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Analysing sediment pathways from rockfaces to a glacier forefield - a contribution to proglacial sediment budgets

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1 Introduction

Glacier recession and its causes have lead, and will continue to lead, to changes in permafrost distribution, river runoff, soil development, vegetation and the activity of geomorphic processes, with all of these components generally interacting. The formation of paraglacial sediment storage landforms from the erosion or (re-)mobilisation of glacigenic sediments (e.g. moraines), and the successive reworking of the latter, are being witnessed at great intensity in the forefields of alpine glaciers, within the area that has become ice-free since the end of the LIA, which we refer to as the proglacial area. Knight & Harrison (2009) argue that paraglacial processes reworking stores of unconsolidated sediment will, under conditions of present and future climate change, be ranked among the most relevant processes of sediment and landscape dynamics in low- and mid-latitudes. While single processes have been the subject of several case studies, field studies of proglacial areas including multiple processes, their rates and interactions are rare (Warburton 1990, O'Farrell et al. 2009).

The issue of **sediment connectivity** is very important for establishing sediment budgets, and for assessing the potential impact of hypothesised future sediment availability and increased morphodynamics on sediment yield and processes in the fluvial system downstream of the proglacial area. We present a **graph theoretical approach** towards regionalising sediment transfer by rockfall processes, including the connectivity of rockfall trajectories from bedrock sources to the proglacial system.

References:
* Knight, J. & Harrison, S. (2009) Sediments and future climate. *Nature Geosci*, 2 (4), 230.
* O'Farrell, C.R., Heimsath, A.M., Lawson, D.E., Jorgensen, L.M., Evenson, E.B., Larson, G. & Denner, J. (2009) Quantifying periglacial erosion: insights on a glacial sediment budget, Matanuska Glacier, Alaska. *Earth Surf. Process. Landforms*, 34 (15), 2008–2022.
* Warburton, J. (1990) An Alpine Proglacial Fluvial Sediment Budget. *Geogr. Annaler. A*, 72 (3/4), 261–272.

2 The PROSA project

The PROSA joint project (High-resolution measurements of morphodynamics in rapidly changing **PRO**glacial **S**ystems of the **A**lps; 2011-2015) aims at establishing the **proglacial sediment budget with respect to different geomorphic processes**. It will employ high-resolution surveying methods to quantify surface changes and sediment fluxes, including terrestrial and aerial LiDAR. Hillslope-scale results will be upscaled using geomorphological maps and modelling approaches. Sediment output will be gauged at the outlet of the proglacial system and at a delta within the Kaunertal reservoir which can be LiDAR surveyed when the lake level is lowered in a controlled manner.

Aims

Mass Movements
* rockfall: collector nets + LiDAR (rock slopes and talus)
* landslides: shallow: aerial LiDAR; deep-seated: extensiometers (e.g.)

Slope wash, linear erosion
* repeat terrestrial LiDAR surveys
* upscaling based on geomorph. map and models

GM2.2=>XL236
(EGU2012-13310)

Debris flows
* repeat terrestrial (slope scale) and aerial (catchment scale) LiDAR surveys
* historical aerial photos
* upscaling based on geom. map and models

Fluvial processes
* monitoring at gauges (bedload, suspended l.)
* repeat LiDAR surveys: channel changes

GM7.6=>XL246
(EGU2012-9278)

Connectivity
(lateral = slope-channel, longitudinal = within channel network)
Connectivity assessment from measurements, geomorph. map and models (graph theory)

Proglacial sediment budget
* sediment yield at gauge (outlet of proglac. system)
* sum of sediment fluxes and storage change
* lake delta at Kaunertal reservoir

GM2.3=>XL264
(EGU2012-14233)

GM7.6=>XL250
(EGU2012-13205)

Research disciplines

Geomorphology (chronosequences)
* Geomorph. mapping
* Changing rates of geom. processes since deglac.
* Connectivity assessment
* Sediment budget (upscaling from hill-slope scale)

Geology
* Geotechnical assessment of slope stability and bedrock structure
* rates of slope deformation and rockfall processes

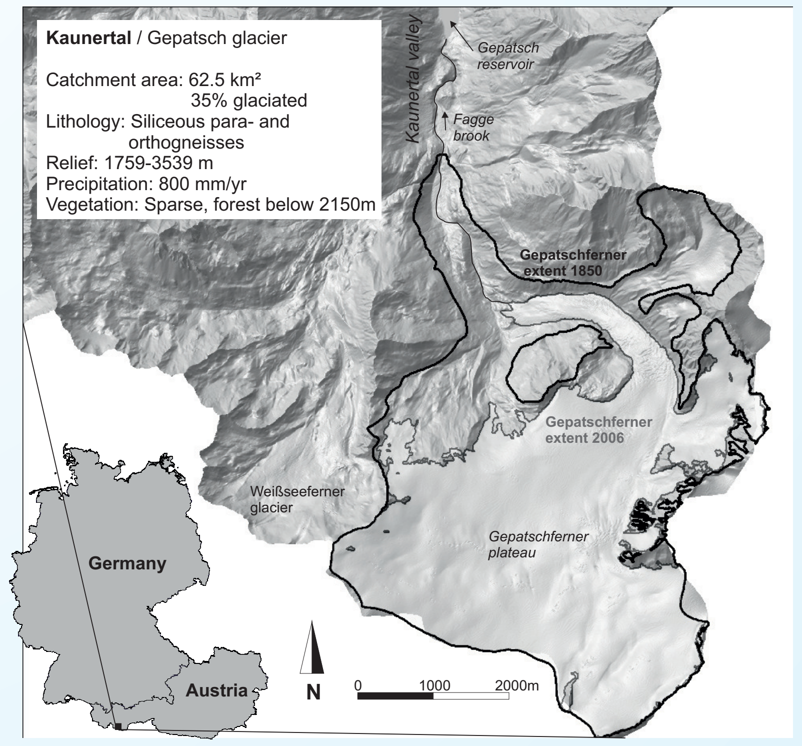
Glaciology
* glacier dynamics and mass balance past, present, future
* sediment at the glacier-bedrock interface

Geodesy
* Coregistration of terr. and aerial LiDAR epochs
* error models for DEMs of difference
* geometric and radiometric classification

Geophysics
* sediment at the glacier-bedrock interface
* ice content of glacigenic sediments

The rockfall sediment budget
will be established by
* measuring rockfall rates using collector nets and terrestrial LiDAR repeat surveys on the hillslope scale
* modelling rockfall sources, pathways and deposition on the catchment scale (this paper), and
* coupling measured rates to the modelled sediment pathways

Study Area

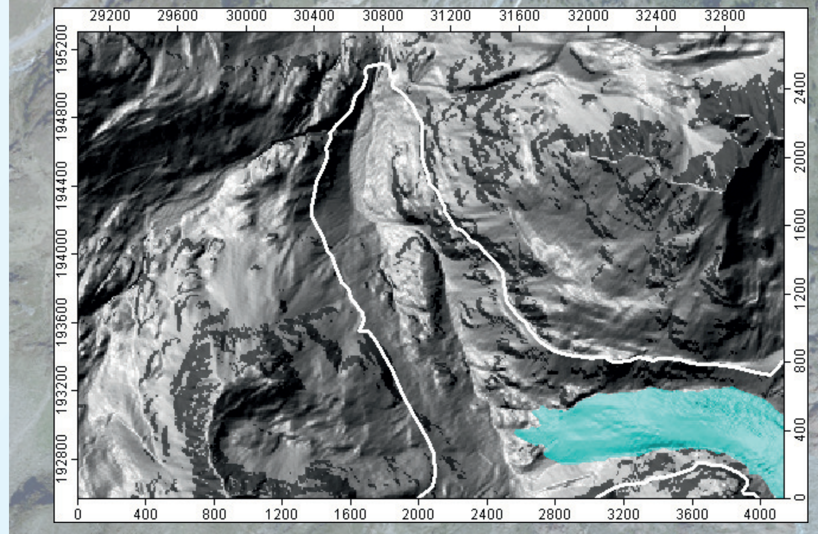


Kaunertal / Gepatsch glacier

Catchment area: 62.5 km²
35% glaciated
Lithology: Siliceous para- and orthogneisses
Relief: 1759-3539 m
Precipitation: 800 mm/yr
Vegetation: Sparse, forest below 2150m

3 Model Approach

Rockfall sources



Glacier extent
1850 (end of LIA)
2006

Rockfall sources (slope >40°)

A simple approach is used to delineate rockfall sources from a DEM: All cells steeper than a threshold (40°) are selected.

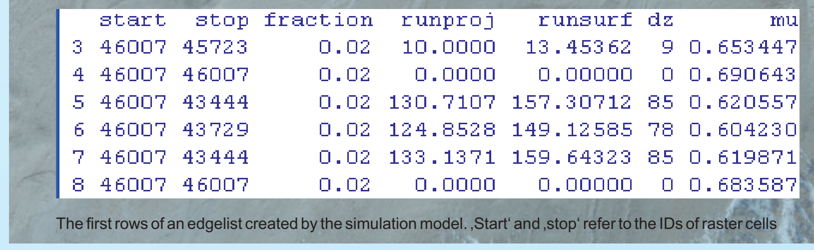
Rockfall simulation model

Starting from source cells, rockfall trajectories are simulated using a stochastic approach (Wichmann & Becht, 2006).
Repeated random walk simulations allow **rockfall trajectories** to diverge from their source cell; the procedure is controled by three parameters:
* slope threshold (no divergence above threshold)
* divergence exponent (controls tendency to diverge from direction of steepest descent
* persistence factor (increases transition probability for previous direction

Rockfall velocity is modelled using a numerical one-parameter friction model with the following properties:
* Slope threshold for modelling free fall
* Energy loss upon impact after free fall (75%)
* Gliding friction μ (between 0.6 and 0.7)
A simulated particle stops when velocity reaches 0.

Additionally, an **edgelist** is stored which contains the unique ID of start and stop cells, and properties of the respective trajectory. The edgelist is used to generate a **graph model** of sediment trajectories.

Alternatively, graph nodes can be represented by terrain subunits, e.g. landforms. The resulting graph can then be used to analyse coupling of units with respect to sediment transport. The degree to which the components of the system are coupled can be addressed as sediment connectivity.

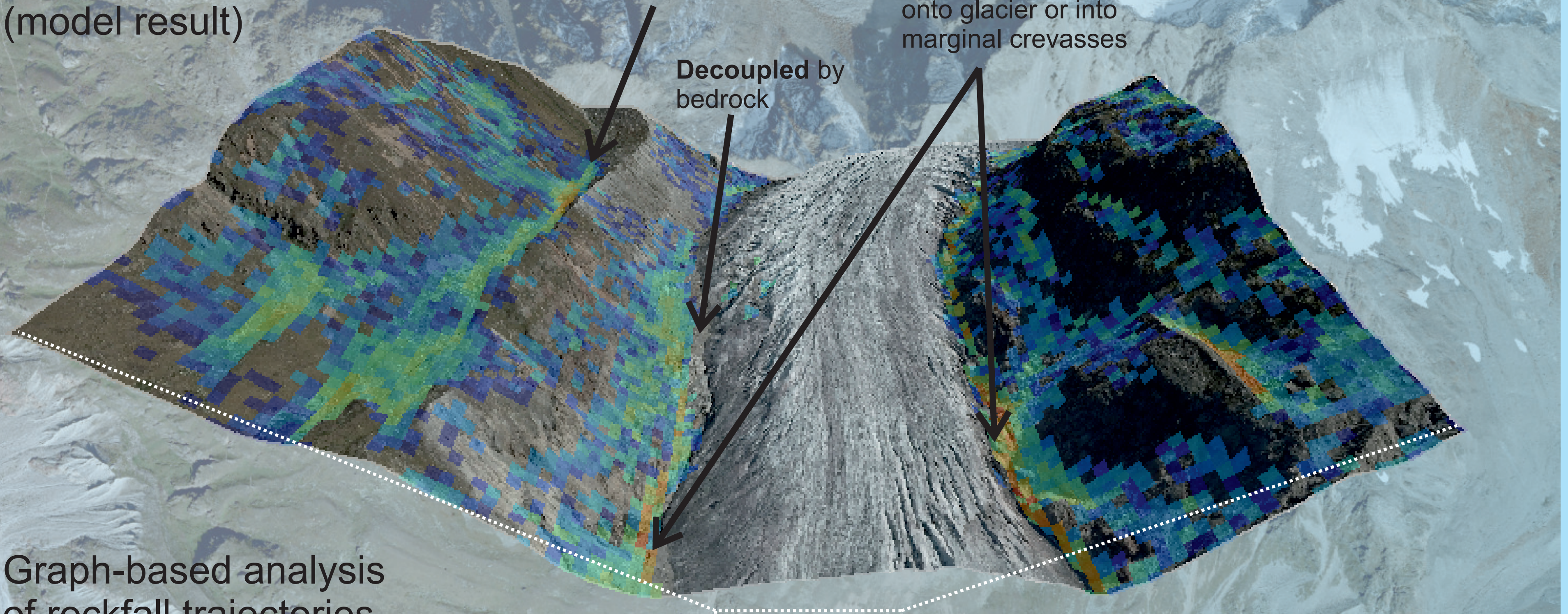


```
  start  stop fraction  runproj   runsurf dz       mu
3 46007 45723     0.02  10.0000  13.45362  9 0.653447
4 46007 46007     0.02   0.0000   0.00000  0 0.690643
5 46007 43444     0.02 130.7107 157.30712 85 0.620557
6 46007 43729     0.02 124.8528 149.12585 78 0.604230
7 46007 43444     0.02 133.1371 159.64323 85 0.619871
8 46007 46007     0.02   0.0000   0.00000  0 0.683587
```

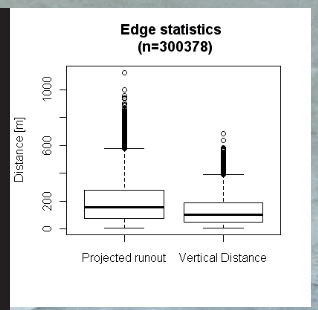
The first rows of an edgelist created by the simulation model. ‚Start' and ‚stop' refer to the IDs of raster cells

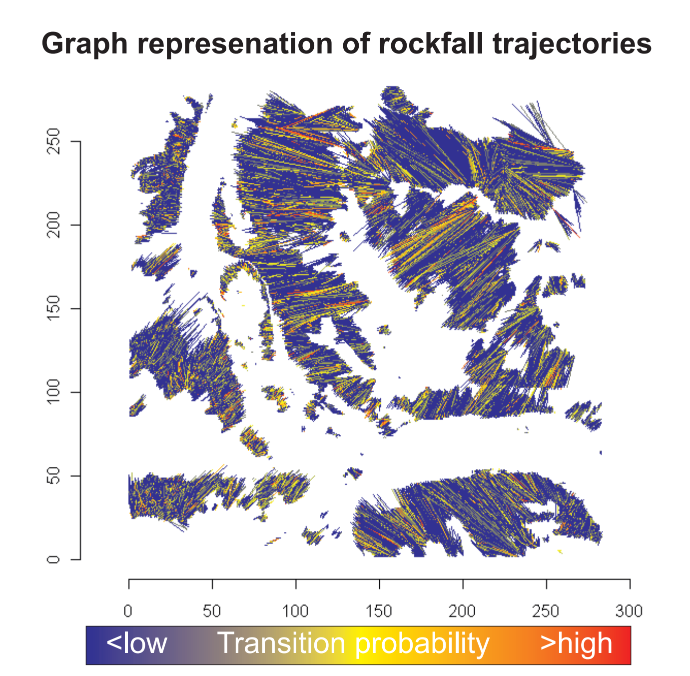
4 First results

Rockfall deposition (model result)

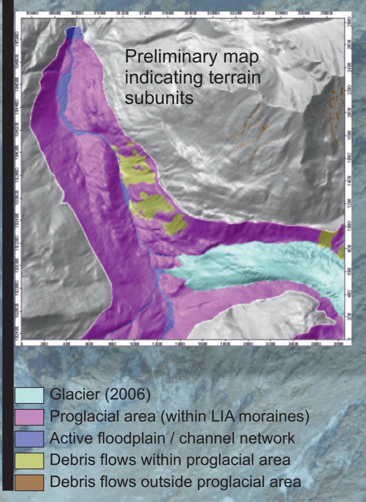


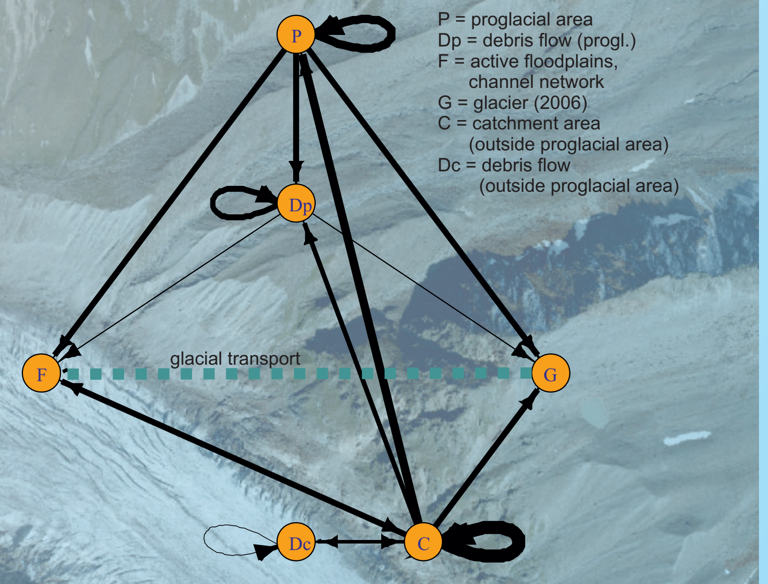
Graph-based analysis of rockfall trajectories and connectivity to the proglacial area





Graph represenation of rockfall trajectories





Graph representation (above) and adjacency matrix (below) of rockfall trajectories within part of the study area.

%		trajectories to...						
		G	F	P	Dp	Dc	C	Sum
trajectories from...	G	0	0	0	0	0	0	0
	F	0	0	0	0	0	0	0
	P	0,2	0,4	**3,1**	0,2	0	0	3,9
	Dp	0	0	0	0,3	0	0	0,3
	Dc	0	0	0	0	0	0	0
	C	0,2	0,2	**1,6**	0,1	0,1	**93,5**	95,7
	Sum	0,4	0,6	4,7	0,6	0,1	93,5	99,9

These preliminary results show that **most rockfall transport (93,5%) occurs outside of the proglacial area**, i.e. the corresponding trajectories do not reach the proglacial area. This is obviously due to the **buffering effect of lateral moraines** and the **spatial distribution of rockfaces** acting as rockfall sources. Only 4,7% of all rockfall trajectories reach the proglacial area (from outside or from within it).

5 The next steps

* Attaching transport rates (measured, from literature, uniform vs spatially distributed) to modelled trajectories
* refining preliminary map for a more differentiated picture of rockfall connectivity
* including other processes in graph analysis
  => analysis of sediment cascades