

FINAL REPORT FOR NPS PERMIT WRST 00126

NPS Study/Permit Title: Rapidly degrading alpine escarpments and dynamic landscape evolution: impacts of arctic warming and deglaciation

Report Title: *Geomorphic Response of Glacial Decoupling in Alpine Regions in Response to Climate Warming: Icy Debris Fans and Early Paraglacial Landscape Evolution*

Summary

Icy debris fans are largely unexplored landforms that occur along the margins of valley glaciers in high alpine regions where glaciers have become disconnected from high-level icecaps as climate warmed. Ice and sediment shed from icecaps and escarpment walls moves through small bedrock catchments and is delivered to the fans, and ultimately flows into the subjacent valley glacier. Flow from icy debris fans may represent a major mode of ice supply to the annual budget of glaciers lacking tributaries or direct connections to icecaps. Direct field observations documented exceptional rates of depositional activity at McCarthy Creek Glacier in the Wrangell Mountains of Alaska (in Wrangell-St. Elias National Park and Preserve, Fig. 1) and at Mueller, La Perouse, and Douglas Glaciers in the Southern Alps of New Zealand (in Aoraki/Mt. Cook and Westland/Tai Poutini National Parks). Our study approach integrated multiple modern techniques that produced a 4-D characterization of icy debris fans for the first time, including: 1) time-lapse photography over periods of 1-2 years, 2) ground penetrating radar (GPR), and 3) terrestrial laser scanning (TLS).

Collectively, our results document: 1) higher frequency and volume of mass flow events than previously recognized (ice avalanches, slush flows, icy debris flows, and rockfalls), including more activity during winter months (fans received between 200 – 2,300 significant depositional events per year, dominated by ice avalanches); 2) variations between mass flow processes (flow transformations) related to relative proportions of ice, snow, water, and lithic material; 3) more significant flow of ice and lithic (sediment) material to subjacent valley glaciers than previously documented, improving our knowledge of glacier budgets; 4) significant variations between the geometry of feeder catchments and the nature and pace of depositional processes – which results in differences in the evolution of icy debris fans.

TLS surveys between 2013 and 2015 indicate that icy debris fans contribute 1.5% – 5% of glacier volume annually to their valley glaciers. This contribution, in some cases, appears to be slowing thinning and deglaciation of valley glaciers and represents an important contribution to annual ice budgets. For example, McCarthy Glacier, the smallest glacier studied that has large icy debris fans, thinned about 1 m/yr while New Zealand glaciers lost 5 – 10 m/yr during our study (Fig. 5). Our results improve models

for landscape evolution in deglaciating alpine regions and have also provided guidance to parks in management of geologic hazards in these areas frequented by the general public.



Figure 1. Icy debris fans at McCarthy Creek Glacier, showing diversity related to the geometry of catchments feeding ice and sediment to them from the icecap above. The area of the terminus of the icecap above the large fan on the right contributes frequent ice avalanches to the fan through a relatively simple ramp-like catchment. The smaller fans on the left receive less ice because there is less icecap face above them. Additionally, the left fans receive a mix of ice avalanches and debris flows because rockfall and avalanche material is temporarily stored in their complex catchments and remobilized by later events.

Objective #1 – Surface Processes: quantify the nature, pace, and volume of mass wasting deposits on icy debris fans throughout the year.

Results for Objective #1. We successfully completed this objective through field observations and installation of time-lapse cameras at each study site. Time-lapse imagery documented five key processes actively delivering material to the icy debris fans: 1) ice avalanches, 2) slush avalanches, 3) slush flows, 4) icy debris flows, and 5) rockfalls. We quantified the timing and nature of 3,701 depositional events captured by time-lapse photography. Our key finding is that ice avalanches accounted for more 90% of the events at every site. Depositional activity occurred throughout the year, but slowed somewhat during mid-winter. For example, as many as 1,624 depositional events took place on one icy debris fan during one year. The pace of depositional activity on icy debris fans typically increased following major rainfall events, especially for slush flows and debris flows. We observed seasonal changes in the dominance of depositional processes. Ice avalanches occurred throughout the year with a higher pace during summer months. Slush flows and slush avalanches were most active during summer, spring, and fall. Debris flows were most common in summer months. Rockfalls occurred randomly without relationship to season. Rockfalls were uncommon but were sometimes characterized by exceptionally large events. The pace of depositional activity observed on icy debris fans was extraordinarily active compared to alluvial fans. Time-lapse imagery, together with scaling from field observations and TLS surveys quantified the volume of every deposit added to the fans during the observational period. Individual events varied considerably in size but ranged up to 60,000 m³ by volume. The volume of material (largely ice) added to the fans was up to 12,000,000 m³/yr. These results allow for comparison with depositional landforms that have been extensively studied, such as alluvial fans. The pace of deposition on icy debris fans is orders of magnitude higher than on alluvial fans, which experience just a handful of events annually, many of them experiencing no events. Resurfacing rates on icy debris fans are also orders of magnitude higher than for alluvial fans, whose resurfacing rates are never more than 100%, and are usually much less. For example, the rate of resurfacing on the icy debris fans in New Zealand ranged between 598% to 3,447%. These results should be useful to national park officials for assessing natural hazards that impact the general public.

Objective #2 – Subsurface architecture: quantify the nature and volume of icy debris fans.

Results of Objective #2. We successfully completed this objective through collection of ground penetrating radar (GPR) surveys at each study site. We collected wide angle reflection/refraction (WARR) soundings to determine the GPR signal velocity at each icy debris fan site so that the depth to GPR reflections could be determined. Multiple GPR

profiles were also collected at each icy debris fan to non-invasively image the subsurface architecture. The key finding from the GPR surveys was the difference between GPR reflections from the icy debris fans and the glacial ice at the distal portion of each fan. This difference was also observed beneath several fans, suggesting that these icy fans are sitting above glacial ice.

The GPR data indicates that each fan has 15-75 m thick packages of lenticular fan deposits, which thin toward the perimeter of the icy debris fans. Multiple packages with varying geometries, separated by a strong reflector, indicate complex fan histories. We interpret the strong reflector as a period with little resurfacing leading to lithic concentration, or a rockfall event.

Objective #3 – Quantify fan and valley glacier area/volume changes over time

Results of Objective #3. We successfully completed this objective through collection of repeat terrestrial laser scanning (TLS) surveys at each site. Repeat TLS surveys characterize the morphology of the fans, glaciers, and to limited extent, the catchments, enabling quantification of changes in surface area and volume over a 2-year period. Results demonstrated complex changes in icy debris fan area/volume; three fans decreased (-5% to -24%) and eight increased (+2% to +33%). Fans that decreased in volume appear to be linked to sites with decreased supply from icecaps. All valley glaciers decreased (evident by surface deflation) but by varying degrees. McCarthy Glacier showed minor deflation, < 1 m/yr, while New Zealand glaciers experienced a minimum of 5 m/yr deflation. Quantifying these changes allows us to better understand connections between upper level icecaps, the icy debris fans, and the intervening catchments between them.

Objective #4 – Fan catchments: document variations in catchment morphologies

Results of Objective #4. We successfully completed this objective through aerial helicopter-based imagery and TLS surveys at each site. Larger fans have extensive icecap exposure-supply, short catchments, and small catchment storage areas. Fans with greater icecap exposure are dominated by avalanches and slush flows. The variation in geomorphic complexity between catchments generates varying dominance of flow processes. Fans with large catchments and abundant storage area experience a mix of avalanches, debris flows, and slush flows. Fans with small catchments experience only ice avalanches and occasional slush avalanches and slush flows. Catchment lengths range from 274m to 1400m. Surface area and geomorphic complexity play a large role in fan morphology by affecting the nature of flow processes delivered to the fans. Temporary storage of ice and lithic debris is transformed within the catchment and remobilized during later events. As an example, the McCarthy Creek Glacier, small icy debris fans occur below catchments with significant morphologic complexity (large space for temporary ice/sediment storage) and little icecap surface area contributing to the catchment. A larger fan has less complex catchment morphology (little space for

temporary ice-sediment storage) and more icecap surface area. For example, an ~888-m-long catchment with abundant storage space, including multiple bedrock basins, and ~40,000 m² of icecap supply face has a fan volume of ~3,125,000 m³, whereas an ~686-m-long catchment with less storage space and ~95,000 m² of icecap supply face has a fan volume of ~24,660,000 m³. Between 2013 and 2015, smaller fans decreased in volume by up to 1,200,000m³, whereas the large fan increased in volume by 700,000 m³. These changes reflect the smaller volume of ice/sediment supplied to the smaller fans compared with the larger volume of ice/sediment deposited on the larger fan, documented by time-lapse imagery of depositional events.

Integration of these findings provides an improved understanding of the complex interplay between retreating upper-level icecaps, icy debris fans, and valley glaciers. Valley glaciers are deflating, which provides increased accommodation space for icy debris fans to enlarge. Icy debris fans only get larger if they have sufficient supply from their icecaps. However, while most icy debris fans increased their volume over the survey period, some did not as a result of decreased supply rates from the icecap. Despite the high frequency and volume of deposition on icy debris fans compared to other types of fans, the volume contributed by them is still unable to prevent glaciers from diminishing. For example, at La Perouse Glacier, two icy debris fans experienced volume increased of > 400,000 m³ in one year, but the glacier deflated as much as 5 m. At Mueller Glacier, where > 12,000,000 m³/yr of was deposited, the lower portion of the glacier is collapsing, causing the fan to begin to collapse into the glacier.

TRAINING AND PROFESSIONAL DEVELOPMENT

PI Jacob mentored PIs Trop and Kochel on geophysics. PIs Kochel and Trop mentored PI Jacob on surficial processes; Keith Williams (UNAVCO) mentored PIs on terrestrial laser scanning. PIs Kochel, Jacob, and Trop mentored fourteen undergraduate students during 2013-2016: Darin Rockwell ('13), Stew Kabis ('14), Tracey Smith ('14), Chris Duda ('15), Mattie Reid ('15), Erica Rubino ('15), Alex Pellicciotti ('15), Seamus McLaughlin ('15), Liz Wills ('15), Steve Grune ('16), Katherine Wagner ('18), Kim Lapszinski ('17), Charles Scales ('17), Sandy Logan ('18), Brian Moretti ('18), and Ben Bliss ('19). Each student analyzed, interpreted, and disseminated scientific data as part of a discrete project; one student collected field data in Alaska (Smith); four collected field data in New Zealand (Duda, Pellicciotti, Reid, Rubino); eight disseminated results at a national conference (Bliss, Duda, Kabis, Moretti, Reid, Rubino, Scales, Smith); six presented at a campus symposium (McLaughlin, Reid, Rubino, Scales, Wagner, Wills) four completed senior theses (Grune, Reid, Rubino, Smith) and eight completed written reports (Kabis, Lapszinski, Logan, McLaughlin, Pellicciotti, Rockwell, Scales, Wills).

DISSEMINATION

The PIs and students have delivered ten presentations at national conferences and recently submitted two journal articles for peer review; four theses have been completed.

We also provided conference posters to National Park Service personnel at Wrangell-St. Elias NP (Alaska) that highlight the objectives, methods, findings, and implications of our research. We provided research summary posters to park personnel at two New Zealand National Parks - Aoraki/Mt. Cook NP and Westland/Tai Poutini NP.

PI Kochel presented public outreach talks about our research objectives and findings in two remote villages within our study areas (Fox Glacier, NZ and Aoraki/Mt. Cook, NZ). The audience was composed of local villagers as well as National Park officials from Aoraki/Mt. Cook NP and Westland/Tai Poutini NP – both of which are World Biosphere Reserves.

An article in the Bucknell University alumni magazine Bucknell World explains the scientific objectives, methods, student participation, and implications of our research.

A project website (<https://icydebrisfans.blogs.bucknell.edu>) highlights the scientific objectives, methods, key findings, and implications of our research. This website is currently under development; preliminary information can be found there, but substantial revisions are planned.

PUBLICATIONS

Theses

Grune, S., 2014, Dynamics of Icy Debris Fans on the McCarthy Glacier, Wrangell Mountains, Alaska: Two Years of Time-Lapse Imagery Analysis: Honor's Thesis, Bucknell University, Lewisburg, PA.

Reid, M.M., 2015, Mass Wasting Processes, Geomorphic Response, and Seasonal Variation of Icy Debris Fans on the La Perouse Glacier and Douglas Glacier, Tai Poutini, Westland National Park, Southern Alps, New Zealand: Honor's Thesis, Bucknell University, Lewisburg, PA.

Rubino, E.M., 2015, Geophysical Investigation of Icy Debris Fans with Ground Penetrating Radar, Southern Alps, New Zealand: Honor's Thesis, Bucknell University, Lewisburg, PA.

Smith, T., 2014, Geophysical Investigation Of Subsurface Three-Dimensional Architecture Of Icy Debris Fans With Ground Penetrating Radar In The Wrangell Mountains, Alaska.

Articles

Jacob, J.W., Trop, J.M., Kochel, R.C., Smith, T.D., Rubino, E.M., GPR to image subsurface characteristics of icy debris fans in New Zealand and Alaska: GPR Conference, 16th Annual International Conference of Ground Penetrating Radar, in revision following review.

Kochel, R.C., Trop, J.M., and Jacob, R.W., Geomorphology of Icy Debris Fans: Delivery of Ice and Sediment to Valley Glaciers Decoupled from Icecaps: Geosphere, submitted 10/17, in review.

Conference Abstracts

Kochel, R.C., Trop, J.M., Jacob, R.W., 2017, Critical lifelines for alpine glaciers decoupled from icecaps: mass flow contribution from icy debris fans in Alaska and New Zealand: Geological Society of America Abstracts with Programs, Annual Meeting.

Kochel, R.C., Trop, J.M., Jacob, R.W., Bliss, B., Moretti, B., Scales, C.A., Williams, K., and Grune, S., 2017, Morphology, Depositional Pace, and Ice Volume Contribution of Icy Debris Fans to McCarthy Creek Glacier, Wrangell Mountains, Alaska (2013-2015): An Integrated Approach Using Field Observations, Time-Lapse and Drone Imagery, Ground Penetrating Radar, and Terrestrial Laser Scanning: Geological Society of America Abstracts with Programs, Cordillera Section Meeting, vol. 49, no. 4.

Bliss, B., Scales, C., Moretti, B., Grune, S., Kochel, R.C., Trop, J.M., Jacob, R.W., and Williams, K., 2016, The effects of catchment morphology on the transfer of ice and sediment from ice caps to icy debris fans and valley glaciers in deglaciating alpine environments: Geological Society of America Abstracts with Programs, v. 48, no. 7.

Jacob, J.W., Trop, J.M., Kochel, R.C., Smith, T.D., Rubino, E.M., 2016, GPR to image subsurface characteristics of icy debris fans in New Zealand and Alaska: GPR Conference, 16th Annual International Conference of Ground Penetrating Radar.

Jacob, R.W., Smith, T., Kochel, R.C., Trop, J.M., Rockwell, D., Kabis, S., and Williams, K., 2015, Icy debris fans: a dynamic landform in deglaciating alpine environments – an example from McCarthy Creek glacier, Wrangell Mountains, Alaska: Geological Society of America, Abstracts with Programs, v. 47, no. 4.

Reid, M.M., Kochel, R.C., Trop, J.M., Jacob, R.W., Duda, C.M., Rubino, E., and Williams, K., 2014, Mass wasting processes, geomorphic responses, and temporal evolution of icy debris fans along the la Perouse and Douglas glaciers, southern Alps, New Zealand: Geological Society of America, Abstracts with Programs, v. 46, no. 6, p. 340.

Rubino, E.M., Jacob, R.W., Kochel, R.C., Trop, J.M., Reid, M.M., Scales, C., Duda, C., Williams, K., 2014, Geophysical investigation of icy debris fans with ground penetrating radar on the la Perouse and Douglas glaciers, southern Alps, New Zealand: Geological Society of America, Abstracts with Programs, v. 46, no. 6, p. 342

Smith, T., Jacob, R., Trop, J.M., Williams, K., Kochel, R.C., 2013, Geophysical investigation of subsurface characteristics of icy debris fans with ground penetrating radar in the Wrangell Mountains, Alaska: Geological Society of America, Abstracts with Programs, v. 46, no. 2, p.107.

Smith, T., Jacob, R., Trop, J.M., Williams, K., Kochel, R.C., 2013, Geophysical investigation of subsurface characteristics of icy debris fans with ground penetrating radar in the Wrangell Mountains, Alaska: EOS, American Geophysical Union Transactions, abstract NS42A-04.

Kochel, R.C., Trop, J.M., Jacob, R., Smith, T. ['13], Rockwell, D. ['12], Kabis, S. ['13], Williams, K., 2013, Integrating terrestrial laser scanning, ground-penetrating radar, and time-lapse photography to understand surficial processes/morphology and subsurface architecture of icy debris fans in deglaciating alpine environments: Geological Society of America, Abstracts with Programs, v. 45, no. 7, p. 578.