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An Overview of Postglacial Sediment Records from Colluvial Accumulations in Northwestern and North Iceland

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Abstract

Active denudation processes occurring on slopes in north and northwestern Iceland have contributed to the buildup of large colluvial cones. These processes have been active since around 10,000 ^{14}C yr BP when the ice sheet retreated during the last deglaciation. Stratigraphic records provide information of the kind of sedimentary transfer processes that have been active on slopes through time. Vertical sections in colluvial cones in north and northwestern Iceland exhibit a characteristic stratigraphy with successions of material from mass-movements interbedded with soil horizons occurring throughout the Holocene, under periglacial conditions of varying intensity. The alternating organic and minerogenic units are indicators of phases of slope activity and stability.

The dating of the deposits is possible with tephrochronology and ^{14}C dating. The quantitative analysis of sediment on colluvial cones shows the relative importance of aggradation due to slope processes vs. soil formation during the Holocene. Increasing accumulation rates have been observed over historical time since at least A.D. 1104. The clastic deposits observed in north and northwestern Iceland are thought to provide information on extreme events during the Holocene, as the occurrence of mass-wasting release cannot be clearly related to Holocene climatic trends.

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Introduction

It is thought that slopes of northwestern and northern Iceland record the Holocene history of denudation processes, extending back to when the ice sheets retreated from the study areas between 10,300 and 9800 ^{14}C yr BP (Norðdahl and Pétursson, 2005). Since the ice retreat, the landscape evolved under periglacial conditions of varying severity. According to the numerous well developed colluvial cones and talus, snow avalanches, debris flows, and rockfall were significant sediment transfer agents during the Holocene. Present-day climate in Iceland is generally classified as subpolar-oceanic according to the Köppen climate classification. However, the northern and northwestern coast of the island is directly exposed to strong arctic influences. Cold-climate geomorphic processes are still dominant and have dominated during the whole Holocene, or since the glaciers retreated from the investigated areas.

In this study three areas were selected for investigating the postglacial colluvial accumulations in fjord and valley areas: the Bolungarvík site in northwestern Iceland, the Reykjaströnd site in the Skagafjörður fjord, and the Fnjóskadalur valley in northern Iceland (Fig. 1). These areas reflect a large variety of postglacial sediment records in the northernmost part of Iceland, providing new insights into magnitude and frequency of slope dynamics during the Holocene. The topographic and geologic setting in these areas consists of high rockwalls bordering basaltic plateaux. The rockwall is highly dissected into gullies of various sizes, which lead to talus and colluvial cones (Fig. 2), which in turn extend down to the foot-slope zone. The relief ranges from 530 to 900 m. At the head of the colluvial cones the incision can reach 20 m and decreases downslope. Vegetation is rare in the upper talus/cones and even in the most heavily vegetated site (Fnjóskadalur valley) only two-thirds of the slopes are covered with birch bushes. The Bolungarvík site is the only inhabited site; the distal part of the Reykjaströnd site is cultivated; and the Fnjóskadalur valley area is remote, with the only human influence being sheep grazing.

At present recurrent snow avalanches and debris flows are the main processes recorded on the investigated slopes. In all sites except in the Fnjóskadalur valley area, these slope processes pose a threat to either residential buildings, or traffic on the roads. Recent studies concentrate on this aspect and on the geomorphic conditions for snow-avalanche and debris-flow release (Björnsson, 1980; Keylock, 1996; Jóhannesson and Arnalds, 2001; Decaulne, 2001; Sæmundsson et al., 2003; Icelandic Meteorological Office reports: http://www.vedur.is/ofanflod/haettumat/). Meteorological triggering factors have also been analyzed (Björnsson, 2002; Decaulne et al., 2005; Sæmundsson and Decaulne, 2007). A combination of historical, geomorphological, and phytogeographical approaches has been used to show that the recurrence frequency of these processes over the last few decades ranges from <0.01 to 1 y^{-1} (Decaulne, 2004; Decaulne and Sæmundsson, 2003, 2006a).

The aim of this paper is to investigate the temporal variability of debris accumulation originating from a range of mass movements occurring on slopes during the Holocene period through the investigation of colluvial sedimentary sequences.

Methods

In this study, topographical, geomorphological, stratigraphical, sedimentological, and chronological analyses have been

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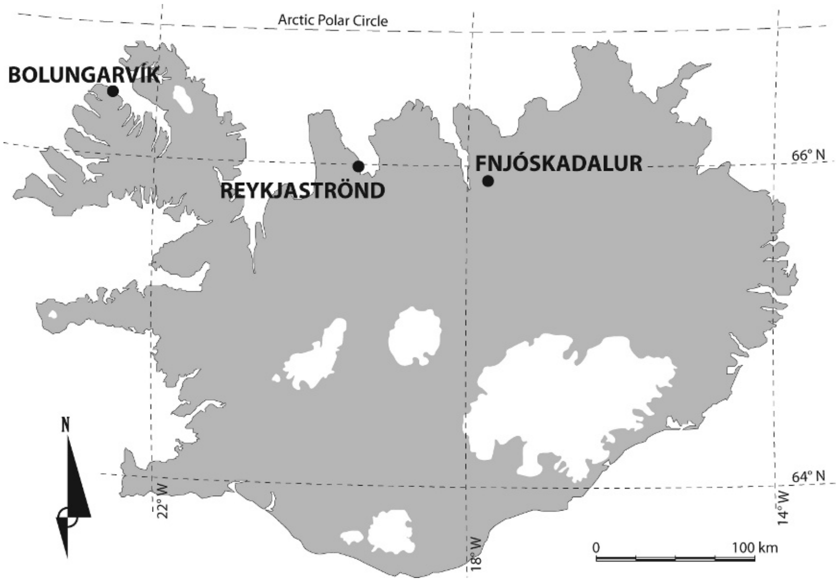

FIGURE 1. **Location map of the investigated areas.**

carried out. Topographical analyses of the colluvial cones were done with a tape and an inclinometer, enabling us to survey the microtopography of the depositional and erosional landforms, both parallel and transverse to the main flux line (Decaulne and Sæmundsson, 2006b). Maps, aerial photographs, and field mapping were used to provide supplementary information. The stratigraphy of the colluvial accumulations was studied in natural and artificial exposed sections, with excavation being undertaken at certain localities. Distal, median, and apical sections were selected for analyses. Relative dating of landforms and/or surfaces was achieved by mapping the vegetal cover and the superposition of landform elements. Sediments from the exposures were dated using tephrochronology, taking benefit of the known tephrochronological record in the volcanic Icelandic environment. Geochemical analyses have been carried out to identify the volcanic eruption responsible for the ash fallout (Jakobsson, 1979). These analyses were done at the Laboratory Magmas & Volcans, in Clermont-Ferrand, France, by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Where tephra layers were not visible, radiocarbon dates of wood pieces were obtained. Three samples were taken from organic-rich layers at various heights in the stratigraphic sequences. ^{14}C radiocarbon analyses were done in the Van de Graaff laboratory at the Utrecht University, the Netherlands.

Postglacial Sediment Records

The stratigraphic sequences expose a variety of alternating organic and minerogenic layers, which represent buried paleosols and sediment deposits originating from a range of slope processes. Most of the units are subparallel with the slope surface. Although the aim of the paper is to focus on colluvial aggradation, not on process recognition, interpretations of the slope dynamics are made according to (i) the thickness of the layers, (ii) the size of the material representing the layer, (iii) the structure of sediments, and (iv) the organization of debris within each unit (Blikra and Nemec, 1998). Figure 3 shows examples of the sedimentary characteristics observed in the investigated sediment profiles, and the associated interpretation of deposits. Seven types of deposits are distinguished, as follows:

(i) Organic-rich layers and peat representing calm periods, which lack any major activity in slope processes. These soils belong to the brown andosol type (Arnalds, 1990).

(ii) Gravel-rich organic layers with clastic material from silt to 1–2 cm gravel embedded in the organic material. These layers are probably associated with water flow events. When the layer is thin and lacking large grains it is associated with slope-wash. This moves the fine to small gravel size colluvial sediments further downslope, where it fills the interstitial spaces (Blikra and Nemec, 1998). When the layer is thicker and more gravel-rich, with silt to 4 cm gravel, it is associated with stream flow. When scattered boulders (>20 cm) are found within the layer, a contribution from snow avalanche is inferred, especially when the profile is located in the distal part of the cone.

(iii) The presence of clay minerals is associated with waterlain deposits and is exclusively observed in the distal profiles. This suggests that the flow was either very low energy or temporarily ponded at the time of formation.

FIGURE 2. **Views of the investigated colluvial accumulations in (A) Reykjaströnd, (B) Fnjóskadalur valley, and (C) Bolungarvík, showing the topographic setting of the studied areas. (Photos A and B from A. Decaulne, C from Þ. Sæmundsson).**

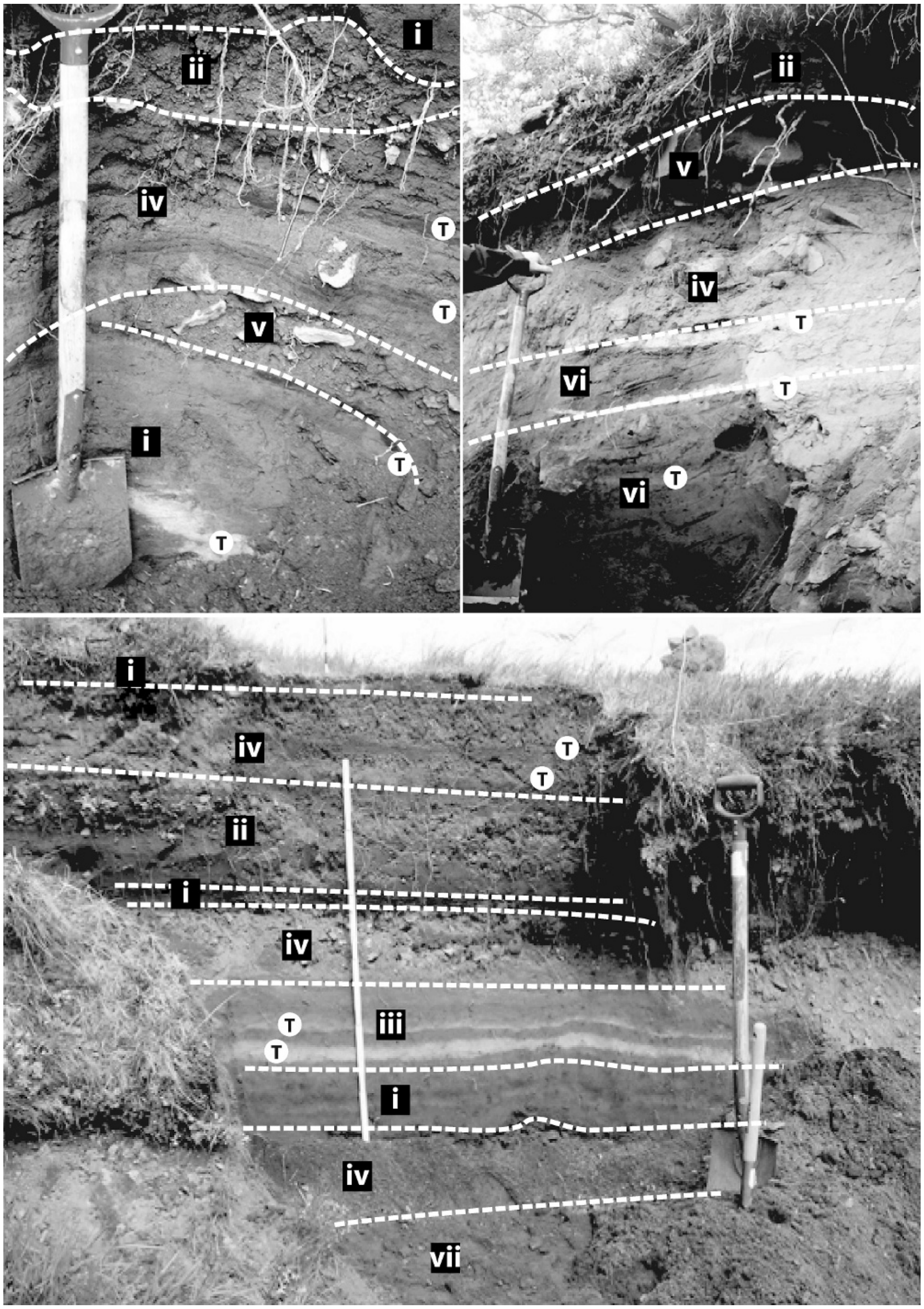

FIGURE 3. Examples of investigated sediment profiles and interpretation of deposits. Refer to the text for explanations on the roman numbers identifying stratigraphic units. The encircled T symbols show the location of visible tephra layers, which enabled dating of the sequences (Photos A. Decaulne).

(iv) Units that have a matrix-rich material incorporating gravels and scattered larger clasts are assumed to be deposited by high-viscosity debris flows with contribution from snow avalanches. The role of snow avalanches in this case is deduced from observations of present-day slopes where boulders transported by snow avalanches are scattered on slopes and are easily buried/incorporated into matrix-rich debris flows.

(v) Clast-rich and clast supported units, which are rarely openwork, are associated with low-viscosity debris flows and potentially slush flows. The infill of the interstitial spaces by fine sediment is thought to come about by the percolation of fine material through the coarse debris, particularly during slope-wash episodes.

(vi) Some horizons present homogeneous silt to fine sand sized deposits. These are interpreted as eolian deposits and they are often mixed with varying amounts of organic-rich material. Snow-avalanche activity is inferred when large clasts are found scattered in the horizon.

(vii) Grayish muddy diamicton formation, which is variably clast-rich and poorly sorted, is found at the base of some profiles. While the upper described sediment horizons (ii–v) show a strong preferred downslope orientation of rock debris, indicating mass wasting origin, the clasts of this basal formation show an across-slope orientation, i.e. a parallel to the fjord axis. The diamicton is therefore interpreted as glacial till.

The main aim of the study is to quantify the sediment fluxes over the available record of the Holocene, without direct reference to the specific slope process producing the deposits. Therefore, this investigation concentrates on the distinction between minerogenic units (i–vii) and organic units (soil forming episodes) to extract the record of alternating stable and unstable slope phases.

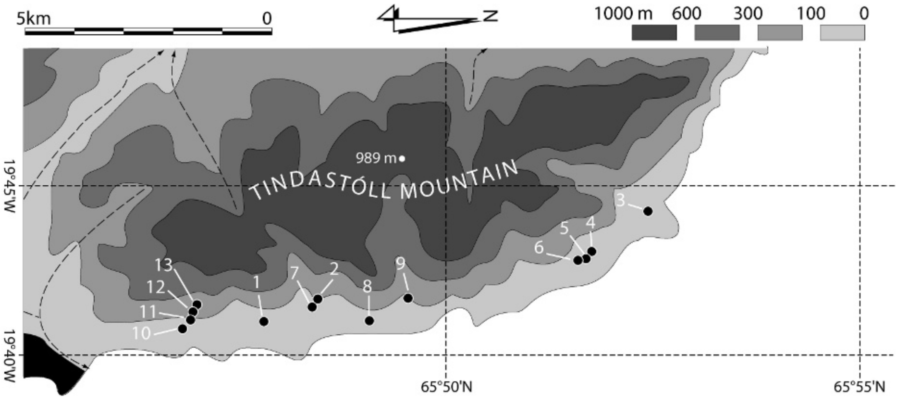

FIGURE 4. Location of investigated sediment profiles in the Reykjaströnd area.

THE REYKJASTRÖND SITE

Thirteen profile sections were investigated along the Reykjaströnd area (Fig. 4). Most of them are located in the distal parts of the slope, but some of them exhibit exposures in the upper parts of colluvial cones (nos. 2, 7, 9, 12, and 13). At present, the area is affected by widespread debris flow activity and snow avalanches, which are concentrated within some well-confined paths. Fresh levees and large boulders resting on the surface without lichen cover attest to the recent activity of both debris flows and snow avalanches. The profiles represent both cone and talus material and most of them are taken on natural exposures. Therefore, the sequences show the history of debris accumulation on slopes and colluvial cones in the area. All profiles show snow avalanche and debris flow deposits interbedded with soil horizons and water flow deposits (Fig. 5). The beds range in thickness from units of only few centimeters, which contain fine to gravel sized material, to diamict units over 2 m thick containing large boulders. The boundaries between the units are sharp. Two of the investigated sections encompass most of the Holocene period (nos. 5 and 10). The other sections go back to more than A.D. 1104, 2900 BP, or 4500 BP. The most frequently occurring deposits are in the category "high viscosity debris flows and snow avalanches." These layers are observed very close to the surface in most of the profiles including those in both upslope and downslope areas.

The dating of the deposits in the Reykjaströnd area is facilitated by the presence of well known tephra layers from the Mt. Hekla volcanic system (southern Iceland). Five tephra layers are widespread in the area: three light colored silicic layers (H1 [from the Mt. Hekla eruption in A.D. 1104], H3 [2900 ^{14}C BP], and H4 [4500 ^{14}C BP]) and two dark basaltic layers from Mt. Hekla eruptions in A.D. 1300 and 1766 (Larsen and Þórarinsson, 1977; Ólafsson, 1985). Using these marker horizons enables us to quantify the sediment accumulation vs. soil formation in the area. Since both mass-movement deposits and soil development may appear within the same period of time, Figure 6 presents graphs concerning both the rocky material accumulation and the soil development. This feature is remarkably apparent in profile 1. In this case, the period A.D. 1104–1300 displays a significant aggradation originating from both clastic material and soil. The two graphs complement each other, with the horizontal lines in the left side (no activity on the slope) corresponding to oblique lines in the right side (soil formation). We also notice that the soil formation diagram does not display horizontal lines, as the left diagram does, meaning that soil development quickly starts when the slope activity decreases. So, the age-thickness diagrams provide a temporal distribution of the stable and unstable phases of the Holocene at a coarse resolution up to historical time, with finer resolution thereafter. Figure 6 clearly shows the importance of downslope aggradation, with a dominance of material originating from slope processes, particularly during historical time. The presence of Hekla 1 in most of the sediment profiles provides a good marker, highlighting the strong accumulation of debris of different sizes after H1, while soil development is slow.

THE FNJÓSKADALUR VALLEY SITE

To compare to the results from the Reykjaströnd area, two profiles were analyzed in the Fnjóskadalur valley site, along the natural incision of the large colluvial cone shown in Figure 2B. Contemporaneous debris flows are channelized along this gully. Snow avalanches are more widespread over the cone (Decaulne and Sæmundsson, 2008). One of the profiles was taken in the distal part of the cone (no. 1), while the other was taken in the low apical zone (no. 2). Figure 7 shows the various minerogenic and organic layers that are exposed, with the upper parts of the profiles dominated by slope process deposits.

In the Fnjóskadalur valley area, the very low soil development is apparent, within the lower profile (no. 1) showing a relative lack of soil formation even before A.D. 1417. After A.D. 1417 the aggradation of the colluvial cone is chiefly done by debris flow and snow avalanche deposits. In the upper profile the deposition is dominated by eolian deposits mixed with snow avalanche deposits, represented by large boulders embedded within a fine matrix. The uppermost soil layer observed in profile 2 is located in a perched position, and only lateral erosion can occur. The incision is about 4 m deep and channelizes all fluxes downslope. This prevents strong impact on the cone surface, which is therefore covered by birch bushes.

Figure 8 presents the age-thickness distribution of the observed stratigraphic units, highlighting a significant aggradation since 2900 BP. The finer resolution of the profile 1 in Fnjóskadalur valley shows the significant aggradation of the cone due to recurrent slope activity during the historical period. During the same time, the soil development was slow.

THE BOLUNGARVÍK SITE

The site of Bolungarvík is inhabited and the town reached its present-day upslope extension by 1970–1980. Three profiles were excavated by the uppermost part of the town in order to investigate past snow avalanche and debris flow events. Figure 8 still shows a trend of recurrent slope activity during the late Holocene period, despite the coarse resolution of the Bolungarvík data. This is emphasized by the low soil thickness present on the slope. A thick soil unit, however, appeared in one of the profiles (no. 1) in between 7400 and 6200 BP, indicating a long calm

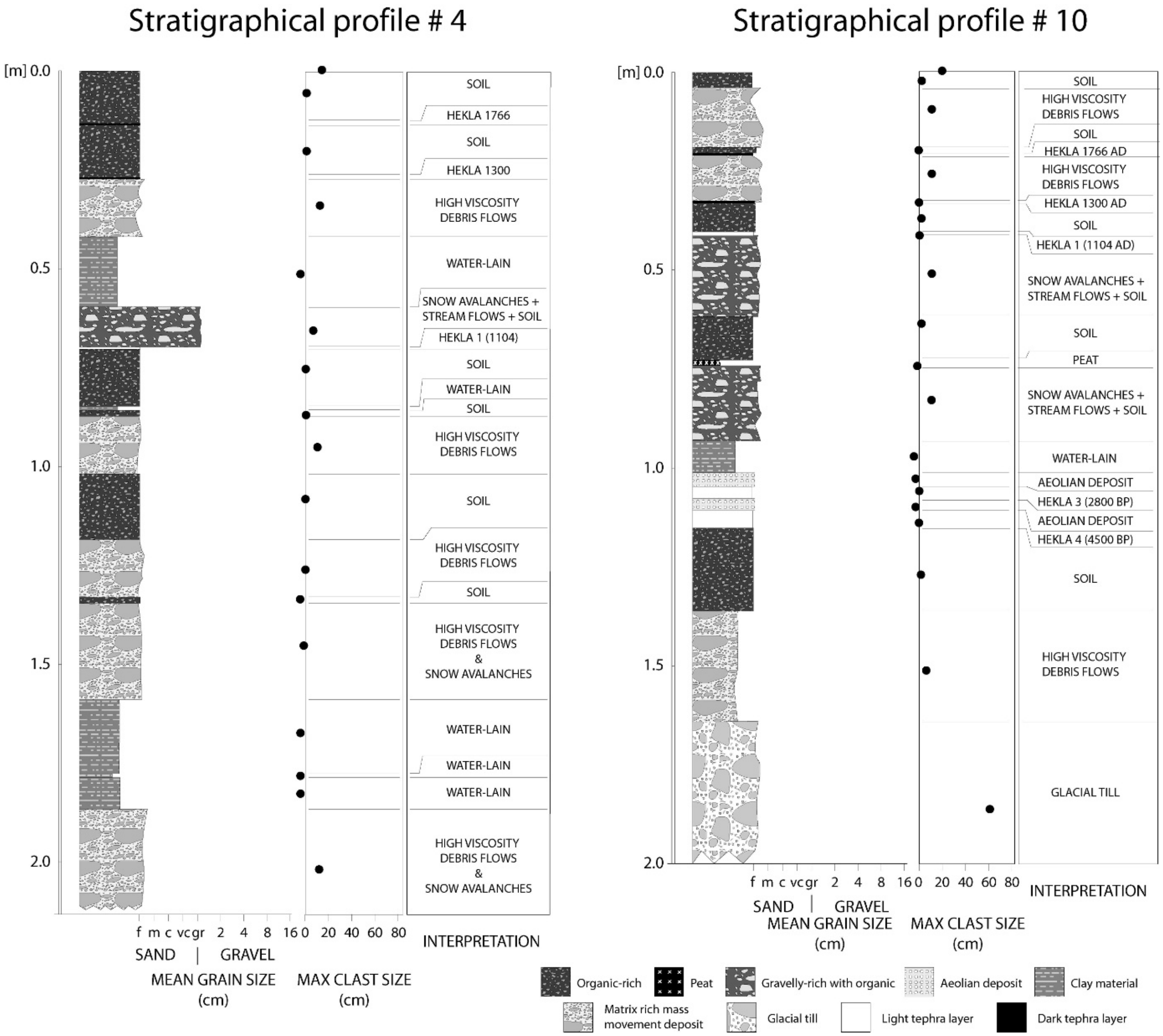

FIGURE 5. Two of the sediment profiles in the Reykjaströnd area. Note the relative importance of sediment supply vs. soil formation.

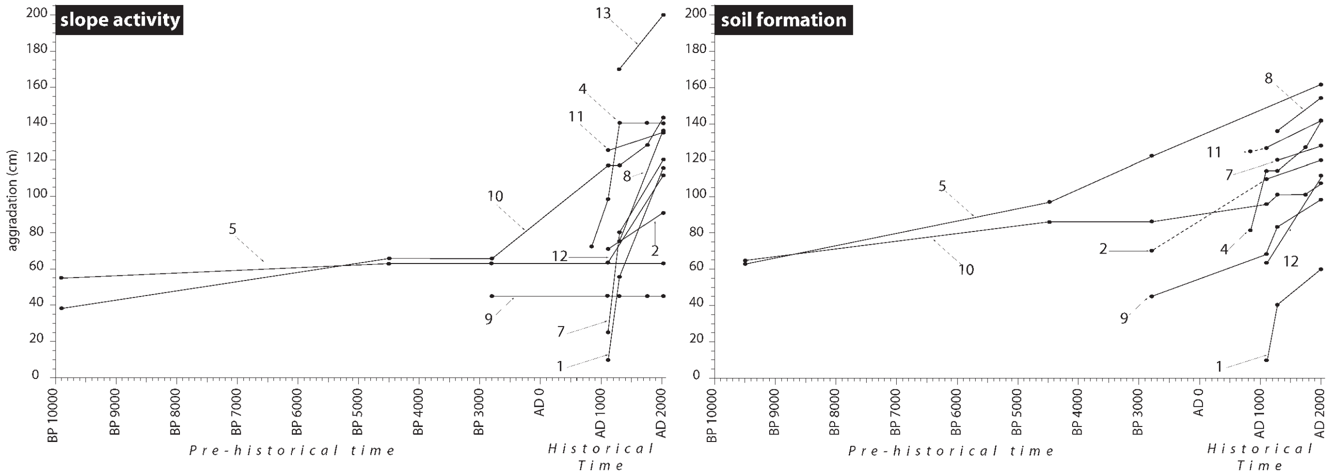

FIGURE 6. Quantification of the material aggradation downslope in the Reykjaströnd area vs. soil formation during the Holocene. The historical period is mainly documented and dating is possible with tephrochronology. Material from slope activity is clearly more significant that the formation of soil.

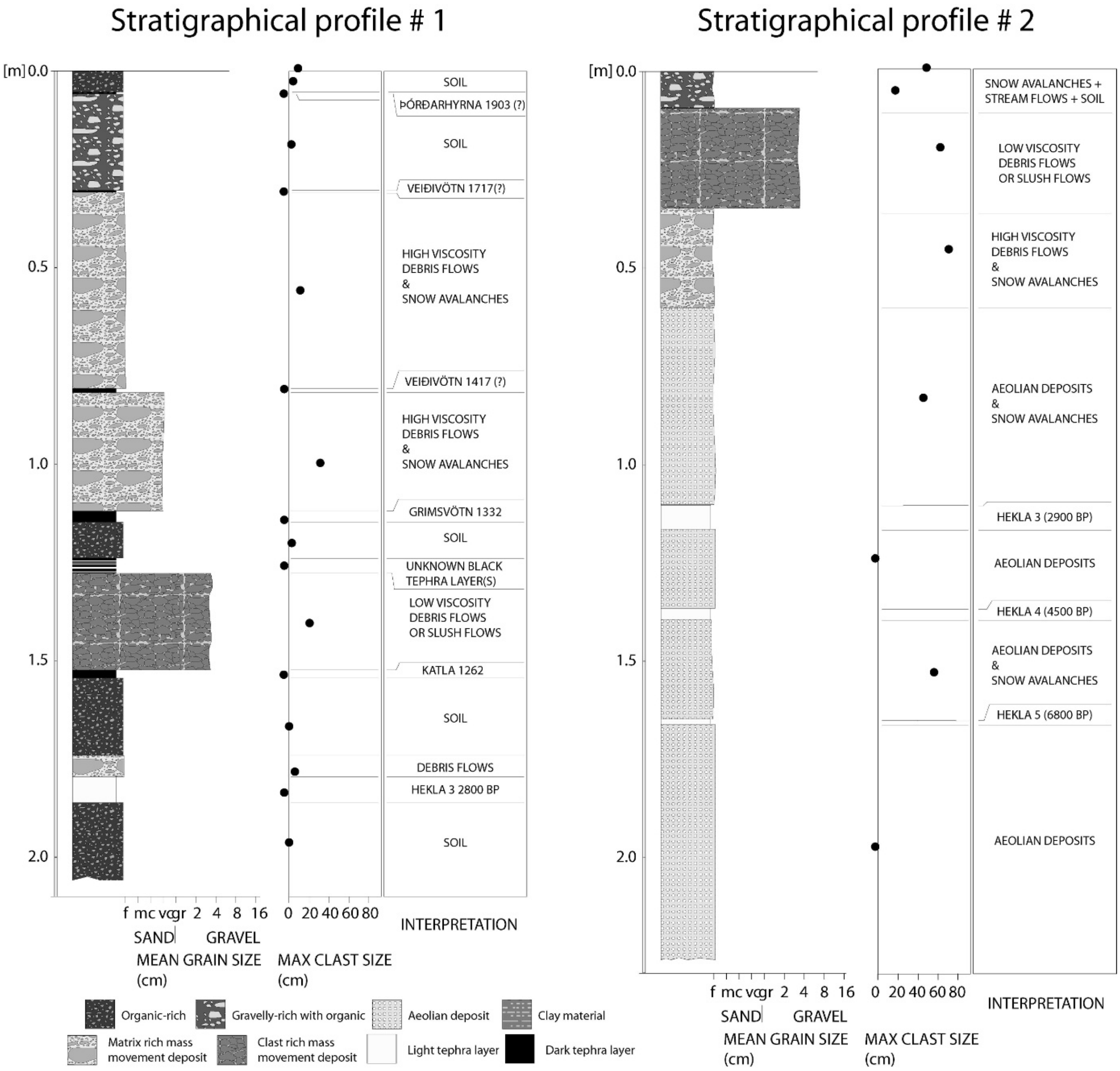

FIGURE 7. The two profiles in the Fnjóskadalur valley area. Note the relative importance of sediment supply vs. soil formation, in both distal (no. 1) and apical (no. 2) parts of the cone.

period, suggesting that the profile was located away from the main activity on this slope at this time.

Numerous large clasts are observed within the most recent units, indicating that snow avalanches, debris flows, and dense water flows are reaching the area (Fig. 9). The Holocene aggradation is smaller in the town of Bolungarvík than in the other investigated areas. The glacial sediment at the base of the profiles is relatively shallow, meaning the total Holocene aggradation is less than 1.5 m in this area. It appears, as for the other studied profiles, that slope activity prevents significant soil formation. The slope above the uppermost houses exposes fresh debris flow levees, and large debris can be found on the slope surface. Nevertheless, all evidence of slope activity has disappeared or has been removed from the surface close to or within the inhabited area. The sediment profiles attest to the recent occurrence of debris accumulation downslope.

Discussion

POSTGLACIAL SEDIMENT RECORDS

The topography and climate of northern Iceland has favored widespread post-glacial slope processes. Therefore the Holocene was a period of active slope development, with the formation of large colluvial cones. The sediment profiles are therefore interpreted as records of alternating stable and unstable slope phases, with a succession of organic-rich and debris-rich units. However, we assume that a large quantity of material has been removed from the slopes by erosion. In particular, the thick units of eolian deposits suggest wind has an important role, both in terms of supply and removal (van Steijn et al., 2002), even if it is not quantified in this study. Also, running water originating from either meltwater or rainfall has washed a large quantity of finer material out of the deposits. Wind and running water erosion has

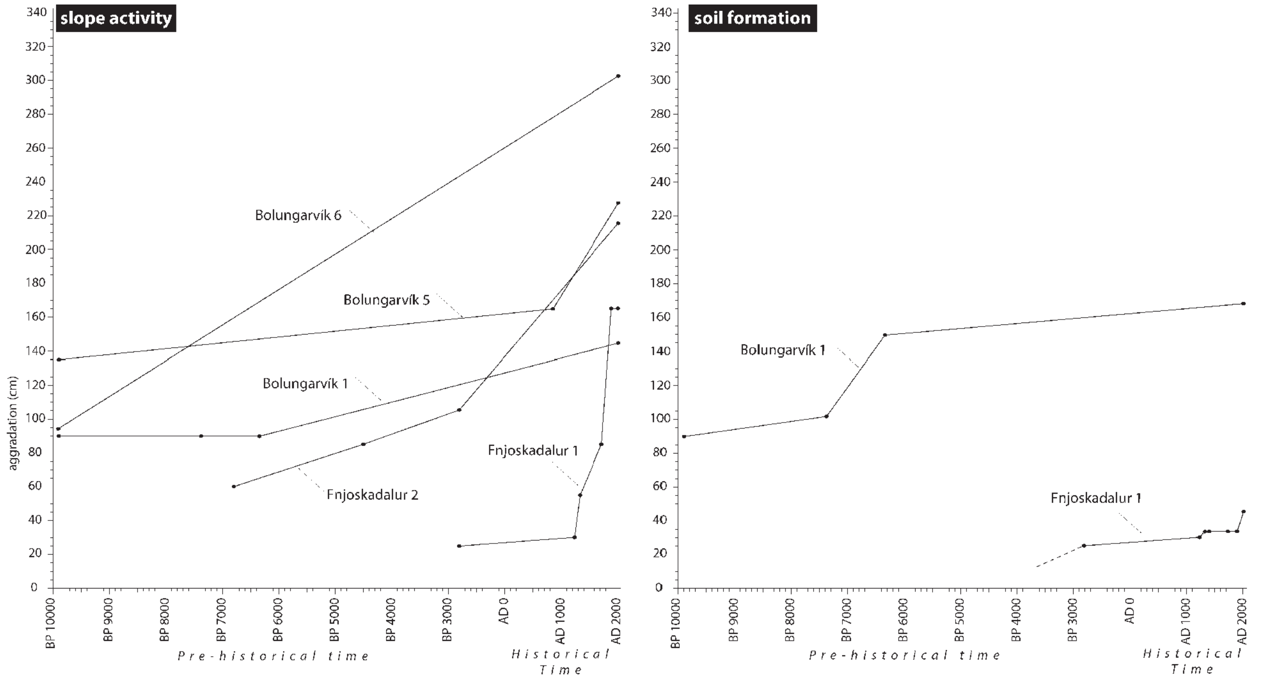

FIGURE 8. Quantification of the material aggradation downslope in the Fnjóskadalur valley and Bolungarvík sites vs. soil formation during the Holocene. The historical period is mainly documented and dating is possible with tephrochronology (Fnjóskadalur valley) and radiocarbon (Bolungarvík). Material from slope activity is clearly more significant than the formation of soil.

obviously caused truncation of the thinnest tephra layers, which are absent in some of the profiles within specific areas. Although not all the sediment profiles reach glacial sediment or bedrock, the results obtained lead to the conclusion that a substantial colluvial cone/talus slope accumulation has occurred over the late Holocene period. Specifically, the stratigraphic records expose thick units showing the dominance of debris flow and snow avalanche sediments post-4500 BP, with a significant rise in debris supply downslope since 2900 BP and a higher frequency since A.D. 1104. Soil development does not follow this trend. Several authors have also noticed an increase of slope activity in the late Holocene, especially in the Scandinavian regions (Jonasson, 1993; Blikra and Nemec, 1993; Blikra and Nesje, 1997).

The debris accumulation downslope has to be coincident with a shift from accumulation to incision upslope. A preliminary analysis of sedimentary records from major colluvial cones in the Reykjaströnd area (Decaulne et al., 2007) showed that significant incision started in the area after A.D. 1300, based on geomorphological evidence and tephrochronological dating. This incision results in a significant accumulation in the distal part of the slopes. The deep incisions provide confined paths that control the present-day dynamics. It enables the flows to achieve much greater runout distances. This period also coincides with more significant human activity in Iceland, but it is difficult from our results to implicate anthropogenic causes. To strengthen these results, the study needs to be extended to include longer sediment profiles and profiles on other slopes, as results from this study could be biased by the lack of long-depth sections in the upper part of the colluvial cones.

PALEOCLIMATIC IMPLICATIONS

The sediment profiles reconstruct an episodic sediment transfer system, with several phases of low activity interspersed with more rapid aggradational episodes. The rhythms of slope development vs. soil formation may be indicators of paleoclimatic conditions, as several authors have already argued (e.g. Blikra and Nemec, 1993, 1998; Jonasson, 1993; Blikra and Nesje, 1997). The resolution of the dating obtained in the study areas is not detailed enough to propose a narrow chronology, with organic-rich and debris-rich layers occurring during the same period of time in each section. However, according to our knowledge of (i) triggering factors, (ii) recurrence, and (iii) terrain conditions for present-day debris flow occurrence in Iceland (Decaulne and Sæmundsson, 2007; Sæmundsson and Decaulne, 2007), we know that a range of meteorological conditions lead to the release of mass movements. For example, debris flow occurrence is often correlated with high precipitation records in eastern Iceland, similar to reported observations under Scandinavian and Alpine conditions (Rapp, 1985; Blijenberg, 1998). In north and northwestern Iceland debris flows are triggered by rapid snowmelt and long-lasting rainfall. "Extreme" meteorological events or at least "unusual" events are responsible for the debris flow release in Iceland. For snow avalanches, the winter snow conditions are highly variable at intra-annual, inter-annual, intra-regional, and inter-regional scales. The results of this study also underline a large spatial variability of accumulation within the same area and between areas, reflecting different rates of sediment accumulation together with the local character of denudation processes. Most of the slope dynamics responsible for sediment transfer are linear, concentrating in one path or channel, while other paths on the same slope remain inactive. At present, snow avalanche transported boulders appear sparsely distributed across slopes, and debris flow deposits within the distal parts of slopes are 10–100 cm thick. Thus, the thicker units observed in the distal parts could as well refer to a single event or to a succession of episodes during a short period, which is not easily quantifiable. Moreover, the occurrence of snow avalanches and debris flows simultaneously is known from the present-day and thus this same behavior is highly probable during the Holocene. This contradicts previous results from Norway where debris flows and snow avalanches have distinct temporal occurrences (Blikra and Nemec, 1993; Blikra and Nesje, 1997). Also, in terms of debris accumulation within a single stratigraphic

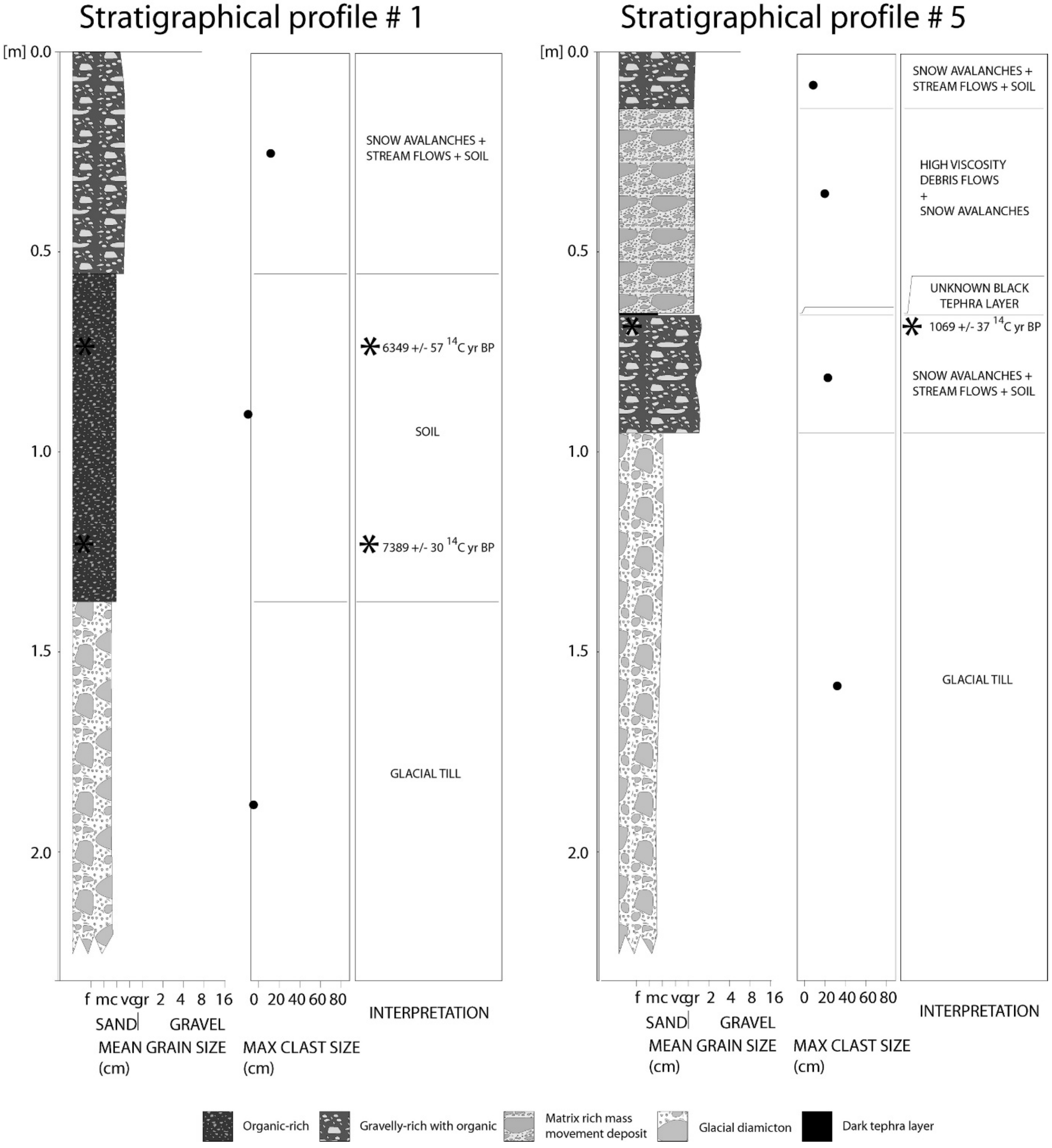

FIGURE 9. Two profiles from the Bolungarvík area, showing a smaller Holocene aggradation dominated by slope deposits.

unit, debris flows or slush flows dominate over snow avalanches. According to the analyzed sediment profiles, debris flow has been the most efficient debris transfer process in the Icelandic study sites during the Holocene. Climatic conditions for: (i) debris flow occurrence are cold conditions that will cause micro- and macrogelivation upslope, supplying debris, and wet conditions or sudden snowmelt to trigger the flow, (ii) snow avalanche occurrence are cold and wet conditions to supply the snow that will release a snow avalanche and eventually transfer rock debris downslope. Such conditions are prevailing now, and have presumably prevailed for a large part of the Holocene. Following Matthews et al. (1997), large Holocene climatic variations occurred on time scales of decades, centuries, and millennia, leading to slope instability for varying lengths of time. These sudden Holocene temperature changes are also supported by Mayewski et al. (2004) and Caseldine et al. (2006). These authors also emphasize local- and regional-scale changes. Figure 10 compares the slope and soil formation curves with the July temperature reconstruction obtained from lacustrine subfossil midges in northern Iceland, from northwest to northeast (Axford et al., 2007). The last 2000 years are among the coldest periods of the Holocene, which coincides with a higher slope activity.

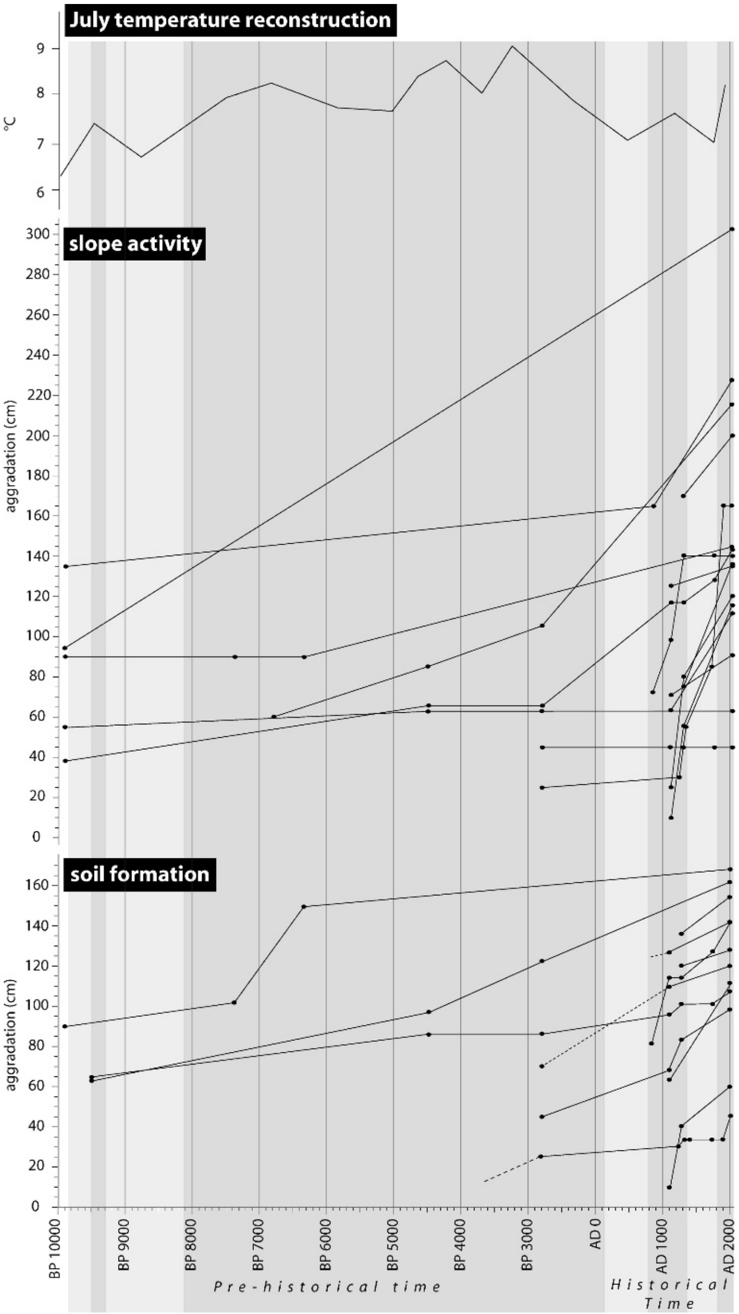

FIGURE 10. **A comparison of the slope activity and soil formation on colluvial accumulations from northern Iceland, with the reconstructed July air temperature. The submillennial-scale temperature curve comes from Axford et al. (2007). It represents the July temperature reconstruction from Stóra Viðarvatn, in northeast Iceland, and is used to infer the cool periods (light gray shade) and the warmer periods (darker gray shade).**

However during the last 2000 years, slope aggradation occurred during both the warmer and the cooler periods without preference. The Little Ice Age period, for example, does not show more frequent slope activity than the Middle Ages climate optimum. However, the soil formation phases appear to correlate with the warmer periods. The reconstruction of slope activity during historical time suggests that the variability of triggering factors for debris flows in Iceland reflects the occurrence of ''extreme'' but episodic weather conditions. This has also been suggested by Matthews et al. (1997) and Hinchliffe (1999) after investigations in Norway and Scotland, respectively. In this way, the postglacial colluvial accumulations in Iceland are a good record of extreme events during the Holocene. More data are therefore needed to propose a clearer picture of the colluvial aggradation distribution during the whole Holocene period. The tephra layers observed in several profiles provide good resolution for the historical period, but a finer resolution for the mass-movement occurrence and slope development is still lacking.

Conclusions

(1) Exposures in colluvial cones and talus from northern and northwestern Iceland show a range of matrix-rich and clast-rich diamicts related to episodes of debris flows, snow avalanches, slush flows, and water flow dynamics, which are interbedded with organic layers (soil). This provides an insight into periods of slope activity and inactivity during the Holocene.

(2) The radiocarbon dating and tephrochronology provide time markers during the Holocene. Tephrochronology is particularly useful for historical time in northern Iceland, as it offers a finer resolution. It picks out the acceleration of accumulation during the last 1000 years.

(3) The increasing accumulation rates during the historical time in the downslope sections are interpreted to be a result of wider incision on the slopes. The incisions in the upper

cones and talus channelize the flows, which then reach further downslope. Increasing accumulation also coincides with the settlement of Iceland; however, a causal link can not be verified in this study.

(4) Evidence for climate-induced processes acting on slopes is lacking. Both the Middle Ages climatic optimum and the Little Ice Age period record the occurrence of mass wasting processes when the periglacial conditions were of differing severity. This suggests that extreme events are responsible for the triggering of mass wasting processes, rather than climatic factors. This observation is reinforced by our knowledge of the present-day triggering factors, which have a large variability at regional and local scale. This again is highlighted by the alternating minerogenic and organic layers in the profile sections.

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