Publishable Summary

This project focused on transformation of proglacial landscapes and the evolution of glacial landsystems in the Arctic at various temporal and spatial scales. The most important scientific objectives of the project were to: (1) map and quantify landform development within glacial forelands, and (2) evaluate the most important geomorphological processes responsible for landscape changes in proglacial environments.

The research linked fieldwork with the analysis of remote sensing data. Summer expeditions to Svalbard and Iceland were carried out in 2013 and 2014. During the fieldwork we: (1) collected ground control points using differential GPS (for further photogrammetric processing of aerial images), (2) performed repeated geodetic surveys for the ice-marginal zones, focusing on debris flow dynamics as well as dead ice backwasting and downwasting, (3) conducted flight campaigns with unmanned aerial vehicle (UAV) during which we collected very high resolution (3-5 cm) aerial images, and (4) performed geomorphological mapping and sedimentological analysis.

Laboratory work included creation of time-series of orthophotos and DEMs for Svalbard glaciers: Ferdinandbreen, Svenbreen, Horbyebreen (from 1960/61, 1990, 2009); as well as for Icelandic glaciers: Virkis&Falljökull, Svinafellsjökull, Skaftafellsjökull, Morsarjökull (2007), Breiðamerkurjökull (2007/2009), east part of Myrdalsjökull (2007); Kviarjökull (2007), Snæfellsjökull (1998), Hofellsjökull (1998). In addition, very high-resolution orthophotos and DEMs from 2014 (5 cm) were created for parts of the glacier snout and forelands of Horbyebreen, Kviarjökull, Fjallsjökull, Flaajökull and Hofellsjökull.

Quantification of the decadal volume transformations of landforms were investigated based on DEM of Differences (DoDs). Evolution of glacial landsystems were studied using time-series of geomorphological maps created for the studied glaciers based on archival aerial photographs, recent satellite images (2014) and UAV images (2014) for detailed analysis.

The most important findings of the project are related to the quantification of proglacial landscape changes. Based on the analysis of time-series of DEMs we classified proglacial areas into one of the three conditions:

- Stable, i.e. completely de-iced and not undergoing any intensive transformations;
- Temporarily stable - in balance with current climatic conditions, but still containing ice and therefore prone to future de-icing and relief changes;
- Active – actively transformed by mass wasting processes and/or meltwater activity.

The mass balance of the studied glaciers is strongly negative. In decadal time-scales it varies from -0.8 m/year to -1.45 m/year. However, the large part of the proglacial areas, despite the existence of the dead-ice under the relatively thin (<2 m) debris cover, are now in temporarily stable condition. These temporarily stable areas cover between 50 to 95 per cent (Figure 1). Mostly, stable conditions are related to the frontal (end) moraines, which in 50-years' time scale are in equilibrium with topographic and climatic conditions. Active areas are related mostly to the lateral moraines. Their short-term mass balance can reach -1.8 m/year; however, such high values were recorded only for short periods and for specific locations. In decadal time-scales an average annual mass balance of active parts was between -0.05 to -0.3 m/year.

Debris flows were identified as the most important resedimentation processes leading to transformation of the active parts of the forelands. However, their spatial and temporal distribution and intensity varied during the deglaciation period. At the first stage, shortly after ice margin retreat, when the debris cover was thin (thinner than the thickness of permafrost active layer), mass movement processes were widespread. They were facilitated by the dead-ice melting and steepness of the slopes. Hence, when glaciers started to retreat from their LIA maximum extent, debris flows were common within the end moraines complexes, which is confirmed by sedimentological analysis of debris flow deposits. Ongoing mass wasting processes transferred sediments from steep slopes to more stable positions. As the thickness of the sediments increased, the debris cover protected the dead-ice from melting and also contributed to the decrease in slope gradient. Thus, the resulting landscape was relatively stable and in equilibrium with current climatic and topographic conditions. This stage now characterizes most parts of the frontal (end) moraine complexes of the studied glaciers; thus, their transformation rates are either very low or close to zero. However, despite their temporal stabilization, end-moraines still contain large amounts of dead-ice. The zone of highest intensity of debris flows migrated up-valley following the retreating exposed ice surface, and at present most of the active debris flows occur within lateral moraines Lateral moraines are characterized by steep slopes, abundance of active mass movement processes, and by consequence a high degree of transformation.

Some parts of the stable landscape can be subsequently transformed again into unstable (i.e. active) conditions, mainly due to the effect of external factors such as streams or meltwater channels. This can lead to the development of mass movement processes and further slope instability, which could facilitate subsequent generation of debris flows. The stages described above can occur in a sort of spatio-temporal cycle, and, depending on local and external factors, the changes between stabilization of landforms and activation of mass flows can be repeated several times for any given area until the dead-ice is completely melted.

The most important drivers behind the switching from stable to active conditions (and vice versa) are topography and meltwater. The increase in slope gradient can cause an increase in the activity of mass movement processes. Some of the possible factors contributing to the over-steepening of a slope are streams and meltwater channels. They cut into a slope and remove the material from the basal part of the slope, thus changing the topographic profile and increasing the slope gradient. In that way, mass movements are facilitated. Subsequently, mass movements remove debris from slopes, leading to the creation of instability in the upper part of the slope, and thereby propagating mass movement development in the upslope direction. Topography and water are usually related to each other. An increasing amount of water within a slope increases the mass of sediments, and at the same time separates grains, causing a reduction in friction and shear strength. If the critical value of the slope is then crossed, sediments will flow down, causing an increase in gradient and instability in the upper part of the slope. Sediments which slump, flow, or fall to the base of the slope can be subsequently removed by streams. Removal of sediments from the slope base efficiently eliminates support for the upper part of the slope, subsequently causing slope instability.

In summary, many of the modern moraine complexes on Svalbard and Iceland are composed of large amounts of dead-ice covered by a relatively thin veneer of debris, often less than a couple of metres thick. During deglaciation, these ice-cored landforms are subjected to various resedimentation processes, which finally will lead to the creation of a more stable landscape. Our results demonstrated a spatio-temporal switching between stable and active conditions within an ice-marginal environment and investigated drivers responsible for changing from stable to active conditions. The spatial and temporal distributions of volume changes were very diverse and for the most part related to local geomorphic conditions such as slope gradient and abundance of meltwater rather than climate changes. The findings of the project are especially important for reconstruction of the glacial systems as well as proper understanding of the geological records. Recognition of drivers related to changes from stable to active conditions is also valuable for landscape management in the Arctic.

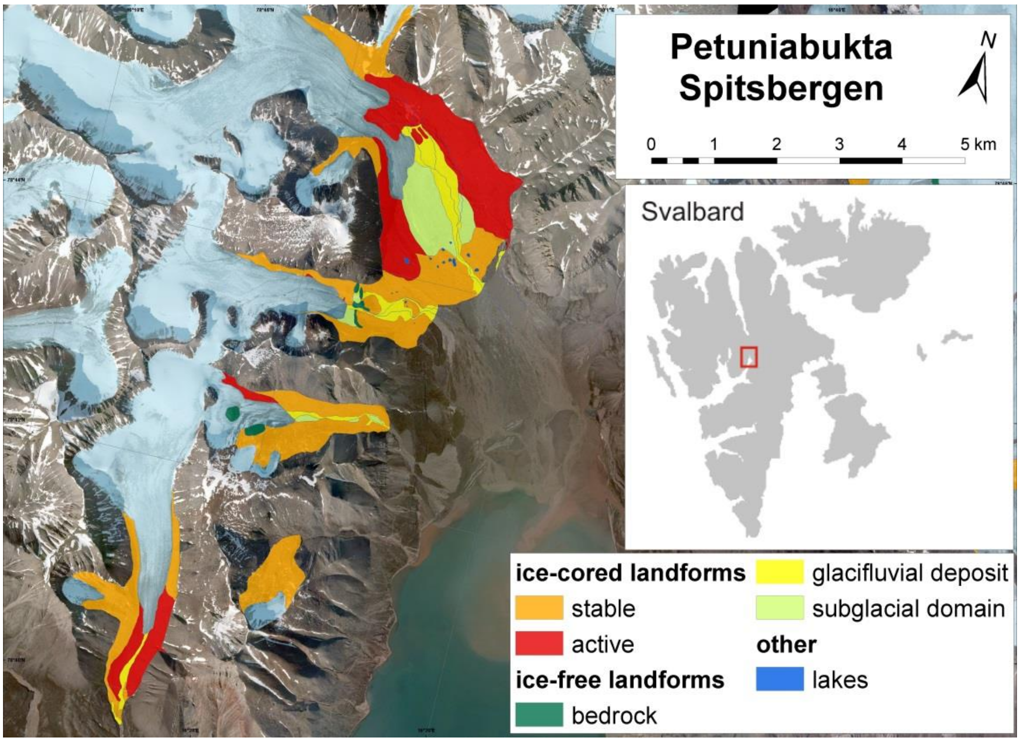

Figure 1. Active and stable areas of proglacial landscape - an example from Petuniabukta, Svalbard