Collaborative Research: Systematic Analysis of Landscape Evolution and Surface Ages in Southern Transantarctic Mountains

Introduction and motivation

Little is known about the landscape evolution in the coldest deserts on Earth; the deserts exposed on the southern Transantarctic Mountains, Antarctica. These dirt islands in the vast sea of ice are increasingly viewed as rare archives of information on the history of glacial fluctuations and thus climate, and repositories of both plant and microbial activity and evolution. The exposed land also serves as the best terrestrial analog of Martian surface processes and conditions including the fate of soil ice over time periods of millions of years.

The unspoken assumption for meaningful research on above mentioned topics is the stability and preservation of these surfaces. For example if the land surface follows the typical spatial pattern of erosion, transportation, and deposition that is dictated by the local topography, many signs of past surface processes would be eradicated at a relatively short time period of about 1 Myr (depending on the amplitudes and wave lengths of the topographic features). Therefore the geologic evolution of the landscape sets the limits to the longevity of the deposits as well as our ability to assign (cosmogenic exposure) ages to them. Currently the little quantitative knowledge that exists of the landscape evolution in the Antarctic deserts come from the McMurdo Dry Valleys which may poorly represent the rates and processes found in the interior of the Antarctica.

The past research in the Dry Valleys by our team indicates that erosion of regolith deposits there is slow but pervasive and that over the lifespan of several million years the deposits have degraded for many meters and some drifts have been completely eradicated (more details are given below).

Currently it is unclear if these relatively high rates of erosion are limited to the Dry Valleys that is located at the perimeter of the Antarctic continent and close to the seasonally open ocean or whether they apply in the more continental and much colder southernmost segment of the Transantarctic Mountains as well. This lack of understanding of the landscape evolution of TAM was also prominently noted In a recent NSF sponsored Antarctic workshop and resulting report to the NSF OPP (Elliot, 2007) where the geological surface processes and their role in the landscape evolution of the TAM was highlighted as one of the fundamental questions to be addressed in future Antarctic research.

Moreover, the central quest in geomorphology is to understand the rates and patterns of landscape evolution; the mobility of the surficial deposits, and the rate that the bedrock is down-wasting. Much of the scientific effort by geomorphologists has been devoted to areas that experience high rates of landscape evolution such as monsoon ravaged Himalaya. Areas of low erosion rates have received less attention but are scientifically just as important and can reveal insights of processes and rates that have dominated in those areas for maybe millions of years and even longer in other planets.

Antarctica is recognized as the closest terrestrial analog to the current conditions in Mars where no running water or biological activity contributes to sediment erosion or transportation (excluding the recent press release on gully erosion by water (NASA, 2006)). However, strong winds are commonly observed in both Antarctica and Mars. Therefore the improved understanding of the rates and processes that contribute to regolith degradation in the coldest terrestrial desert would provide much needed quantitative basis to interpret high resolution images such as NASA HiRISE and Phoenix lander imagery from Mars.

For these reasons we propose to expand our research on landscape evolution and surface ages into the Transantarctic Mountains (TAM) to meet three specific goals: 1) to determine the past and current rate of sediment transport and surface degradation in the southern TAM, 2) assign (minimum) exposure ages for the representative soil surfaces, 3) determine possible past shielding/burial of the surfaces by non-eroding ice.

The scientific significance of the proposed research:

Currently the general understanding of surface degradation and sediment transport in typical midlatitude environments and climates is relatively good (e.g. Culling, 1960; Carson and Kirkby, 1972; Bucknam and Anderson, 1979; Andrews and Hanks, 1985; Andrews and Bucknam, 1987; Birkeland and Burke, 1988; Bursik, 1991; Avouac, 1993; Hallet and Putkonen, 1994; Enzel et al., 1996; Bierman et al., 1998; Birkeland et al., 2003; Bullard, 2003; Putkonen and Swanson, 2003; Bierman et al., 2005; Putkonen and O'Neal, 2006; Putkonen et al., 2008b). However, in addition to the recent work by our team in the Dry Valleys little else is known of the quantitative sediment transport rates in the coldest and driest deserts on Earth. This proposed research will directly quantify the current and long term erosion and sediment transport rates in the southern TAM. This will potentially establish the lowest measured terrestrial erosion rates that will enable realistic modeling and assessment of surface preservation in other similar environments and planets. Our research has a high potential of transforming the current assumption of little to no degradation over periods of millions of years in TAM.

Background

Unaltered geological landforms and preserved geomorphic features at the Earth's surface tell us about the past geological processes and environments. However, soon after the original deposition of those landforms, or regolith, or glacial drifts they are subjected to erosion that slowly deforms and eventually eradicates them. Therefore the oldest landforms that are dated in the mid-latitudes tend to be only few hundreds of thousands of years old (e.g. Putkonen and Swanson, 2003) effectively limiting the temporal applicability of the morphological analyses.

In typical terrestrial conditions regolith and sedimentary landforms are most susceptible to erosion that is caused by water and biological activity including fluvial processes, rilling, rain splash, burrowing creatures, and toppling of trees. The current climate in Antarctica is not conducive to any of these processes and therefore the expectation is that the landforms and drifts there may have survived for millions of years bearing records of ancient geological events and climatic shifts.

Previous work in the McMurdo Dry Valleys area has suggested almost total preservation of drifts and landforms under apparently in situ deposited volcanic ash layers that establish minimum ages for those surfaces exceeding 5 Ma and often reaching 10 Ma (Marchant et al., 1993a; Marchant et al., 1993b; Marchant and Denton, 1996; Marchant et al., 1996). We studied the cosmogenic isotope concentrations in vertical soil profiles on some of the same deposits and found that our technique is well suited for the Antarctic environment and allowed us to directly date the drifts or establish minimum ages for them. We also determined the long term mean degradation rates of some of them.

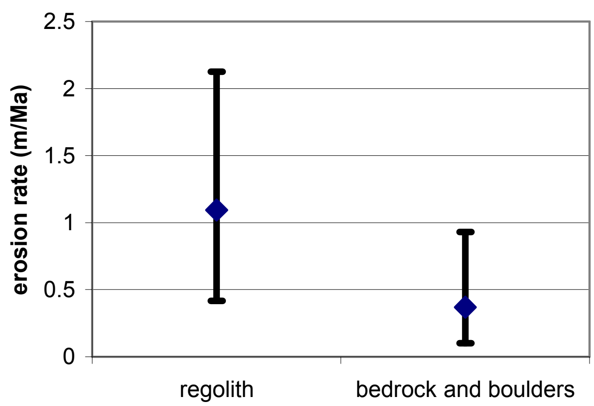

Figure 1. Preliminary results of mean, maximum and minimum surface erosion rates in the Dry Valleys. Statistics are based on: our own unpublished regolith samples, and means of individual published studies of bedrock and boulder erosion rates (Brook et al., 1995; Ivy-Ochs et al., 1995; Bruno et al., 1997; Schafer et al., 1999; Summerfield et al., 1999; Margerison et al., 2005; Staiger et al., 2006).

We found that some of the same surfaces where the ash dates have been obtained are subject to slow but persistent erosion and that they have degraded for several meters over the past few million years (Putkonen et al., 2008a; Putkonen et al., 2008b; Putkonen et al., 2008c). This can be interpreted to reflect the heterogeneity of the surfaces and spatially varying rates of degradation. Our most important findings are that: 1) the surfaces are at least few million years old, 2) they have degraded for several meters over that time period, and 3) they have not been shielded by non-erosive ice (Putkonen et al., 2008a).

Our findings in the Dry Valleys show that although the tephra-dating and related chronology of the drifts (Marchant et al., 1993b; Marchant and Denton, 1996; Marchant et al., 1996) suggest almost perfect preservation of some surfaces, other parts of the landscape are more ephemeral and unstable than previously assumed (Figure 1). It is worth pointing out here that although the regolith surfaces are relatively unstable in Antarctic sense, the absolute regolith (loose soil) degradation rates in the Dry Valleys are still much smaller than bedrock (solid rock) erosion rates in many mid latitude climates (e.g. Burbank et al., 2003).

A consistent picture is emerging from the research in the Dry Valleys of slow but persistent erosion of both bedrock and regolith. It is also comforting to note that although much of the research has been completely independent the preliminary results seem to converge. The mean regolith erosion rate

(~1.1 m/Ma) is found to be almost three times the magnitude of the mean bedrock erosion rate (~0.4 m/Ma).

Prior geomorphological research and surface dating in TAM

Transantarctic Mountains (TAM) are perhaps the least studied terrestrial area on Earth due to the inaccessibility and inhospitability of the environment. Most of the prior research has been concentrated on glaciology, paleontology, bedrock geology, volcanic provinces, and evolution of the rift margin. Only a handful of scientists have studied the geomorphology, surface processes, and glacial geology (e.g. Grindley, 1967; Mercer, 1968; Mayewski, 1975; LaPrade, 1984; Mayewski and Goldthwait, 1984; Bockheim et al., 1989; Denton et al., 1989; Ackert and Kurz, 2004; Todd et al., 2007).

Our field plan is guided by the prior work in the Miller Range by Grindley (1967), who mapped much of the area and describes the deposits. One of our primary targets in the Ong Valley is the channel network that Grindley (1967) reports as a proof of warmer climate in the past.

Ackert and Kurz (2004) recently dated possibly the oldest deposit in the southern TAM (Sirius Tillite in the Dominion Range) and suggested that the erosion rate of the steeply sloping semi-lithified deposit is 2.5 m/Ma. This is a very interesting finding because the degradation rate is higher than what we found in the Dry Valleys on a completely loose regolith surface (2 m/Ma (Putkonen et al., 2008a)). This comparison suggests that the regolith mobility in the TAM maybe higher than in Dry Valleys.

Mayewski (1975) mapped the Moraine Canyon in the Queen Maud Mountains, which forms the basis for our field plans and sampling strategy there. Meltwater related features that were formed during interstadial were described also in many locations in the Queen Maud Mountains by Mayewski (1975), although not specifically mentioned in the context of Moraine Canyon.

In addition to the Sirius formation that is found in numerous locations throughout the southern edge of the TAM three glaciations and related deposits are typically described; low, middle, and high moraine and corresponding Amundsen, Shackleton, and Scott glaciations (Mayewski, 1975). The two oldest ones are typically separated by fluvial deposits that may suggest an interstadial. The best currently existing published dating control is for the low moraine (following the nomenclature by Mayewski (1975)) (Beardmore moraine of Ackert and Kurz (2004)) and undivided moraine (Dominion moraine) at Dominion range and recently dated to be about 20 ka and 2 Ma old respectively (Ackert and Kurz, 2004). No quantitative estimates of the degradation (except 2.5 m/Ma for the semilithified Sirius Tillite) or regolith transport rates exists. The lowest moraine has now been extensively dated at Reedy Glacier in the southernmost TAM and is LGM in age, exposure dates are 10-18 ka (Todd et al., 2007).

Hypotheses and objectives

Currently little is known about the past and present landscape evolution in the southern TAM. The general expectation is that most geomorphological surface processes are inactive rendering the regolith surfaces stable. Therefore it is generally thought that moraines and drifts of ancient glaciations are perfectly preserved. Our hypothesis is that most regolith surfaces in the TAM are currently experiencing surface erosion and sediment transport, but we suggest that minimal deposition is taking place. This hypothesis is based on our recent and current work in the McMurdo Dry Valleys.

Our objectives are: 1) to determine the rates of current and past regolith erosion, transport, and deposition in TAM. 2) Date the previously mapped fluvial features. 3) Determine minimum ages for mapped drifts and surfaces. 4) Determine erosion rate of the bedrock surfaces.

The importance of the expected results

1) We will quantify both the current and long term erosion rates in the TAM. This is important for fundamental understanding of the terrestrial geomorphology since little is known about the landscape evolution of coldest and driest deserts on Earth. As images of Martian surface such as are provided by HiRISE are approaching the resolution where geomorphology can be easily resolved we lack the basis to quantitatively interpret them. Direct and quantitative measurements of the surface processes from an environment that closely resembles the conditions on Mars are becoming increasingly important.

2) It is generally thought that the climate in the southern Antarctica has been consistently cold and hyperarid although the ice extent along the margin of the continent has fluctuated significantly within the past several millions of years as seen in ANDRILL sediment core (Naish et al., 2008). However, fluvial deposits have been mapped in the southern TAM and they testify of running water and imply significantly warmer conditions at some time in the past. By dating and mapping such features we can establish the

timing and spatial extent of much faster landscape evolution than currently. Any age information about these features would provide information about past climate changes in the interior of Antarctica that are currently based on marine sedimentary records and oxygen-isotope records of global ice volume, but for which little direct evidence exists.

3) Most of the drifts in the southern TAM lack any absolute dating control. Although the dating of the drifts is not the primary objective of this project we will determine the minimum ages of the drifts and surfaces that we sample. The minimum ages of the representative surfaces allow us to understand better the past fluctuations of the ice and the climate in this region where little dating control exists.

4) Our current work in the McMurdo Dry Valleys has shown how the bedrock surface can erode beneath old, glacially deposited boulders. The erosion of the bedrock essentially erases all the signs of the past glacial abrasion and makes the bedrock surface appear much younger than the glacial drift of resistant lithologies that cover it (Balco et al., 2008). As the erosion of the regolith surfaces is transport limited and the bedrock surface is erosion limited it is important to establish both rates to fully understand how the landscape evolves over periods of millions of years under the Antarctic conditions.

Research plan

We propose to visit two separate field areas in the southern TAM 1) to sample the regolith and bedrock surfaces for cosmogenic isotope analyses in order to determine the long term rates of landscape evolution, 2) to install instrumentation and establish study sites in order to determine current sediment transport rates of representative surfaces.

Details of sample processing, planned analyses, determination of sediment transport rates, and related assumptions and errors are given below.

Field work plan

Based on published reports, maps, and air-photos we have identified prominent moraines and drifts in the field area. In the field we will verify those observations and identify additional targets as we successfully did while working in the Dry Valleys. Pertinent locations on these deposits will be sampled for degradation studies and (minimum) age determinations.

We will work around the perimeter of isolated ice domes (e.g. Kreiling Dome) to date and assess the emergence (burial?) of patterned ground from under the local, small ice cap. In a safe location we will make an attempt to tunnel a few meters into the ice to access the regolith underneath, to verify the presence of patterned ground under the ice, and to sample the soil for evaluation of burial history.

Based on airphoto analyses and field reconnaissance we plan to install 30 soil traps that will be retrieved on year three. These are located on representative terrains at all available altitudes, exposures, and slopes. These sites will be paired with repeat photo sites.

We will make a special effort to find, date, and assess the environmental significance of the previously reported fluvial features in the field areas.

Description of methods and techniques

All the methods that we plan on using in the TAM have been employed by us already in the Dry Valleys with good results. Therefore we are confident that they will perform well in the southern TAM as well. However, we have also learned from past experiences and are currently refining and improving the methods especially keeping in mind that the absolute regolith transport rates may be much smaller in the TAM than what we have documented in the Dry Valleys.

Cosmogenic isotopes

We will use cosmogenic-nuclide measurements to determine rates of landscape-forming processes over the long term: thousands to millions of years. We propose to measure three cosmogenic nuclides: Be-10, Al-26, and Ne-21. For Be-10 and Al-26 measurements, we will carry out wet chemical preparation and AMS measurements at PRIME Lab, Purdue University. We will make Ne-21 measurements in the noble gas laboratory at the Berkeley Geochronology Center (see facilities and resources section).

The Earth's surface is continually bombarded by cosmic rays; these induce nuclear reactions in mineral grains, producing trace isotopes of many elements. The concentration of these trace isotopes in minerals reflects the total cosmic ray dose the minerals have experienced. This is scientifically useful because the vast majority of cosmic rays stop within a few meters of the Earth's surface, so the cosmogenic-nuclide inventory reflects the length of time a rock sample has resided near the surface. Therefore the inventory of cosmogenic isotopes can be used to determine exposure ages (the age of a surface-forming event that exposed fresh rock) or erosion rates (because the erosion rate of a surface is inversely proportional to the length of time that a sample currently at the surface spent in the zone of nuclide production as it was exhumed, and thus to the cosmogenic-nuclide concentration). The technique is by now commonly used in a range of geological applications (Cerling and Craig, 1994; Gosse and Phillips, 2001). Next we outline several sampling and measurement strategies, and the information we can gain from each of them.

1. Surface exposure ages and erosion rates from bedrock surfaces. A single measurement of a single cosmogenic nuclide in a bedrock surface sample yields either an exposure age (under the assumption that the surface is not eroding) or an erosion rate (under the assumption that the surface has been eroding steadily for a long enough time for the nuclide concentration to come to equilibrium with the erosion rate). This approach has been widely applied in the Antarctic Dry Valleys, mainly to show that surfaces at high elevations, where stratigraphic evidence showed that the surfaces had been stable for millions of years, displayed extraordinarily high cosmogenic-nuclide concentrations. This information was used to support the stratigraphic evidence for long-term polar desert conditions, by showing that the land surfaces in the Dry Valleys were stable during the length of time represented by the exposure ages (Bruno et al., 1997; Schäfer et al., 1999; Summerfield et al., 1999; Margerison et al., 2005). In this project, we are less interested in showing only that some surfaces are very stable than we are in quantifying the actual rates of degradation and landscape change. The challenge in achieving this using surface samples only is that, with measurements of nuclide concentrations only, it is difficult to determine whether or not one is measuring an exposure time or an erosion rate (Gillespie and Bierman, 1995). We propose to deal with this ambiguity through sampling strategies in which we will analyze multiple samples whose exposure histories are linked in some way. For example, previously we measured Be-10 concentrations in sandstone bedrock surfaces at a range of altitudes at Mt. Dewitt, in the upper Dry Valleys (Figure 2).

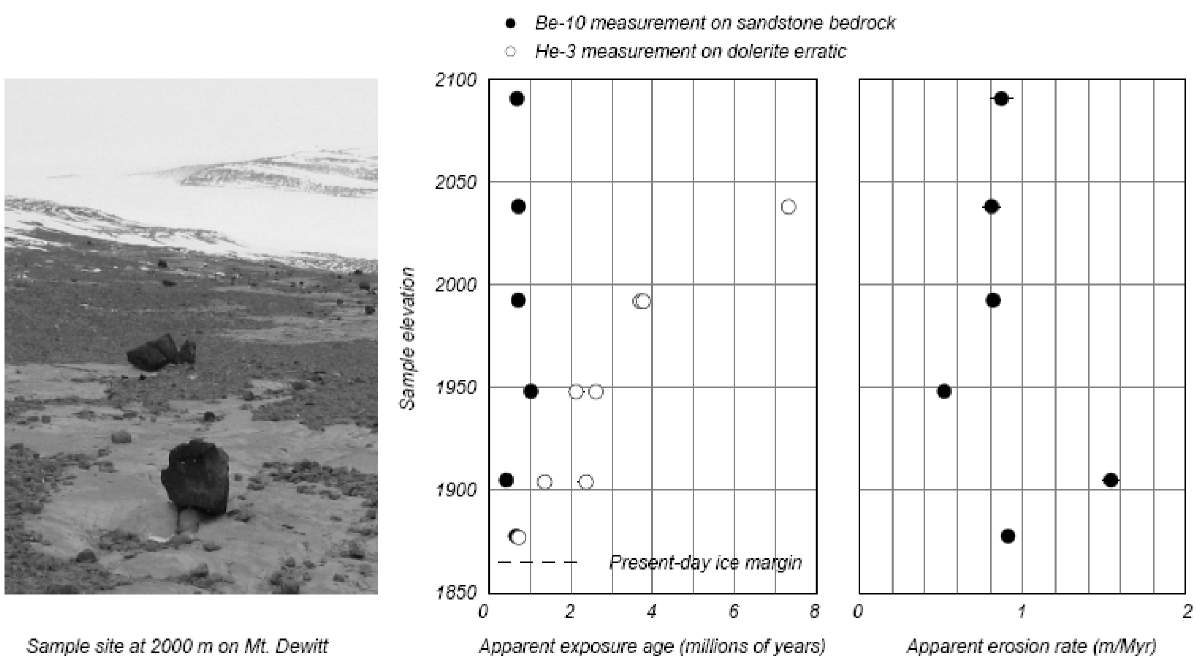

Figure 2. Cosmogenic nuclide measurements at Mt. Dewitt, a nunatak in the upper Dry Valleys. Dolerite cobbles have He-3 exposure ages of several million years, increasing with elevation and presumably reflecting long-term ice retreat at this site. The sandstone surfaces that the erratics lie on have much lower apparent Be-10 exposure ages, that vary little with elevation. This mismatch is best explained by bedrock erosion. The right-hand panel shows the result of interpreting the Be-10 concentrations as erosion rates rather than exposure ages. Sustained bedrock erosion rates of 0.5-1.5 m/Myr explain the discrepancy.

Apparent exposure ages of these surfaces were near 0.5 Myr. This could be interpreted to indicate that the peak was exposed by ice retreat at this time. However, dolerite erratics lying directly on these surfaces had much older exposure ages, up to several million years, and the exposure ages increased with elevation. The age-elevation relationship of the erratic ages suggests that they record a long-term decrease in ice surface elevation at this site, and that the higher-elevation surfaces have been exposed for a much longer time than the apparent bedrock exposure ages indicate. This in turn tells us that the Be-10 concentrations in bedrock should be interpreted as erosion rates and not exposure ages. Bedrock erosion rates of 0.5-1.5 m/Myr explain the discrepancy between bedrock and erratic ages. Thus, this approach not only gives confidence to our erosion rate measurements, but reveals that the extreme difference in the erosional resistance of different rock types is important in understanding the landscape history and dynamics.

2. Depth profiles of cosmogenic isotope concentrations. As we are interested in measuring erosion rates or exposure ages of sedimentary deposits and regolith, there is an added complication in that the sediment may arrive at the site with an inherited nuclide concentration. If true, surface nuclide concentrations would overestimate the exposure age, or underestimate the erosion rate. It is possible to correct for inheritance by analyzing both surface and subsurface samples (e.g. Repka et al., 1997). For example, at a site in Arena Valley (Figure 3, *(Putkonen et al., 2008a)*), the depth-nuclide concentration in a sedimentary deposit conforms to that expected from the sum of postdepositional production (which decreases exponentially with depth) and inherited nuclide concentration (which is constant with depth if the deposit is well-mixed at the time of deposition). Thus, we can use these data to correct the surface concentration for inheritance and, in this case, better determine the erosion rate of the landform. Another important observation from these data is that the nuclide concentration-depth relationship conforms precisely to the expected production rate-depth relationship. This shows that vertical mixing of sediment has not occurred during the period of time recorded by the Be-10 concentration (2-3 million years in this case). This is a nearly unique observation - similar depth profiles in temperate regions typically show a nearly flat concentration profile near the surface (Perg et al., 2001), reflecting vertical soil mixing by bio- or cryoturbation - and it provides us with information about sediment transport processes (or the lack thereof) in the Dry Valleys.

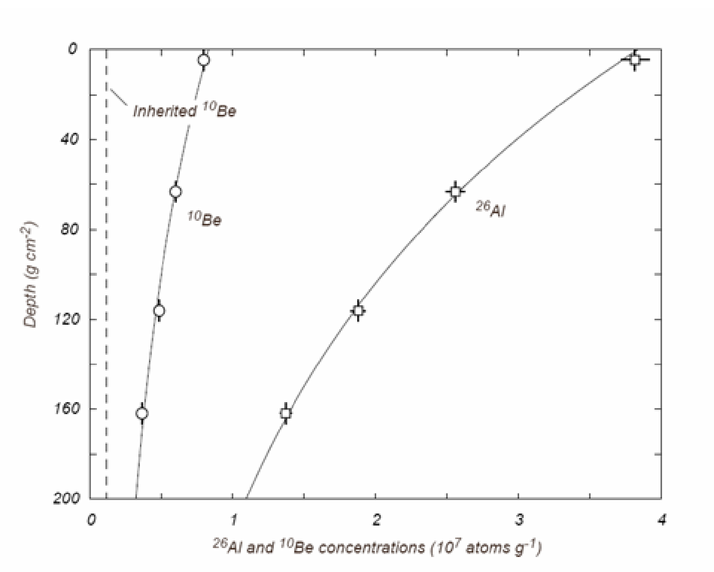

Figure 3 (Arena valley depth profile). Measured and modeled nuclide concentrations in the upper 1 m of sediment at a site in Arena Valley. The measurements agree precisely with a model in which nuclide inheritance is initially well-mixed and there is no postdepositional vertical mixing. After correction for inherited Be-10, the measurements yield a surface erosion rate of 2.1 m/Myr (Putkonen et al., 2008a).

3. *Multiple cosmogenic nuclides.* Finally, measuring several cosmogenic nuclides that have similar production mechanisms, but different half-lives, in the same sample yields more information about the exposure history of the sample than can be gained from a single measurement alone. First, this approach can be used to identify past periods of ice cover. This is important from the perspective of landscape evolution because geological evidence for the long-term stability of landscape surfaces might arise not because rates of erosion and degradation have been vanishingly small for millions of years, but instead because the surfaces were protected by cold-based ice for a significant fraction of the time. In addition, learning about the past ice cover history of surfaces gives information about long-term ice sheet

stability. For example, Al-26 and Be-10 concentrations in the set of bedrock samples from Mt. Dewitt discussed above show that the majority of the samples show the relationship between Al-26 and Be-10 concentrations that is expected if the surfaces have experienced steady exposure and erosion for several million years (Figure 4). However, Al-26 and Be-10 concentrations in the lowest sample (only a few meters above the present ice margin) do not show this relationship, indicating that this sample has experienced both periods of exposure and periods of shielding by ice. These data: a) increase our confidence that the surprisingly low Be-10 concentrations in sandstone bedrock at higher elevations reflect steady erosion and not periods of ice cover, and b) show that the ice sheet elevation has not been significantly higher than present for any detectable fraction of the exposure history of these sites, which provides information about the stability of the East Antarctic Ice Sheet.

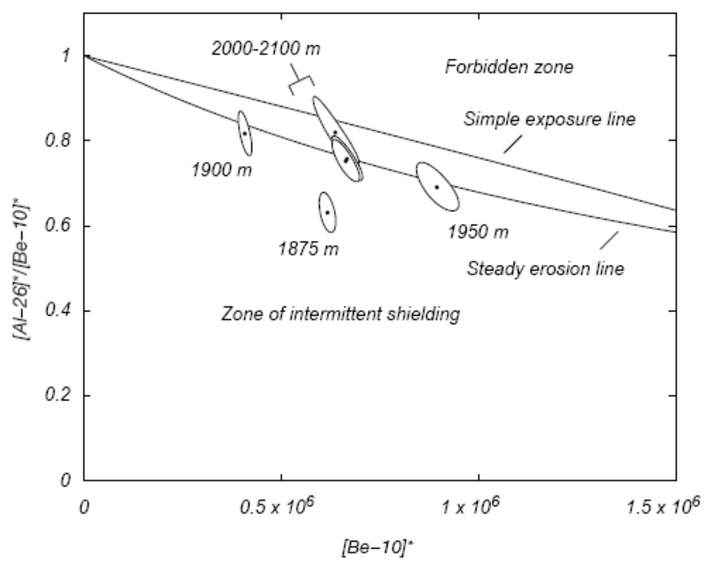

Figure 4. Al-26 and Be-10 concentrations in sandstone bedrock samples from Mt. Dewitt elevation transect. All the samples above 1900 m lie on the steady erosion line; the lowest sample, at 1875 m, only a few meters above the present ice margin, shows evidence for intermittent ice cover of the site. The superscripted star indicates that the nuclide concentrations have been normalized by their respective production rates, so that data from multiple sites can be compared on the same diagram.

Second, multiple cosmogenic nuclides can also be used for 'burial dating,' to determine the depositional age of sediments from the ratio of inherited concentrations of cosmogenic nuclides with different half-lives (e.g. Granger, 2006). In previous work (Putkonen et al., 2008a), we tried to use this approach with the depth profile data from Arena Valley (discussed above), but obtained inaccurate results because the sediment was excessively old relative to the half-life of Al-26. This difficulty brings up an important improvement in the present project, which is the use of Ne-21 measurements on quartz samples in combination with Al-26 and Be-10 measurements. Ne-21 is stable, so the Ne-21/Be-10 pair can be used to date events that happened too long ago to be dated with the Al-26/Be-10 pair (~7-8 Ma vs. ~3-4 Ma). We view this capability as particularly important in light of recent evidence (Naish et al., 2008) for significant deglaciation in Antarctic ca. 4 Ma. If Antarctic climate was warmer or wetter at this time, many landscape features suggestive of erosion or sediment transport in excess of present rates may date from this time. It would be possible to determine this by combining Ne-21 with radionuclides of different half-lives. First, as noted above, we can potentially use the Be-10/Ne-21 pair for burial dating of sedimentary units or landforms suggestive of deposition during a period of more active sediment transport processes, e.g. colluvial or mass-flow deposits. Second, we can potentially combine Ne-21, Be-10, and Al-26 measurements to look for possible changes in the activity of soil-forming processes. For example, if we observed that the Be-10 concentration - depth relationship in a soil pit conformed to the production rate-depth relationship (as in the example above), but the Ne-21 concentration-depth relationship showed a mixed layer, we could conclude that vertical soil mixing had taken place during the time recorded by the Ne-21 concentrations, but not during the shorter period of time recorded by the Be-10 concentrations.

Field sampling

About 0.2 liter of bulk soil or rock is required for the cosmogenic isotope analyses. To reconstruct the concentration profile a series of samples is required from surface to a depth of approximately one meter. The deeper samples are of more importance in the case of mixed profile or complex sedimentation or shielding history.

Our sampling needs can be met with simple manual excavation of near surface soil (0-1 m) by using shovels and picks as we have done in the Dry Valleys area. We recognize the need to minimize the unnecessary adverse effects in the delicate environment of TAM by making use of tarps. The samples are sectioned, labeled and packaged in the field for transportation to McMurdo and home institution.

Current sediment transport: background and theory

The objective of the following analyses is to determine the amount of regolith that travels downslope today in a given time period and on a given slope angle. With those data at hand we can calculate the topographic diffusivity κ (m^2/yr) that describes the efficiency of regolith transport (Culling, 1960; Culling, 1963; Culling, 1965; Carson and Kirkby, 1972; Nash, 1980; Hallet and Putkonen, 1994; Fernandes and Dietrich, 1997; Hanks, 2000; Putkonen and O'Neal, 2006; Putkonen et al., 2008b). Topographic diffusivity has been determined for a wide range of climates and environments and allows a direct comparison of sites regardless of slope angle.

Our formal understanding of landform degradation follows a widely accepted mathematical formulation (Culling, 1960; Culling, 1963; Culling, 1965), which states that the mass transfer along the ground surface is equal to the local slope angle and a transport coefficient.

Topographic diffusivity is a key parameter that integrates the substrate and climate. Published values of topographic diffusivity range over three orders of magnitude (10^{-1}–10^{-4} m^2/yr) (Hanks et al., 1984; Fernandes and Dietrich, 1997; Heimsath et al., 1997; Roering, 1999; Hanks, 2000; Oehm and Hallet, 2005). The only values that currently exist for Antarctica (10^{-4}–10^{-5} m^2/yr) are at or below the range given above and come from McMurdo Dry Valleys (Putkonen et al., 2008c).

We recognize the importance of non-linear transport law for steep terrain at slope angles that are close to the angle of repose (Roering, 1999; Roering et al., 2001; Pelletier and Cline, 2007). However, as little is known currently about the general landscape evolution in the TAM we will begin our analyses with a linear transport law that is applicable to the lower slope angles where most of our work is centered.

Our mathematical formulation generally follows the derivation that was clearly presented by Hanks et al. (1984) and Fernandes and Dietrich (1997) both based on original ideas by Culling (1960). For more details of the mathematical derivation please refer to Putkonen et al. (2008c). At all field sites the local slopes will be measured with a handheld clinometer and will be accurate to 1.0°.

Soil traps

The soil traps that we have used in the past are small wooden boxes that are open on the top. Inside dimensions are 25.5 cm x 7.5 cm x 4.5 cm. The wall thickness is 0.7 cm. The boxes are buried on the slope so that the open top of the box is flush and even with the soil surface. The ground surface uphill of the box is left undisturbed and the boxes are free of any debris when installed.

As the regolith is transported downhill along the soil surface over the course of the study period (typically one year) it will cross the lip of the soil trap, fall in and get trapped in the box. All the boxes with their regolith contents will be removed after one to two years exposure in the field for laboratory analyses of the trapped regolith. The soil traps will effectively retain the regolith that is transported on the soil surface.

It is well known that in other regions depth distributed soil creep accounts for a large fraction of the total sediment transport downhill. This type of soil creep would transport the whole box downhill and not trap any of the moved regolith. Based on our prior work in Dry Valleys we expect no depth distributed soil creep. Moreover, the vertical profiles of cosmogenic isotopes that we plan on collecting and analyzing will unequivocally reveal the depth distributed transport through the related mixing of the soil profiles.

We are also prepared to install a number of fixed GPS markers in shallow boulders to determine if the boulders and the soil are creeping downhill. In the Dry Valleys area no boulder movement over the noise was detected within the 5 year study period, which confirms the findings of the cosmogenic isotope profiles that suggested no vertical mixing in the soil.

For more details of the mathematical derivation please refer to Putkonen et al. (2008c). See figure 5 for the results of all regolith transport measurements from Dry Valleys that are guiding our research in the TAM.

The main error in this method comes from the unintended disturbance of the soil immediately adjacent to the box. The disturbed soil is more prone to erosion and sediment transportation and therefore the soil traps tend to overestimate the actual regolith transport on undisturbed surface. We are currently experimenting with new designs of the soil trap to either minimize the installation disturbance by immobilizing the soil adjacent to the trap or covering the disturbed soil after the installation with binding substrate such as wax or glue.

The soil traps although prone to overestimation are used in tandem with repeat photography, because the soil traps collect all grain sizes and repeat photography reveals only transport of pebbles and larger diameter grains.

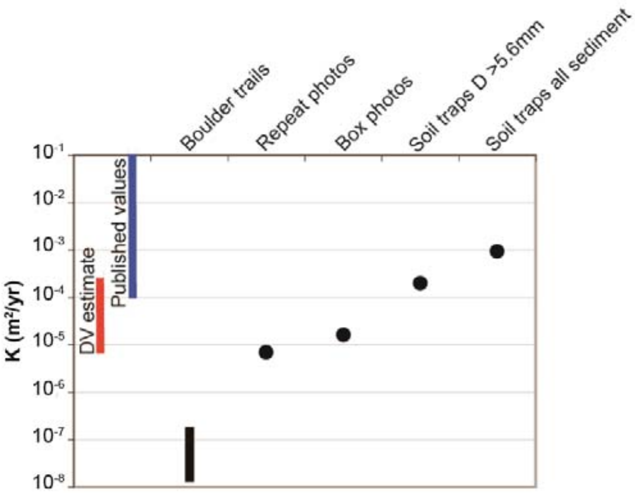

Figure 5. Mean topographic diffusivities for all methods. For detailed explanation of field methods and calculations see text and references. Blue vertical bar (published values) shows the range of published topographic diffusivities on Earth. Red vertical bar (DV estimate) shows the estimated range of mean topographic diffusivity in the Dry Valleys of Antarctica based on the data points shown in black (boulder trails are excluded from the estimate because they provide only a minimum estimate as well as the soil traps which provide only maximum estimate). For more details on the data and calculations that are shown in this figure see Putkonen et al. (2008c).

Repeat photos of undisturbed surface

Since the installation of the soil traps will nonetheless disturb the surrounding ground surface to some degree, separate undisturbed repeat photo sites will be established at all areas of interest. At these sites the ground surface will be photographed with a digital camera once at the beginning and at the end of the observation period, which is typically 1-2 years. The photographs will be taken about 1.35 m above the soil surface covering an area of approximately 0.75 x 0.75 m (Figure 6).

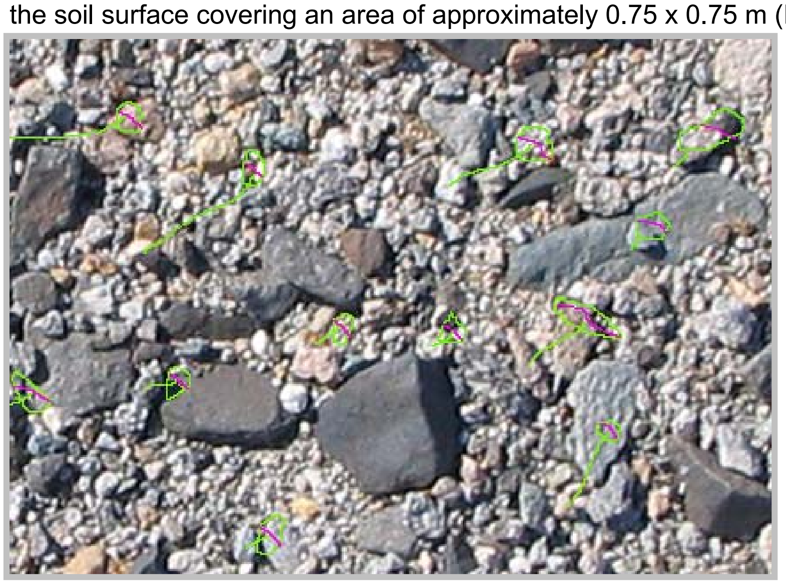

Figure 6. Example of a repeat photo analysis of a field site in Dry Valleys. The green traces show the outlines and the purple lines cut through the pebbles in their initial location. The green line shows the approximate path and the final location of the same pebble after one year. The background image was taken after one year field exposure. More information of the method provided in Putkonen et al. (2008c).

To determine the topographic diffusivity from repeat photos requires several steps: 1) the photo pairs are first rectified in image processing software, 2) the scale is determined by measuring markers of known dimensions within photos, 3) the photo pair is overlaid in an image manipulation software, 4) all the exposed pebbles within the reference area are compared between the two images to determine whether the pebbles moved and how far. This technique allows detection of pebbles down to about 0.5 cm diameter. For more details of the mathematical derivation please refer to Putkonen et al. (2008c).

The main uncertainty in this method arises from the difficulty in detecting the pebbles that move and matching them between the two photographs. This uncertainty tends to underestimate the actual regolith transport. Our experience in the Dry Valleys has shown that results from adjacent sites tend to converge and that the detection and matching of the pebbles that moved is labor intensive but not difficult. An additional uncertainty comes from the limitations of this method. Only pebbles that are larger than about 5 mm in diameter can be identified between the photos. Therefore the finer grain sizes are totally missed with this method. In reality, most surfaces are well armored by desert pavement.

Based on our experiences in Dry Valleys (Putkonen et al., 2008c) we find this method to give an accurate account of the transport of the larger regolith fraction along the soil surface.

Environmental monitoring

The weather and climate in the Dry Valleys region are well monitored by the LTER microclimate network, however, only temporally sporadic and spatially limited weather data is available from the ice free areas of the continental interior. As part of this project we propose to install two microclimate stations; one per field area to collect continuous environmental data for the duration of the project. These data will directly aid in understanding and modeling of the current regolith transport processes in the TAM.

Our proposed monitoring systems are based on the multiyear experience in running similar systems in the Dry Valleys that the PI designed and installed in 1998 (Putkonen et al., 2003; Sletten et al., 2003). Since the installation the systems have operated continuously and are still operational as of this writing. We propose building the systems around Campbell Scientific datalogger powered by two 12V/40 Ahr batteries charged by 40W solar panels when the sun is above the horizon. In addition to the basic atmospheric variables of air temperature and relative humidity, we want to measure the wind speed that is directly related to the transport of the regolith. We also plan on monitoring the snow cover and soil moisture that indicate the potential of frost heave at the site. A digital camera pointed at the surface and soil electric conductivity probes will give good indication of changes in snow cover and pebble movement.

Benefits of varying temporal and spatial scales of the proposed research

The two main results of the proposed research will be: 1) the long term rate of landscape evolution, and 2) the current rate of sediment transport. These both bear a fundamental interest in geomorphology since very little is known about the mobility of the regolith and preservation of landforms in cold deserts.

The long term rates are crucial for understanding and modeling the relatively large changes that the landscape has gone through over periods of millions of years. They help us answering such fundamental questions like: how did this landscape look millions of years ago, can we expect to find remnants of millions of years old life or volcanic activity preserved at the surface where it was laid down, how does our physical environment evolve over periods of millions of years? With these results at hand we can start asking follow up questions such as: what are the geomorphic processes responsible for the observed landscape evolution, do the same processes operate today that have modified the landscape in the past?

In order to compare the current and past landscape changes and to determine whether today's environmental conditions might have prevailed in the past we need to understand the current rates of sediment transport and the corresponding geomorphic processes.

The proposed research provides information inherently on small spatial scale as study sites are in the order of few square meters. However, the ultimate goal of this proposed research is to determine the landscape evolution in the scale of the landscape (~10 km by ~10 km). This problem of incoherence of the scales is common in the Earth science and is typically solved by sampling all or many of the representative segments of the landscape and by multiple sampling of similar segments. More information on our sampling scheme is provided in the section on *field sites* (below).

In temperate regions cosmogenic isotopes are routinely used to measure watershed wide erosion rates from cosmogenic-nuclide concentrations in river sediments (Brown et al., 1995; Bierman, 1996; Granger, 1996). As there is no surface drainage in the field area, this method is not applicable in our study.

We have allocated 50 paired cosmogenic isotope samples for this project. We typically take 4 samples of the soil profile per one soil pit. Therefore we intend to process six individual soil pits per field area (4 samples/pit x 6 pits/field area x 2 field areas = 48 samples). We are confident that we can characterize the typical landscape segments with those samples. However, before visiting the field area it is impossible to give the actual coordinates of the sampling sites.

As will be discussed in more depth below, we have theorized that the wind is an important geomorphic agent in areas such as TAM. Therefore our sample site selection will also be aided by air flow analyses of the two valleys in question. The detailed air flow analysis of the field areas will take place prior to the first field deployment. To illustrate the type of spatial information that can be learned from the airflow analysis we show below preliminary results of similar analyses of air flow through Arena Valley. Arena Valley is similar to the proposed field sites in general dimensions and configuration but located in the Dry Valleys area (Figure 7). The air flow analysis is based on following assumptions and constraints: predetermined pressure-gradient at the inflow boundary and free dissipation at the far end of the model domain, incompressible fluid, and conservation of fluid volume.

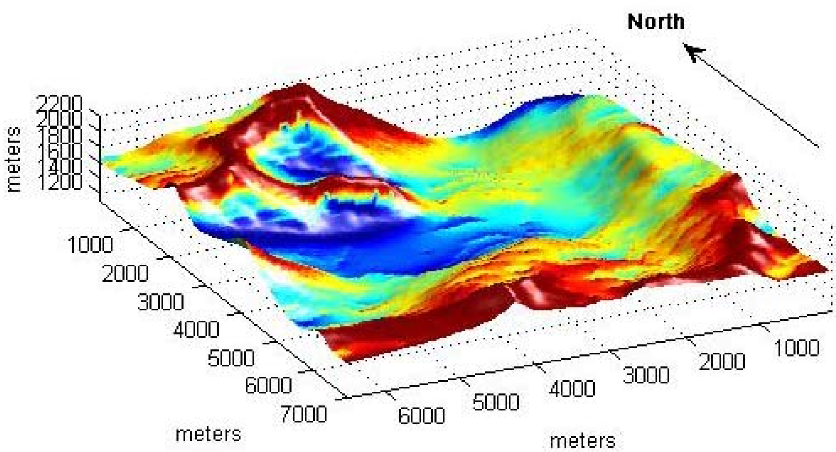

Figure 7. Preliminary results of an air flow analysis through Arena Valley, located in the Dry Valleys region (view towards North). The topography is based on 50 m DEM. The color scheme shows the relative wind speeds at the soil surface. The general air flow direction is from South to North. The wind speeds are meaningful only in a relative sense and have units of distance per time. The red and yellow colors depict areas where the wind erosion and transport is the highest, while shades of blue mark areas of relative stability.

Field sites

Two field sites are chosen based on: the flight distance from McMurdo, previously reported melt water features, available landing sites, access to variable terrain, spatial representation of the very long mountain range, and distance from the coast.

Both field areas are large and allow relatively easy access to variable surfaces that are covered with deposits of different glaciations. The exposed bedrock and soil allow for safe travel on foot to distant corners of these nunataks and therefore eliminate the need for close air support. Potentially good glacial landing sites for Twin Otter can be seen in the maps and photos adjacent to both of these valleys.

Ong Valley (E157 deg 30 min, S83 deg 15 min) is located at Miller Range between Nimrod and Marsh glaciers, approximately 600 km from McMurdo station (Figure 8). The site was visited and described by Grindley (1967). Miller Range is composed of high grade Precambrian metamorphic rocks invaded by lower Paleozoic Granites. No Beacon sedimentary rocks or Ferrar dolerites are found in this area. Three separate and presumably different age glacial surfaces are described that we plan to sample for degradation determination. Also the Ong Valley bottom is reported to have deposits of differing age which can be seen in the airphotos as well. We plan to sample those for age determination and degradation rates. Perhaps the most intriguing comment on the Grindley's report is about the meltwater channels that indicate warmer than present climate in the past. "Whether subglacial or entirely postglacial, the presence of meltwater is indicated, and since no water can form under the present climate, a warmer climate clearly prevailed between deposition of the two moraines" (Grindley, 1967). We plan on verifying, mapping, sampling, and dating these features.

Additionally, we plan on working in the perimeter of the Kreiling Mesa which is completely isolated ice dome just East of Ong Valley which can potentially tell us about the long term deglacial history and climate at this field site.

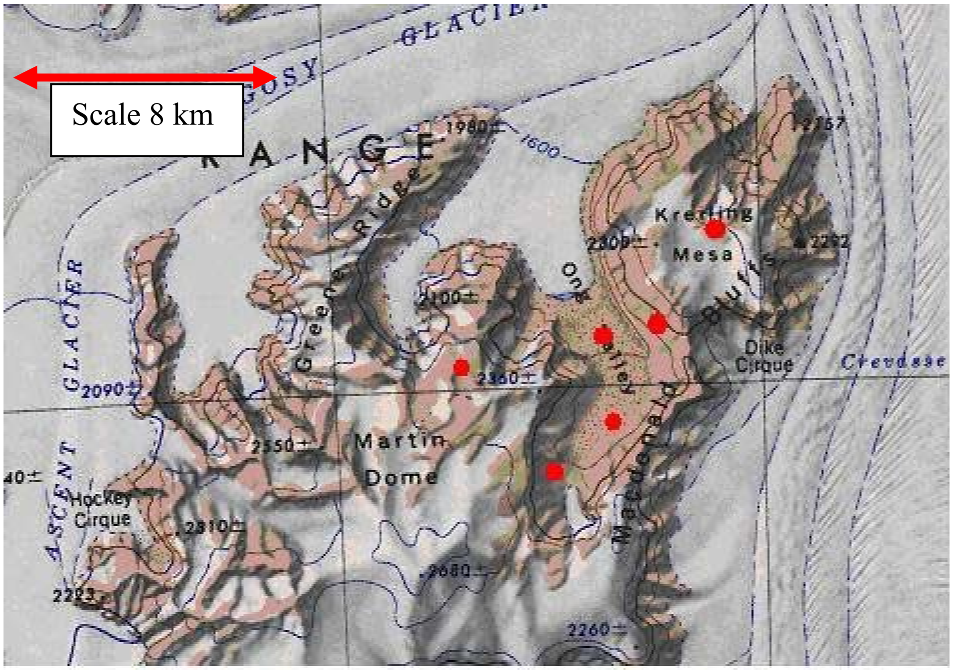

Figure 8. Field area in Ong Valley is located at Miller Range between Nimrod and Marsh glaciers. Potential cosmogenic isotope sampling sites are marked with red circles.

Based on airphotos and descriptions the Ong valley floor is gently sloping and covered with patterned ground, which typically signifies either buried ice or ice cemented soil. The recently received first images from the Phoenix lander (http://www.nasa.gov/mission_pages/phoenix/main/) showed very similar looking terrain surrounding the lander. Thus, terrestrial analogues for patterned ground overlying buried ice will be important in understanding the results of the Phoenix mission. At present, there are only few known such analogues found in Dry Valleys. It would be good to identify and study additional such sites, especially in colder and drier environment that more closely resemble the conditions in Mars.

Moraine Canyon (E158 deg 10 min, S86 deg 07 min) is located at Queen Maud Mountains between Amundsen and Scott glaciers, approximately 1100 km from McMurdo station (Figure 9). The bedrock geology of the area consists of metamorphic basement rocks overlain by Tillites, Dolerites, Limestones, Shales, and Sandstones. The canyon has been mapped previously and three moraines that represent different stages and altitudes of glaciation are described (Mayewski, 1975). Like Grindley in the Ong Valley Mayewski also describes meltwater channels between the oldest (High) moraine and intermediate (Middle) moraine at many of the field areas in the Queen Maud Mountains. However, Mayewski does not mention them in the Moraine Canyon. As the name suggests the large ice free area is dominated by well preserved moraines and drifts. This field area provides access to a large variety of landscapes and landforms for sediment transport and degradation analyses, and exposure age determination.

Time schedule

-Year 1: (9/1/2009-8/31/2010): field work in Moraine Canyon and surrounding terrain that is accessible overland on foot.

-Year 2: (9/1/2010-8/31/2011): 2nd field season, field work in Ong Valley and Miller Range

-Year 3: (9/1/2011-8/31/2012): evaluation of missing or bad samples, final push for comprehensive data coverage, 3rd field season, field work in Moraine Canyon and Ong Valley, removal of soil traps and repeat photography of all sites. Publication of the results in peer reviewed journals.

Sample processing

The soil samples will be processed in the cosmogenic isotope laboratory at PRIME Lab, Purdue University and Berkeley isotope laboratory under supervision of Dr. Balco. The details of Beryllium extraction methods, experimental methods and calculations can be found at the UW Cosmogenic Isotope Lab website: www.depts.washington.edu/cosmolab/chem.html. The AMS measurements will be done at PRIME Lab, Purdue University.

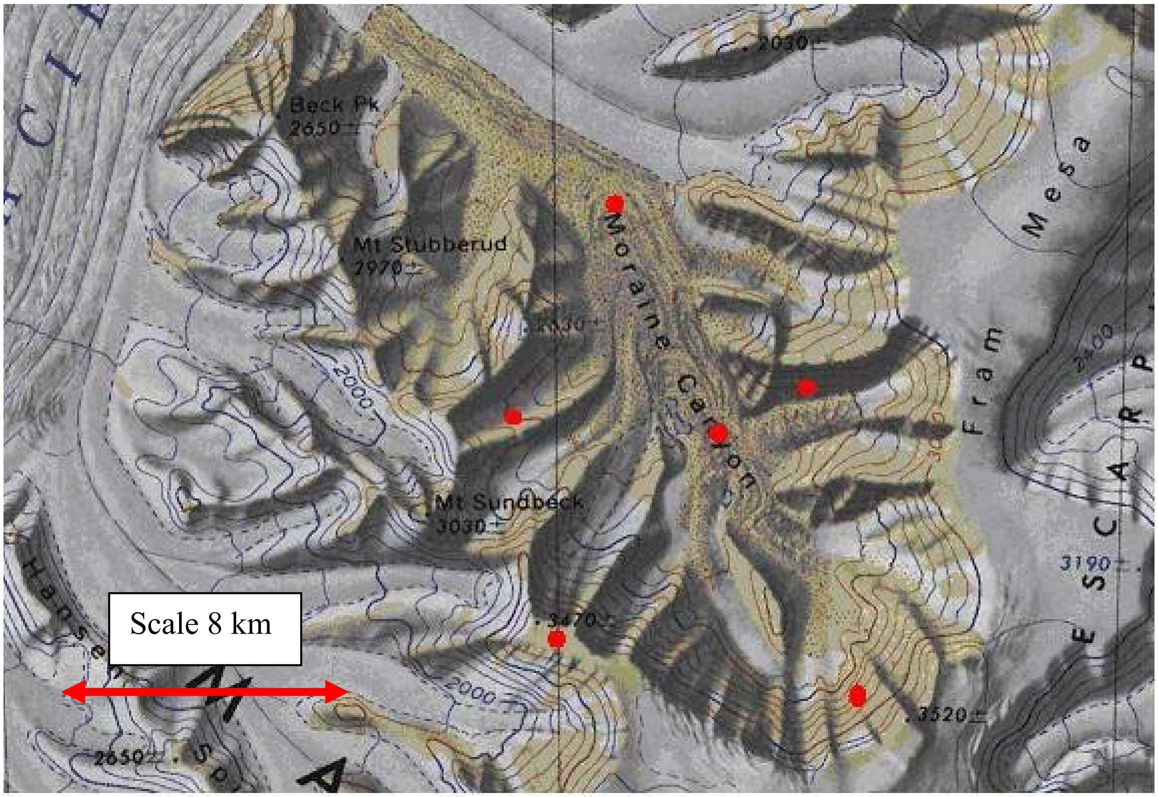

Figure 9. Field area in Moraine Canyon at Queen Maud Mountains between Amundsen and Scott glaciers. Potential sampling sites are marked with red circles.

Computer modeling

The isotope concentration profiles will be analyzed with the aid of the one dimensional coupled sediment transport and isotope accumulation model following our own previously successful approach (Putkonen et al., 2008a). The modeling provides internally consistent means to test hypothesis and model the observed concentration profiles, to determine the age and stability, and sedimentation history for a variety of key sites in the TAM. The soil stability and isotope accumulation model will be augmented and improved as necessary by the graduate student under the supervision of Drs. Putkonen and Balco.

Significance of the proposed research

Much of the research on past environments is based on the preservation of surficial deposits and sampling of the regolith. Many of the methods like cosmogenic isotope dating or interpretation of the landforms is based on the assumption of little or no surface erosion and degradation. In the Antarctica where at least currently the environment appears to suppress some of the more effective erosive processes such as rain splash, rilling, and bioturbation, the expectation is that little has changed since the deposition of the drifts and landforms. However, direct measurements in the Dry Valleys have revealed slow but persistent degradation of the landscape which will significantly affect the appearance of the landforms and length of surface exposure of the regolith. No quantitative estimates currently exist of the regolith degradation rates in the southern TAM.

We expect that the regolith degradation for the past few million years in the southern TAM is less effective than what has been determined for Dry Valleys for the same period. If this turns out to be true it would attest of the persistence of the cold desert conditions in this area. Moreover, it would establish a terrestrial lower limit on the regolith degradation rate. This is important for the general computer modeling of the landscape evolution over widely varying climatic periods or for analyzing the potential preservation of terrestrial deposits.

As we determine the degradation rates for deposits of various ages we will also define their minimum age which will directly help in deciphering the climatic history and related ice sheet dynamics in the southern TAM, where little dating control currently exists.

In Antarctica the cold based, non-eroding ice sheet may have expanded over rock surfaces and significantly altered the exposure ages of the submerged rocks due to the shielding of those rocks from cosmic radiation. If not accounted for, this may result in erroneous exposure ages for the exhumed deposits. Our experience in dry Valleys with similar systematics and application of paired isotopes allows us to determine within certain limits whether the regolith in question has been shielded in the past. It is not known if such expansion may have taken place in the past, however, to our knowledge no-one has ever tried to directly look into this. This is one way for us to assure that the ages that we determine signify the dynamics of the ice sheet rather than some combination of past burial and exposure.

At the broadest level the proposed research will determine the current and past regolith mobility in an area and climate where no direct measurements exist. This will advance the fundamental geomorphological understanding of geological processes and rates that operate in coldest and driest parts of the Earth.

Since a good understanding of the landscape evolution in the northern TAM (Dry Valleys) already is emerging why should similar research be done in the southern TAM?

Within Antarctica the Dry Valleys is the best studied land area due to its close proximity to McMurdo station and relatively easy access. Much of our current understanding of Antarctic environment comes from this geographically limited area that is located at the perimeter of the continent, close to seasonally open ocean, and where the major valley floors are just few hundred meters above the sea level. This is generally a poor representation of the majority of the ice free areas that are located within the interior of the continent.

Broader impacts of the proposed research

A graduate student will be funded to do his/her Doctorate degree research on a topic that is closely related to the objectives of the project. To excite and impact a number of undergraduate students two (preferentially different) students will be hired each year to aid in the fieldwork in Antarctica. To expand the educational impact of the project a supplemental Research Experience for Undergraduate funding is also sought, An effort will be made to fill at least one of the 3 (+1 REU) student positions with a representative of the underrepresented groups.

We will continue our collaboration with the Yakama Indian Tribal school and engage the students in the reservation through a series of lectures and films that we have produced of our prior work in Antarctica. We will also continue our work with the University of Washington Office of Minority Affairs and their annual Native American recruitment event.

No specific funding is requested for the outreach activities, however, all the funded students will be required to lead either school visits or participate in community events.

Results from prior support

Jaakko Putkonen: STABILITY OF LANDSCAPES AND ICE SHEETS IN DRY VALLEYS: A SYSTEMATIC STUDY OF EXPOSURE AGES OF SOILS AND SURFACE DEPOSITS (9/2004-8/2007)

Estimates of regolith degradation in the Dry Valleys of Antarctica are currently based on indirect evidence and ancient ashes at or near the soil surface that suggest great preservation of surfaces. On the other hand, the existing cosmogenic-nuclide surface exposure ages from many parts of the Dry Valleys are generally younger than the age of surface deposits inferred from stratigraphic relations. They suggest some combination of surface erosion or past ice cover, both of which would reduce the apparent exposure age. We quantified the regolith degradation and/or past ice cover by measuring ^{10}Be and ^{26}Al from a landslide deposit that contains 11.3 Ma volcanic ash. The surface sample yielded an apparent exposure age of only 0.4 Ma. However, measurements of the subsurface nuclide concentrations show that the deposit has not been shielded by ice, and that the age of the ash does not conflict with the apparent exposure age when slow degradation of the deposit (2 m Ma^{-1}) is taken into account. Soil creep, which is a common degradational process in a wide variety of environments, is non-existent at this field site, which likely reflects the persistent lack of bio- and cryoturbation.

Based on analyses of repeat photographs, soil traps, and pebble transport distances it was found that there is a large spatial variation in topographic diffusivities at least in the annual basis and that counter intuitively the highest topographic diffusivities are found in the alpine valleys that are located further inland from the lowest values near the coast. An average topographic diffusivity for the Dry Valleys was determined to be 10^{-5}–10^{-4} m^2/yr. This average topographic diffusivity is surprisingly large equaling or bordering the smallest values from elsewhere on Earth.

This project supported the ongoing dissertation research of one graduate student who participated in the both field campaigns. The project also funded the field work for three undergraduates and an additional graduate student as well as data analyses at the University of Washington by three additional undergraduates. Five of those undergraduates have been co-authors on published, peer-reviewed publications (listed below).

POSTDOCTORAL RESEARCH FELLOWSHIP: COSMOGENIC-NUCLIDE GEOCHRONOLOGY OF GLACIATED SURFACES IN THE UPPER DRY VALLEYS (Balco, OPP-0443535; $108,840, 7/05-6/07). This project was an extension of the larger grant to Putkonen described above. It provided funding for Balco to focus on the cosmogenic-nuclide measurement aspects of the project, applying dating techniques based on multiple cosmogenic nuclides to learn about deposit ages, erosion rates, and landscape evolution in the McMurdo Dry Valleys. Some results of this work are highlighted above in Figures 2 and 4.

Resulting publications:

Putkonen, J., Balco, G., and Morgan, D. (2008a). Slow regolith degradation without creep determined by cosmogenic nuclide measurements in Arena Valley, Antarctica. *Quaternary Research* **69,** 242–249, doi:10.1016/j.yqres.2007.12.004.

Putkonen, J., Connolly, J., and Orloff, T. (2008b). Landscape evolution degrades the geologic signature of past glaciations. *Geomorphology* **97,** 208-217, doi:10.1016/j.geomorph.2007.02.043.

Putkonen, J., Rosales, M., Turpen, N., Morgan, D., Balco, G., and Donaldson, M. (2008c). Regolith transport in the Dry Valleys of Antarctica. *In* "Antarctica: A Keystone in Changing World. Proceedings of the 10th International Symposium on Antarctic Earth Sciences. doi:10.3133/of2007-1047.srp103." (A. K. Cooper, P. J. Barrett, H. Stagg, B. Storey, E. Stump, and W. Wise, Eds.). The National Academies Press., Available at http://pubs.usgs.gov/of/2007/1047/srp/srp103/index.html.

In reviw:

Putkonen, J., and Morgan, D. M. (In Review). Soil Transport Quantified by Topographic Indicator, McMurdo Dry Valleys, Antarctica. *Journal of Geophysical Research*.

Manuscript in progress abstract published:

Balco, G., Putkonen, J., Morgan, D., Schaefer, J., and Winckler, G. (2008). Bedrock erosion rates in the Antarctic Dry Valleys. *In* "Goldschmidt conference." Vancouver, BC, Canada.

Data at hand and manuscripts currently in progress on: 1) Age and degradation of Beacon moraine, 2) Degradation of drifts in Arena Valley, and 3) Deglaciation history near Mt. DeWitt and West Groin.

Several abstracts in GSA meetings and University of Washington undergraduate student research symposiums.

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