S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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ENVIRONMENTAL DRIVERS AND TRENDS OF POSTGLACIAL RELIEF DEVELOPMENT IN SELECTED MOUNTAIN REGIONS IN ICELAND, SWEDEN AND NORWAY

Abstract. The various mountainous landscapes of Iceland, Sweden and Norway are characterized by Pleistocene glaciations and, connected to this, a dominance of glacially sculpted landforms like U-shaped valley systems, cirques, lakes and hanging valleys. The thickness of glacigenic deposits from this period can vary significantly across different mountain landscapes. In consideration of such legacies, these formerly glaciated landscapes today can be considered at a unique stage of re-adjustment (recovery) with respect to spatial organization of currently active geomorphic process domains and the magnitude and patterns of sediment storage and sedimentary fluxes. Accordingly, the postglacial relief development in these landscapes is controlled by a wide range of environmental drivers. This study focuses on trends of postglacial relief development in five selected valley systems in formerly glaciated mountain landscapes in eastern Iceland, northern Sweden and western Norway. The selected valley systems Austdalur (23.0 km^2) and Hrafndalur (7.0 km^2) in eastern Iceland, Latnjavagge (9.0 km^2) in northern Sweden, and Erdalen (79.5 km^2) and Bødalen (60.1 km^2) in western Norway are considered to be representative valley systems for the respective mountain regions they are situated in. Our investigations include a quantitative compilation of contemporary mass transfers in the five valley systems, the quantitative analysis of current Ho/Hi index values for the slope systems in the valleys as well as a semi-quantitative description of changes of valley cross-sectional and longitudinal profiles since deglaciation. As a result, all U-shaped valley systems are characterized by an ongoing valley widening due to the continuing retreat of the existing rock-walls. However, the different valley systems show significant variations in the intensity of slope-channel coupling, in their slope and valley-floor storage behavior, in the development of their longitudinal valley profiles, and in the general intensity of postglacial relief modification. Accordingly, trends of postglacial relief development appear to be rather complex in the different mountain landscapes. It is found that the specific characteristics of the glacially sculpted and inherited valley morphometries are the most important control of the detected differences in slope-channel coupling, storage behavior and longitudinal valley profile development. Lithology and the given weathering resistance of the predominant bedrock are most important for the general intensity of postglacial relief modification. Apart from Hrafndalur which is characterized by rhyolites with particularly low weathering resistance, postglacial modification of the inherited glacially sculpted valley morphometries is altogether little and the landforms have not yet adjusted to the geomorphic surface processes that have been operating under postglacial morphoclimates.

Keywords: relief development, formerly glaciated landscapes, inherited glacially sculpted landforms, environmental drivers, postglacial, mountain landscapes, cold-climate environments

INTRODUCTION

Various mountainous landscapes worldwide are characterized by Pleistocene glaciations and, connected to this, a dominance of glacially sculpted landforms like U-shaped valley systems, cirques, lakes and hanging valleys. The thickness of deposited mantles of glacigenic materials from that period can vary significantly across different mountain landscapes. In consideration of such legacies, these formerly glaciated landscapes today can be considered at a unique stage of readjustment (recovery) with respect to the spatial organization of currently active geomorphic process domains (e.g. Brardinoni, Hassan 2006) and the magnitude and patterns of sediment storage and sedimentary fluxes (Church, Slaymaker 1989; Hewitt et al. 2002; Warburton 2007; Beylich 2012, 2016c). Accordingly, sedimentary fluxes and the postglacial relief development in these landscapes are controlled by a wide range of environmental drivers (Warburton 2007; Beylich et al. 2006a; Beylich 2012, 2016a, 2016b, 2016c, 2016d; Dixon 2016; Ballantyne 2018).

Especially in Germany there have been various early attempts to describe trends of postglacial relief development in cold climate environments (e.g. Büdel 1963, 1969, 1972, 1981; Dedkov 1965; Tricart 1970; Weise 1983; Semmel 1994), and these purely descriptive early approaches were followed by more quantitative surveys, pioneered by the famous work of A. Rapp (1960), and being based on careful geomorphological mapping and quantitative geomorphic process studies combined with morphometric analyses (e.g. Jäckli 1957; Rapp 1960; Washburn 1979; Barsch 1981; French 1996; Beylich 1999, 2000, 2012, 2016b, 2016d; Laute, Beylich 2014a, 2016). However, by today there is still only limited information on trends of postglacial relief development in the various cold climate environments and, accordingly, on the spatial differentiation of cold climate environments worldwide (e.g. Barsch 1984, 1986; Beylich 1999, 2016b, 2016d; Beylich et al. 2006a; Ballantyne 2018).

This study focuses on trends of postglacial relief development in five selected valley systems in formerly glaciated mountain landscapes in eastern Iceland, northern Sweden and western Norway. The main goals of our work are to

- Detect trends of postglacial relief development in the selected study regions.
- Determine key environmental drivers of these detected trends of postglacial relief development.
- Explain the spatial variability of these trends across the different selected study regions.

Our investigations include a quantitative compilation of contemporary mass transfers (Jäckli 1957; Rapp 1960; Barsch 1981; Beylich 1999) in the different study areas, a quantitative analysis of current Ho/Hi index values (Statham 1976; Francou 1988; Mercier 2002; Sellier 2002) for slope systems of the studied drainage basin systems, and a semi-quantitative description of changes of valley cross-sectional and longitudinal profiles since deglaciation comparing the three different stages (i) immediately after deglaciation, (ii) current state and (iii) expected future.

STUDY AREAS

This research was conducted in five selected valleys (drainage basin systems) situated in (i) the mountainous landscape of the Eastern Fjords in eastern Iceland (Austdalur and Hrafndalur), (ii) the mountainous landscape in northernmost Swedish Lapland (Latnjavagge), and (iii) the steep and mountainous fjord landscape of western Norway (Erdalen and Bødalen) (Fig. 1). The environmental conditions and key catchment characteristics of these five drainage basin systems are compiled in Table 1, and further detailed descriptions of the study sites are published in, e.g., A.A. Beylich et al. (2003, 2004a, 2004b, 2006b, 2017), A.A. Beylich and C. Kneisel (2009), A.A. Beylich (2003, 2011, 2012, 2016b), K. Laute and A.A. Beylich (2012, 2013, 2014a, 2014b, 2016), and A.A. Beylich and K. Laute (2014, 2015, 2016).

All five drainage basin systems are logistically reachable year-round, suitable for the quantitative or semi-quantitative analysis of morphometric slope and catchment parameters and valley cross-sectional and longitudinal profiles as well as for quantitative long-term geomorphologic process monitoring and analysis. Austdalur and Hrafndalur are characteristic glacially sculpted and non-glacierized drainage basin systems of the steep mountainous landscape of the Eastern Fjords in eastern Iceland. Both valleys are located close to each other and are characterized by a similar deglaciation history, similar environmental conditions and catchment characteristics. However, there is a significant difference in their lithology, with predominant and low-resistant rhyolites in Hrafndalur and much more weathering-resistant basalts in Austdalur (Table 1, Fig. 1). The non-glacierized Latnjavagge drainage basin is a characteristic catchment system of the less steep mountainous landscape in northernmost Swedish Lapland with significant areas of permafrost, an almost completely closed vegetation cover and a typical combination of glacially sculpted main valley and defined plateau areas. A glacially sculpted lake is situated at the valley bottom of Latnjavagge. The partly glacierized Erdalen and Bødalen catchment systems in the very steep fjord landscape of western Norway are typical parabolic-shaped drainage basin systems. The two neighboring valley systems have a similar deglaciation history as well as similar environmental conditions and catchment characteristics. However, these two drainage basin systems show significant differences in their glacier coverage and catchment morphometry (Table 1, Fig. 1).

It should be pointed out that deposited mantels of glacigenic material from the Pleistocene are generally rather shallow (Austdalur, Hrafndalur, Latnjavagge) or even nearly absent (Erdalen, Bødalen) in the different glacially sculpted mountain valleys presented and discussed here.

Table 1

Environmental conditions and key drainage basin characteristics of the five selected valley systems in eastern Iceland, northern Sweden and western Norway.

Valley system	Geo-graphical coordinates	Area (km^2)	Elevation range (m); Topographic relief (m)	Lithology	Mean annual air temperature (°C)	Annual precipitation (mm)	Runoff period	Glacier cover; Bedrock areas (%)	Vegetation coverage in areas with sedimentary covers (%)
Austdalur (Iceland)	65°16`N, 13°48`W	23.0	0-1028; 1028	Basalt	3.6 at sea level	1431	year-round	0; 20	55
Hrafndalur (Iceland)	65°28`N, 13°42`W	7.0	6-731; 725	Rhyolites	3.6 at sea level	1719	year-round	0; 14	56
Latnjavagge (Sweden)	68°20`N, 18°30`E	9.0	950-1440; 490	Mica-garnet schists	–2.0 at 1000 m a.s.l.	852	May- November	0; 35	94
Erdalen (Norway)	61°50`N, 07°10`E	79.5	29-1888; 1859	Gneisses	5.5 at 360 m a.s.l.	1500	year-round	18; 45	71
Bødalen (Norway)	61°48`N, 07°05`E	60.1	52-2083; 2031	Gneisses	5.5 at 360 m a.s.l.	1500	year-round	38; 43	70

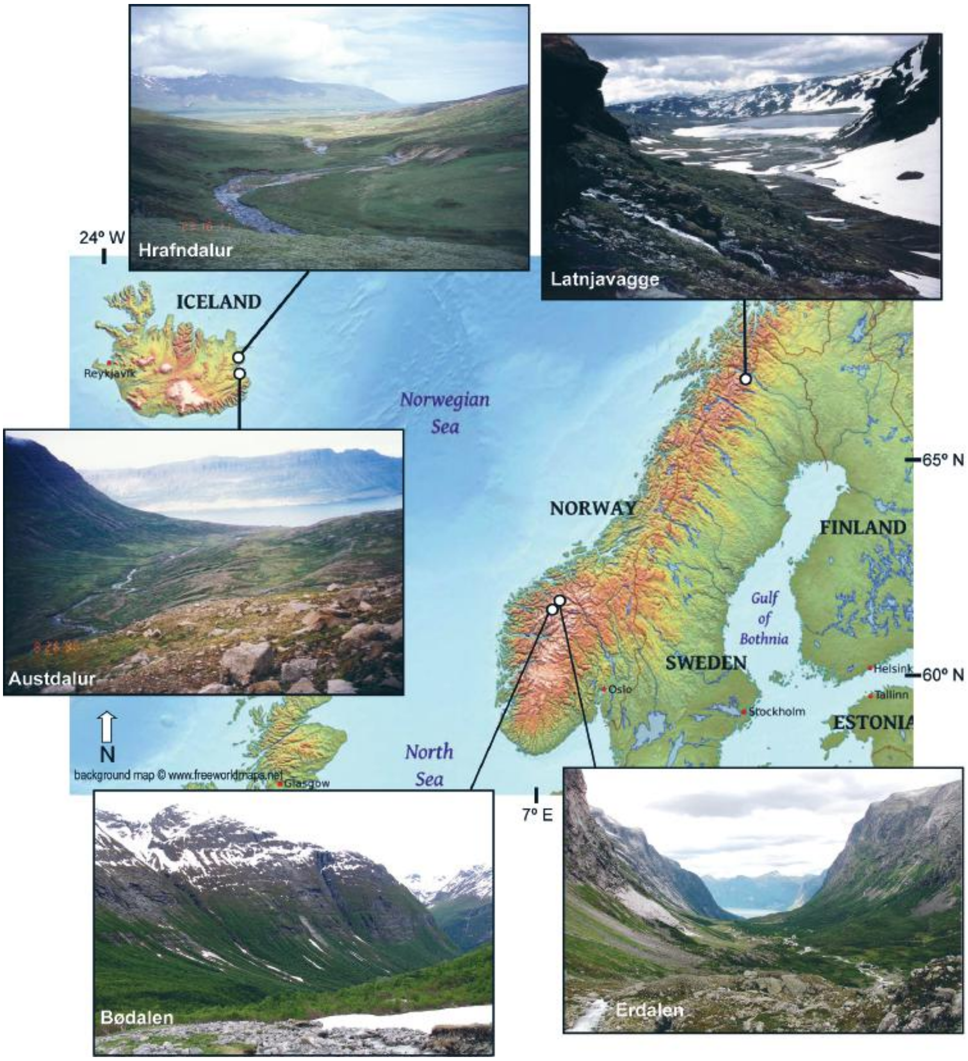

Fig. 1. Locations and views of the selected mountain regions and the five representative valley systems in eastern Iceland (Austdalur and Hrafndalur), northern Sweden (Latnjavagge) and western Norway (Erdalen and Bødalen).

MATERIAL AND METHODS

The five drainage basin systems were selected after detailed analyses of topographical maps, aerial photographs, existing orthophotos, and digital elevation models, and after extended field pre-investigations. All selected catchment systems are clearly defined landscape units and are considered to be representative for the landscapes in which they are situated (Fig. 1, Table 1). The range

Table 2

Comparison of contemporary annual mass transfers (A) and the relative importance (B) of different denudational surface processes in the five selected valley systems in eastern Iceland (Austdalur and Hrafndalur), northern Sweden (Latnjavagge) and western Norway (Erdalen and Bødalen). Data compiled from A.A. Beylich (2012, 2016b), A.A. Beylich and K. Laute (2015, 2016), A.A. Beylich et al. (2017), K. Laute and A.A. Beylich (2014a, b; 2016).

A	Process	Mass transfers (t m yr^{-1}) **Austdalur**	Mass transfers (t m yr^{-1}) **Hrafndalur**	Mass transfers (t m yr^{-1}) **Latnjavagge**	Mass transfers (t m yr^{-1}) **Erdalen**	Mass transfers (t m yr^{-1}) **Bødalen**
Slope denudation	Rock falls and boulder falls	37300	351550	25808	5544000	3427000
	Avalanches and slush flows	42340	10810	13720	3317600	694500
	Debris flows	1920	3300	279	122500	510000
	Slides	42	263	11	minor	minor
	Creep and/or solifluction	19440	19800	5040	20	14
	Chemical denudation	138000	81200	22000	1089000	937000
	Mechanical fluvial slope denudation	724500	53200	10500	1446500	378000
	Deflation	90	16	5	Minor	Minor
Stream work	Solute transport	515200	355250	101200	2475000	2342500
	Suspended sediment transport	2704800	232750	29400	3287500	945000
	Bedload transport	24000	155750	2000	712000	182750

B	Austdalur	Hrafndalur	Latnjavagge	Erdalen	Bødalen
Relative importance of processes	Fluvial suspended sediment plus bedload transport	Fluvial suspended sediment plus bedload transport	Fluvial solute transport	Rock falls and boulder falls	Rock falls and boulder falls
	Fluvial solute transport	Fluvial solute transport	Fluvial suspended sediment plus bedload transport	Fluvial suspended sediment plus bedload transport	Fluvial solute transport
	Mechanical fluvial slope denudation	Rock falls and boulder falls	Rock falls and boulder falls	Avalanches and slush flows	Fluvial suspended sediment plus bedload transport
	Chemical slope denudation	Chemical slope denudation	Chemical slope denudation	Fluvial solute transport	Chemical slope denudation
	Avalanches and slush flows	Mechanical fluvial slope denudation	Avalanches and slush flows	Mechanical fluvial slope denudation	Avalanches and slush flows
	Rock falls and boulder falls	Creep and/or solifluction	Mechanical fluvial slope denudation	Chemical denudation	Debris flows
	Creep and/or solifluction	Avalanches and slush flows	Creep processes and/or solifluction	Debris flows	Mechanical fluvial slope denudation
	Debris flows	Debris flows	Debris flows	Creep and/or solifluction	Creep and/or solifluction
	Deflation	Slides	Slides	Slides	Slides
	Slides	Deflation	Deflation	Deflation	Deflation

Table 3

Ho/Hi index values for the five selected valley systems in eastern Iceland (Austdalur and Hrafndalur), northern Sweden (Latnjavagge) and western Norway (Erdalen and Bødalen) based on four selected and investigated slope profiles in each drainage basin system.

Valley system	Profiles	Ho (m)	Hi (m)	Ho/Hi
Austdalur	A1	380	820	0.46
	A2	420	740	0.56
	A3	460	760	0.60
	A4	380	680	0.56
	mean			0.55
Hrafndalur	H1	320	460	0.70
	H2	260	420	0.62
	H3	320	360	0.89
	H4	400	400	1.00
	mean			0.80
Latnjavagge	L1	60	180	0.34
	L2	60	140	0.43
	L3	60	200	0.30
	L4	80	200	0.40
	mean			0.37
Erdalen	E1	215	575	0.37
	E2	415	1100	0.38
	E3	500	1300	0.38
	E4	660	1320	0.50
	mean			0.41
Bødalen	B1	375	870	0.43
	B2	280	665	0.42
	B3	190	410	0.46
	B4	260	660	0.39
	mean			0.43

of varying environmental conditions and catchment characteristics given for the five selected drainage basin systems allows the detection of environmental controls and the careful analysis and explanation of the spatial variability of trends of postglacial relief development through direct comparisons among the five different study sites.

The morphometric surveys and the geographical information systems (GIS) and digital elevation model (DEM) computing for the analysis of current morphometric slope and catchment parameters, current valley cross-sectional and longitudinal profiles, and the calculation of surface area proportions (Tables 1–3, Fig. 2) were based on topographical map interpretation, existing orthophotos and digital elevation models and were performed with the ESRI Arc GIS 9.3 software.

The field work for the detailed geomorphological mapping and the monitoring and quantification of the relevant denudational surface processes operating

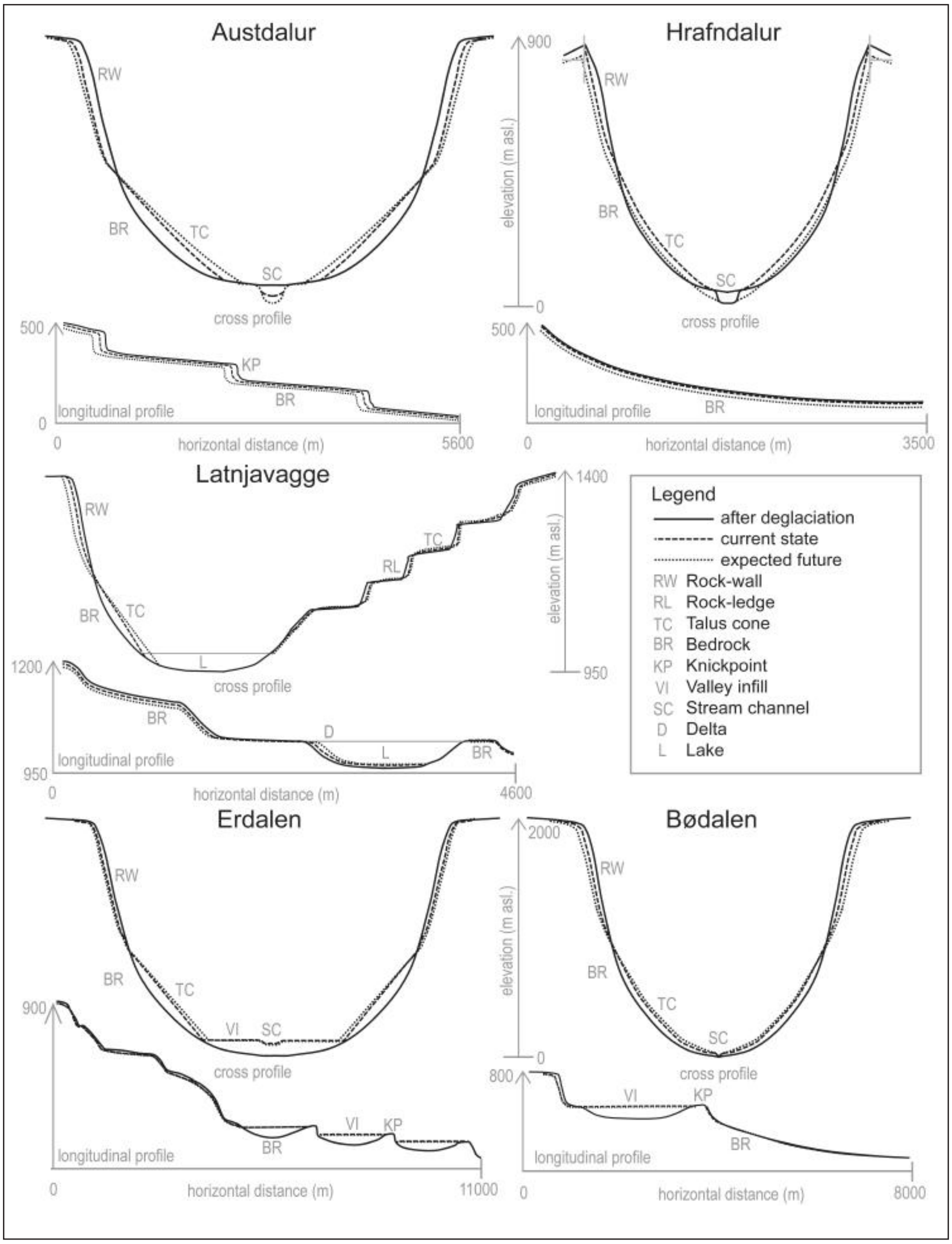

Fig. 2. Trends of postglacial relief development (comparing valley cross-sectional and longitudinal profiles) in the five selected valley systems in eastern Iceland (Austdalur and Hrafndalur), northern Sweden (Latnjavagge) and western Norway (Erdalen and Bødalen) (comparing three stages: immediately after deglaciation, current state, expected future). Please notice the variation of scale for the different valley profiles.

in the different valley systems (Table 2) was conducted during the investigation periods 1996–2010 (Austdalur), 2001–2010 (Hrafndalur), 1999–2010 (Latnjavagge), 2004–2015 (Erdalen) and 2008–2015 (Bødalen). The mass transfer data given in Table 2 are based on this previous work and are compiled from existing publications of the authors (e.g. Beylich 2012, 2016b; Laute, Beylich 2014a, 2014b, 2016; Beylich, Laute 2015, 2016; Beylich et al. 2017).

RESULTS AND DISCUSSION

Figure 2 shows trends of postglacial relief development for the five selected drainage basin systems with a compilation of valley cross-sectional and longitudinal profiles for each valley system comparing the three different stages (i) immediately after deglaciation, (ii) current state, and (iii) expected future. The displayed profiles for the current state are based on field surveys combined with orthophoto, topographical map and DEM analyses whereas the profiles for the time immediately after deglaciation are constructed and interpolated based on existing and mapped remnants of the profiles from that time. The expected future cross-sectional and longitudinal profiles are prognoses and are based on the assumption that the contemporary trends of relief development will continue. As a result, the trends of postglacial relief development show a detectable spatial variability across the different study regions.

Relief development in Austdalur is characterized by the continuing retreat of rock-walls and the ongoing formation of talus cones beneath the rock-walls, resulting in a continuing valley widening. The talus cones developed down to the valley floor are not reaching the main stream channel which is accordingly largely decoupled from the slope systems. An active down-cutting of the main stream bedrock channel occurs mostly through the retreat of lithologically (varying basalt layers) caused convex bedrock knickpoints in the stream channel longitudinal profile. With respect to the relative importance of mass transfers caused by contemporary denudational processes (Table 2), fluvial transport dominates over slope processes and mechanical denudation is more important than chemical denudation. Avalanches and slush flows are more important than rock-falls and boulder-falls whereas creep and solifluction processes, debris flows and deflation are of little importance. The facts that material produced by weathering processes and transferred down-slope by different geomorphic processes is largely stored within the slope systems, and that the growing talus cones are by today not reaching the main stream channel are largely explained by the rather wide U-shaped valley cross-sectional profile form caused by Pleistocene glaciations. A sediment transfer from slope systems into the main stream channel occurs solely through small streams draining the slope systems (Beylich 1999, 2000, 2012). These small streams do not cut down into the valley bottom and drain into the main stream channel with convex knickpoints. The mean Ho/Hi index for Austdalur, based on four investigated slope profiles within the valley, is 0.55 (Table 3) indicating that the postglacial modification of the glacially sculpted and inherited relief is altogether not much advanced. A major reason for the only moderate intensity of postglacial relief modification is the high weathering resistance of the predominant basalt in the area (Beylich 1999, 2012, 2016b).

Compared to this, postglacial relief development in Hrafndalur is significantly different. Slope processes have also here caused a valley widening but, different from Austdalur, the talus cones that have been developing since deglaciation are today reaching the main stream channel. Material that is transferred from the slope systems into the fluvial system through various denudational slope processes is completely transported further within the main stream channel and fluvially exported from the Hrafndalur drainage basin system (Beylich, Kneisel 2009; Beylich 2012). In some parts of the drainage basin the growing talus cones are already today nearly reaching the catchment water divide and it can be expected that a lowering of the water divide in the same order of magnitude than fluvial down-cutting of the main stream channel can be expected for the future. As in Austdalur, fluvial transport dominates over slope processes (Table 2) but rock-falls and boulder falls are the most important slope processes. Avalanches and slush flows are of lower importance than in Austdalur. Slope and stream channel systems in Hrafndalur are strongly coupled which is favored by the much more narrow form of the glacially sculpted U-shaped valley cross-sectional profile form. Altogether, the intensities of denudational processes and the degree of postglacial modification of the glacially sculpted relief are clearly larger than in Austdalur which is also documented in a clearly higher mean Ho/Hi index of 0.80 (Table 3), and which is mostly explained by the low weathering resistance of the predominant rhyolites in Hrafndalur (Beylich, Kneisel 2009; Beylich 2012, 2016b).

The topographic relief in Latnjavagge is clearly smaller than in the Icelandic drainage basin systems. Visible trends of postglacial relief development are a continuing retreat of existing rock-walls and rock-ledges and the connected formation of talus cones beneath these rock-faces, resulting in an ongoing slight valley widening since deglaciation. The talus cones do mostly not reach the main stream channel and the material produced by mechanical weathering and transferred down-slope through various slope processes is largely stored within the slope and valley floor systems. Along the glacially sculpted lake (Latnjajaure) that is situated on the valley bottom of Latnjavagge the talus cones are reaching directly into the lake. Fluvially transported sediments from the upper parts of Latnjavagge are almost entirely deposited within the lake system. As a result, the postglacial modification of the glacially sculpted valley is characterized by an ongoing valley widening and a continuing deposition and storage of material within the slope systems and the valley bottom. No significant fluvial down-cutting of the main stream channel is detectable, and is not expected as long as the lake is serving as a significant sediment trap. Almost no sediments are fluvially exported from the Latnjavagge drainage basin and chemical denudation dominates over mechanical denudation (Beylich et al. 2006b; Beylich 2012). Rock- and boulder falls are the most important slope processes (Table 2). Both the intensity of denudational processes and of the degree of postglacial modification of the glacially sculpted and inherited valley landforms are altogether little. The mean Ho/Hi index for Latnjavagge is 0.37 (Table 3) confirming a rather low degree of postglacial relief modification in this study area. The low intensity of denudational processes is explained by the moderate topographic relief and by a nearly continuous and very stable vegetation cover in the area (Beylich et al. 2006b; Beylich 2012, 2016b).

The Erdalen and Bødalen valleys in western Norway are the clearly steepest drainage basin systems of the study areas investigated in this paper. Both valleys have a significantly larger topographic relief than the other drainage basin systems and are in their uppermost parts glacierized (Table 1, Fig. 1). Postglacial relief development in Erdalen is described by an ongoing retreat of rock-walls and the continuing formation of talus cones situated beneath the rock-faces. In the entire drainage basin system the talus cones are reaching down on the valley floor. However, only in one tributary valley of the drainage basin the talus cones are reaching into the main stream channel. The valley floor is characterized by a stepped longitudinal profile with several convex knickpoints and a series of sediment infill basins. The main stream channel developed on these sediment infill areas and crossing the various bedrock knickpoints is largely decoupled from the slope systems and fluvial down-cutting is minor due to the high resistance of the various bedrock knickpoints controlling the elevation of the main stream channel and preventing significant fluvial erosion. As a result, postglacial relief development is characterized by an ongoing valley widening and a largely stable elevation of the main stream channel. The various infill basins within the valley floor are in the current state entirely filled with sediments. As a result, the largest share of sediments is currently still stored within the slope and valley floor systems. Rock falls and boulder falls are the most important process types in the valley, followed by fluvial sediment transport, and avalanches and slush flows (Table 2). The intensity of the denudational processes is altogether moderate and the postglacial modification of the glacially sculpted and inherited U-shaped valleys is not very much advanced. The mean Ho/Hi index for Erdalen is 0.41 (Table 3) reflecting the low degree of postglacial modification of the glacially sculpted landforms. The high weathering resistance of the predominant gneisses in the area is a main reason for the altogether only low intensities of denudational processes and relief development in this drainage basin system (Laute, Beylich 2012, 2014a, 2016; Beylich, Laute 2015; Beylich 2016b; Beylich et al. 2017;).

The Bødalen drainage basin is a neighboring valley of Erdalen. As in Erdalen, postglacial relief development in this valley system can be described by a continuing retreat of rock-walls and the connected formation of talus cones beneath the rock-walls. However, a major difference between Erdalen and Bødalen is that the talus cones in the lower part of Bødalen are reaching down into the main stream channel. Only in the upper part of Bødalen the stream channel is still largely decoupled from the slope systems. This key difference beween Erdalen and Bødalen is explained by significant differences in the given valley morphometries inherited from Pleistocene glaciations. The lower Bødalen valley is clearly narrower than the lower Erdalen valley. In addition to that, the longitudinal valley profile in Bødalen is clearly steeper and only in its upper part characterized by a relevant convex bedrock knickpoint and a valley infill area situated up-valley from this knickpoint. As a result, postglacial relief development in Bødalen is, as in Erdalen, characterized by an ongoing valley widening and a largely stable elevation of the main stream channel. However, only in the upper part of Bødalen sediments are still stored within the slope and valley floor systems whereas in the lower part of Bødalen all sediments delivered from the slope systems into the main stream channel through various slope processes are fluvially exported from the drainage basin system without significant temporal in-channel storage. The most important process types in Bødalen are again rock falls and boulder falls. As in Erdalen, the intensities of denudational processes and postglacial relief development are altogether rather low in Bødalen which is again reflected in a low Ho/Hi index of 0.43 (Table 3) and can be explained by the high weathering resistance of the predominant gneisses in the inner Nordfjord area (Laute, Beylich 2012, 2014a, 2016; Beylich, Laute 2015; Beylich 2016b; Beylich et al. 2017).

Summarizing the findings from the different cold climate drainage basin systems investigated in this study, it can be pointed out that trends of postglacial relief development and the relative shares of slope and valley formation appear to be quite variable across different cold climate environments. Apart from Hrafndalur, which is characterized by rhyolites with very low weathering resistance, the intensity of postglacial relief modification is altogether low. A general trend that can be observed in all investigated drainage basin systems is an ongoing widening of the glacially sculpted U-shaped valley systems. However, significant differences exist in the degree of slope-channel coupling, in the directly connected slope- and valley floor storage behavior and in the development of valley longitudinal profiles. These detected variations appear to be largely determined by differences in the morphometry of the glacially sculpted valley systems given after deglaciation. As a result, the degree of slope-channel coupling, the storage behavior of slope and valley floor systems and the postglacial development of valley cross-sectional and longitudinal profiles are to a significant extent controlled by the specific characteristics of the drainage basin morphometry found after deglaciation, with broader valleys favoring decoupled slope and stream channel systems and narrower valleys favoring coupled slope and stream channel systems with reduced storage capacity. In Latnjavagge the still existing lake on the main valley bottom forms a significant and efficient sediment trap which is, until today, almost entirely preventing sediment export out of the drainage basin system.

A significant share of the early discussions on drivers and trends of relief development in cold regions was based on estimations which particular relevance the climate has for specific geomorphic process mechanisms and intensities, slope and valley formation, and relief development in cold climate environments (e.g., Büdel 1963, 1969, 1972 1981; Dedkov 1965; Tricart 1970; Weise 1983; Semmel 1994; McEwen, Matthews 1998; Beylich 1999; Ballantyne 2018). The early studies and also some of the later investigations have possibly underestimated the role of valley morphometry when discussing key environmental drivers of the spatially differentiation of cold climate environments with respect to postglacial slope and valley formation (e.g. Barsch 1984, 1986; Beylich 1999, 2012, 2016b). Postglacial relief development and the relative roles of slope and valley formation appear to be quite variable and complex processes and it seems to be difficult to postulate a general trend of postglacial relief development for cold climate environments. Our study can serve as an example that highlights the importance of inherited valley morphometry for postglacial relief development in cold climate mountain environments with Pleistocene glaciations.

CONCLUSIONS

This study describes and explains trends of postglacial relief development in selected cold climate mountain environments with Pleistocene glaciations. Five drainage basin systems in eastern Iceland, northern Swedish Lapland and western Norway were investigated. The study includes a quantitative compilation of contemporary mass transfers in the five valley systems, a quantitative analysis of current Ho/Hi index values for the slope systems of the valleys as well as a semi-quantitative description of changes of valley cross-sectional and longitudinal profiles since deglaciation comparing the three stages (i) immediately after deglaciation, (ii) current state and (iii) expected future. The following main conclusions can be drawn from this work:

- Trends of postglacial relief development appear to be complex and variable across the different cold climate mountain environments.
- All U-shaped valley systems are characterized by an ongoing valley widening due to the continuing retreat of the existing rock walls.
- The different valley systems show, however, significant variations in the intensity of slope-channel coupling, in their slope and valley floor storage behavior, in the development of their longitudinal valley profiles, and in the general intensity of postglacial relief modification.
- The specific characteristics of the glacially sculpted and inherited valley morphometries found after deglaciation appear to be the most important

environmental driver of the detected differences in slope-channel coupling, storage behavior and longitudinal valley profile development.

- The predominant lithology and the given weathering resistance of the predominant bedrock seem to be most important for the general intensity of postglacial relief modification.
- Postglacial modification of the glacially sculpted valleys is altogether rather little and the inherited landforms sculpted during Pleistocene glaciations have generally not yet adjusted to the geomorphic surface processes that have been operating under postglacial morphoclimates.
- In the discussions on environmental drivers of the spatial differentiation of postglacial relief development in cold climate environments worldwide, the inherited valley morphometry found after deglaciaton should be given more attention and consideration than so far.
- Due to the complexity of the process of postglacial relief development, it appears to be difficult to postulate general trends for postglacial relief development and slope and valley formation in cold climate environments.

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