Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **98**, 1–13, 2007

Holocene slope processes and landforms in the northern Faroe Islands

Hanne H. Christiansen[1], Lars H. Blikra[2] and Lis E. Mortensen[3]

[1] Geology Department, The University Centre in Svalbard, UNIS, P.O.Box 156, 9171 Longyearbyen, Norway.
E-mail: hanne.christiansen@unis.no
[2] Geological Survey of Norway/International Centre for Geohazards, 7491 Trondheim, Norway.
Present address: Åknes/Tafjord project, Estenstadveien 93, 7049 Trondheim, Norway.
[3] Faroese Geological Survey, Brekkutun 1, 188 Hoyvik, Faroe Islands.

ABSTRACT: The exposed nature of the northern Faroe Islands high relief landscape enabled widespread Holocene slope process activity and deposition of related landforms, which seem largely controlled by extreme meteorological conditions. Three different slope landforms – the large colluvial Glyvurs fan, the lower Marknastiggjur mountainside debris-flow deposits in the town of Klaksvik, and the mountain top aeolian sediment cover on Eidiskollur – were investigated by a combination of geomorphological, stratigraphic, sedimentological, chronological and modern process studies.

Sporadic Holocene snow-avalanche and debris-flow activity were documented, with sedimentation starting significantly before 8000 cal yr BP in the Glyvurs fan, which still sporadically experiences activity. The largest amounts of Holocene slope sedimentation seem to occur in colluvial fans, such as the Glyvurs fan, which are located below large dyke canyons, called gjogvs. The lower Marknastiggjur mountainside consists of mainly debris-flow deposits, which started before 7800 cal yr BP. A relatively small amount of precipitation, but with high precipitation intensity after a dry summer, triggered modern small-scale debris-flows in the northern islands, also at the Marknastiggjur mountainside, early in Autumn 2000. Extensive continuous mountaintop aeolian sedimentation from cliff weathering started around 6900 cal yr BP on the Eidiskollur peninsula.

No direct influence of settlement on slope process activity was found at the different investigated slope landforms in the northern Faroe Islands.

KEY WORDS: climate change, colluvial fan, debris-flows extreme events, highland aeolian deposits, Klaksvik, periglacial geomorphology, Saksundalen, snow avalanche.

The Faroe Islands are located in the main branch of the North Atlantic Drift, an important part of the global thermohaline circulation (Bigg 1996), with a cool temperate climate at sea level, and an arctic climate in the more than 50% of land which is above 350 m asl. (Christiansen & Mortensen 2002). The boundary to the modern periglacial environment is located at 150–300 m asl (Christiansen & Humlum 2003). When the North Atlantic Drift earlier weakened or changed position, colder polar water approached the islands. This happened as recently as the Little Ice Age (LIA) (Humlum & Christiansen 1998a). In such periods arctic conditions occur all over the Faroese landscape. Therefore, cold-climate geomorphic processes have dominated large parts of the Faroe Islands landscape for a significant part of the Holocene, enabling widespread periglacial slope activity.

The landscape is largely controlled by the Tertiary basalt bedrock, and associated tectonic activity. In particular, there is a fairly high concentration of near-vertical dykes, some of which have developed to become narrow canyons, called gjogvs, found all over the Faroese landscape. During Quaternary glacial stages, glacial erosion and less significant deposition was the dominant influence on the landscape below glacial trimlines, whilst permafrost and periglacial activity dominated in the higher ground above the trimlines. In this landscape periglacial Holocene slope processes and landforms have been potentially significant, yet they have so far not been extensively investigated. Therefore this present paper focuses on some of the most widespread slope landforms: large colluvial fans, mountainside debris-flows and mountain top aeolian sedimentation from high coastal cliffs.

Settlement of the Faroe Islands only occurred in the Late Holocene around AD 800 (Arge *et al.* 2005), when the Norse arrived in the islands from Norway. The landscape has thus only been affected by agriculture during a small part of the Holocene, and mainly just around the settlements (Lawson *et al.* 2005). Therefore, the widespread periglacial slope landforms offer a good opportunity to reconstruct natural pre-late Holocene slope activity. Today slope processes commonly affect infrastructure and especially housing. As the villages expand they can often only extend up-slope into the geomorphologically more active parts of the slopes. The main aim of this paper is to evaluate the activity of three dominant slope landforms in the Faroe Islands during the Holocene, and thus indirectly assess the influence of settlement on the geomorphology of the slopes.

1. The highland landscape of the northern Faroe Islands

The areas studied are located in the northern part of the Faroe Islands, on the islands of Bordoy, Eysturoy and Streymoy (Fig. 1). Here the mountains consist of Tertiary basalt plateau bedrock 50–60 million years old (Rasmussen & Noe-Nygaard 1970, 1990). The present landscape consists of mountain

doi:10.1017/S1755691007000047

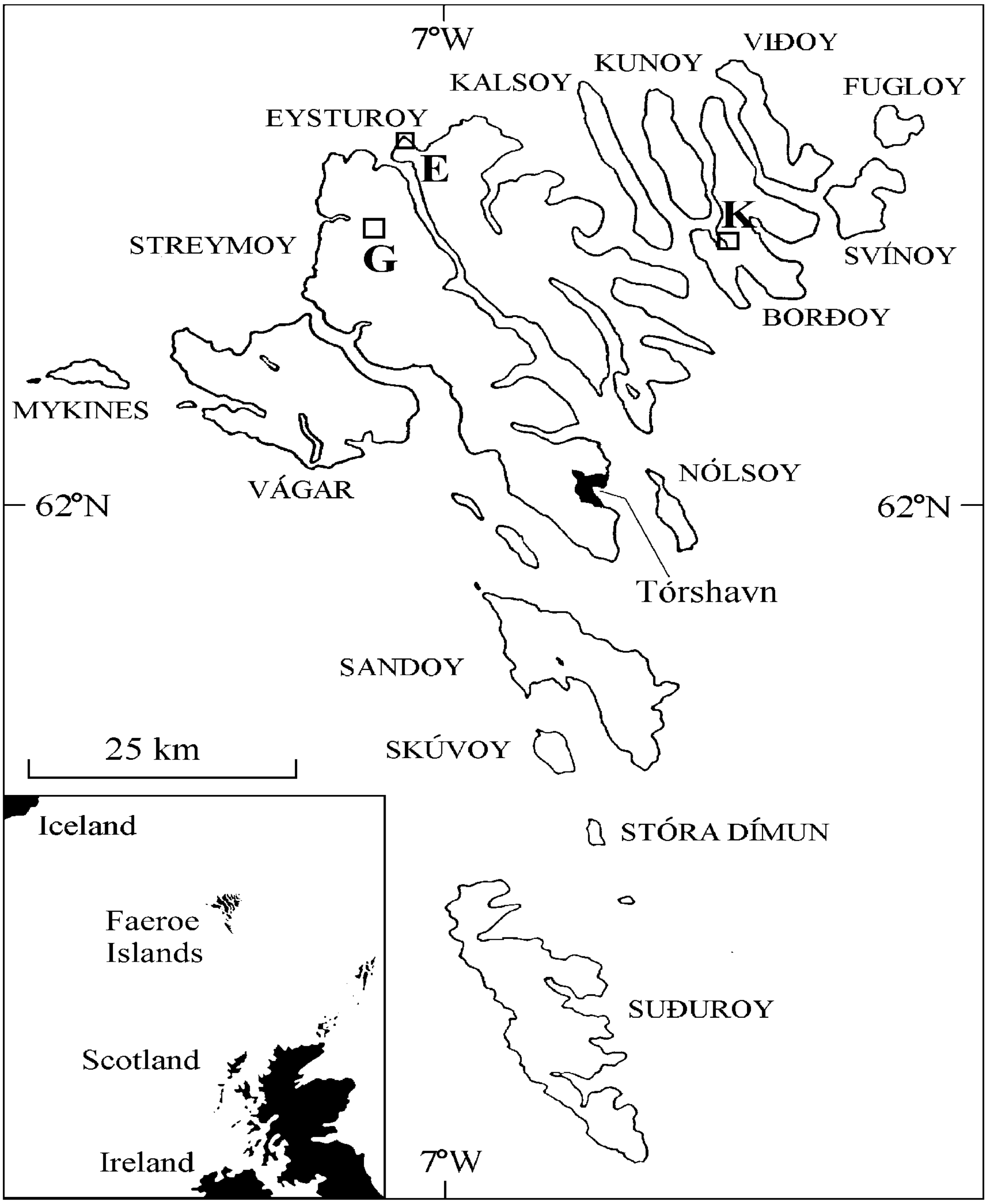

Figure 1 Location of the Faroe Islands in the North Atlantic Sea, and position of the study areas in the Faroe Islands. (E)=Eidiskollur; (G)=Glyvurs fan; (K)=Klaksvik.

ridges, typically 500 m to almost 900 m in altitude, and intervening valleys and fjords. Near-vertical, several hundred metres high free rock faces and cliffs exist, especially along the coast. Colluvial and alluvial fans are widespread at the foot of mountain slopes, and are often located down-slope of large gjogvs (canyons). Solifluction is active mainly on the sediment-covered mountainsides. The overall alpine topography developed mainly during the Quaternary glaciations, with the youngest glaciation being the Younger Dryas. Thus periglacial slope activity has potentially been active during the entire Holocene period. No permafrost occurs on the islands today, but it probably existed in the mountains tops during colder parts of the Holocene, and possibly as late as the Little Ice Age (Humlum & Christiansen 1998a). This might have caused even greater slope activity due to increased weathering on the highest ground.

2. Mountain meteorology in the Faroe Islands

The Faroe Islands represent an extreme maritime southern limit of the Northern Hemisphere periglacial zone (Christiansen & Humlum 2003). Arctic meteorological conditions exist above 200 m asl (Christiansen & Mortensen 2002), and periglacial activity occurs down to 150–300 m asl (Christiansen & Humlum 2003). This locates most of the source areas for the slope processes in the arctic zone with significant periglacial activity.

Measurements from the Sornfelli mountain meteorological station show a mean annual air temperature (MAAT) at 722 m asl of only 1·7 °C in the year 2000 (Christiansen & Mortensen 2002). Air temperatures have also been measured close to the ground surface in high ground on Slættaratindur mountain (1995–2002), with a MAAT of 1·3 °C at 850 m asl (Christiansen & Humlum 2003).

The northern part of the islands receives most precipitation, with around 3300 mm/yr at Hvalvik, at the south end of Saksundalen, and 2700 mm/yr at Strond, a short distance north of Klaksvik (Cappelen & Laursen 1998). These large amounts are mainly due to orographic effects. The largest recorded 24-hour precipitation amounts are from the same two stations, with up to 137 mm d^{-1} at Hvalvik and 180 mm d^{-1} at Strond (Cappelen & Laursen 1998). A continuous winter snow cover exists on the Faroese mountains, with snowpatches lasting into the summer (Christiansen & Humlum 2003), whilst at sea level the mean annual snow cover is only around 44 days (Cappelen & Laursen 1998). Historical records indicate that most snow avalanches occurred on slopes with southerly aspects; just as today, when snow mainly comes with northerly winds, causing snowdrifts on south-facing slopes (Humlum & Christiansen 1998b).

Mean wind speed is generally high in the Faroe Islands. This is due to frequent passages of cyclones along the polar frontal zone that is located in the Faroese area for large parts of the year (Cappelen & Laursen 1998). Winds are mainly from the west to southwest in the islands, but also from the north and southeast (Cappelen & Laursen 1998; Christiansen & Mortensen 2002). There is almost no natural tree vegetation on the islands, mainly due to wind stress.

3. Previous work on periglacial slope landforms in the Faroe Islands

The present day periglacial landforms in the Faroe Islands were first briefly described by Schunke (1977). Later Humlum and Christiansen (1998b) also described the range of periglacial landforms, and their climatic control. Some papers present detailed work on periglacial landforms, but only a few focus on slope processes and landforms.

Relict rock glaciers were mainly active during the Late Weichselian period, when permafrost was widespread (Humlum 1998). Large-scale rockfalls or landslides have been described on the southernmost island, Suðuroy (Jørgensen 1982). A large rock fall occurred in 1870 at Tjørnuvik in the northern end of the Streymoy, and was probably triggered by melting snow or extremely large amounts of rain.

The extreme exposure of the terrain, and especially of free faces where weathering releases sediment particles that can subsequently be entrained by strong winds, initiates distinct aeolian transport and sedimentation. The location, morphology and sedimentology of highland aeolian deposits up to 4 m thick have been described, and their potential for palaeoenvironmental reconstructions identified (Christiansen 1998). On Suðuroy, Edwards *et al.* (2005) have studied the geomorphology, focusing on the period around settlement time. They concluded that increased aeolian deposition has occurred within the last 1600 years as a consequence of human impacts exacerbated by climate.

A few individual radio carbon dates exist for three colluvial fans, indicating activity mainly prior to 8000 cal yr BP and after 3000 cal yr BP (Humlum & Christiansen 1998b). The frequent accumulation and disappearance of the winter snow cover has been suggested as enhancing modern colluvial and alluvial fan sedimentation (Humlum & Christiansen 1998b). Recently, Lawson *et al.* (2005), in a multidisciplinary study on the island of Sandoy (Fig. 1), found that the Faroese landscape was geomorphologically more stable in the mid-Holocene than today. They also concluded that from 2000–4000 cal yr BP, a general destabilisation of the slopes occurred, most likely caused by climatic changes. Edwards *et al.* (2005) found evidence for localised destabilization of the landscape at a large debris fan between the mid sixth–mid seventh century and the late eighth–late tenth century AD. There is no other detailed published geomorphological or stratigraphical work focusing on slope processes and landforms in the Faroe Islands.

4. Methods

A combination of geomorphological, stratigraphical, sedimentological, chronological and modern process studies have been used in this investigation. The geomorphology was studied using maps, aerial photographs and field mapping. The stratigraphy of the investigated landforms was studied in natural sections and profiles excavated at selected locations.

Chronology was determined using ^{14}C AMS dates of organic material from the studied sections. Samples were obtained from the upper- or lowermost one or two centimetres of organic-rich layers. The samples were packed in the field into double plastic bags. All samples were stored cold until laboratory proceedings could be carried out under clean room conditions. Roots were carefully removed in the laboratory. Then the organic samples were dispersed in distilled water in petri dishes, and macrofossils were picked with a Pasteur pipette using a binocular microscope. The extracted macrofossils were given an acid–base–acid pre-treatment consisting of 1% HCl (8–10 hrs just below boiling point), and 0·5% NaOH (<1 hr at room temperature). Extracted macrofossils were acidified to pH 3 and dried. The rest of the organic samples were given an acid–alkali–acid pretreatment consisting of a 1% HCl (8–10 hrs just below boiling point) and 1% NaOH (8–10 hrs just below boiling point). Adding concentrated HCl precipitated the soluble part that was extracted by centrifugation around 3500 rpm. The precipitate, consisting mainly of humic acids, was washed until pH 4 and dried (SOL fraction, Table 1). Prior to making the accelerator measurement, all material was combusted to CO_2 and converted to graphite using a Fe-catalyst reaction. The radiocarbon analyses were determined with the Uppsala EN-tandem accelerator. A small fraction of approximately 0·05 mg carbon of the CO_2 gas was used for the measurement of the natural mass fractionation, $\delta^{13}C$, in a conventional mass spectrometer (VG OPTIMA). Radiocarbon dates are reported in radiocarbon years Before Present (yr BP), with the present defined as AD 1950. To calibrate the data, the OxCal v.3.8 software (Bronk Ramsey 2000) was used, and a standard deviation of 2σ was used for the calibrated dates (Table 1).

Meteorological and geomorphological process studies were carried out for a large debris-flow event. Process measurements of modern aeolian sedimentation on a mountain aeolian sediment cover have also been carried out. This was done using small (15 × 25 cm) green plastic mats, with very thin 2 cm-long plastic pins protruding from the mat, to catch the windblown sediment. The mats were nailed to the ground with 10 cm-long nails.

5. Colluvial fan sedimentation in Saksundalen

In the valley of Saksundalen in northern Streymoy, one of the largest colluvial fans in the Faroe Islands was studied. It is called the Glyvurs fan, after the place-name Glyvur. It has its apex where the canyon Glyvursgjogv appears in the mountainside (Fig. 2).

5.1. Morphology and depositional stages

The Glyvursgjogv area is a large, complete and typical slope landform system with a niche source area, a gjogv transport

Table 1 Radiocarbon dates of different specific fractions and macrofossils from organic layers in the northern Faroe Islands. K=Klaksvik, G=Glyvurs fan and E=Eidiskollur. SOL=soluble organic liquid. Depth is the sampling depth below the terrain surface. ^{14}C age is the measured ^{14}C age. All calibration was done using OxCal v.3.10 (Reimer *et al.* 2002) based on the calibration data set of (Stuiver *et al.* 1998). A standard deviation of 2σ was used for the calibrated dates. The AAR-3180 sample (Humlum & Christiansen 1998b) was calibrated by the Seattle calibration programme ver. 3.03, and is reported with a standard deviation of ± 1σ

Sample fieldname	Sample no	Dated material	Depth (cm)	^{14}C age	^{14}C error	OxCal cal yr BP	∂^{13}C (‰)
K, section A sample A	UA-23699	Salix wood, Juniperus leaves	145	4310	45	4820–5040	− 27·1
K, section A sample B	UA-23906	Very decayed vegetative material	55	875	40	690–920	− 27·8
K, section A sample C	UA-23907	Very decayed vegetative material	80	2175	40	2060–2330	− 27
K, section A sample D	UA-23700	Very decayed vegetative material	110	2990	45	3000–3340	− 27·7
K, section C sample E	UA-23701	SOL	130	3780	45	3980–4350	− 28·1M
K, section C sample F	UA-23702	SOL	35	2290	45	2150–2360	− 30·2
K, section B sample G	UA-23703	SOL	75	2470	45	2360–2720	− 27·6
K, section B sample H	UA-23908	Very decayed vegetative material	115	6970	55	7680–7940	− 25
K, section D sample I	UA-23704	SOL	138	5385	50	6000–6290	− 27
K, section D sample J	UA-23705	SOL	51	4125	45	4520–4830	− 28·5
G, Section B sample 1	UA-23706	SOL	175	7200	60	7930–8170	− 26·6
G, Section B sample 2	UA-23707	SOL	28	3935	45	4240–4520	− 27·3
G, Section C sample 3	UA-23708	*Hylocomicum splendens*	83	2150	45	2000–2310	− 22·6
G, Section C	AAR-3180	Plant parts, not roots	108	2040	45	2015–1935	− 26·8
G, Section C sample 4	UA-23709	Unidentifiable wood fragment	144	2580	40	2490–2770	− 27·8
G, Section C sample 5	UA-23909	Badly decayed plant material (rootlets)	178	2215	45	2120–2340	− 25·6
G, section D sample 6	UA-23710	Moss stems, lacking leaves	120	1715	40	1530–1720	− 28·2
E, sample 7	UA-23711	SOL	225	6030	55	6730–7150	− 25·4

zone and a large colluvial fan, the SW facing Glyvurs fan (Fig. 2). The shallow, wide niche source area is approximately 0·5 km^2 in extent, and rises from 250 to 550 m asl, reaching the mountaintop. Glyvursgjogv drains the source area, starting from around 300 m asl, and flows out in the valley side at 110 m asl. It is 650 m long. Glyvursgjogv is a dyke-controlled 4–5 m-wide canyon in which basalt benches are exposed in the steep sides (Fig. 3). The large Glyvur fan has accumulated below Glyvursgjogv. The Glyvurs fan is approximately 300 m long and 300 m wide in the lowermost part, and has an average gradient of 10°.

The fan-surface morphology shows that it accumulated in different stages, initially with the development of a small and steep fan close to the apex. Subsequent accumulation occurred farther from the apex, forming the present central and finally distal parts of the fan (Fig. 2). These different parts of the fan, located at different levels, reflect the successive, progradational growth stages of typical colluvial fan sedimentation (Blikra & Nemec 1998). Fan stage 1, represented by zone one (Fig. 2), involved deposition of the proximal and highest parts, with the apex of the fan at around 120 m asl. These initial deposits are now incised by the channel containing the creek that drains Glyvursgjogv. Stage 2 (zone 2 on Fig. 2), involved extension to the present proximal part of the fan across most of its present area. At least three substages of stage 2 can be identified in the morphology of zone 2 of the fan, and can be chronologically arranged on the fan. Stage 3 (zone 3 on Fig. 2) occupies only the central and southern, lower section of the fan, whilst stage 4 (zone 4 on Fig. 2) is restricted to the lower north-western end of the fan. Finally, the recent and most active part, stage 5 (zone 5 on Fig. 2), occupies the northwesternmost section of the fan. Erosion occurs along the channels cut into older fan sediments, which are exposed in sections along the channel sides, and also in the toe of the fan, where the main stream has exposed fan sediments.

5.2. Active slope processes

The niche is partly covered by sediment, but also consists of large areas with exposed basalt bedrock. The northern part is capped by a discontinuous cover of about 0·5 m of aeolian sediments, deposited mainly by northerly winds. Small streams drain the niche area through Glyvursgjogv and transport sediment from the source area.

In Glyvursgjogv, weathering of the basalt causes large blocks to fall into the gjogv (Fig. 3). During intensive precipitation events or during snow melt, large amounts of water drains through Glyvursgjogv, transporting large blocks down the gjogv, and in some cases also out from the gjogv on to the fan.

On the distal part of Glyvurs fan large blocks are partly embedded in the sediment or rest on the surface (Fig. 3). Most have a significant lichen cover, but some appear to be fresh, indicating recent deposition. Some of the blocks have been reworked, probably by snow avalanches since deposition, as they have either pushed sediment on their down-slope side, or have some local sediment accumulations around them.

5.3. Fan stratigraphy and sedimentation

The sedimentological characteristics of debris-flow and snow-avalanche deposits, as described in detail by Blikra & Nemec (1998), were observed in the investigated sections (Fig. 4). Snow avalanches are capable of transporting large amounts of debris, including large boulders. The deposits from single events are often represented by irregular lobes of unsorted debris, no more than one-cobble or -boulder thick (Blikra & Nemec 1998). These deposits are often mixed or capped by water-lain stratified sand or gravel, deposited by nival melt-water. The deposits found in the Glyvurs fan show the distinct snow-avalanche features, characterised by scattered blocks interlayered by sorted and stratified sand and fine gravel (Fig. 4A). Debris-flows are gravitational movements of highly concentrated mixtures of debris and water, and sometimes also involve snow or slush. Their deposits are the result of the immobilisation process during deposition, and are normally a diamict unit of pebbly to bouldery beds ranging from matrix- to clast-supported (Blikra & Nemec 1998). Debris-flow deposits have frequently been observed in the sections studied (Fig. 4B), and may range from relatively thin diamict units a

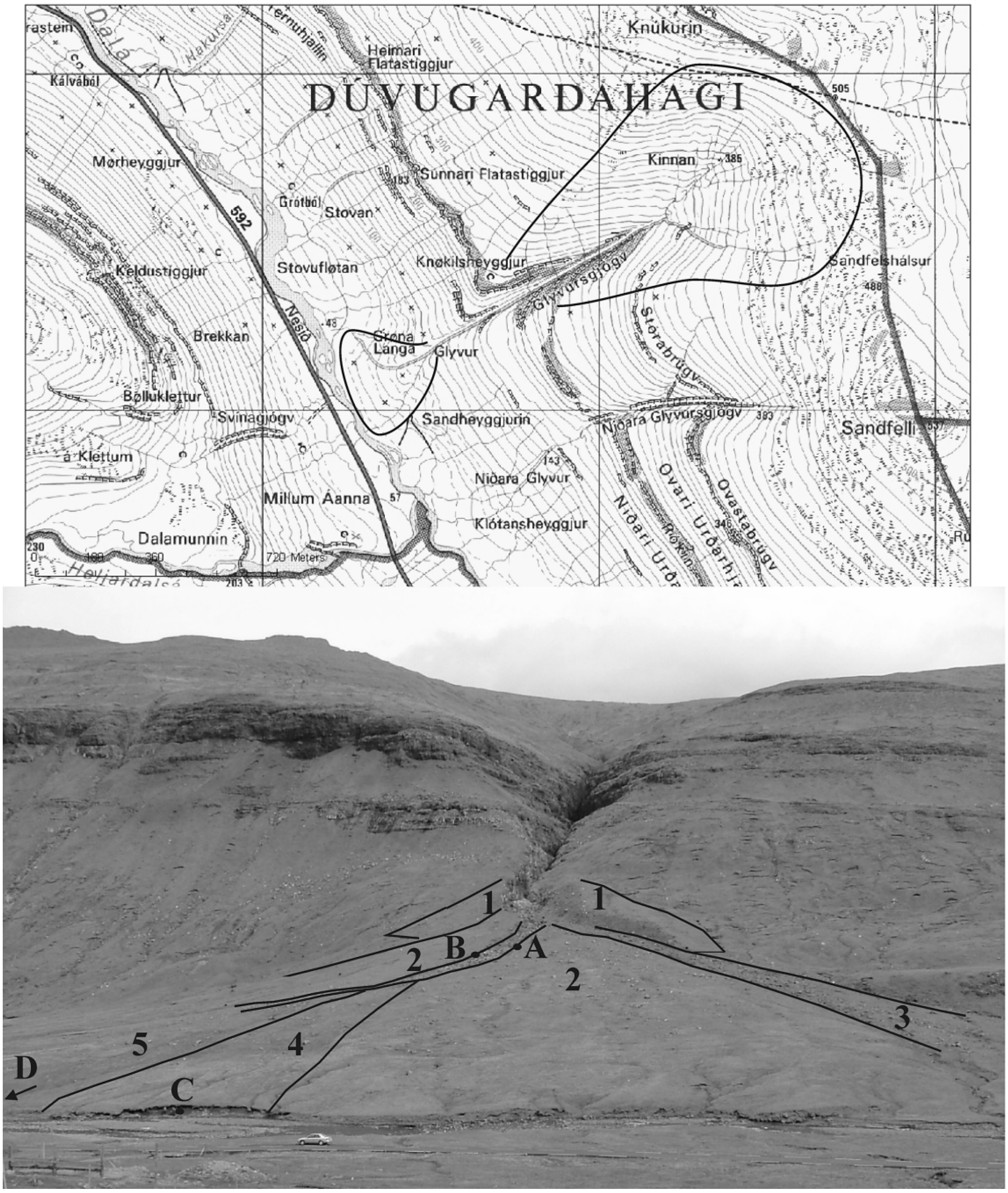

Figure 2 (Upper) Map of the Glyvursgjogv area in Saksundalen, with the source and fan areas. North is towards the top of the map. The distance between grid lines is 1 km. (Lower) Glygvursgjogv with Glyvurs fan. The five stages in the deposition of Glyvurs fan are shown represented by numbered zones from 1 to 5. The location of the investigated A, B, C and D sediment sections are indicated. Note car for scale in the lower part. Photo from 28 May 2004.

few to 10 cm thick, to thicker and bouldery units of more than 1 m in thickness.

Fan stratigraphy was investigated in four sections. Two are located in the upper parts of zone 2, and two in the lowermost parts of zones of 3 and 4 (Fig. 2). Both sections A and B are natural exposures in a large channel side. The stratigraphy in the channel is horizontally continuous.

Section A is located about 50 m from the apex of zone 2. It is 2·5 m high and is interpreted as consisting solely of large clasts and boulders interpreted to be of snow-avalanche origin (Fig. 4A), with interveining stratified thin layers of fine-sands (Fig. 5A). Blocks up to 1–2 m in diameter occur in this unit. The boulders are often flat-lying; also a characteristic typical of snow-avalanche deposits (Blikra & Nemec 1998). As there is no organic material in this unit, this part of the fan could not be dated.

Section B is located approximately 125 m down-slope from the apex. Here 2·2 m of mainly diamict units dominate. These are interpreted as very coarse-grained debris-flow and snow-avalanche deposits (Figs 5B and 4B). However, the top 30 cm mainly comprise organic-rich sediments, with some clasts up to 20 cm long. Soluble organic liquid derived from a sample in the lower 2 cm of this layer was dated by ^{14}C AMS to 4520–4240 cal yr BP (UA-23707, Table 1). At 175 cm below the fan surface in profile B, soluble organic liquid derived from a sample obtained from a shallow dark-coloured organic-rich layer was dated to 8170–7930 cal yr BP (UA-23706, Table 1). The overall stratigraphy was found to be consistent along the approximately 100 m section exposed in both sides of the creek in the upper part of zone 2. Therefore, fan sedimentation in stage 2 is assumed to have started prior to 8000 years ago, and most of the sediment in this section was deposited before

Figure 3 (Left) Inside the canyon Glyvursgjogv, where blocks are on their way out to Glyvurs fan. The entrance to the gjogv is seen in the photo background. (Right) Blocks partly embedded or standing on the lower Glyvurs fan surface. Photos 28 May 2004.

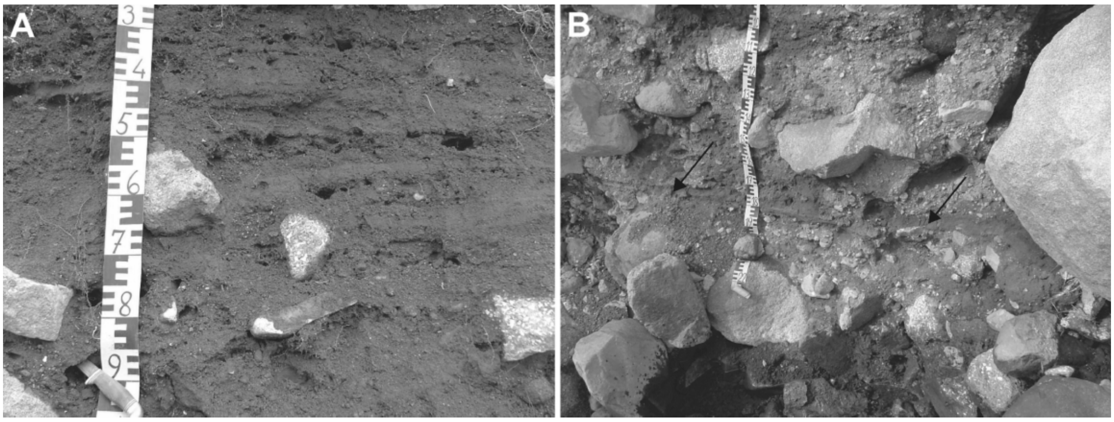

Figure 4 Sedimentological characteristics of deposits from the Glyvurs fan. (A) Snow-avalanche deposits showing large blocks interbedded with stratified sediments (from section A in Figure 5). (B) Two debris-flow units separated by a stratified organic-rich layer (from section B in Figure 5).

4400 years ago. Since then, mainly vegetation had accumulated on the zone 2 fan surface, interrupted by a few snow-avalanche events transporting individual smaller blocks onto the fan surface.

At the lowermost distal part of fan zone 4 (Fig. 2), the 2 m-high section C was investigated. Here the fan consists of interbedded organic-rich layers and clast-supported coarse-grained units with a sandy–gravelly matrix and clasts up to 1 m long in the thickest layer (Fig. 5). The units increase in thickness and maximum grain-size upwards through the profile, culminating in a 40 cm-thick layer with clasts up to 1 m in length. This unit is interpreted as having been deposited by several individual snow avalanches, and represents most of the sediment deposited during fan stage 4 at this location. Four ^{14}C AMS dates on plant fragments from different organic-dominated layers constrain the sedimentation chronology (Fig. 5). These indicate fairly rapid sedimentation at the base of the profile in the period from 2300 to 1900 years ago (UA-23708, UA-23709, UA-23909, Table 1; AAR-3180, Humlum & Christiansen 1998b). There is significant overlap in the four dates, with one slightly older (2770–2490 cal yr BP), most likely reflecting incorporation of older organic debris. The overall stratigraphy exposed along the creek cliff along the lower fan zone 4 is consistent and is assumed to be representative for the sedimentation in fan stage 4. Most of the snow-avalanche deposits in stage 4 are assumed to have occurred after 2200 years ago.

In the youngest part of the fan (zone 5), the 1·7 m-high section D is eroded by the main stream in the valley bottom. This section is located next to an active fan channel, and there is also evidence of channel-fills in the exposure (Fig. 5). From the top of a basal organic dominated layer, moss stems, lacking leaves, were ^{14}C AMS dated to 1720–1530 cal yr BP. Above this layer are two coarse-grained units, separated by a channel filled by water-lain deposits. These coarse-grained units are clast-supported and seem to occur as lenses. The upper has clasts up to 15 cm long, while the lower one has clasts up to 30 cm long, both in a sandy–gravelly matrix. The lower unit, which is 0–60 cm thick, reflects the main zone 5 deposit in this part of the fan. Both units are interpreted as the products of deposition by several snow avalanches; while the intervening channel infill probably represents fluvial deposition. Section D is most likely the most complete section in zone 5, as the area is today also partly being eroded by the modern creek draining Glyvursgjogv. Therefore, we assume that the section D sedimentation history is representing most of the stage 5 activity. Snow-avalanche activity in stage 5 started around 1600 years ago, and has probably been more or less ongoing since then, in order for the entire section D to be deposited.

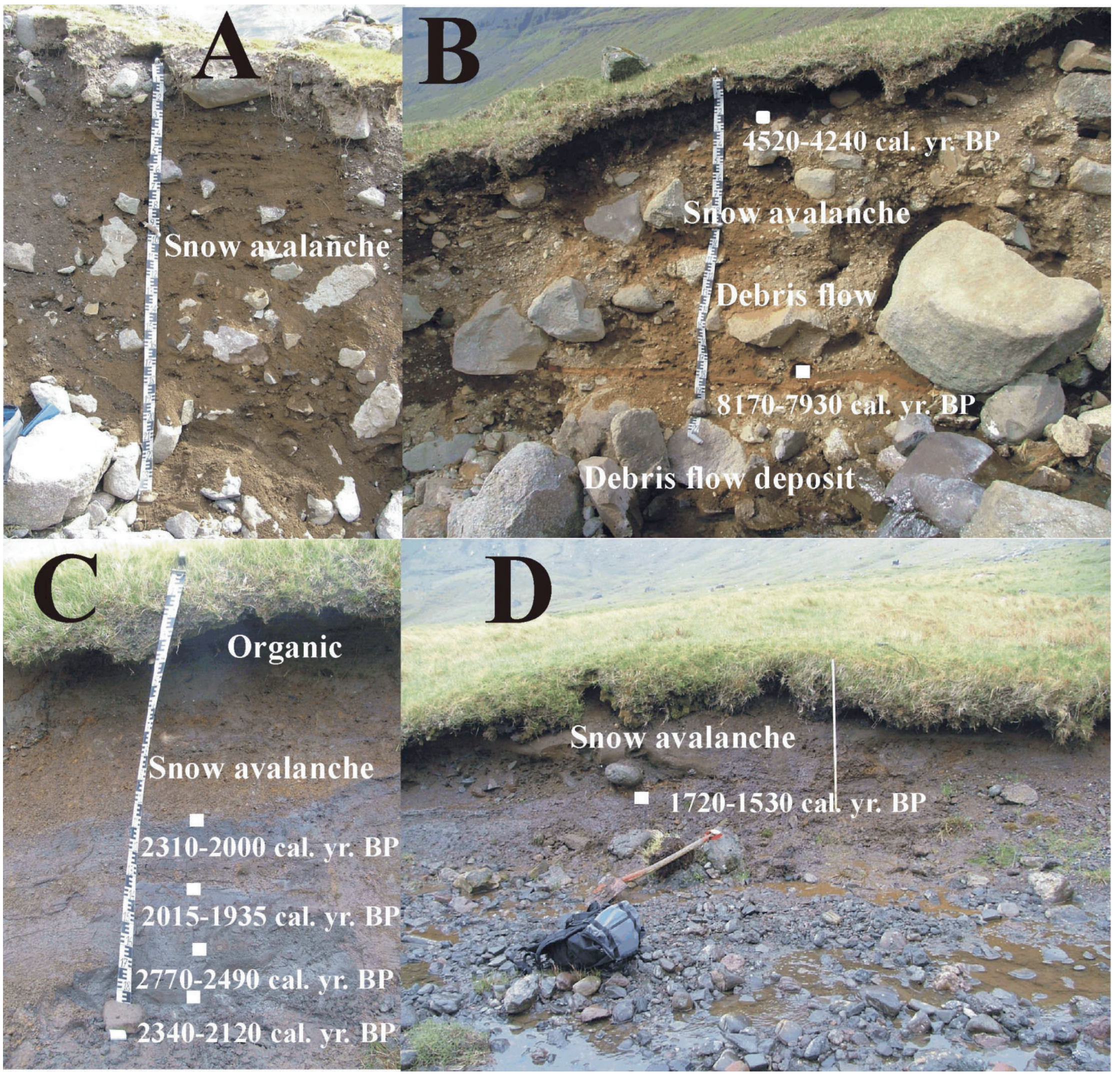

Figure 5 Investigated sediment profiles A, B, C and D in Glyvurs fan, with ^{14}C AMS dates and interpretation of deposits. The ruler has cm intervals.

In conclusion, fan sedimentation must have started significantly before 8000 yr BP, with the accumulation of the most proximal upper fan stage 1. Deposition probably commenced soon after deglaciation of the valley, which is thought to have occurred around 15 000 yr BP. Stage 2 sedimentation commenced prior to 8000 years ago, but the central part of this stage was deposited mainly before 4400 years ago, and was most likely deposited both by debris-flows and snow avalanches. A major channel, fan stage 3 (zone 3 Fig. 2), was incised into fan zone 2 sometime between 4400 yr BP, when stage 2 sedimentation ceased, and 2200 yr BP, when stage 4 started to develop. Stage 4 sedimentation only started when the main sediment transport route on the fan was directed towards the northern fan part. At that time the channel representing stage 3 was abandoned, with its bottom located higher than the bottom of the still active main creek in the proximal part of the fan. Fan sedimentation reached the outermost part of the present day fan with the main snow-avalanche activity after 2200 cal yr BP in stage 4. The bulk of the sedimentation subsequently shifted towards the north-westernmost part of the fan and the main development of stage 5, started briefly after 1600 cal yr ago. This part is still the active zone, demonstrated by quite recent snow-avalanche events. Zones 3, 4 and 5 to some extent reflect fluvial incision into the main fan zone 2.

The present study demonstrates snow-avalanche and debris-flow sedimentation to dominate in the accumulation of the different zones of the Glyvurs fan, showing the successive stages in the fan accumulation and incision. Snow-avalanche sedimentation can be more horizontally spread over larger areas of the fan, but based on the consistency of the dated sections, it is believed that the majority of the avalanche sedimentation occurred within the respective fan zones, when they were active. Based on the presented studies it is assumed that sedimentation and development of the large Glyvurs fan must have occurred recurrently throughout the Holocene.

6. Debris flows in Klaksvik

The second largest Faroese town of Klaksvik, on the island of Bordoy (Fig. 1), is almost completely surrounded by steep mountainsides and by the sea towards the NW and SE. Expansion of the town has occurred mainly up the slopes. The Marknastiggjur mountain slopes NW of the town of Klaksvik (Fig. 6) were studied mainly to assess the frequency of slope activity and the meteorological conditions when a large debris flow reached the upper parts of the settlement in 2000.

6.1. Morphology

The Marknastiggjur mountainside NE of Klaksvik (Fig. 6) has an average gradient of around 23° and extends up-slope to a plateau at 320 m asl. There are no prominent colluvial or alluvial fans, but rather a more or less continuous, thin

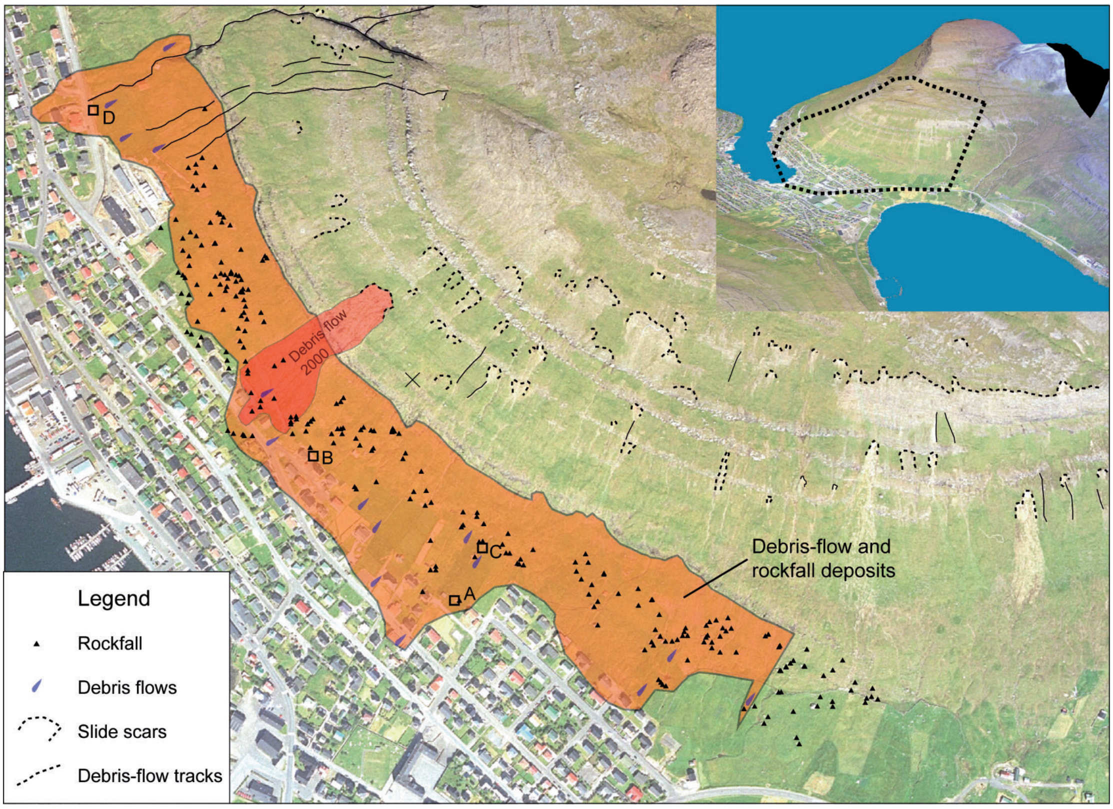

Figure 6 The investigated areas in Marknastiggjur showing the distribution of rockfall and debris-flow deposits. Note also the amount of slide scars and debris-flow tracks on the slope. The location of the studied sections is shown (A, B, C and D). The inset gives an overview of the Klaksvik landscape seen from the south. The land surface is represented by an aerial photograph from 2001. The extent of the debris flow in 2000 that occurred in the investigated area can be seen directly above the town.

sediment cover on the mountainside, with protruding basalt benches at several levels (Fig. 6). Rockfall and debris-flow deposits dominate. The sediment cover is dissected by many small gullies, some extending all the way down the mountainside, but otherwise it is covered by almost continuous grass vegetation (Fig. 7A). Some small-scale rock falls occur from the basalt benches. There is no free face above the mountainside. An eroded dyke extends down parallel with the mountainside forming a gjogv, Lidargjogv. A fan extends down to the town from the foot of Lidargjogv.

At the SW end of the mountainside, large snow avalanches twice destroyed the farm Gerðar at the foot of the mountain slope, on 12 March 1745 and 12 March 1765. The latter avalanche killed nineteen persons. No new houses have been built here, which is today a memorial site.

6.2. Debris-flows of 18 September 2000

In the mid afternoon on the 18 September 2000, three debris-flows were released a little more than halfway up the Marknastiggjur mountainside (Figs 6, 7). At the same time, several other debris flows were released, but only in the northern Faroe Islands, on the islands of Streymoy (northern part), Eysturoy, Kalsoy, Kunoy and Bordoy. All were initiated as translational slides, which are nearly always triggered by heavy rain (Selby 1982).

On the Marknastiggjur mountainside, one of the debris-flows reached all the way down the mountainside into the upper part of the town (Figs 6 and 7). At the crown of this slide a steep 1–2 m-high scarp was exposed in fine-grained sediment, from which large undeformed sediment blocks slid downhill. The failure plane did not reach the basalt bedrock, but occurred within the soil cover. Further down, more small blocks were transported down-slope within the flowing debris, and at the lower part of the mountainside liquefied debris-flows occurred, covering almost all of the run-out zone with a thin, approximately 1 to 15 cm-thick layer of sediment, but with intervening areas without any sedimentation (Fig. 7). Many large boulders were transported down-slope by the debris-flow from a basalt bench that was overrun by the flow. The debris-flow hit a house (Fig. 7) in the outer run-out zone, and partly destroyed a neighbouring area that was being prepared for a new building.

Most of the run-out zone of the 2000 debris-flow was already almost completely re-vegetated by grass again by 2004, but the back scarp was still clearly evident on the mountainside. Several older debris-flow scarps are also characteristic in the Marknastiggjur mountainside (Fig. 6) demonstrating that sliding and debris flows are a common process on this mountainside.

6.3. Precipitation control on the 18 September 2000 debris-flows

The 18 September 2000 debris-flow event occurred during a 4–5 day passage of a low-pressure system across the islands. The debris-flows were triggered following the first heavy autumn rainfall period (Fig. 8). Precipitation data collected daily at 0700h at the Strond power station at 6 m asl, approximately 3 km north of Klaksvik (Cappelen & Laursen 1998), show that 89·9 mm of rain fell in the period 5–9 September, and a further 51·7 mm of rain fell in the period of 14–19 September. In total, 141·6 mm fell in the 15 days before the debris-flows occurred. Prior to this, only minor amounts of precipitation had occurred since early July. The 18 September event does, however, not coincide with the maximum daily precipitation during the autumn of 2000. The maximum daily total of 46·1 mm fell on 23 October. Similarly

Figure 7 (Upper left) View of the Marknastiggjur mountainside above the houses in Klakvik, where the debris-flow occurred in 2000. Photographed on 24 May 2004. (Upper right) View of the debris-flow that occurred 18 September 2000 on the Marknastiggjur mountainside in Klaksvik, photographed on 25 October 2000. (Lower left) View of slides that also occurred on 18 September at the southern end of the Marknastiggjur mountainside, photographed 25 October 2000. (Lower right) Close-up of debris that reached down and into the house. Note the discontinuous sediment cover containing several large boulders. Photographed on 25 October 2000.

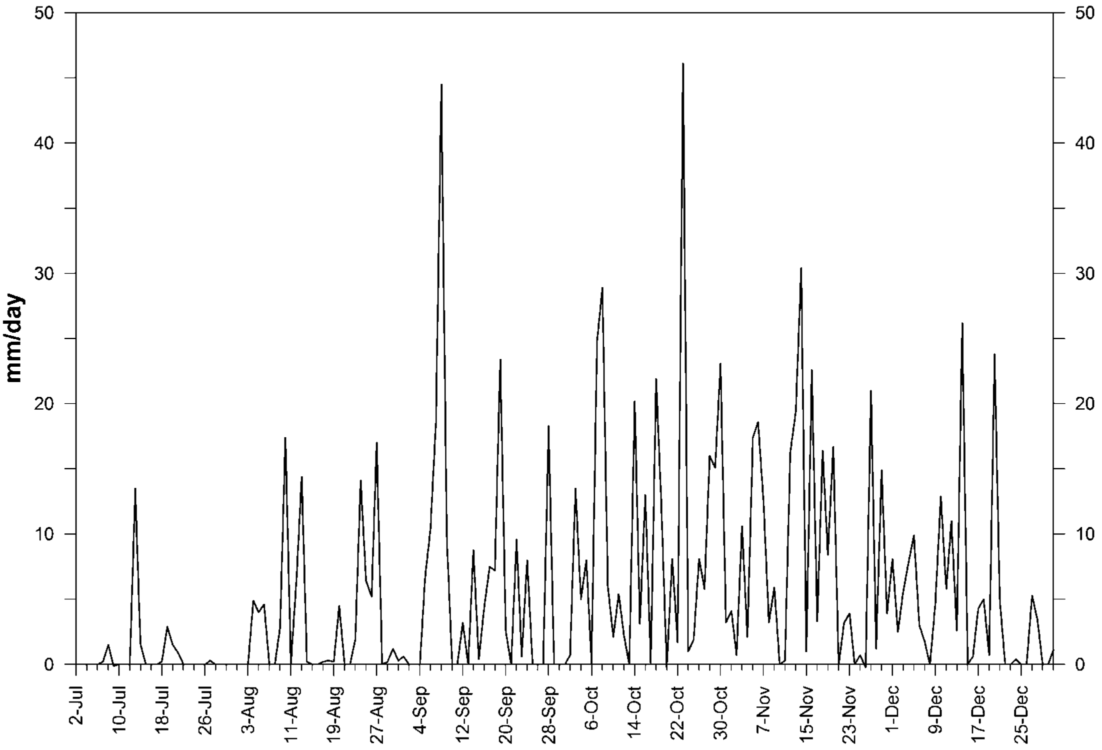

Figure 8 Daily precipitation as measured at the Strond power station at 6 m asl, approximately 3 km north of Klaksvik from 2 July to 31 December 2000. Measurements occur once daily at 0700h. Data from the Faroese Office of Public Works.

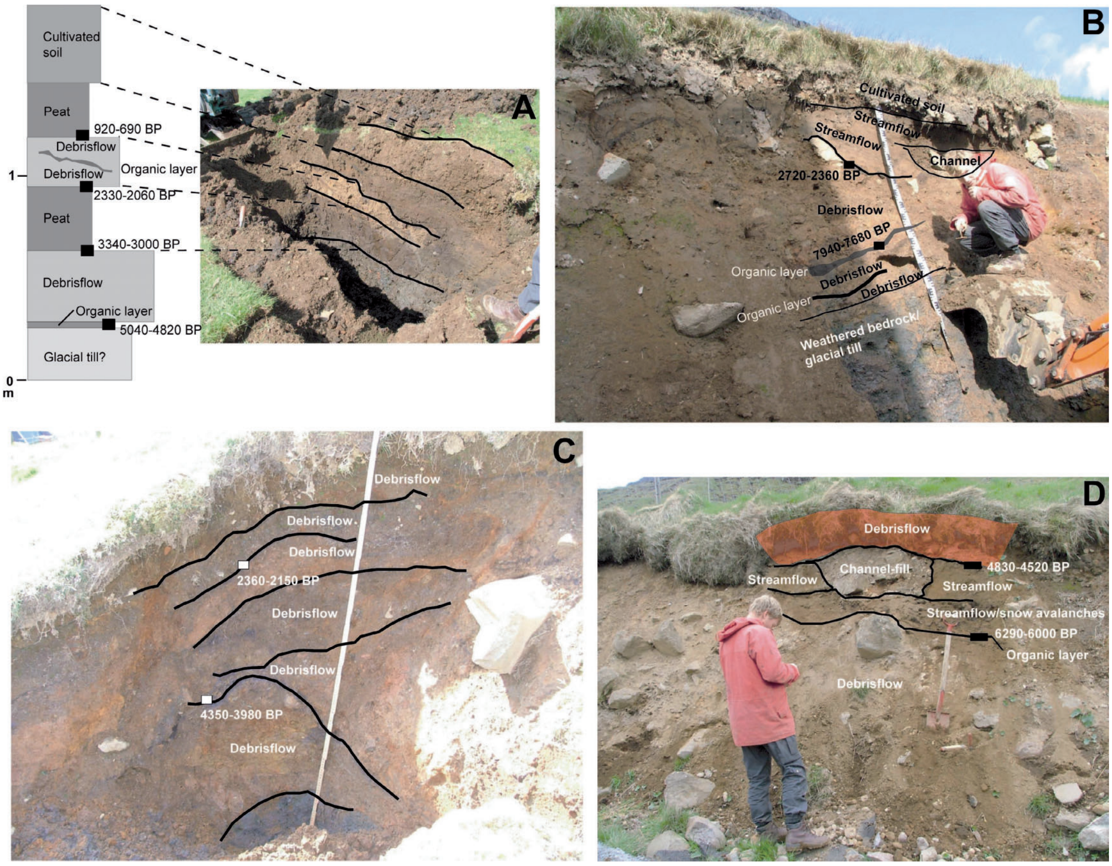

Figure 9 Stratigraphy of the investigated sections in Klaksvik, showing location of dated samples and interpretation of the deposits.

the 141·6 mm that fell before the debris flows occurred was not the largest precipitation event that autumn. Much more precipitation fell during the autumn after 18 September 2000, without triggering debris flows.

6.4. Stratigraphy and sedimentation on the lower Marknastiggjur slope

The stratigraphy of deposits along the lower mountainside was investigated in 17 sections, mainly along existing exposures along streets, in house or road excavations or along creeks. Two sections were excavated to provide additional data in areas without exposures. The stratigraphic and sedimentological investigation demonstrated that debris-flows, snow avalanches and streamflows had been the main processes forming the deposits on the lower slope (Fig. 9). The general extent of debris-flow deposits is restricted to the upper parts of town on the lower Marknastiggjur mountainside (Fig. 6).

The sediments and stratigraphy were examined in detail at four sections located in four different parts of the lower mountainside (see location in Fig. 6). Individual units or events were separated by organic-rich layers enabling dating (Fig. 9).

Section A is 1·7 m deep, and was excavated on the lower mountain slope. It consists of a matrix-supported diamicton at the base covered by an organic layer with leaves and branches (Fig. 9). From the top of this layer *Salix* wood and *Juniperus* leaves were dated to 5040–4820 cal yr BP (UA-23699, Table 1). Above this are diamictons 35 cm and 25 cm thick containing clasts up to 5–15 cm long, interpreted as debris-flow deposits. A 30 cm-thick organic-rich layer with macroscopic plant remains separates these two units. The bottom of this layer was dated to 3340–3000 cal yr BP (UA-23700, Table 1) and the top to 2330–2060 cal yr BP (UA-23907, Table 1). Both dates were obtained from very decayed vegetative material. A 20 cm-thick organic layer caps the upper diamicton, and at its base very decayed vegetative material was dated to 920–690 cal yr BP (UA-23906, Table 1). Finally, the 35 cm-thick top layer represents the cultivated soil.

Section B is 3·3 m deep. It was excavated 10 m from the house that was affected by the landslide in 2000, along the previous excavation for a new house (Fig. 6; Fig. 7 lower right), in the area where debris-flow sedimentation occurred. The bottom 1·6 m was weathered basalt bedrock (Fig. 9). The overlying sediment is composed of coarse-grained, clast- and matrix-supported diamictons, interpreted as debris-flow deposits. Several organic-rich layers separate the debris-flow units, and two of these were dated. The lower sample of very decayed vegetative material gave an age of 7940–7680 cal yr BP (UA-23908, Table 1), while soluble organic liquid from the upper sample was dated to 2720–2360 cal yr BP (UA-23703, Table 1). Stratified sands and gravels cap this upper dated layer, indicating sedimentation by surface runoff processes. Finally a 20 cm-thick dark brown cultivated soil caps the section. A few large boulders occur in the upper two units, most likely representing individual outrunners from snow avalanches or rockfall boulders from the basalt outcrops.

Section C is a 1·7 m-high natural section about 150 m upslope of section A. The section consists mainly of six matrix-supported diamicton units, 1–60 cm thick, separated by five thin organic-dominated layers 1–2 cm thick (Fig. 9). The diamictons are interpreted as debris-flow deposits. Soluble organic liquid from the lowest organic layer was dated to 4350–3980 cal yr BP (UA-23701, Table 1). The second organic layer from the top yielded an age of 2360–2150 cal yr BP (UA-23702).

Figure 10 Eidiskollur peninsula seen towards the south, with the eroding cliff to the right, and the associated mountain top aeolian sediment cover to the left. P marks the location of the investigated sediment section in the aeolian sediments. The solid black line shows the location of the line of eight sedimentation mats, which were in use from 2000 to 2004. A person is standing at the end of the line of mats for scale. Photo 10 June 2000.

Section D is located in the lower part of the fan below the canyon Lidargjogv at the northwestern end of Marknastiggjur (Fig. 6). It is a 3 m-high road-side section, which was partly excavated. The lower half consists of a clast-supported diamicton, with blocks up to 140 cm in a sandy–gravelly matrix (Fig. 9). The unit is interpreted as having been deposited by a debris-flow. On top of this is a unit composed of thin organic-rich layers, small lenses of sorted sand and fine gravel, and individual clasts up to 15 cm long. Soluble organic liquid from a sample from the middle organic horizon was dated to 6290–6000 cal yr BP (UA-23704, Table 1). Overlying this unit is a 70 cm-thick channel fill of clast-supported gravel with clasts up to 40 cm in diameter. Soluble organic liquid obtained from a sample from a 1–2 cm thick overlying organic layer was dated to 4830–4420 cal yr BP (UA-23705, Table 1). The upper 50 cm is a clast-supported diamicton, with clasts up to 15 cm in a sandy–gravelly matrix, interpreted to be a debris-flow deposit. It is possible that the deposits interpreted as having been formed by debris-flows may instead have been snow-bearing debris-flows or slush-flows.

In conclusion, the investigated sections show evidence of a series of debris-flows. Individual dated debris-flow events include one prior to ~7800 cal yr BP; one between ~7800 and ~2500 cal yr BP; one prior to ~6100 cal yr BP, one prior to ~4200 cal yr BP; one between ~4900 and ~3200 cal yr BP; one after ~4700 cal yr BP; three between ~4200 and ~2300 cal yr BP; two after ~2300 cal yr BP; and one between ~2200 and ~800 cal yr BP. The temporal distribution of debris-flow activity indicates sporadic events throughout the Holocene in the lower part of the slope at Marknastiggur, with a possible tendency for increased mid to late Holocene activity.

7. Mountain top aeolian sedimentation at Eidiskollur

Eidiskollur is a plateau-like peninsula extending into the sea at the northern end of Eysturoy Island (Fig. 1). A late Weichselian glacial trimline is located at an altitude of ~150 m asl at Eidiskollur, implying that the mountain-top plateau may have been exposed to severe periglacial activity during the late Weichselian. The high coastal cliffs of the Eidiskollur peninsula are associated with significant aeolian mountain-top sedimentation.

7.1. Morphology and active processes

The west side of the peninsula consists of near-vertical cliffs extending from the sea to the plateau around 300 m asl (Fig. 10; Christiansen 1998, fig. 1). On the cliffs weathering of the basalt benches is occurring. The exposed setting gives rise to aeolian sediment transport by strong winds up from the cliffs to the plateau surface above, where wind speeds are reduced, allowing sediment deposition (Christiansen 1998). The plateau supports a discontinuous cover of vegetated aeolian sediment, with a maximum thickness of 2·25 m approximately 26 m from the plateau edge. The aeolian sediment cover often consists of a shallow ridge, with the highest part reflecting the location of the zone of maximum sedimentation some distance from the crest of the cliff (Ballantyne 1998). The margins of the aeolian sediments are exposed unvegetated scarps, without vegetation (Fig. 10), indicating localised erosion.

A line of eight small, 700 cm^2 plastic mats, with 1 m between the mats, was installed 1–8 m from the cliff edge and onto the ridge top of the aeolian sediment cover (Fig. 10). Mats were installed in June 2000, and the sediment collected by the mats was sampled in June 2001, and again in late May 2004. The largest amounts of sediment on the individual mats were 13–17 g in 2001 and 33–40 g in 2004. These amounts were collected in the zone 4–6 m from the cliff top in 2001. The annual sedimentation rates for all eight mats were 0·01–0·02 g/cm^2, both in 2000–2001 and in 2001–2004. In the period 2000–2004, a maximum amount of 53 g was collected at the mat 5 m from the cliff edge. These results indicate that aeolian sediment transport from the adjacent cliff is ongoing, enabling sedimentation on the plateau.

7.2. Stratigraphy and sedimentology

Along the edge of the aeolian sediment cover on Eidiskollur, a section was excavated to study the sediment. The sediment was massive, homogenous and brown throughout the profile, and consisted of gravel in a fine-grained sandy matrix. No sediment structures were found, except a weak tendency for a horizontal layering, though without distinct individual units. Basalt bedrock was reached in the bottom of the profile. A bulk sample from the lowermost part of the aeolian sediment just above the bedrock was collected for ^{14}C AMS dating. Soluble organic liquid derived from this sample yielded an age of 7150–6730 cal yr BP (UA-23711, Table 1).

Because of the homogenous massive sediment, continuous sedimentation is assumed. Division of sample depth by sample age yields an average Holocene sedimentation rate of 0·3 mm/yr. This seems to correspond nicely with the largest modern sedimentation rate as measured in the mat profile, which is about 0·06–0·13 mm/yr. The evidence from the Eidiskollur aeolian sediment cover therefore probably implies continuous Holocene aeolian sedimentation, at least since ~6900 cal yr BP.

8. Discussion of Holocene slope activity in the northern Faroe Islands

The very exposed nature of the Faroese high relief landscape in the northern islands, in combination with the large precipitation, high precipitation intensity, large wind activity and winter snow cover in the mountains, seem to have favoured widespread Holocene slope-process activity and deposition of related landforms. The fact that no continuous tree cover seems to have existed on the Faroe Islands during the Holocene (Lawson *et al.* 2005) has also probably favoured slope activity. As no larger animals were present until the time of settlement (Lawson *et al.* 2005), their influence on the slope processes can only have occurred in the late Holocene.

The greatest amounts of Holocene slope sedimentation occur in colluvial fans like Glyvurs fan, which have accumulated downslope from dyke controlled canyons, the gjogvs. The gjogvs are the major sediment sources for large colluvial fans, which mainly comprise snow-avalanche (slush-flow) and debris-flow deposits. The very large, still active colluvial Glyvurs fan, with its evidence for at least five depositional stages, have been accumulating since before ~8000 yr BP, and probably since deglaciation at approximately 15 000 yr BP. Sedimentation has probably occurred periodically throughout the Holocene. There is evidence for both depositional and erosional phases, particularly in the mid and late Holocene. As the earliest fan deposits could not be dated, the timing of the stage 1 and the onset of stage 2 fan deposition could not be determined.

Similar sedimentological, stratigraphical, chronological and palynological studies of large colluvial fans in neighbouring western Norway were used to reconstruct significant snow-avalanche and debris-flow activity during much of the Holocene (Blikra & Nemec 1998; Blikra & Selvik 1998). These types of colluvial sediments were also interpreted as representing extreme weather events in the form of winter snowstorms and extreme rainfall events respectively (Blikra & Selvik 1999). In the Scottish Highlands, Ballantyne & Whittington (1999) used the same combination of methods in studies of a Late Holocene alluvial fan. They also concluded that substantial alluvial-fan and debris-cone accumulation is controlled mainly by extreme rainstorm-generated events, and not by human interaction or long-term climate changes.

On sediment-covered lower mountain slopes such as that at Marknastiggjur above Klaksvik, debris-flows dominate the sedimentological record, with some influence of snow avalanches and rockfalls from basalt benches upslope. The debris-flow that occurred in AD 2000 at Marknastiggjur demonstrates that such an event can occur even after relatively small amounts of precipitation, in total 142 mm, early in the autumn. It is possible that the debris-flows that occurred in 2000 were caused partly by desiccation cracking of the slope sediment during the preceding relatively dry summer, leading to rapid access for the first large amounts of rain in the autumn to the lower part of the sediment cover. This, in combination with the first large autumn precipitation event, which most likely saturated the ground 10 days before the debris-flow, and then the high short-term rainfall intensity on 18 September, must have triggered the event. The precipitation caused a rapid rise in pore water pressures, reduction in shear resistance and consequent translational failure on 18 September. As the Klaksvik area has the highest measured daily rainfall intensity in the Faroe Islands of 180 mm/day, even larger debris-flows are likely to happen in the future and to have happened in the past. This is also demonstrated by the sedimentological record, which reveals several debris-flow units significantly thicker than that deposited by the September 2000 event. However, some of these units may also represent several individual events. Debris-flows have occurred since before ~7800 yr BP on the lower Marknastiggjur mountain slope. The dating results indicate recurrent debris-flow activity throughout the Holocene, with a possible tendency for increased mid to late Holocene activity. However, glacial sediments or bedrock were not reached in all investigated sections, preventing full reconstruction of early Holocene slope activity.

The dominance of snow-avalanche and debris-flow sediments in the stratigraphical record, and the meteorological conditions associated with the AD 2000 debris-flow event, demonstrate that these deposits are mainly controlled by local extreme meteorological events such as rapid snowmelt or large and/or intense rain storms possibly following significant autumn precipitation. Therefore, the data presented in this paper strongly indicate that the incidence of extreme meteorological events is a more important control on the slope processes than long-term climatic changes.

Coastal cliffs such as those on the Eidiskollur peninsula provide sediments by weathering. Rockfall debris accumulates as talus at the foot of such cliffs. Fine-grained sediment is transported upwards by strong winds and deposited as an aeolian sediment cover on the Eidiskollur plateau. The wind speeds are reduced over the plateau and the sediment trapped in the vegetation cover. Measured present-day aeolian sedimentation rates of 0·06–0·13 mm/yr correspond fairly well with the mean Holocene rate of around 0·3 mm/yr since ~6900 cal yr BP at Eidiskollur. Similarly, aeolian mountain-top deposition started between 7·1 and 5·5 cal ka BP on a basalt plateau in northern Skye in the Scottish Highlands (Ballantyne 1998), and with a similar reconstructed mean

Holocene sedimentation rate as that obtained at Eidiskollur. Progressive accumulation of the aeolian sediments is also suggested for the Scottish deposits (Ballantyne 1998). The present data, as well as those from the Scottish Highlands, do not correspond with the findings from Suðuroy, where Edwards *et al.* (2005) concluded that increased aeolian deposition had occurred within the last 1600 years as a consequence of human impacts exacerbated by climate.

The data presented here from three different slope landforms all indicate that the geomorphological activity at the study sites is unrelated to settlement, as we have documented periodic Holocene slope activity prior to the late Holocene Faroese settlement period. These data also suggest that it is not valid to infer that the landscape of the northern Faroe Islands was geomorphologically more stable in the mid-Holocene than today, as has been concluded by Lawson *et al.* (2005) for the island of Sandoy in the centre of the Faroe Islands.

A possible tendency is detected for increased mid to late Holocene slope activity, though this may reflect a bias in sampling more recent slope deposits. Alternatively, this could indicate that mid to late Holocene cooling (Dahl-Jensen *et al.* 1998) caused increased overall slope activity. No evidence has been found for increased LIA slope activity in the Faroe Islands, nor any significant changes in the geomorphological slope activity after settlement in these islands.

9. Acknowledgements

Dr Anne Hormes carried out the ^{14}C AMS dates at the Uppsala AMS facility. Klaksvik County assisted in digging pits for sediment investigation in Klaksvik, and has partly funded the Klaksvik part of the work. Parts of the work were funded by the LINK research project grant from the Danish Science Research Council. Meteorological data was kindly provided by the Faroese engineering service in Torshavn. Professor Colin Ballantyne and an anonymous reviewer are thanked for constructive comments on an earlier version of the manuscript.

11. References

Arge, S. V., Sveinbjarnardottir, G., Edwards, K. J. & Buckland, P. C. 2005. Viking and Medieval Settlement in the Faroes: People, Place and Environment. *Human Ecology* **33**, 597–620.

Ballantyne, C. K. 1998. Aeolian deposits on a Scottish Mountain summit: Characteristics, provenance, history and significance. *Earth Surface Processes and Landforms* **23**, 625–41.

Ballantyne C. K. & Whittington G W. 1999. Late Holocene floodplain incision and alluvial fan formation in the central Grampian Highlands, Scotland: chronology, environment and implications. *Journal of Quaternary Science* **14**, 651–71.

Bigg, G. R. 1996. *The Oceans and Climate*. Cambridge: Cambridge University Press.

Blikra, L. H. & Nemec, W. 1998. Postglacial colluvium in western Norway: depositional processes, facies and palaeoclimatic record. *Sedimentology* **45**, 909–59.

Blikra, L. H. & Selvik, S. F. 1998. Climatic signals recorded in snow avalanche-dominated colluvium in western Norway: depositional facies successions and pollen records. *The Holocene* **8**, 631–58.

Bronk Ramsey, C. 2000. Comment on the use of Bayesian statistics for 14C dates of chronologically ordered samples: a critical analysis. *Radiocarbon* **42**, 199–202.

Cappelen, J & Laursen, E. V. 1998. *The Climate of the Faroe Islands – with Climatological Standard Normals, 1961–1990*. Danish Meteorological Institute, Technical Report 98–14.

Christiansen, H. H. (1998). Highland aeolian deposits in the Faroe Islands. *Fróðskaparrit* **46**, 205–14.

Christiansen, H. H. & Mortensen, L. E. 2002. Arctic Mountain Meteorology at the Sornfelli Mountain in Year 2000 in the Faroe Islands. *Fróðskaparrit* **50**, 93–110.

Christiansen, H. H. & Humlum, O. 2003. The southern boundary of the Northern Hemisphere periglacial zone at the Faroe Islands. *In* Philips, M; Springman, S. M. & Arenson, L. U. (eds) *Proceedings of the Eighth International Conference on Permafrost*, **Vol. 1**, 139–44. Lisse: A. A. Balkema.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G. D., Johnsen, S. J., Hansen, A. W. and Balling, N. 1998: Past temperatures directly from the Greenland Ice Sheet. *Science* **282**, 268–71.

Edwards, K., Borthwick, D., Cook, G., Dugmore, A. J., Mairs, K.-A., Church, M. J., Simpson, I. A. & Adderley, W. P. 2005. A Hypothesis-Based Approach to Landscape Change in Suðuroy, Faroe Islands. *Human Ecology,* **33**, 621–50.

Humlum, O. 1998. Rock glaciers on the Faeroe Islands, the North Atlantic. *Journal of Quaternary Science* **13**, 293–308.

Humlum, O. & Christiansen, H. H. 1998a. Late Holocene Climatic Forcing of Geomorphic Activity in the Faroe Islands, North Atlantic Ocean. *Fróðskaparrit* **46**, 169–89.

Humlum, O. & Christiansen, H. H. 1998b. Mountain Climate and Periglacial Phenomena in the Faeroe Islands. *Permafrost and Periglacial Processes* **9**, 189–211.

Jørgensen, G. (1978). Landslides and related phenomena on Suduroy, the Faeroe Islands. *Bulletin of the Geological Society of Denmark* **27**, 85–9.

Lawson, I. T., Church, M. J., McGovern, T. H., Arge, S. V., Woollet, J., Edwards, K., Gathorne-Hardy, F. J., Dugmore, A., Cook G., Mairs, K-A., Thomson, A. M. & Sveinbjarnardottir, G. 2005. Historical Ecology on Sandoy, Faroe Islands: Palaeoenvironmental and Archaeological Perspectives. *Human Ecology* **33**, 651–84.

Rasmussen, J. & Noe-Nygaard, A. 1970. *Geology of the Faeroe Islands*. Geological Survey of Denmark, first series, no. 25.

Rasmussen, J. & Noe-Nygaard, A. 1990. *The origin of the Faeroe Islands in text, pictures and maps*. Ministry of the Environment, Geological Survey of Denmark. Edited by K. Binzer.

Reimer, P. J.; Hughen, K. A.; Guilderson, T. P.; McCormac, F. G.; Baillie, M. G. L.; Bard, E.; Barratt, P.; Beck, J. W.; Brown, D. M.; Buck, C. E.; Damon, P. E.; Friedrich, M.; Kromer, B.; Ramsey, C. B.; Reimer, R. W.; Remmele, S.; Southon, J. R.; Stuiver, M. & van der Plicht, J. 2002. Preliminary Report of the first workshop of the IntCal04 Radiocarbon Calibration/Comparison Working Group. *Radiocarbon* **44**, 653–61.

Resen, P. H. 1972. *Atlas Danicus, Færøerne*. J. Rischel and P. Skårup (eds), reprint of Petri Resenii: Descriptio Færoarum (translated from Latin into Danish by J. Brunsmannus). Munksgård, Copenhagen.

Schunke, von E. 1977. Periglazialformen und -formengesellschaften in der europäisch-atlantischen Arktis und Subarktis. *In* Poser, H. (ed.) *Abhandlungen der Wissenschaften in Göttingen. Mathematisch-Physikalische Klasse, Dritte Folge* **31**, 39–62.

Selby, M. J. 1982. *Hillslope materials and processes*. Oxford University Press.

Stuiver, M., Reimer, P. J., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, G., van der Plicht, J., & Spurk, M. 1998. INTCAL98 Radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon* **40**, 1041–83.

MS received 5 January 2006. Accepted for publication 26 February 2007.