected in orthophoto 1. For a thorough description see Kääb and Vollmer (2000). If a displacement has taken place during the time interval between the two acquisitions, this displacement is measured as the horizontal distance between the two homologous points (i.e. this method does not measure the vertical displacement). A reference block size of 15 × 15 pixels was used for all locations. This size seems to be sufficient to contain enough information for matching 0.3 and 0.5 m resolution photos of the coarse-grained boulders found on the landforms mapped in this study. Boulders ranging in diameter from 1 m to a few metres were used for the manually selected points. The size of the test area was 50 × 50 pixels for the slow movements and 100 × 100 pixels for the faster ones. The test area has to be large enough to detect a displacement of the expected magnitude, and the size was determined by some initial testing. According to Kääb and Vollmer (2000) the accuracy of the method is in the order of one pixel and at least at the same level as results from conventional photogrammetry. Although originally used for deformation mapping of rockglaciers by the use of aerial orthophotos, this method has also been used to map glacier movement using ASTER data (Kääb, 2002).

After a sufficient number of points have been matched by cross-correlation, it is possible to perform filtering on the resulting data. Displacement vectors with low cross-correlation factors or unnatural direction can easily be filtered out. A cross-correlation threshold of 0.5 was used for all locations together with a directional filter, filtering any vector deviating greatly from the assumed flow direction. The filtered data were then imported in to the GIS ArcView and some manual removal of points was also undertaken. In the areas where manual point picking was used the filtering and manual edit removed about 25% of the original matched points, while being closer to 50% for the areas where a regular grid was used to define the points.

By integrating streamlines through time and the measured displacements, surface age estimates can be obtained for the landforms. This is based on the assumption that the present velocities can be taken as a constant velocity for the whole existence of the landform and thereby give the time it takes for a surface particle to travel the whole length of the debris cover. This is of course a crude surface age estimate, but nevertheless it can give some valuable information on the history of the landforms. The streamlines are generated using the technique discussed by Kääb et al. (1998). The velocity profiles presented are taken from displacement fields interpolated from the measured displacements by the use of Kriging. Both interpolation and velocity profiling are done using ESRI Arc Map.

5. Displacements and streamlines

5.1. Hóladalur

The combination of the georeferencing and cross-correlation matching accuracy is about 0.5 m for the data from Hóladalur and Fremri-Grjótárdalur, and for the period of 9 years between 1985 and 1994 the displacements must be larger than 0.06 m a^{-1} in order to be significant (see Table 2). The displacements of the debris-covered glacier (Fig. 5) have a pattern of

Table 2
Time interval between the air photo acquisitions, with total and per year accuracy for the displacement measurements

Location	Time interval	Accuracy (m)	Accuracy (cm a^{-1})
Hóladalur	1985–1994	0.5	5.56
Almenningsnöf	1977–1985	0.5	6.25
Almenningsnöf	1985–1994	0.5	5.56
Seyðisfjörður	1964–1994	0.3	1.00

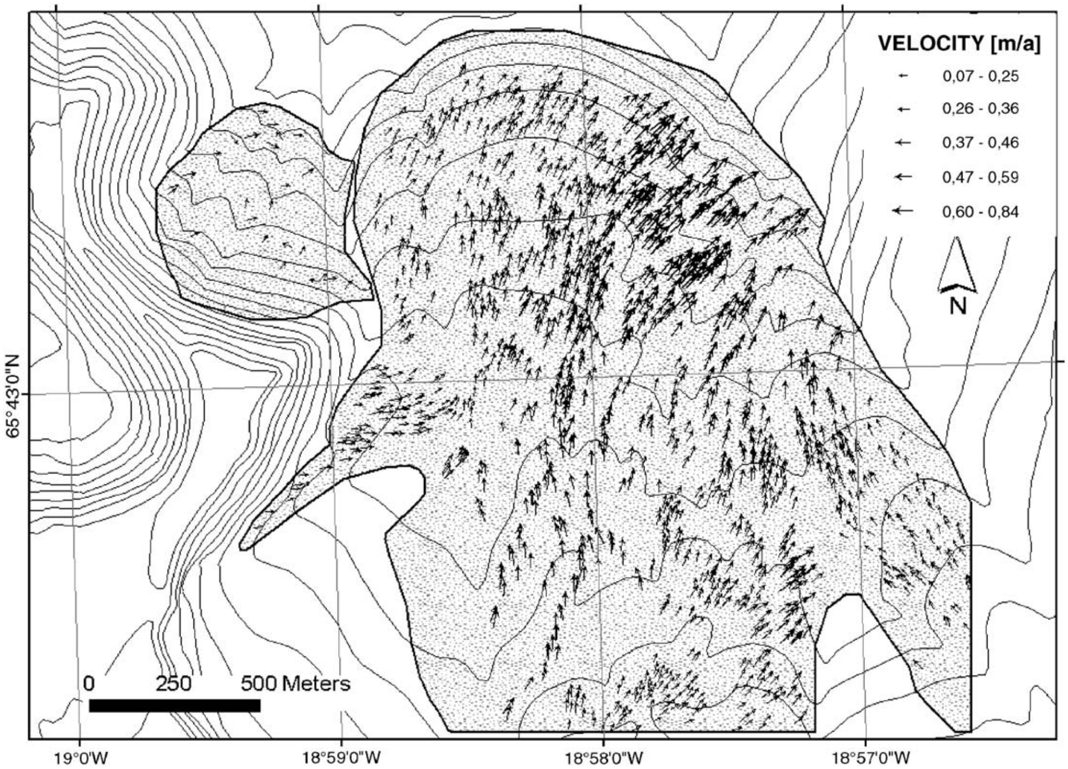

Fig. 5. Measured displacements for the debris-covered glacier and the rock glacier in Hóladalur (nr. 1 and 2 in Fig. 2) based on the 1985 and 1994 air photos.

increasing velocities towards the middle and also towards the terminus, and range from less than 0.10 m a^{-1} to a maximum of 0.84 m a^{-1} at the front. This is also seen from the profiles in Fig. 6. The areas of the greatest displacement coincide with the areas of steepest slope. The small rock glacier located west of the debris-covered glacier in Hóladalur (nr. 2 in Fig. 2) only gave very few matched points with velocities ranging from around 0.11 m a^{-1} to 0.39 m a^{-1}.

The displacements of the rock glacier complex in Fremri-Grjótárdalur show a different pattern with the greatest displacement for the upper lobes, and for form nr. 7 (Fig. 2) also increasing velocities with elevation (Figs. 7 and 8). Maximum velocity for the rock glacier complex is 0.74 m a^{-1}. One can also see that the different generations outlined in Fig. 2 show differences in displacement, with the uppermost and youngest forms moving 2–3 times faster than the lower and older ones. Landform nr. 3 (Fig. 2) is believed to be a collapsed rock glacier and has the smallest displacements. The DTMs and orthophotos show that both the geometry and front position for all the ten identified landforms have been stable over the period from 1985 to 1994, considering the significance level of data and measurements.

The streamlines of the Hóladalur debris-covered glacier inferred from the 1985–1994 velocities suggest a total surface development age for the debris cover of about 4500 to 5000 years, assuming the present velocity field to be representative over a long time span (Fig. 9). For the rock glacier complex in Fremri-Grjótárdalur the surface development ages of the youngest and upper forms are around 1000 to 1500 years (Fig. 10). For the talus-derived rock glacier (nr. 11 in Fig. 2) and the three easternmost forms (8, 9 and 10 in Fig. 2) there are not enough displacement measurements to establish reliable streamlines. The velocity of the lowermost and collapsed form is very low and implies an additional surface age of at least 1500 years. In the northernmost part of this form few measurements inhibit any surface age estimates to be made.

5.2. Almenningsnöf

The velocity measurement accuracy at Almenningsnöf is believed to be around 0.5 m, so that any significant displacements must be larger than 0.06 m a^{-1} (Table 3). The displacement based on orthophotos from 1985 to 1994 from Almenningsnöf depicts the greatest velocities

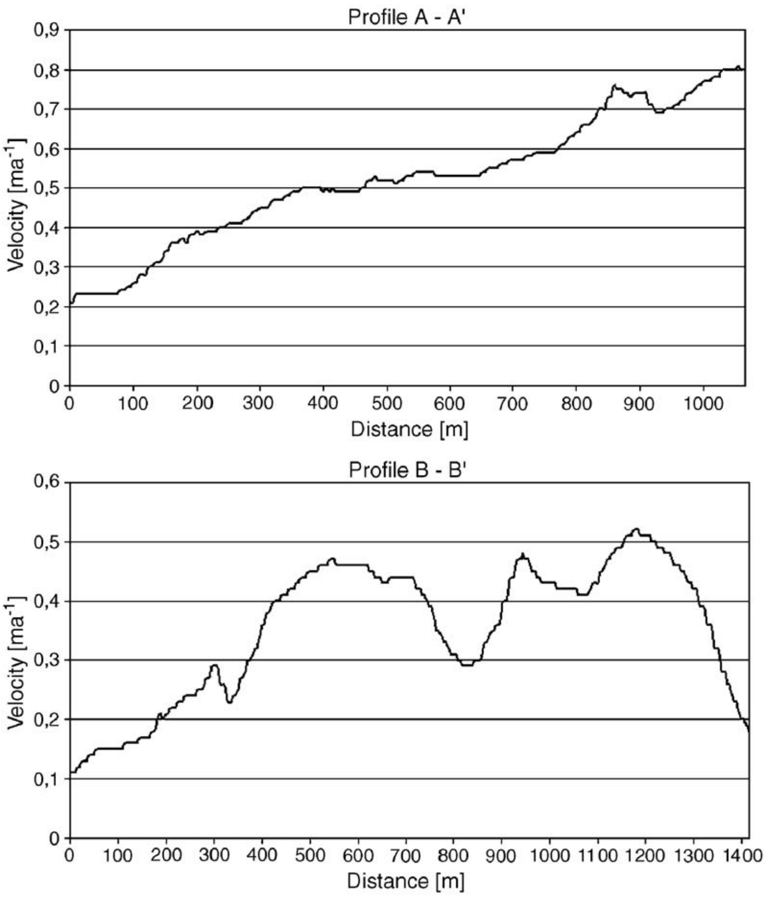

Fig. 6. Velocity profiles A–A′ and B–B′ on the debris-covered glacier in Hóladalur. The location of the profiles is shown in Fig. 2.

in the south-western part with an average of 0.57 m a^{-1} (Fig. 11A). The velocities are around 0.33 m a^{-1} in the mid section and around 0.13 m a^{-1} in the upper part of the body. The part of the body draining northwest has an average velocity of 0.17 m a^{-1}. At some places the movements show a discrete rather than a continuous pattern where the velocity changes rapidly over small areas (Fig. 12). Here the velocity differs greatly on the two sides of a marked fissure parallel to the direction of movement. This type of fissure can be found on both sides of the fast moving area 1 below the road. The overall pattern and magnitude of the displacement are also confirmed by the cross-correlation matching of all sets of orthophotos from 1977, 1985 and 1994 (Fig. 11A, B), with the same average velocity of 0.19 m a^{-1} for the 1977–1985 and 1985–1994 periods (Table 3). For the four different areas, velocities are more or less the same for the two periods, except for the fastest moving area in the south-western part of the body (area 1, Table 3). In this area the average velocity is 0.38 m a^{-1} from 1977 to 1985 and 0.57 m a^{-1} from 1985 to 1994. There is also a slight difference for area 2 (Table 3). The velocity measurements from 1977 to 1985 seem to have a higher density, with 2422 points matched compared to the 792 points from the 1985 and 1994 orthophotos. The measurements are also in agreement with the GPS measurements along the road (Fig. 11).

The streamlines inferred from the 1985 to 1994 velocities predict a travel time of at least 7000 years (Fig. 13). This is the time it takes for a surface particle to travel from the upper areas of the landform and down to the shore, using modern velocities for extrapolation. Since there is coastal erosion taking place along the terminus, and the material origin is uncertain, this surface age estimate based on travel time should be treated with great care. The 1977–1985 data give a travel time of at least 5000 years and the trajectories are much straighter than the ones from the later period (Fig. 13). From Fig. 12 it can also be seen that it was not possible to start any of the trajectories all the way back at the headwall, due to few matched points in the 1985–1994 data set. Extrapolating the trajectories back to the

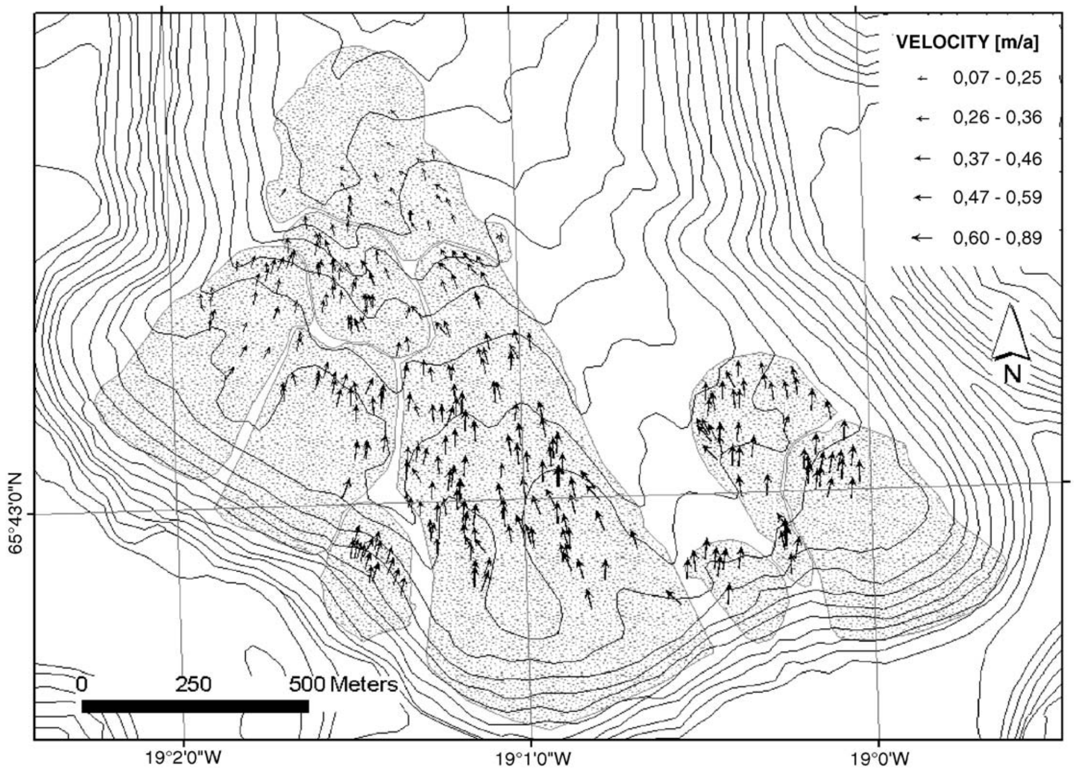

Fig. 7. Measured displacements for the rock glacier complex in Fremri-Grjótárdalur based on the 1985 and 1994 air photos.

headwall would increase the estimated travel time 60–70%, resulting in surface age estimates around 8000 and 12,000 for the 1977–1985 and 1985–1994 data sets.

The accuracy of an automatically generated DTM from air photos taken from an altitude of 5500 m (1985 and 1994 photos) is 1–2.5 m (0.2–0.4‰ of the flying height), hence, differencing two DTMs adds up the error to 2–5 m. Taking into account this degree of accuracy the difference between the DTMs does not reveal any significant changes in geometry for any of the investigated areas. Only an area some 200 m north of area 1 at Almenningsnöf, where road works have lowered the surface with more than 15 m, is taken to be a significant change.

5.3. Seyðisfjörður

Velocity measurements for Seyðisfjörður based on photos from 1964 and 1994 show velocities ranging between 0 and 0.13 m a^{-1}, reaching the highest velocities in the two steeper areas (Fig. 14). In the more gently sloping areas in between, velocities are lower, averaging around 0.01–0.02 m a^{-1}. The overall accuracy is about 0.3 m corresponding to a displacement of 0.01 m a^{-1} over the 30-year period (Table 3). This implies that the measured displacements in Seyðisfjörður in general are not significant given the 0.01 m a^{-1} accuracy.

6. Discussion

6.1. Accuracy and technique evaluation

Kääb and Vollmer (2000), who developed the CIAS software, estimate an average deviation originating from the cross-correlation method, relative orientation and the DTM to be about one pixel. In our case this means 0.5 m at Hólar and Almenningsnöf and 0.3 m at Seyðisfjörður. Given this orthophoto resolution and the time span between the acquisitions of the air photos, the one pixel error therefore results in a 5.6 cm a^{-1} error for the 1985–1994 data from Hólar and Almenningsnöf, a 6.3 cm a^{-1} error for the 1977–85 data from Almenningsnöf and a 1.0 cm a^{-1} error for the 1964–1994 data from Seyðisfjörður (Table 2). Looking at the average velocities in Table 3 this means that all measured displacements can be taken to be significant, except for the measurements from area 3 at Almenningsnöf and at Seyðisfjörður where the measured values are just twice the expected error. But for all these areas the direction of

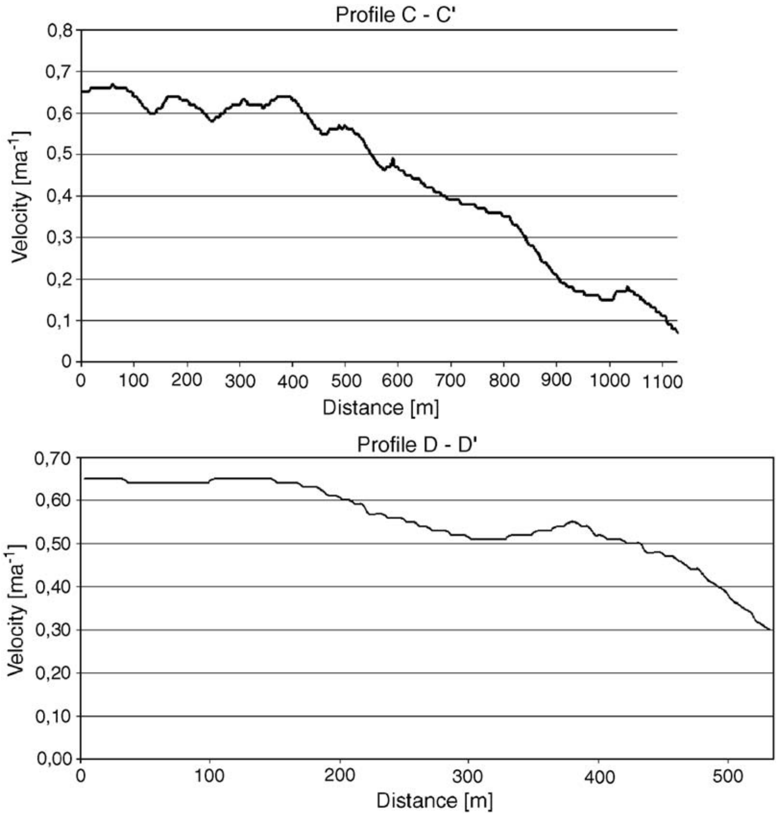

Fig. 8. Velocity profiles C–C′ and D–D′ from the rock glacier complex in Fremri-Grjótárdalur. The location of the profile is marked in Fig. 2.

the displacement shows a clear trend perpendicular to the contour lines. This is in contrast to areas outside the accumulation where the direction of the displacements has a more chaotic and random appearance. Velocities with a yearly displacement of more than 0.06 m at Hólar and Almenningsnöf, and 0.01 m at Seyðisfjörður are therefore included in the result. At Seyðisfjörður the average displacement is around the accuracy level, but there are still parts of the areas moving faster with significant displacements and these are included in the results.

Comparing the accuracy and applicability of cross-correlation matching of orthophotos with other methods like differential GPS surveying, satellite SAR interferometry and permanent scatter technique, the main advantage is the combination of accuracy and density of measurements. Differential GPS will achieve a higher accuracy for each measured point, down to less than a 1 cm per measurement and around 1.5 cm when measuring displacements (Berthling et al., 1998). But it is very time consuming and costly to measure displacements with the same density as achieved by cross-correlation matching of orthophotos. Using satellite SAR interferometry one can measure displacements down to 1.5 mm for vertical movements and 4 mm for horizontal movements (Goldstein et al., 1993), but the spatial resolution is only around 20 m. For satellite SAR interferometry there is also the aspect of decorrelation between acquisitions due to temporal effects (Weydahl, 2001), and the availability of scenes with surface motion towards the satellite sensor (i.e. orbit). The permanent scatter technique in SAR interferometry faces fewer problems concerning decorrelation. Only objects with strong radar back scatter can be used (e.g. constructions, visible bedrock etc.), and for the areas used in this study such strong reflectors are scarce. The technique also requires long series of data (Ferretti et al., 2000; Ferretti et al., 2001).

On Almenningsnöf the difference in travel times from the 1977–1985 and the 1985–1994 data set is the most striking, having streamlines giving 5000 years for the first period and 7000 for the second (Fig. 13). Both displacement data sets are estimated to have a similar accuracy. If one investigates the data closely it is apparent that the streamlines from the second period are much more curved and undulating. They also show low displacements in areas where the velocity vectors differ in direction. The method uses the 10 closest

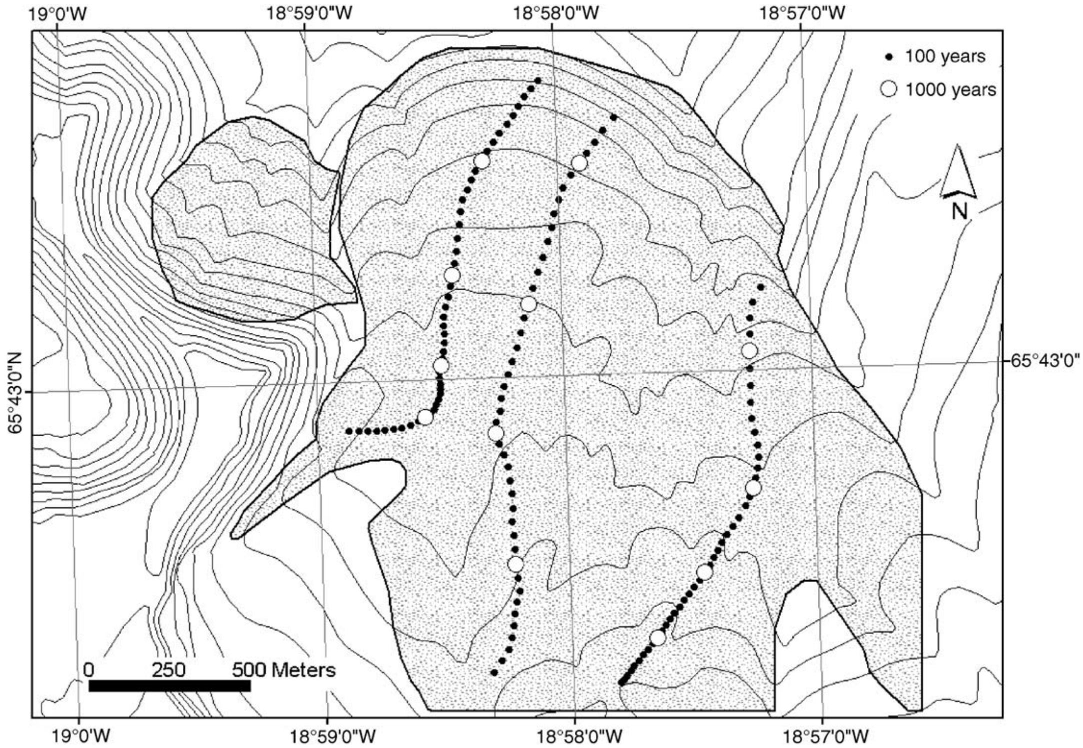

Fig. 9. Streamlines for the debris-covered glacier in Hóladalur (nr. 1 in Fig. 2) based on the displacement field from the 1985–1994 data.

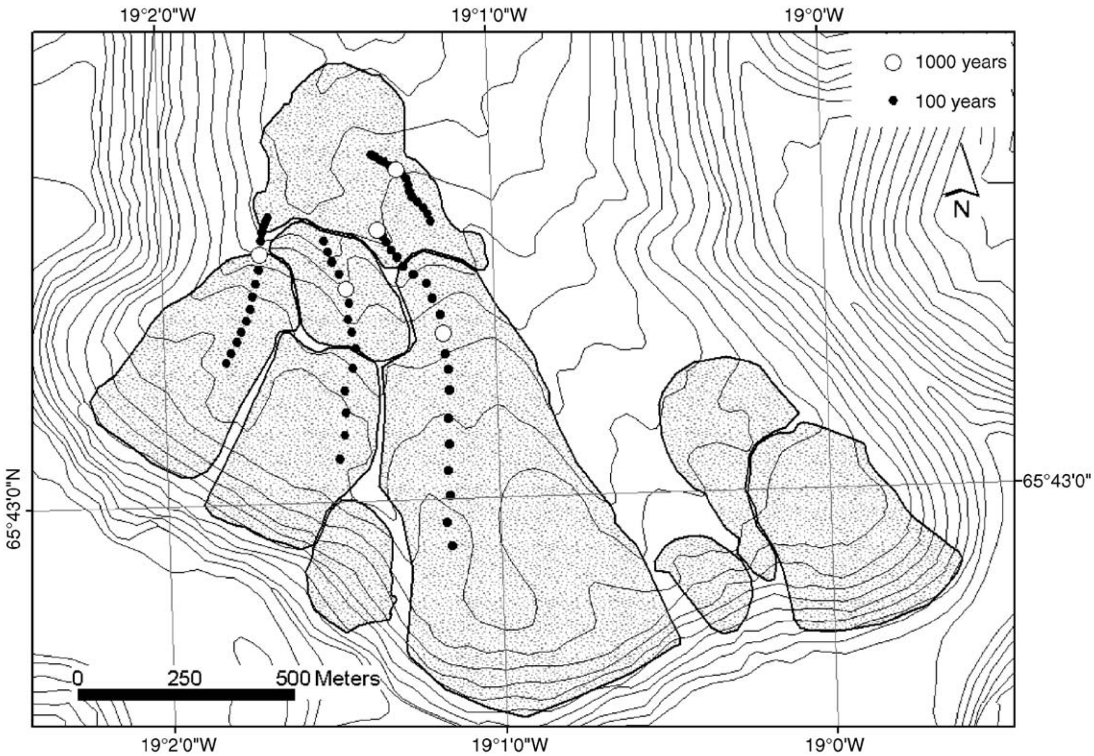

Fig. 10. Streamlines for the rock glacier complex in Fremri-Grjótárdalur based on the displacement field from the 1985–1994 data.

Table 3
Measured velocities at the three locations Hóladalur, Almenningsnöf and Seyðisfjörður

Location	Time period	Average velocity ($m\ a^{-1}$)	Maximum velocity ($m\ a^{-1}$)
Hóladalur 1	1985–1994	0.37	0.84
Hóladalur 2	1985–1994	0.19	0.39
Hóladalur 3	1985–1994	0.14	0.26
Hóladalur 4	1985–1994	0.33	0.54
Hóladalur 5	1985–1994	0.27	0.44
Hóladalur 6	1985–1994	0.46	0.66
Hóladalur 7	1985–1994	0.54	0.74
Hóladalur 8	1985–1994	0.67	0.72
Hóladalur 9	1985–1994	0.67	0.70
Hóladalur 10	1985–1994	0.58	0.74
Hóladalur 11	1985–1994	0.57	0.89
Almenningsnöf	1977–1985	0.19	0.67
Almenningsnöf	1985–1994	0.19	0.84
Almenningsnöf 1	1977–1985	0.38	0.62
Almenningsnöf 1	1985–1994	0.58	0.84
Almenningsnöf 2	1977–1985	0.29	0.67
Almenningsnöf 2	1985–1994	0.41	0.80
Almenningsnöf 3	1977–1985	0.15	0.39
Almenningsnöf 3	1985–1994	0.13	0.38
Almenningsnöf 4	1977–1985	0.20	0.51
Almenningsnöf 4	1985–1994	0.17	0.52
Seyðisfjörður	1964–1994	0.02	0.13

velocity measurements when interpolating. So the reason for the difference in the estimated travel times is most probably due to differences in density and homogeneity of matched velocity points. The reason for this may be attributed to differences in the data used. As seen from Table 1 the air photos from 1977 have an original resolution of 0.21 m while the photos from 1984 and 1994 have a resolution of 0.44 and 0.45 m respectively. All the orthophotos were generated with a resolution of 0.50 m, and both periods include the 0.44 m resolution air photos from 1985. However, the better contrast in the orthophotos from 1977 increases the number of points that are possible to match, and therefore also the density of the resulting velocity measurements and the quality of the surface age estimates. Thus, images with dense velocity measurements should be preferred for surface age estimates using streamlines. This means that one should emphasise the travel times from the first period rather than the last and that the travel time is around 5000 years (i.e. 8000 years interpolating the streamline back to the headwall). It is also important to note that this is the time it takes for a surface particle to travel from the headwall to the shore. Since the origin of the landform is not known it is difficult to apply this as a surface age estimate for the landform.

6.2. Flow regime

There is very little work done on surface displacement of debris-covered glaciers and rock glaciers in this area. Martin and Whalley (1987) report of a 2-m displacement between 1977 and 1985 of the Nautardálur rock glacier, a debris-covered glacier located some 30 km to the southeast of Hóladalur on the same peninsula. This corresponds to a yearly displacement of 0.25 m. From lichenometric studies Hamilton and Whalley (1995) infer an age of 200 years for the debris cover of this glacier.

The flow regime of the debris-covered glacier in Hóladalur (Figs. 5 and 6) seems to be dominated by glacier flow as the main component of movement. Here, the velocity increases towards the middle of the glacier and also downslope. The velocity increase near the front is more difficult to explain by glacial dynamics. It is found in an area where the surface slope is steeper than for the rest of the glacier, but this area is probably considerably thinner (approximate thickness of 20–40 m). Hence, an acceleration of a glacier at this point must include other processes. Another explanation may be related to periglacial processes, as an increase in slope would affect any creep processes taking place within the debris cover itself. The surface pattern of the debris cover with furrows and ridges transverse to the flow direction also implies that there is additional creep taking place in the debris cover. However, based on our data it is not possible to be certain on this issue.

The velocity of the adjacent rock glacier in Hóladalur (Fig. 5) has a more chaotic appearance than the debris-covered glacier and no clear directional trend in the movements, prohibiting conclusions about flow regime. The hummocky surface of this landform is most likely the result of thermokarst and appears to be formed by a partly melted rock glacier.

The velocity measurements of the rock glacier complex in Fremri-Grjótárdalur (Figs. 7 and 8) reveal different velocities for the different landforms identified. The upper rock glaciers have a greater velocity than the lower ones. This strengthens the idea of several generations of landforms overrunning each other. Some of the larger rock glaciers also experience an increase in velocity with altitude. However, there does not seem to be a clear connection between velocity and slope. The surface of the rock glacier complex also shows signs of creep-like furrows and ridges, and the forms are more pronounced than on the debris-covered glacier. This might be caused by deforming glacier ice or some additional surface creep. Based solely on the

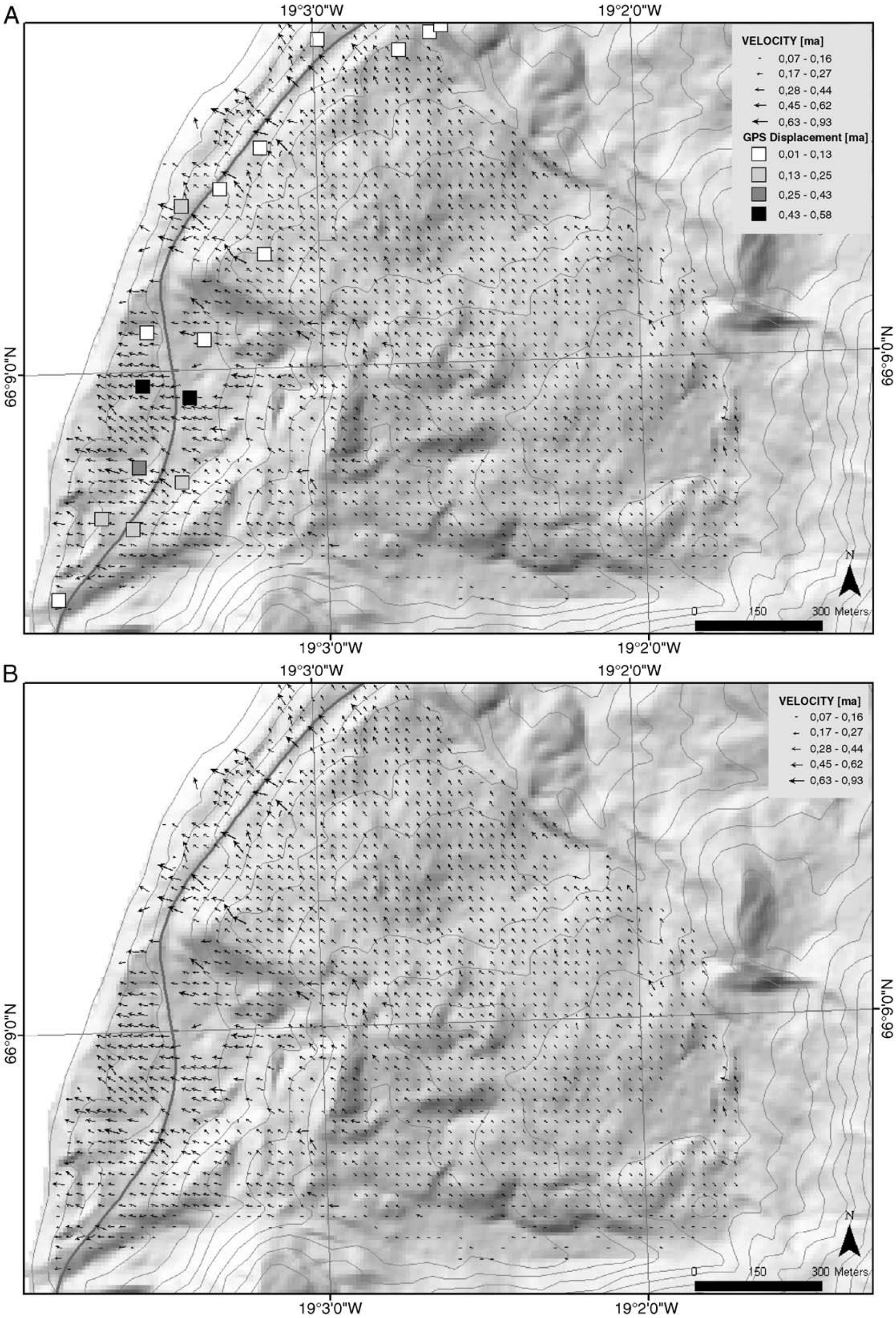

Fig. 11. A) Measured displacements of the debris accumulation by Almenningsnöf based on the air photos from 1985 and 1994. GPS measurements undertaken by Vegagerðin (Icelandic road authorities) are shown for comparison. B) Measured displacements of the debris body by Almenningsnöf based on the air photos from 1977 and 1985.

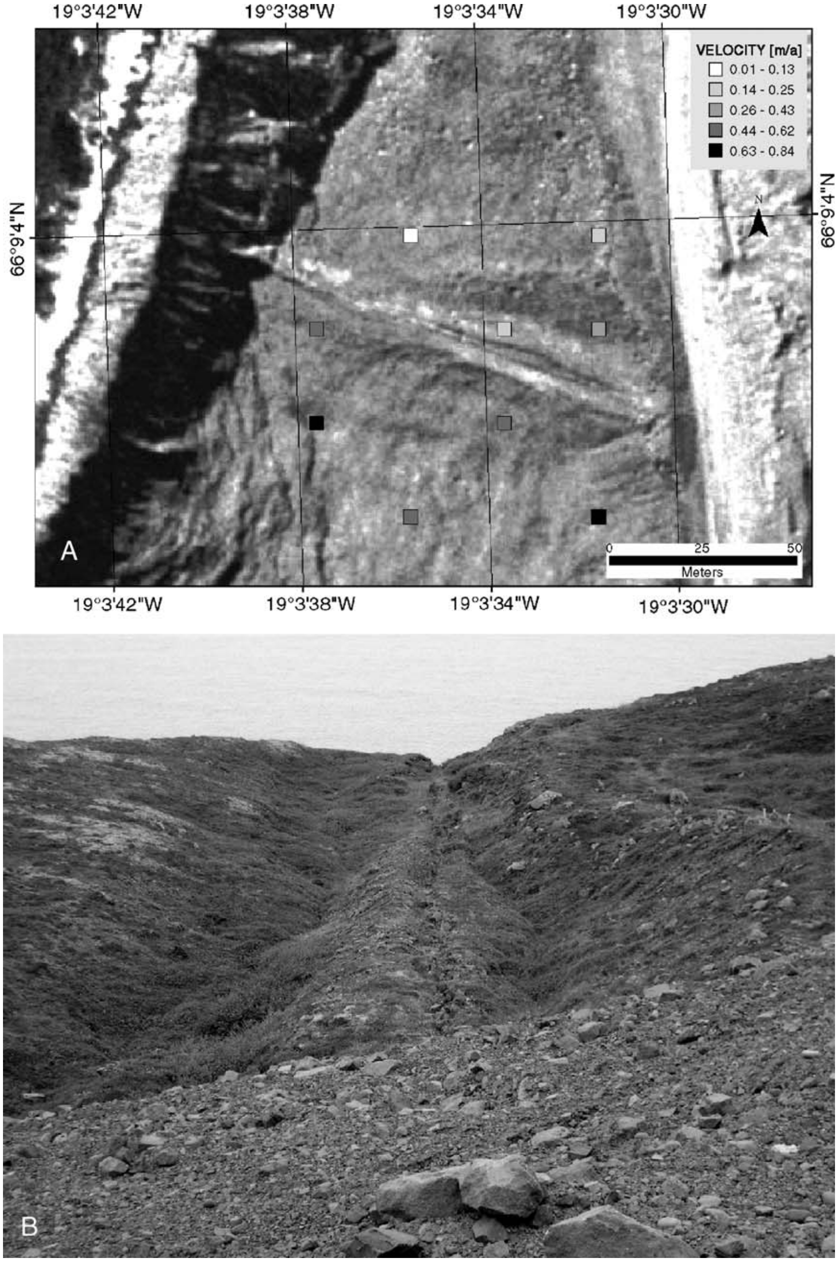

Fig. 12. A) Measured displacements on both sides of a fissure north in area 1 (Fig. 4). The orthophoto is used as background. There is a marked difference in the velocity on the two sides. B) A photo of the same fissure (photo: Trond Eiken).

motion pattern it is difficult to say anything on the relative importance of the two causes of flow.

The movement on Almenningsnöf is relatively uniform in areas 3 and 4 (Fig. 11), with average velocities of 0.13 to 0.19 m a^{-1} for both investigated periods. These areas do not have any smaller area that differs greatly in velocity from the rest, except from a small speed up close to the shore. Along both sides of the debris accumulation there are distinct ridges that indicate a surface lowering and differential movement of the accumulation and the surrounding terrain. This homogenous movement could be due to movement along a sliding plane or deformation within the debris itself; however, it is difficult to interpret the cause of movement from the displacements and topography alone. An exception of that is the fast moving area 1

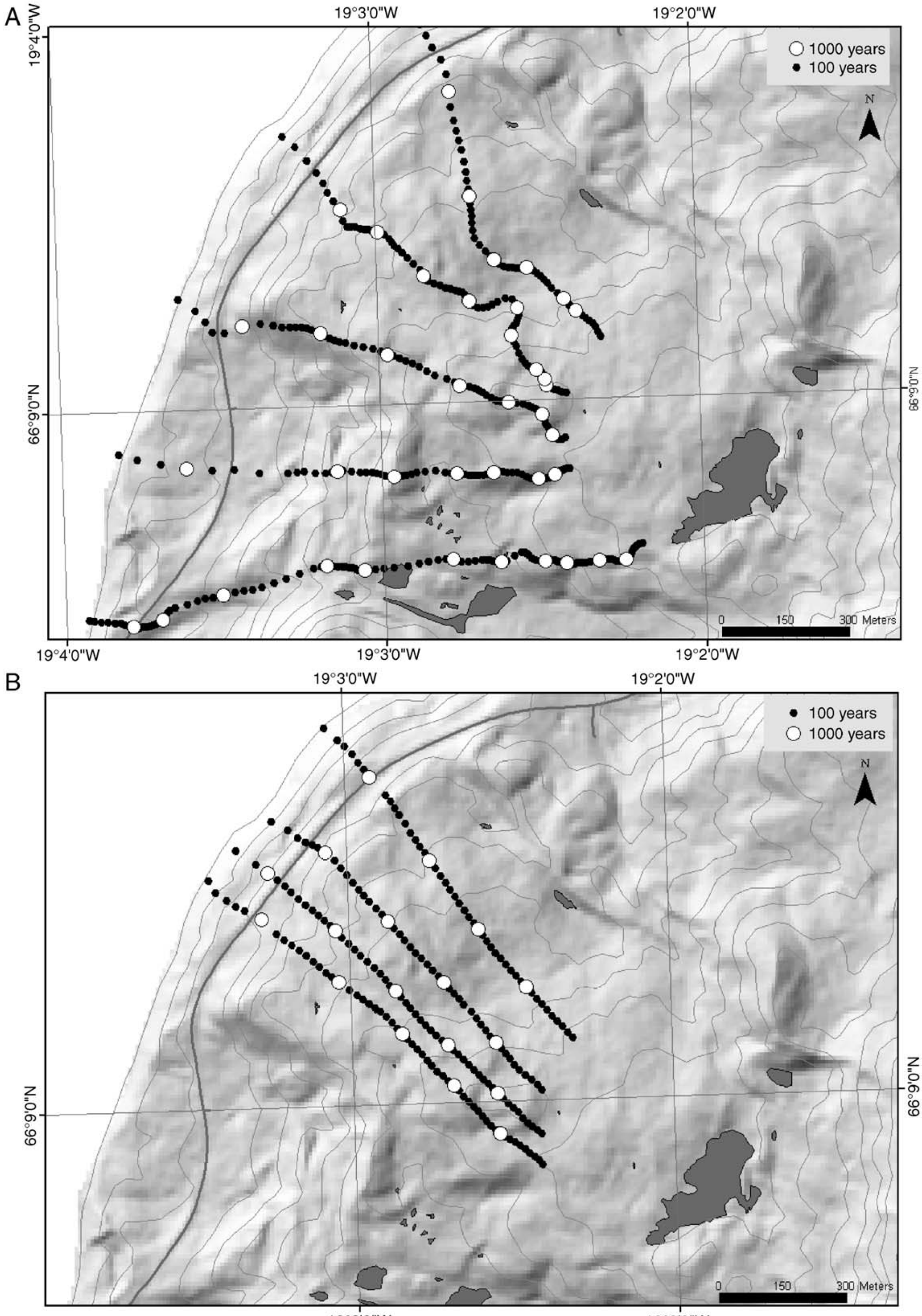

Fig. 13. Streamlines for the site at Almenningsnöf based on the displacement field from A) the 1985–1994 data and B) the 1977–1985 data.

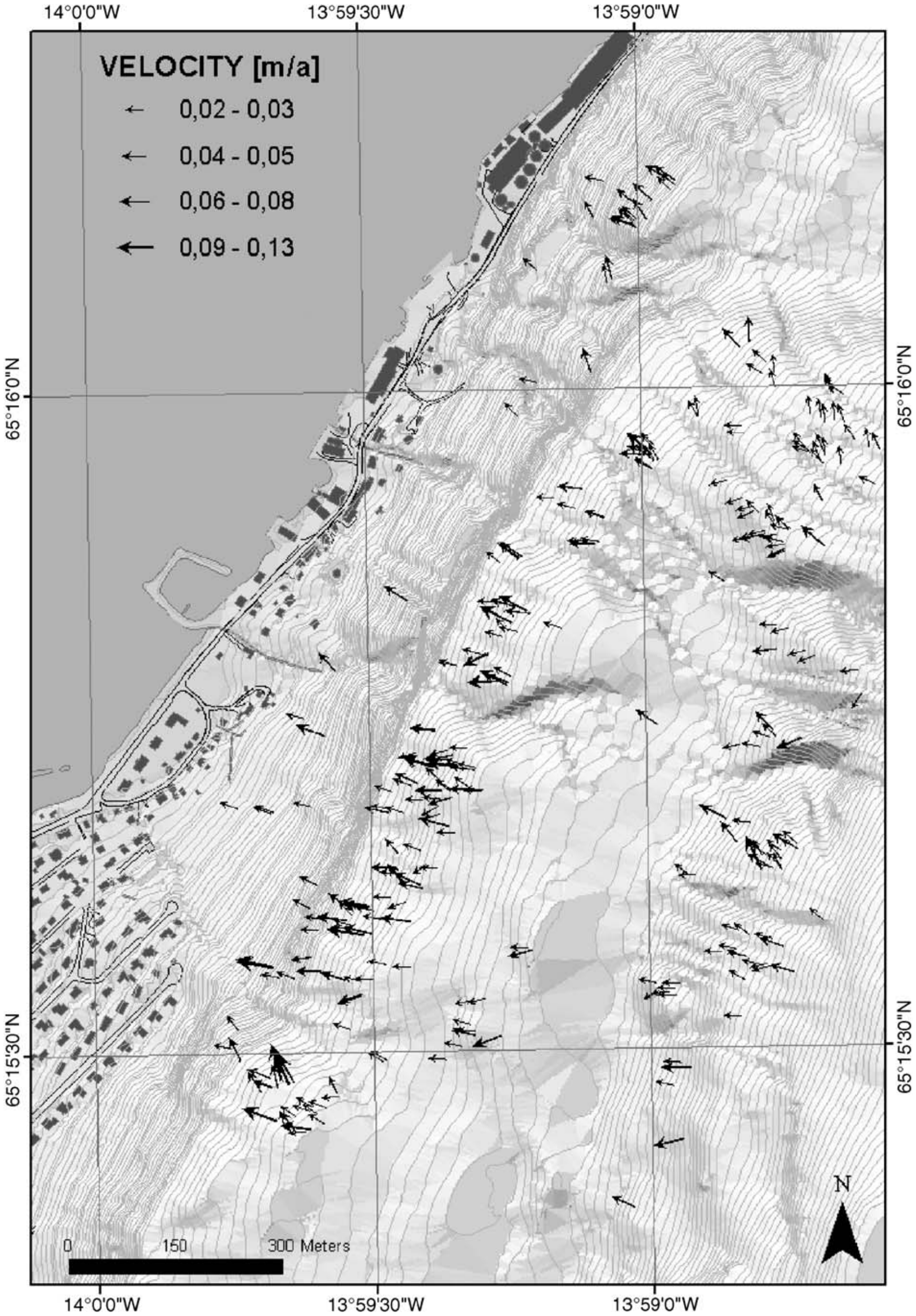

Fig. 14. Measured displacements for the debris layer by Seyðisfjörður based on the air photos from 1964 and 1994.

(Fig. 4). High and uniform velocities in this area (Fig. 11) indicate that this part of the debris accumulation is moving independently from the rest. The homogenous displacement indicates some kind of slide movement along a horizon within the mass. Since the surface is quite planar and does not show any vertical movement one can assume that the slip surface also is planar. This indicates a translational slide (Cruden and Varnes, 1996; Dikau et al., 1996), and considering the high debris thickness (Guðmundsson, 2000) we assume this area being a slow moving slab slide (Dikau et al., 1996). The assumption of a translational slide is also strengthened by the fact that the movements are not constant. Instead, they increase in wet periods and almost cease in dry periods just like the large annual variability seen in Sæmundsson (2004). Velocities increase more than fivefold during wet years for some of the GPS points measured by the Icelandic road authorities in area 1. The movement of such slides usually takes place along an abrupt change in rock type or along a permeable/impermeable soil junction (Dikau et al., 1996). Area 2 shows scarps which are typically seen at the back of transitional slides (Dikau et al., 1996). The increased velocity in area 2 can be explained both by the slope angle and by the stress relieving effect of the fast moving area in front.

The velocities measured in Seyðisfjörður (Fig. 14) are much lower than the ones measured at the two other locations and also close to or at the level of accuracy for the method used. From the measured velocities one can see that velocity increases with slope angle and that the greatest displacements are found close to the bedrock threshold 80 to 120 m a.s.l and also in the steeper upper part of the investigated area. There are few points matched in the relative flat area in between these two steep areas due to few blocks of a desirable size. The slow displacement rates imply that the movement occurs at shallow depth. One should not elaborate more on these results since they do not show the desired significance.

6.3. Surface age estimations and preliminary implications on Holocene landscape development

For the debris-covered glacier in Hóladalur the trajectories suggest a surface age between 4500 and 5000 years for the debris-covered glacier, while the more active landforms in the rock glacier complex in Fremri-Grjótárdalur have a suggested surface age of 1000 to 1500 years. The lowermost and slow moving landform of the complex has an additional surface age of at least 1500 years. This means that landforms in both cirques have been initiated between 3000 and 5000 years ago. This agrees well with the onset of Holocene cooling 4000 years BP found by ice core drilling on Greenland (Dahl-Jensen et al., 1998) and the onset of neo-glaciation of western Norway around 5300 years BP (Nesje, 1992).

The assumption of constant velocity during the last 3000 to 5000 years is of course crude. The velocities may have been greater during the Little Ice Age due to increased glacier thickness and probably lower during the early evolution of the glaciers in this area, while the colder temperatures during the Little Ice Age would have had the opposite effect on the debris creep. Both of these facts contribute to the uncertainty of the surface age. From lichenometric studies Hamilton and Whalley (1995) report on an age of 200 years for the debris-covered glacier in Nautardálur, some 30 km to the southeast. However, combining present velocity measurements and length profiles for the same glacier they get an age of 2000 years. The discrepancy is explained by a greater velocity during the Little Ice Age, which they believe has been around 2 m a^{-1} before slowing down to the present velocity of 0.25 m a^{-1}. They concluded that the initiation of the glacier took place during the Little Ice Age. In Hóladalur and Fremri-Grjótárdalur there are no end moraines or glacier forefields found that support a greater glacier extent during the Little Ice Age. The surface of the landforms could have been somewhat steeper during the Little Ice Age but not to the extent needed to support a velocity justifying an initiation during the Little Ice Age.

Stötter et al. (1999) report on several glacier advances during Holocene in the Tröllaskagi area from moraine dating. In front of Vatnsdalsjökull, situated some 10 km to the northeast of Hóladalur, they found evidence of advances around 4700 BP and ca. 3200–3000 BP. In front of Barkárdalsjökull, situated some 10 km to the east of Hóladalur, they found evidence of advances around 2000 BP and 1500 BP. Judging from the surface age estimates in this study the landforms could very well have been initiated during the same periods as the advances for the glaciers in the vicinity. The debris-covered glacier, which is the oldest landform, may have been initiated during the first reported advances 4700 BP and the youngest rock glaciers during one of the two later periods (2000 or 1500 BP). The time of initiation for the older rock glaciers in Fremri-Grjótárdalur is more uncertain, but they are most likely older than the two latest glacial advances and therefore probably conform to the 3200–3000 BP advance. The proposed initiation of the landforms also agrees quite well with the four latest glacier advances in Scandinavia 7.5, 5.1–4.5, 3.2–2.8, 2.2–1.9 and 1.5–1.1 ka BP presented by Karlén (1988) from lacustrine sediments. Nesje et al. (1991) find evidence for advances at similar times in Norway, but with a discrepancy attributed to dating problems and/or differences in topography and topographic effects.

Based on this discussion we suggest that most of the landforms in the high mountains of northern Iceland have developed during the late-Holocene cooling period after the Atlanticum. The initiation of the oldest forms (5000 years) coincides with findings from Scandinavia (Nesje, 1992). The surface ages of around 3000 years agree with glacier advances found on Svalbard (Svendsen and Mangerud, 1997) and western Greenland (Kelly, 1985). The surface ages of the different landforms also coincide with local glacier advance periods described in literature (Stötter et al., 1999). The surface ages of all investigated landforms in Hóladalur agree with the Scandinavian glacier and climate fluctuations found by Karlén (1988).

For Almenningsnöf the streamlines and the discussion of accuracies imply a travel time of around 8000 years, under the assumption of constant movement. But since the origin of the landform is uncertain, other creep and landslide processes may have contributed to its formation, and it is therefore difficult to use the travel time for surface-age estimates.

6.4. Implications for mountain permafrost distribution

In our discussion the question of permafrost processes in this maritime, high mountain environment becomes important. In Hóladalur, the flow analysis indicates a mixture of glacial flow and additional creep of the debris.

The mountain areas of Northern Iceland show high periglacial activity. Whalley and Martin (1994) state that the Tröllaskagi peninsula has been marginal for permafrost for the last 200 years and that permafrost only may appear on the snow-blown summit plateaus at ca. 1250–1300 m a.s.l. Recent empirical spatial modelling indicates probable mountain permafrost above 850 to 950 m a.s.l. (Etzelmüller, unpublished data). This means that the landforms in Hóladalur and Fremri-Grjótárdalur are at or close to the lower level of permafrost in this area. Considering that the thermal offset effect of coarse, blocky material, decreases ground temperature significantly (Harris and Pedersen, 1998), coarse-grained slope bodies will promote the generation of permafrost. The initial hypothesis of permafrost conditions is also strengthened by the DTM analysis and visual inspection of the air photos from different years of the rock glacier and glacier bodies, showing that the landform geometry is stabile through the period from 1964 to 1994. This means that the ability of the debris layer to protect the ice beneath from melting during this period has been high for most of the landforms. Landforms nr. 2 and 3 in Fig. 2, on the other hand, show signs of partial melt. This could indicate that the landforms are situated at a level marginal for debris layer protection of glacier ice in the present climate. None of the stable landforms is found below 900 m a.s.l. and the two partially and completely melted landforms (nr. 2 and 3) are situated between 900 and 1000 m a.s.l., and 870 and 920 m a.s.l. respectively. It is important to note that an almost protecting debris layer and ice-cored moraines that have been stable for some decades do not necessarily imply permafrost conditions. Krüger and Kjær (2000) report that in the current humid and subpolar climate it takes 50 years to melt down 40 m of stagnant dirty ice at Kötlujökull (220 m a.s.l.), an outlet from Mýrdalsjökull in southern Iceland. The mean annual air temperature at Kötlujökull is about 2.6 °C (Krüger and Kjær, 2000) while probably closer to −3.0 °C at the front of the studied landforms in Hóladalur and Fremri-Grjótárdalur at 900 m a.s.l. This indicates that melt would be even slower here. Everest and Bradwell (2003) report buried ice that has survived at least 50 years in front of Virkisjökull and Hrútárjökull, and probably more than 200 years at Skeidaràjökull. All three glaciers are outlets of Vatnajökull in southern Iceland and even though no temperature records are given they probably endure a somewhat milder climate than that found in Hóladalur.

7. Conclusion

The displacement results from Hóladalur suggest that there is additional creep taking place in the surface of the debris-covered glacier and the glacier-derived rock glaciers. Based solely on the displacements it is not possible to conclude on the cause of this additional creep. The surface ages of 5000, 3000 and 1500 years also conform to dating from moraines in the vicinity and general knowledge of Holocene climate development. The displacement results from the moving debris accumulation at Almenningsnöf close to Siglufjörður agree well with existing GPS surveyed displacements and add more knowledge on the dynamics of the landform. Due to the uncertain origin of this landform it is difficult to relate the results of the travel times of streamlines to surface age. At Seyðisfjörður the displacement rates during the investigated 30-year period were too small to give significant results taking in account the accuracy of the method, but their uniform direction implies that movement takes place. The results of this work show that cross-correlation of orthophotos is a valuable tool for determining the surface displacement field of selected creeping slope landforms and that the data can be used for estimating surface ages for some of these landforms.

Acknowledgements

The project was financially supported by the Norwegian Research Foundation (NFR), project no. 157837/V30, and the Department of Geosciences, University of Oslo. Ole Humlum and Leif Sørbel provided some valuable discussions on the topics covered in this work. Ole Humlum also gave valuable comments on the manuscript. We also want to thank Jan Boelhouwers and Ivar Berthling for reviewing the manuscript.

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