PROJECT DESCRIPTION: ANTARCTIC PENINSULA EXHUMATION AND LANDSCAPE DEVELOPMENT INVESTIGATED BY LOW-TEMPERATURE DETRITAL THERMOCHRONOMETRY

I. Overview and introduction. We propose to apply methods of low-temperature thermochronometry based on the (U-Th)/He system in apatite to investigate the exhumation history, the development of the present topography, and the pattern of glacial erosion in the central Antarctic Peninsula. Recent studies have used this approach to study the dramatic, high-relief landscapes formed by Pleistocene alpine glaciation in temperate latitudes, for example in New Zealand, The Alps, British Columbia, Alaska and Patagonia (Shuster et al, 2011; Valla et al., 2011; Shuster et al., 2005; Thomson et al., 2010; Berger et al., 2008; Ehlers et al., 2006). This research has revealed not only when the glacial valleys in these landscapes formed -- which is important in understanding the relationship between Plio-Pleistocene climate change, landscape evolution, and tectonics -- but also provided new insights into the pattern and physical processes of glacial erosion.

In this work, we aim to apply this approach to the similarly dramatic glacial landscape of the Antarctic Peninsula. The Antarctic Peninsula is broadly similar to alpine glacial landscapes formed in temperate latitudes during the Pleistocene in that the dominant landforms are deep, steep-sided glacial troughs. Because of the contrast in glacial history between Antarctica and temperate regions, however, we expect the timing and history of its formation to be very different. Specifically, the Antarctic Peninsula has most likely been glaciated since the Eocene (Anderson et al., 2011; Davies et al., 2012 and references therein), and Pleistocene cooling is hypothesized to have suppressed, rather than enhanced, glacial erosion by establishment of polar conditions (e.g., Rebesco et al., 2005). These ideas imply that the glacial landscape of the Antarctic Peninsula developed much earlier than similar temperate landscapes, and may in fact have been relatively inactive during the Pleistocene. Evaluating this hypothesis would shed light on how glacial erosion mediates the effect of climate change on landscape evolution and orogenic mass balance.

A serious challenge to our proposed research is that, unlike Pleistocene glacial landscapes in temperate regions, the Antarctic Peninsula is covered by ice at present. Ice-free rock outcrops exist, but are few, small, and largely inaccessible. Previous thermochronometric studies of glacial landscapes relied on collection of surface rock samples within glacial valleys, which is clearly not possible in this environment. We propose to address the challenge of limited access to bedrock with a strategy of detrital thermochronometry, in which we will analyse apatite and other minerals extracted from glacial sediment collected near the grounding lines of major glaciers draining the central Peninsula. In effect, we cannot sample bedrock in critical locations directly, so we will rely on these glaciers to do it for us.

This idea stemmed largely from discussion between us and Boris Avdeev, a recent Ph.D. graduate of the University of Michigan, whose dissertation research focused on mathematical methods of inferring cooling and exhumation histories, as well as patterns of modern erosion, from detrital thermochronometric data sets (e.g., Avdeev et a., 2011). He assisted us in preparing this proposal, most significantly in carrying out the calculations needed to generate Figures 4 and 5. His applications of these methods focused on fluvial landscapes, but a natural match was immediately evident between his work and the fundamental problem in Antarctic Earth science of inferring past and present geologic processes active on an ice-covered and inaccessible landscape. Specifically, recent advances in understanding the development of glacial landscapes using newly developed methods of low-temperature thermochronometry have, paradoxically, only been possible for glacial landscapes that are not currently glaciated. Recent progress in interpreting detrital thermochronometric data by Avdeev and other researchers offers a means of overcoming this problem.

In the rest of this proposal, we will i) describe the principles of apatite (U-Th)/He thermochronometry and its application to glacial landscapes in temperate regions; ii) introduce recent approaches to inferring landscape development from inversion of detrital thermochronometric data, and iii) outline a plan for applying these approaches to the glacial landscape of the Antarctic Peninsula. We argue that this approach will yield new and important insight into both the geomorphic history of the Peninsula and the overall process of glacial landscape formation.

II. Low-temperature thermochronometry and applications to glacial landscapes. The primary thermochronometer that we will rely on is the (U-Th)/He system in the mineral apatite. This system is typical of thermochronometers based on production and diffusion of a radiogenic noble gas: ^{4}He is produced by alpha particle emission in the U and Th radioactive decay chains, and is mobilized and lost by thermally activated volume diffusion. Apatite (U-Th)/He is the lowest-temperature thermochrometer routinely used in geologic applications, and is sensitive to the temperature range ~80°-40° C, which in most cases corresponds to a depth range of ~1-3 km (Farley, 2000; Farley, 2002; Shuster et al., 2006; Flowers et al., 2009). This sensitivity makes the apatite (U-Th)/He system unusual among thermochronometers, because this depth range is shallow enough that the temperature field is significantly influenced by high-relief surface topography. Thus, (U-Th)/He thermochronometry can be used to learn about past changes in surface topography. This capability has now been applied to a wide array of geomorphic studies aimed at reconstructing the timing of topographic change in mountain landscapes, mainly with the overall aim of learning about interactions between climate, erosional processes, and orogenic development. Examples include dissection of the California Sierra Nevada (House et al., 1998); the history and processes of canyon incision (Schildgen et al., 2010); and the general study of topographic change in actively deforming landscapes (e.g., Braun, 2005 and references therein).

Because some of the most dramatic relief on Earth is associated with alpine glacial landscapes, and the development of these landscapes due to Plio-Pleistocene cooling and glaciation is hypothesized to play a important role in the widely discussed question of the global tectonic consequences of this climate change (e.g., Molnar and England, 1990; Whipple 2009; Yanites et al., 2012), the development of apatite (U-Th)/He thermochronometry was rapidly followed by applications to glacial landscapes. For example, Shuster et al. (2005) used apatite ^{4}He/^{3}He

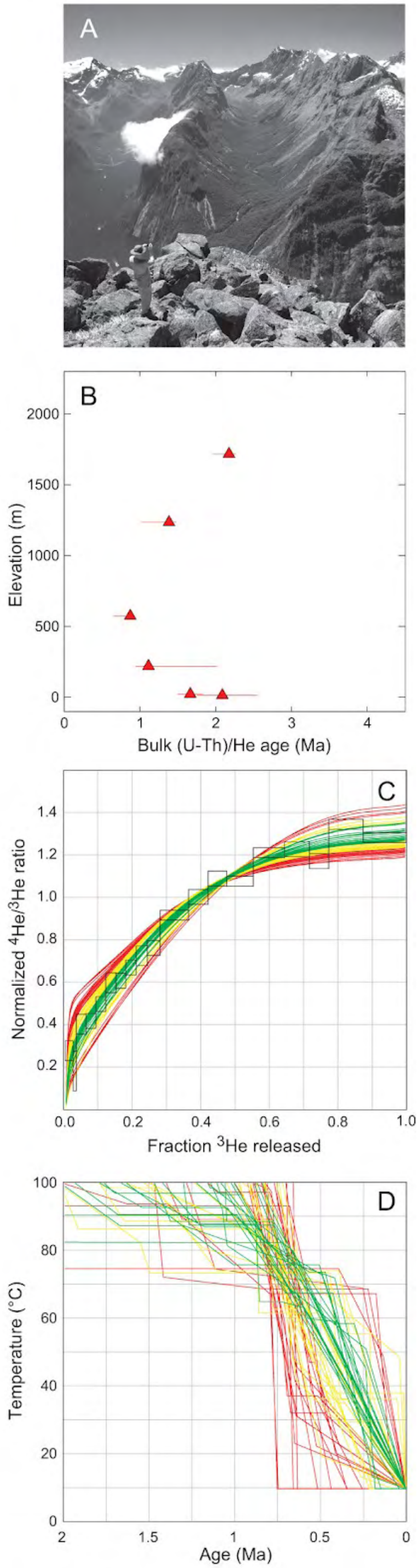


Figure 1 (at right): Apatite (U-Th)/He thermochronometry applied to the alpine glacial landscape (photo A) of New Zealand's Fjordland region. (B) Age-elevation relationship for bulk (U-Th)/He ages in a representative valley in this region. The age minimum at middle elevations cannot be produced by a steady-state erosional process and requires transient valley deepening in the Pleistocene. (C) Apatite ^{4}He/^{3}He release spectrum from a middle-elevation, cirque-floor sample. The black boxes show measured ^{4}He/^{3}He, and the colored lines in this panel and in (D) show simulated release spectra and corresponding thermal histories, inferred from a random-search inversion model, that fit the data (red-yellow-green color indicates increasing goodness-of-fit). The ^{4}He/^{3}He data constrain the onset of valley deepening at this location to ca. 1 Ma. In this proposal we plan to apply a similar approach to the central Antarctic Peninsula. All data in this figure are from Shuster et al. (2011).

thermochronometry (a variant of the (U-Th)/He method described in detail below) to show that erosion of glacial valleys in the coastal ranges of British Columbia significantly accelerated during the Pleistocene, presumably due to glacier expansion. Valla et al. (2011) used essentially the same approach and reached a similar conclusion for glacial valleys in the Swiss Alps. Thomson et al. (2010) used a large data set of apatite (U-Th)/He and other thermochronometric data to argue for i) accelerated denudation of the Patagonian Andes due to the onset of alpine glaciation in the late Miocene, as well as ii) a subsequent reduction in denudation in the southernmost Andes as Plio-Pleistocene cooling increased the area of frozen-based and non-erosive glaciers. Shuster et al. (2011) carried out a spatially dense study of the fjord landscape of New Zealand's South Island and was able to show not only that the majority of the present relief was due to Pleistocene erosion, but also that valley formation occurred by headward retreat of steep slopes, rather than by overall valley deepening (Figure 1). This latter observation is important in understanding the mechanics of glacial erosion and representing it in landscape evolution models. To summarize, the temperature range of apatite (U-Th)/He thermochronometry is well suited to the scale of topographic relief in alpine glacial landscapes formed by selective linear erosion (*sensu* Sugden, 1968), and this approach has resulted in fundamental advances not only in understanding when and how these landscapes formed, but also in understanding the process of glacial erosion at the landscape scale.

III. Importance of the glacial landscape of the Antarctic Peninsula. The Antarctic Peninsula is one of the world's most spectacular alpine landscapes, and its overall character is similar to many temperate glacial landscapes in that the dominant landforms are massive trough-shaped valleys carved by glacial erosion. As such, learning how and when this landscape formed is important in a general sense for the same reasons that it is important to learn about the formation of temperate glacial landscapes: to discern how the mechanics of glacial erosion work, and to understand how glaciers mediate the interaction between climate change and orogenic mass balance.

In addition, the Antarctic Peninsula is very different from temperate glacial landscapes in several ways, and these differences provide a means of significantly broadening the understanding of glacial landscape formation that has stemmed from the research on temperate glacial landscapes described above. New Zealand, British Columbia, and the Alps were most likely first glaciated during the Pleistocene (e.g., Muttoni et al., 2003; Garzanti et al., 2011), and the primary period of valley deepening and relief production was the early to middle Pleistocene (Shuster et al., 2005; Shuster et al., 2011; Haeuselmann et al., 2007; Valla et al., 2011). In contrast, the Antarctic Peninsula hosted alpine glaciers as early as 37-34 Ma, most likely a regional ice sheet by ca. 15 Ma, and almost certainly an ice sheet similar to the late Pleistocene configuration by ca. 6-8 Ma (Anderson et al., 2011; Davies et al. 2011 and references therein). This suggests that glacial valley formation may have taken place well before the Pleistocene. In fact, Rebesco et al. (2008) pointed out that marine sedimentary evidence suggests a decrease in glacial erosion after 3 Ma, and they associated this with Plio-Pleistocene cooling and a consequent transition from a more erosive temperate or polythermal Antarctic Peninsula ice sheet to a less erosive polar ice sheet. Thus, in Antarctica, Plio-Pleistocene cooling may have halted, rather than accelerated, glacial landscape development. The overall form of the landscape -- which consists of an low-relief central plateau partially dissected by steep-walled glacial troughs (Figure 2) -- may be consistent with this idea: whereas many wet temperate glacial landscapes have been fully dissected and resurfaced by Pleistocene glacial erosion, the plateau surfaces of the Antarctic Peninsula appear to represent preglacial topography that has not been effaced despite an order-of-magnitude longer history of glaciation.

To summarize, the history of Antarctic glaciation and some evidence from the marine sedimentary record indicate a significantly different history of landscape formation than that inferred from temperate glacial landscapes. Our goal in the present study is to evaluate these hypotheses by developing a direct thermochronometric record of how and when the present glacial valley relief formed.

Although our focus is on the history of glacial relief development in the Antarctic Peninsula, our proposed work may also yield information important to other fields. First, understanding the exhumation history of the Peninsula is important to reconstructing its tectonic history. The only application of apatite (U-Th)/He thermochronometry that we are aware of in our proposed study area is that of Guenthner et al. (2010), who interpreted exhumation rates derived from several thermochronometers at sites on the west coast of the Peninsula as a record of late Cenozoic tectonics. Although we do not focus on regional tectonics in this proposal, the data we will collect are potentially valuable in further understanding Cenozoic exhumation and discerning its relationship to tectonic events.

Second, a byproduct of our inversion approach for detrital (U-Th)/He data (discussed below) is information about the elevational distribution of present erosion in the landscape. This distribution is a consequence of the physical processes responsible for subglacial erosion, so it provides information about how these processes work. The data we propose to collect can be used to evaluate models of glacial erosion that propose, for example, a dependence of the erosion rate on sliding speed, glacier bed slope, or other glaciological properties (see also Shuster et al., 2011; Egholm et al., 2012).

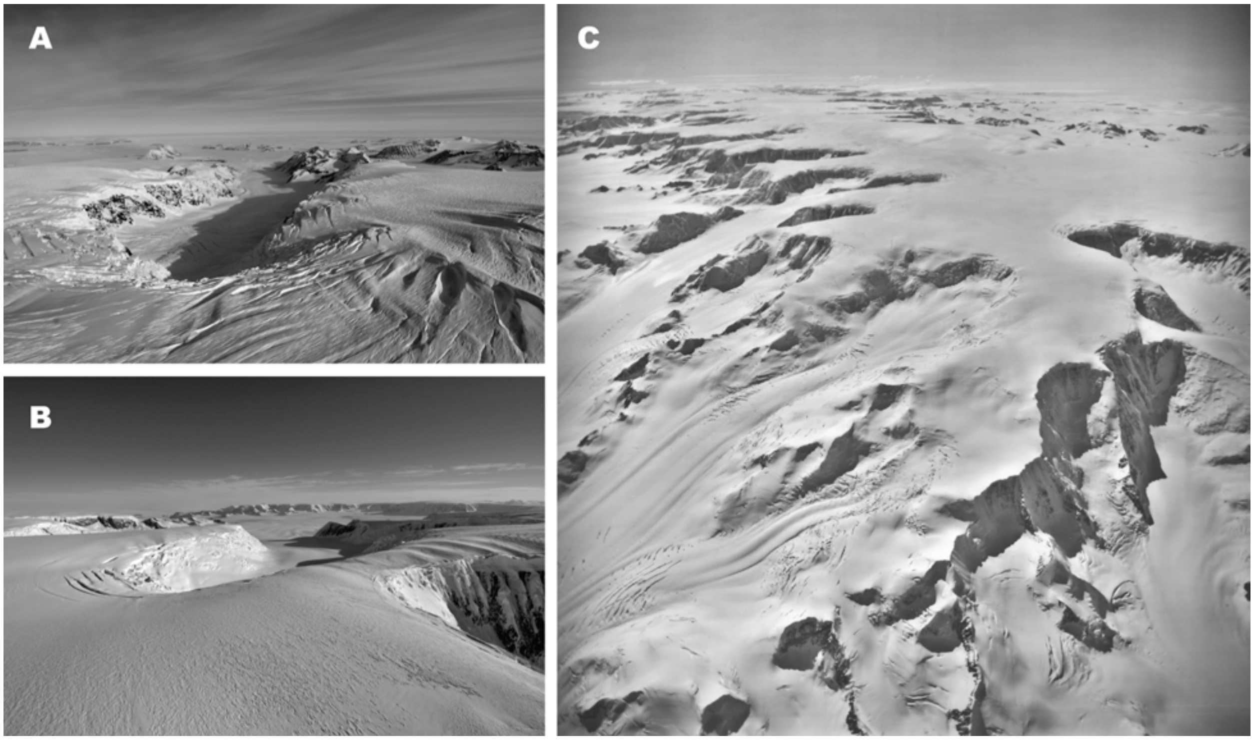
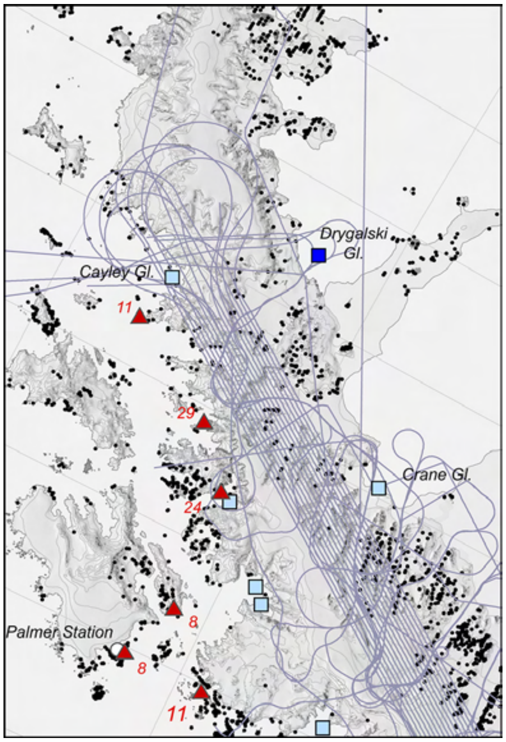


Figure 2. The Antarctic Peninsula landscape comprises a low-relief summit plateau deeply incised by glacial troughs. Steep, arcuate headwalls of major glacier troughs suggest erosion by headwall retreat. (A), headwall of the Boydell Glacier (G. Balco photo); (B), the "Catwalk," a plateau remnant dividing the Drygalski and Cayley glaciers (G. Balco photo); (C), southern end of the Detroit Plateau (1967 U.S. Navy photograph TMA2143-292L). See Figure 3 for locations.

IV. Detrital thermochronometry. The typical approach to thermochronometric study of landscape development is to collect a set of rock samples that are exposed at the present landscape surface, and that span the full range of elevation and topographic position in the landscape (e.g., Reiners and Brandon 2006). Existing such studies of temperate glacial landscapes focused on areas that were ice-covered during Pleistocene glacial maxima, but are ice-free at present, so this approach was possible. As the Antarctic Peninsula is nearly entirely covered by ice at present, this approach is not possible. A few ice-free areas exist, but nearly all of them (with the exception of a few coastal outcrops) are steep, isolated, defended by heavily crevassed glaciers, and inaccessible under normal circumstances. We propose to address this issue in part by collaborating with British Antarctic Survey (BAS) scientists (see later discussion and attached letter of support) to obtain archived rock samples from inland outcrops that were collected during BAS geologic mapping in the 1960's. However, even with these samples, and even if it were possible to obtain additional samples by helicopter or overland traverse, the restricted extent of ice-



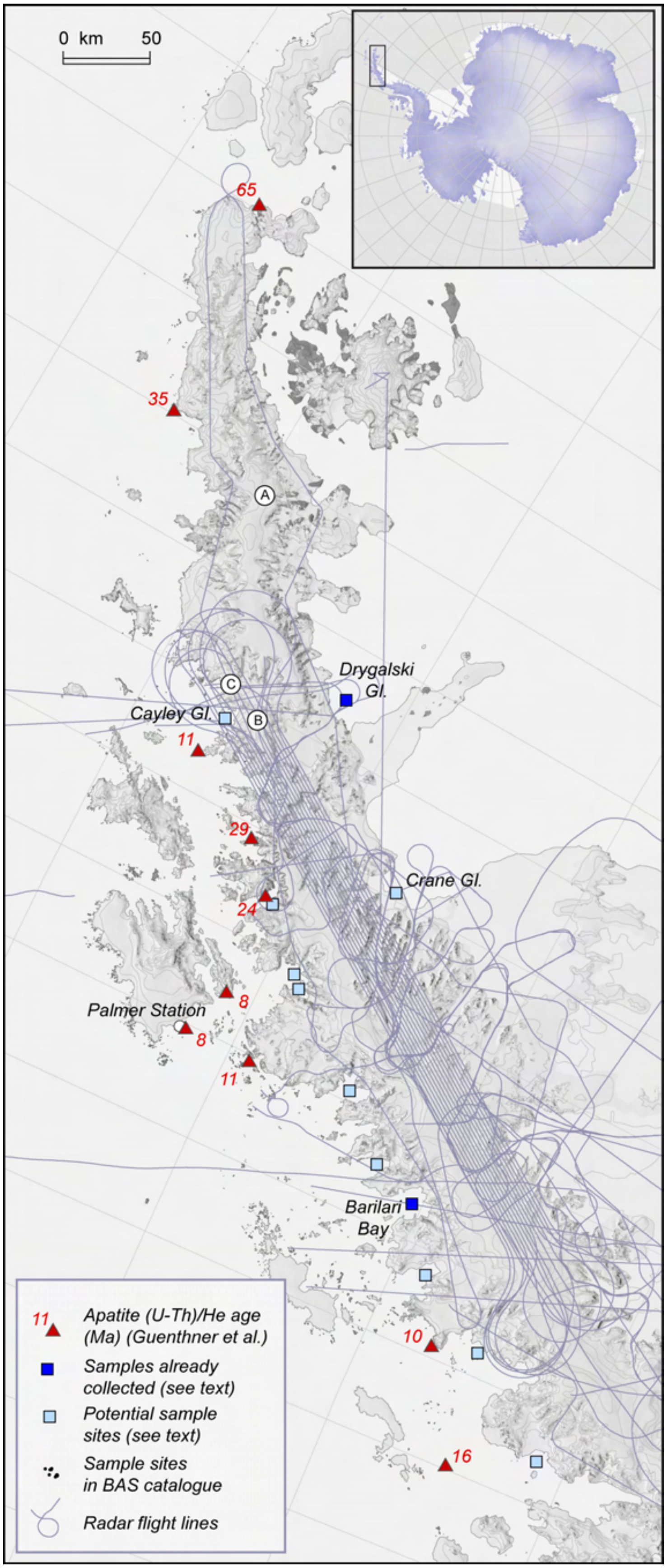


Figure 3. Map of the northern and central Antarctic Peninsula. Red triangles and numbers denote locations and apatite (U-Th)/He ages of samples collected by Guenthner et al. (2010). Dark blue squares are locations of marine sediment samples already collected (see text for details); light blue squares are potential locations for proposed new samples. Blue lines show airborne radar flight lines available from the CRESIS archive. Circled letters indicate locations of photos in Figure 2. The enlargement at top also shows locations of sites visited by British Antarctic Survey personnel during geologic mapping since the 1960's that appear in the BAS catalogue (black dots). Samples were collected at the majority of these sites and are housed in BAS archives.

free areas would most likely preclude assembling complete elevation transects. In addition, and more importantly, the critical sampling locations for reconstructing the timing of glacial valley formation are located within the valleys themselves. The only imaginable way to collect in-place bedrock from the interior of Antarctic Peninsula glacial valleys would be the use of submersibles to access fjord-bottom outcrops. We do not view this as feasible in the near term.

The inaccessibility of surface outcrops is a serious challenge to our proposed research. However, recent advances in the field of detrital thermochronometry offer a way to address this challenge. The basic concept of this approach is that even though we cannot access critical sampling locations beneath glaciers, the processes of glacial erosion, transport, and deposition are bringing rock debris from these sites to glacier fronts and depositing it as proglacial marine sediment, where it is accessible to sampling.

The overall idea of detrital thermochronometry has been in use for some time, primarily for provenance studies and as a strategy for addressing variations in exhumation rates on timescales relevant to orogenic development (Garver et al., 1999; Bernet et al., 2004; Reiners and Brandon, 2006). In Antarctica, detrital thermochronometric studies of glacial sediment have focused on high-temperature thermochrometers (mostly the K-Ar system) and have primarily been designed as i) a means of identifying major orogenic provinces beneath the Antarctic ice sheets, and ii) a means of tracing the provenance of glaciomarine sediment (e.g., Williams et al., 2010; Roy et al., 2007).

Applications of detrital thermochronometry to studying exhumation on time scales relevant to present topography developed more recently. Several authors pointed out the potential value in determining areally averaged exhumation rates in catchments where bedrock is inaccessible (Brewer et al., 2003; Ruhl et al., 2005). More recent work has pointed out that given an known distribution of cooling ages in source bedrock, the distribution of cooling ages in detrital sediment provides a means of evaluating the spatial pattern of present erosion (Stock, 2006; McPhillips, 2011).

Avdeev and others (2011) formalized many of these observations and provided a method of inverting frequency distributions of (U-Th)/He ages of detrital apatites in river sediment to simultaneously estimate both the age-elevation relationship in the catchment (and by extension its cooling history) and the elevational distribution of modern erosion. This inversion relies on the fact that the distribution of (U-Th)/He ages in most landscapes is constrained by the spatial scale of thermal diffusion to be smooth (and in most cases monotonic with respect to elevation), so it can be described by a small number of parameters. In the most straightforward approach, mean (Brewer et al., 2003), or minimum and maximum (Ruhl et al., 2005), detrital ages are presumed to be derived from the mean, or minimum and maximum, elevations, in which case they imply a time- and space-averaged exhumation rate. Adding either an empirical or a process-based model for the geographic distribution of erosion allows one to probabilistically relate the frequency distribution of individual detrital ages to their source location within the catchment. In other words, both i) the thermochronometric age distribution in a source catchment, and ii) the likelihood of sampling sediment from a particular part of the catchment, are not random. They obey physical principles, and can be described with a small number of parameters. An observed distribution of thermochronometric ages in detrital sediment greatly restricts the possible forms of these distributions, and in many cases can be inverted to yield unique solutions.

Figure 4 shows an example of such an analysis for the Lone Pine Creek catchment in the California Sierra Nevada. The input data for the inversion are the hypsometry of the catchment and a set of 50 (U-Th)/He ages measured on detrital apatites from the catchment. An inversion based on these data predicts an age-elevation relationship and an erosion rate-elevation relationship. In this case, the estimate for the age-elevation relationship inferred from the inversion can be tested against a set of bedrock ages, which were not used in the inversion (Fig. 4d). Although there are no independent measurements of erosion rate variability within the catchment, the inferred pattern matches the prediction of a model for glacial erosion (Yanites, in prep.), which is consistent with the facts that i) the catchment has been glaciated throughout the Pleistocene, and ii) the modern river sediment is most likely derived from glacial deposits.

To summarize, recent developments in interpreting detrital thermochronometric data have shown that it is possible to infer cooling histories and erosional processes in source catchments without access to the catchment itself. So far these methods have mainly been tested on catchments that could, in fact, be accessed for sampling to verify the results of the detrital data inversion (Brewer et al., 2003; Ruhl et al., 2005; Avdeev et al., 2011; Duvall et al., 2012). In these test cases, the methods of remotely inferring exhumation history from detrital thermochronometry were, to some extent, a solution in search of a problem. The basic premise of this proposal is that the question of how and when the glacial landscape of the Antarctic Peninsula formed is the corresponding problem in search of a solution. This is a landscape whose exhumation history is of fundamental interest, but that is truly inaccessible. The methods of remotely inferring this cooling history from detrital thermochronometry have now been developed and tested elsewhere. The Antarctic Peninsula, and, more broadly, Antarctica in general, is the place where they can potentially yield important information that cannot be obtained in any other way.

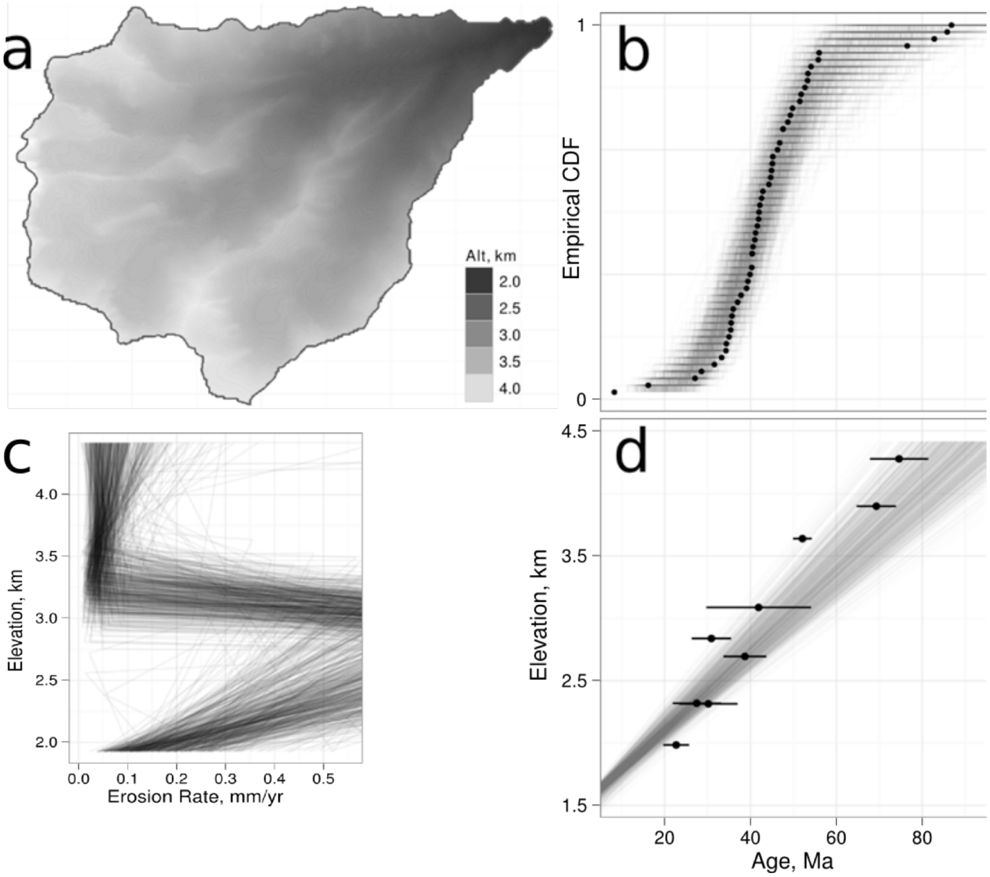


Figure 4. Inversion of detrital (U-Th)/He data for Lone Pine Creek catchment, eastern California Sierra Nevada (topography shown in (a)). The detrital age data set (filled circles in (b)) are used to estimate both the distribution of modern erosion (c ,gray lines) and the bedrock age-elevation relationship (d, gray lines). The gray lines in plot (b) are the synthetic age distributions predicted by the models shown in (c) and (d). Points with error bars in (d) show measured bedrock ages, which are not used in the inversion. Boris Avdeev prepared this figure.

V. Detrital sediment sample collection strategy. In this section we consider in detail whether or not it is possible to obtain the glacial sediment samples needed to accomplish this project. The first basic requirement for the study to be possible is that the glacial troughs whose origin we seek to understand are large enough that their formation would be recorded by the apatite (U-Th)/He system. This requires a valley relief scale of 1-2 km. Ice-covered summit plateaus in the central Antarctic Peninsula lie at 1500-

1800 m elevation. Fjord bottoms near calving fronts of glaciers occupying major troughs commonly lie at 800 m depth and are as deep as 1200 m (Crane Glacier fjord; FIgure 3). Thus, plateau-to-valley relief in major troughs exceeds 2 km, which is adequate for our purposes and is similar to the scale of other landscapes that have been studied with (U-Th)/He thermochronometry.

The second key requirement for this study is that we can obtain samples of detrital sediment that contain suitable apatite grains, and that are derived from the glacial valleys we seek to study. First, we address the issue of apatite content. The overall geology of the central Antarctic Peninsula consists of Mesozoic metasediments, intruded by Jurassic and Cretaceous igneous rocks of dominantly granitic composition (henceforth, "granitoid rocks" for simplicity), and overlain by a variety of Mesozoic and Cenozoic volcanics (Riley et al., 2011 and references therein). Due to ice cover, of course, the exact outcrop pattern of the granitoid rocks is unknown, but they occur throughout the proposed study area. They are apatite and zircon bearing, and Guenthner et al. (2010) were able to extract apatites suitable for (U-Th)/He analysis from 10 out of 13 such lithologies exposed at coastal outcrops on the west coast of the Peninsula (Figure 3). (U-Th)/He ages of samples from the central Peninsula were 8-20 Ma (Figure 3), which tends to validate the general idea that significant exhumation, presumably due to glacial erosion, has taken place in the late Cenozoic. We do not know whether the metasediments contain significant amounts of apatite, but we will be able to investigate this using samples from British Antarctic Survey holdings as discussed below.

In preparation for this proposal, we obtained (from Eugene Domack at Hamilton College) ~0.5 L of water-saturated distal glaciomarine mud from Barilari Bay, on the west coast of the central Peninsula (Figure 3). This mud was collected during sediment coring on NBP10-01 and was surplus to scientific requirements. It contained ~25 g of sand in the > 50 um grain size fraction, which in turn yielded ~25 easily recognizable apatite grains. The condition of these grains ranged from fragmentary to nearly complete crystals with one or both terminations missing. Given the small size of the sample and the fact that it was collected from a fine-grained, ice-distal facies (we propose to sample more ice-proximal sediments), we believe this shows that apatite yields will most likely be adequate for this study. A potential problem is the fragmentation of the grains. This is unsurprising in a glacial environment, but adds potentially large uncertainties to bulk (U-Th)/He ages and may preclude ^{4}He/^{3}He analysis. Later in this section we describe additional sampling strategies intended to address this issue.

The third requirement is that we must be able to obtain samples derived from the glacial valleys whose formation we want to investigate. This requires obtaining ice-proximal glaciomarine sediment that is clearly associated with a single glacier. In turn, this glacier must occupy a trough with adequate relief; not all the glaciers that drain the central Peninsula occupy large and deep enough fjords. Some target glaciers are easily identifiable: these are the largest glaciers that occupy the major topographic troughs, such as Drygalski and Crane Glaciers on the east side of the Peninsula and Cayley Glacier on the west (Figure 3). The first task in this project will be to assemble topographic, glaciological, and bathymetric data (see additional discussion below) to make a detailed assessment of glacier suitability for this project. This inventory will then guide development of a plan for shipborne sample collection, as discussed in the next paragraph.

One important requirement for this project is that we will need to obtain very large sediment samples. This is due to both the implications of our trial apatite extraction (although apatites appear to be common in these sediments, unbroken apatites may be rare) and the high value of collecting large ice-rafted gravel and cobbles as well as sand-sized sediment (see discussion below). We estimate required sample sizes to be on the order of tens of kg or larger; in practice we would attempt to collect 100 kg or more via repeated box cores or grab samples from a particular site. Although archived samples of marine sediment from some of our target areas exist at the Antarctic Marine Geology Research Facility at FSU, we view it as highly unlikely that we could carry out this project using archived samples. The quantities required would quickly consume available archive material.

We propose several strategies to obtain the large marine sediment samples that we need, including samples of opportunity from current and planned cruises that meet our criteria, and a request for ship time to collect additional samples from relatively easily accessible sites on the west side of the Peninsula.

First, we have already collaborated with the shipboard science party on NBP12-03 (LARISSA; chief scientist Maria Vernet). They salvaged, at our request, a ~30-liter sample of surface sediment (that would otherwise have been discarded) collected near the grounding line of the Drygalski Glacier (Figure 3). At present it is in transit to the US with other samples from this cruise. This is a particularly important sample because Drygalski is one of the largest glaciers in the proposed study area, is ideal for our purposes, and the east side of the Peninsula is rarely visited and additional opportunities to collect this sample would be unlikely.

Second, we propose to collaborate with Eugene Domack (Hamilton College) who is the PI of two tentatively scheduled cruises of the *Lawrence M. Gould* to the western Peninsula in 2012 and 2013. The primary purpose of these cruises will be marine-geological studies including sediment coring, and he has agreed to assist us in obtaining large samples of glaciomarine sediment from western Peninsula fjords to the extent compatible with the existing science plan for these cruises (see attached letter of support).

Third, Balco is involved through the "LARISSA" (Larsen Ice Shelf System, Antarctica) project in a collaboration between the USAP and the Korea Polar Research Institute (KOPRI) that will involve a cruise of the Korean *RVIB Araon* to the Larsen B embayment in April 2013. This cruise will attempt to visit Crane Glacier fjord, which would be an extremely valuable sample location for the current project. Through this collaboration, we will seek to ensure that this sample is collected on the *Araon* cruise.

Fourth, we have requested ship time to visit approximately 4-6 additional sites on the west side of the Peninsula (Figure 3) where important target glaciers exist, but that are not proposed to be visited in the cruises for the Domack project described above. In addition, this will provide an opportunity to augment the existing bedrock data set of Guenthner et al. (2010) by visiting additional coastal outcrops. These sites are in the normal operating area of the *Palmer* and *Gould* and we envision that the relatively modest time and berthing requirements of this project (4 berths, ca. 15 ship days) could be combined with other shipborne research in the area.

To summarize, not all glaciers will be suitable for this work and we believe that our strategy of i) a glacier suitability assessment from topographic and glaciological data, ii) acquiring samples of opportunity from a variety of sources, and iii) a modest request for dedicated ship time to collect additional samples from important target glaciers identified in the first phase, is the most efficient way of maximizing our likelihood of success.

VI. Analytical and interpretive strategy; supporting analyses of bedrock samples. Our analytical and interpretive approach is designed to do three things: first, answer basic first-order questions about the timing of glacial exhumation in the study area; second, investigate past and present exhumation of the Peninsula landscape by applying inversion methods modeled on those of Avdeev et al. (2011) to sets of detrital (U-Th)/He ages from several major glaciers; third, use information gained from this exercise to develop hypotheses that can be tested by targeted ^{4}He/^{3}He analysis on a subset of detrital or bedrock samples.

First, an important aspect of this project is that regardless of the results of any further analysis, generating a data set of (U-Th)/He ages of detrital apatites from Antarctic Peninsula glaciers will, with minimal interpretation, answer several important questions that we know little about at present. The most important of these is whether significant Pleistocene glacial valley formation took place at all. An implication of the model calculations and results of recent studies that addressed this issue is the simple test that if most of the present 2 km of relief was formed in the Pleistocene, we should observe Plio-Pleistocene (U-Th)/He ages in glacial debris derived from the bottom of glacial troughs. The range of ages we observe, without any further interpretation, places significant limits on when relief development occurred. Is the landscape largely Plio-Pleistocene, Miocene, or Oligocene?

Second, our main interpretive strategy will be to apply inversion methods to sets of detrital (U-Th)/He ages. This will involve an analysis similar to that shown in Figure 4, in which we will invert observed bulk (U-Th)/He age distributions to obtain information about past and present exhumation of the catchment. The expected results of this task will include an estimate of the geographic and elevational distribution of thermochronometric ages for each study catchment (which implies a cooling history), as well as an estimate of the spatial distribution of present glacial erosion. These will resemble the results shown in Figure 4, but because the exhumation history we are trying to reconstruct in this case (the evolution of a fjord landscape) is more complex than the one-dimensional pattern shown in Figure 4, we will most likely modify this approach by parameterizing thermochronometric age and modern erosion distributions as functions of both elevation and position relative to glacial troughs, instead of elevation alone.

This task will require ancillary information besides the age distribution, specifically the extent and hypsometry of the glacier catchments from which the samples are derived. The extent of glacier catchments is fairly straightforward to map from existing topographic data and delineation of ice divides on satellite imagery. Estimating the bedrock surface hypsometry in an ice-covered catchment is more difficult. We will exploit several data sources to do this, including topographic data for the ice surface at a variety of scales (RAMP-DEM, ICESAT soundings); the existing BEDMAP database; multibeam bathymetry of fjords in front of our target glaciers (compiled at MGDS/Antarctic and Southern Ocean data portal); and airborne radar data from NASA overflights (archived at the Center for Remote Sensing of Ice Sheets; see Figure 3). Inferring bed topography from these radar data is not straightforward, mainly due to mixed data quality and complex side reflections from steep topography. As none of the proposed project staff are expert in this field, we will collaborate with Seth Campbell, an ice-penetrating radar specialist at the U.S. Army Cold Regions Research and Engineering Laboratory (see attached letter of support) on interpreting these data. Although the data are clearly inadequate for producing detailed maps of subglacial topography comparable to maps available for unglaciated areas, this level of detail is not required for our project, and we believe that we will be able to estimate catchment hypsometry with sufficient accuracy to support the detrital (U-Th)/He age inversion.

Third, we will measure ^{4}He/^{3}He spectra on a subset of apatite crystals from selected sites. This method, an example of which is shown in Figure 1, is a refinement of (U-Th)/He thermochronometry in which one irradiates an apatite crystal to produce a uniform distribution of synthetic ^{3}He, gradually degasses the crystal in a series of heating steps, and measures the ^{4}He/^{3}He ratio of each heating step. The ^{4}He/^{3}He ratio evolution then provides information about the spatial distribution of ^{4}He. Because this distribution is the result of He diffusion during grain cooling, it can be used to determine the cooling history of the crystal during the time it resided in the apatite He partial retention zone between ~80-40° C (e.g., Shuster and Farley, 2004; 2005). In contrast to bulk (U-Th)/He thermochronometry, in which a dispersed data set of many samples is needed to determine a cooling history for an entire landscape, the ^{4}He/^{3}He method allows recovery of a thermal history from a single grain. It provides a much denser data set than the bulk age distribution, and we are not aware of any previous efforts to develop a formal inversion of multiple ^{4}He/^{3}He spectra in detrital apatites. This is most likely feasible, but is clearly complex, so our initial approach to the ^{4}He/^{3}He data will be testing of specific hypotheses about landscape evolution that flow from the bulk age observations.

Figure 5 shows an example in which we made forward calculations of the expected distribution of bulk (U-Th) He ages and ^{4}He/^{3}He release spectra in a detrital sample, given a glacial valley landscape with scale appropriate to the Antarctic Peninsula and several different possible scenarios for valley development. Although these reflect end-member and somewhat speculative hypotheses, they imply significant differences in both observed bulk age distributions and ^{4}He/^{3}He spectra. Although these two data types have similar resolving power in this example, they represent nearly independent constraints on permissible thermal histories. Cooling histories derived from ^{4}He/^{3}He data will provide a test for internal consistency; if compatible with the results from bulk age distribution inversion, this would significantly increase confidence in the results.

In addition to these three primary approaches, we will pursue two additional data-collection strategies that may provide additional constraints on the thermochronometric age distribution in the study area, thus improving the accuracy of inversion of the detrital age distributions. These include efforts to: i) collect relatively large (i.e., gravel- to cobble-sized) dropstones in marine sediment samples; and ii) obtain samples of in-place bedrock from several sources.

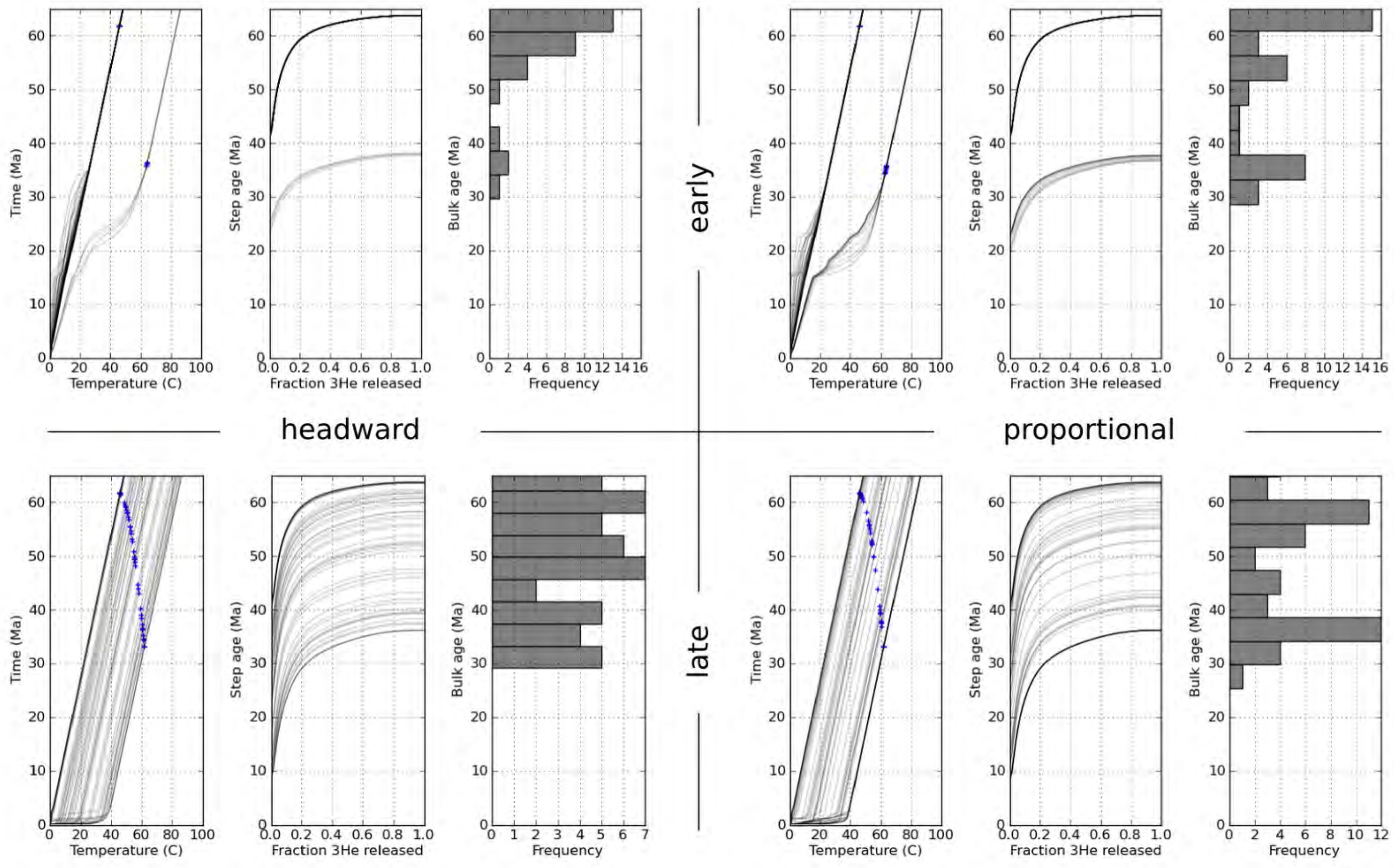


Figure 5. Detrital (U-Th)/He ages and ^{4}He/^{3}He spectra predicted for varying geomorphic and temporal scenarios. Three panels for each scenario show predicted cooling histories for simulated detrital grains (blue dots indicate bulk ages implied by each cooling history); corresponding ^{4}He/^{3}He spectra (in this plot, represented as step ages; see Shuster and Farley , 2005); and implied bulk He age distributions. "Proportional erosion" implies that the shape of a glacial valley remains constant through time and only its size changes. "Headward growth" prescribes headwall retreat at 100x the erosion rate on the valley sides and bottom. In the "early" erosion scenario all carving occurs between 35 and 15 Ma, while in the "late" scenario it postdates 3 Ma. Bulk age distributions include 10% measurement uncertainty. The purpose of this figure is to show that exhumation scenarios we may infer from the bulk age distributions imply specific predictions for ^{4}He/^{3}He spectra in detrital grains (and also in bedrock samples) that can be tested against observations. Boris Avdeev prepared this figure.

Large dropstones are potentially valuable to this project for two reasons. First, it may be difficult to obtain unbroken apatite crystals from fine-grained glaciomarine sediment. It will most likely be easier to obtain them by crushing and separating coherent clasts. Second, large clasts may yield both apatite (U-Th)/He and higher-temperature thermochronometric (for example, zircon (U-Th)/He or apatite fission track) data from the same sample. This is important because the age-elevation relationship for (U-Th)/He in apatite may vary with position relative to glacial troughs, but that for higher-temperature thermochronometers is expected to be primarily a function of elevation and otherwise unrelated to topography. This may permit a strategy of using higher-temperature thermochronometers to estimate elevations from which clasts were derived, and then apatite (U-Th)/He to determine the variance in low-temperature cooling histories at that elevation. Although there is an obverse to this relationship -- for high-temperature thermochronometers, the age-elevation pattern is more likely to be complicated by geographic variation due to structural boundaries -- we believe that this approach may provide valuable information. The potential value of large dropstones is a major motivation for collecting sediment samples that are as large as possible.

Samples of in-place bedrock would be valuable for similar reasons. As already discussed, even with unlimited samples from currently-ice-free areas of the Peninsula, we could not learn about the development of glacial topography from these samples alone. This is simply because the ice-free areas occur on ridges between major troughs, and not in the troughs themselves. However, analysis of bedrock samples, by providing some information about the distribution of bulk (U-Th)/He ages and ^{4}He/^{3}He spectra in the landscape, would constrain cooling histories inferred from the detrital age data set. This would be equivalent, for example, to allowing some of the bedrock ages in Figure 4 to be used as input data to the inversion.

Bedrock samples from the study area are available from two sources. First, scattered coastal outcrops on the extreme west side of the Peninsula are accessible by ship; Guenthner et al. (2010) visited many of these sites and collected a variety of thermochronometric data (apatite (U-Th)/He data from their study appear in Figure 3). Depending on which catchments we select for detrital samples, these existing data may be useful as constraints for our work. It is likely that apatite ^{4}He/^{3}He analyses from some of these sites would also be valuable. In addition. if we identify additional outcrops in key locations that are coastal, accessible by boat, and have not been previously sampled, we will visit them during our requested ship time allocation. Another important reason for revisiting some of these outcrops is the likely presence of glacially transported erratics derived from glacial troughs; we have observed such erratics in the field in the past, and these would have similar value to dropstones as discussed above. We discussed this proposal with Dave Barbeau, whose research group is studying the Cenozoic tectonics of the Antarctic Peninsula region, and who is the present custodian of the Guenthner et al. samples. The research proposed here is complementary to their research in that we and they are focusing on low- and high-temperature thermochronometric data, respectively, from samples in overlapping geographic areas. If this proposal is successful, we have agreed to share existing and future samples (see attached letter of support).

Second, we propose to make use of an extensive archive of samples from inland nunataks that were collected during geologic mapping programs by the British Antarctic Survey (BAS) between the 1960's and the present (Figure 3, enlargement). To do this, we will collaborate with Dr. Joanne Johnson of BAS (see attached letter of support), who will assist us in searching the BAS archive and obtaining appropriate samples. Our budget request includes funds for personnel exchange between BGC and BAS for this purpose. The sites shown on Figure 3 represent locations visited by BAS geologists where samples or other data were collected. Data in the BAS catalogue indicate that samples were collected at nearly all of these sites, but as these samples are stored in a variety of locations and their size and condition are not uniformly documented, we have not yet verified that each location shown on Figure 3 corresponds to a suitable sample for this project. Our initial review of available data indicates that sample material will be available from a majority of the locations shown. Overall, we believe that this collaboration significantly increases the chance that this project will be successful: even a few samples of in-place bedrock from higher-elevation core areas of the Peninsula will greatly improve the performance of the inversion schemes for the detrital data (Avdeev et al., 2011).

VII. Research plan: personnel, division of responsibilities, and timeline. Project personnel include BGC PIs Balco and Shuster, BAS collaborator Joanne Johnson, and a Ph.D. student hosted at BGC (the Ph.D. student will be enrolled at UC-Berkeley under the formal supervision of Shuster, who is a member of the UC faculty). Shuster is a specialist in noble gas geochemistry and thermochronometry. He developed the apatite ^{4}He/^{3}He method and has extensive experience applying He and Ar thermochronometry to many aspects of geomorphology, tectonics, and planetary science. Shuster does not have Antarctic field research experience, although he has provided analytical support to OPP-funded projects. Balco's primary expertise is in cosmogenic-nuclide geochemistry and its application to geochronology and landscape evolution studies. For the past five years, he has also collaborated with Shuster on developing and applying apatite (U-Th)/He and ^{4}He/^{3}He thermochronometry, and is responsible for the random-search inversion software for ^{4}He/^{3}He data used in many recent applications of this technique (Shuster et al., 2011; Valla et al., 2011; Schildgen et al. 2010). Balco has six field seasons Antarctic field experience in the last decade, one of which was spent aboard the *Nathaniel B. Palmer* in our proposed field area in the central Antarctic Peninsula (NBP10-01). Johnson is highly knowledgeable in the geology of the Antarctic Peninsula and has extensive field and analytical experience in geologic mapping and geochronology in that region as well as elsewhere on the continent.

The central activity of this proposal is the quantitative synthesis and interpretation of various types of thermochronometric data from both detrital and bedrock samples, as well as ancillary geographic and glaciological information. Although the Ph.D. student will be trained in detail in the analytical methods necessary to generate the data, our intention is that the synthesis and interpretation of the data will be the primary focus of the student's dissertation research, and the student will devote significant time and effort to developing the quantitative skills necessary to accomplish this. At present, analytical techniques for the thermochronometric data we propose to collect are fairly well established, and in our view, a key route to new understanding of landscape evolution processes is the development of corresponding interpretive methods to deal with the large data sets that we are now capable of developing. We think that the recent developments in quantitative interpretation of detrital thermochronometric data sets that we have discussed above are an important step in that direction, and we intend that this overall concept will guide the student's training and research.

Our proposed research will proceed in three phases. The first phase will focus on assembling geographic and geophysical data necessary to delineate potential study catchments, and on analysing samples of opportunity already collected (primarily the Drygalski Glacier sample). This information will permit modifying the model framework used to generate Figure 5 to simulate changes in the topography of specific Antarctic Peninsula glacier catchments, which in turn will allow us to determine which catchments have the physiographic characteristics needed for best confidence in the inversion results. To some extent this evaluation depends on the timing of glacial erosion, so early analysis of the Drygalski Glacier sample is important to obtain at least a coarse estimate of expected age distributions. The end product of this phase will be a set of 4-6 glaciers targeted for sampling either on cruises of opportunity or during our requested ship time allocation, as well as an assessment of which bedrock sample locations would be most valuable.

The second phase will focus on sample collection and bulk (U-Th)/He age analysis. This phase will include obtaining samples from BAS archives as well as shipborne collection of large detrital samples from target locations on the west coast of the Peninsula. In addition, we will continue to seek additional samples of opportunity during this phase. Analytical work during this phase will be predominantly bulk (U-Th)/He dating; in addition, we will begin ^{4}He/^{3}He analysis on selected samples.

The third phase will focus on inversion modeling of bulk detrital age distributions and bedrock ages, generating hypotheses based on these results, and carrying out additional ^{4}He/^{3}He analysis on detrital and bedrock samples designed to test these hypotheses.

We estimate the total number of analyses required will be approximately ~50 bulk ages from each of ~5 glacial sediment samples, an additional ~50 bulk ages from bedrock samples (total ~300 bulk ages), and a total of ~30 ^{4}He/^{3}He analyses. These analyses will be carried out using in-house BGC facilities (see Facilities and Resources section), and our proposed budget includes corresponding consumables and equipment-upkeep costs. Zircon (U-Th)/He analyses (see discussion above) can also be conducted at BGC, but we have included a small budget for commercial apatite-fission-track analyses if called for.

VIII. Likely outcomes and potential complicating factors. Here we evaluate potential risks and rewards of the proposed project by summarizing likely outcomes as well as potential complications. Overall, we view the potential outcomes of this project described below as highly significant to not only Antarctic regional geomorphology but also to broader questions involving the effects of climate and glacier change on orogenic mass balance. We view the potential risks of this project, due to the complications described here and perhaps others that we have not identified, as non-negligible and, in addition, difficult to evaluate given the lack of existing low-temperature thermochronometric data from the region. However, we argue that the evidence we have indicates that we have adequate resources available, in particular our collaboration with BAS to obtain bedrock samples from key target areas, to overcome the potential complications we have identified.

The primary intended outcome of this project is information about how and when the large glacial troughs of the Antarctic Peninsula landscape formed. This information, in turn, is broadly valuable because of its relevance to understanding the effects of climate change, as mediated by glacier change, on orogenic mass balance. The potential obstacles to achieving this outcome mainly include failure of the assumptions we have made in evaluating the suitability of the apatite (U-Th)/He system for this study. The assumption that the size and relief of major fjords is sufficient that their formation is recorded by the (U-Th)/He system is well justified by the results of several similar studies in temperate landscapes. Harder to evaluate is the assumption that the present pattern of glacial erosion is delivering apatites from critical locations to our sample sites. However, observed sediment flux to present glacier margins indicates that significant subglacial erosion is active at present. Thus, it appears nearly certain that we will obtain apatites from at least the central portions of glaciated troughs which, with the bedrock samples from ice-free areas that we propose to analyse, should represent the full range of thermochronometric ages present in the landscape.

A second intended outcome is information about the geographic and elevational pattern of modern glacial erosion. This outcome is linked to the first in that both are products of our intended inversion procedure. It is more broadly important in that it would increase understanding modern processes of glacial erosion. A potential complication relating to this outcome, and also to the goal of inferring the distribution of ages in the landscape discussed in the prior paragraph, would be a situation in which nearly all detrital apatites were derived from a restricted region of the catchment. This could arise from lithologic heterogeneity, for example, if metasediments are apatite-poor and all apatites were derived from a small outcrop area of granite. We propose to address this issue both by selecting catchments where existing geologic maps suggest that this is not the case, and by evaluating the apatite content of different lithologies from archived bedrock samples. This could also arise from a highly skewed distribution of erosion. This condition is likely to some extent, because the portion of modern glaciers lying on the summit plateau, as well as thin glaciers that mantle steep topography, are frozen to their bed and unlikely to be generating sediment. However, it appears that erosion is actively taking place at headwalls (see Figure 2) and at glacier beds, indicating that the majority of the elevation range present in the landscape will most likely be represented in detrital sediment. We would identify a highly restricted distribution of erosion in the inversion procedure (basically, by observing that the range of detrital ages was much smaller than the range of bedrock ages). In addition, if a highly nonuniform distribution of erosion did impede reconstructing longer-term exhumation histories, this would in itself be a significant finding from the perspective of modern glacier erosion.

A third potential outcome is ancillary information about Cenozoic tectonics in the Antarctic Peninsula. Although this is not the primary focus of our research, understanding the exhumation history of our study area will likely have useful implications for this field.

A final potential outcome is fundamental progress in the study of ice-covered landscapes. The thermochronometric methods we propose to use have yielded significant advances in understanding tectonics and landscape development in regions of the world outside Antarctica. The fact that Antarctica is covered by ice is a fundamental obstacle to applying them here. Even if we are not able to completely achieve all the objectives of this proposal, exploring how to use detrital thermochronometry to study the exhumation history of ice-covered landscapes will result in fundamental progress in how to decipher the geology and geomorphology of Antarctica's hidden landscape.

IX. Broader impacts. This project has potential broader impacts in three areas, as follows.

First, in development of human resources needed to sustain excellence in Antarctic research. this project brings two new researchers (Shuster and a Ph.D. student) into the Antarctic Earth science research community. Shuster has expertise in rapidly developing fields of geochemistry and geomorphology that are highly relevant to important research questions in Antarctic Earth science, and the student will develop expertise in these fields.

Second, in international collaboration. Our collaboration with Joanne Johnson of the British Antarctic Survey works to build international cooperation and foster connections among scientists working with different Antarctic research programs.

Third, in applications to other fields of Earth science. The intended outcomes of this project have applications to specific ancillary fields, in particular glaciology and tectonics. In addition, the overall project addresses a fundamental problem in Antarctic research, that is, the problem of inferring past and present geologic processes active on an ice-covered and inaccessible landscape.

X. Results of prior NSF support.

"Acquisition of a Noble Gas Thermochronometry Laboratory at Berkeley Geochronology Center" (EAR-0618219) $149,757: 8/15/06-7/31/08; PI: D. Shuster. This grant partially funded a versatile, automated noble gas mass spectrometry facility optimized for He analyses. This facility will be used in the current proposal. The NGTL (Noble Gas Thermochronology Lab) was commissioned in January, 2007, and since then has analyzed hundreds of samples while operating 24 hours/day, serving collaborations with more than 20 researchers from throughout the US, including four young investigators, four postdoctoral fellows and seven graduate students. The NGTL is currently a central analytical facility for six active NSF-supported projects, *EAR-0644966 (GLD), EAR-0738474 (PG), EAR-0838572 (OG), ANT-0838757 (AES), EAR-1049988 (PG), and EAR-1111853 (CD)*. Four of these are collaborative research grants to Shuster as PI. Two additional projects are funded by NASA with Shuster as co-PI. Currently, one postdoctoral scholar and 2 graduate students conduct research in the lab. This research has resulted in significant findings in both basic and applied noble gas thermo- and geochronometry, specifically in the area of low-temperature thermochronometric study of landscape-forming processes. Twenty publications which directly resulted from this grant are highlighted by **(NGTL)** in the references section.

"Collaborative Research in IPY: Abrupt Environmental Change in the Larsen Ice Shelf System, a Multidisciplinary Approach - Marine and Quaternary Geosciences" (OPP-0732467); $576,100; 10/1/2007-present; PI: Eugene Domack. Balco is a collaborator on this project via a subcontract (at the time of proposal submission, he was a postdoctoral researcher and could not be a PI). This grant is part of the "LARISSA" (LARsen Ice Shelf System, Antarctica) project, which is a large multidisciplinary project using the RVIB *Nathaniel B. Palmer* as a common platform to investigate the geological, glaciological, and ecological framework and consequences of ice shelf collapse in the Larsen Embayment on the east side of the Antarctic Peninsula. Balco's role in this project is to carry out glacial-geological mapping and cosmogenic-nuclide exposure dating of terrestrial glacial deposits in the Larsen Embayment, with the goal of placing recent ice shelf collapse in a longer-term geological context. Results of this work show that exposure ages of glacially transported erratics provide a record of Holocene ice surface elevation change as well as changes in the extent of ice shelves. These data are an important complement to existing marine radiocarbon chronologies because they provide both an independent time scale and information about past changes in ice thickness as well as extent. A paper describing these results is in review at the journal *Quaternary Science Reviews*; a copy is available from Balco upon request.