PROPOSAL DESCRIPTION: CENOZOIC FORMATION OF THE ANTARCTIC GLACIAL LANDSCAPE INVESTIGATED BY LOW-TEMPERATURE THERMOCHRONOMETRY

Summary: This pre-proposal outlines a drilling program aimed at investigating the origin of the present glacial landscape in the fjord system of the western Antarctic Peninsula by applying novel methods of low-temperature thermochronometry. This, in turn, is important in understanding the Cenozoic geologic history of Antarctica and, more broadly, in understanding the role of glaciation in climate-solid Earth interactions. Accomplishing this requires samples of the present bedrock surface in the location of maximum Cenozoic erosion, that is, glacial valley bottoms. Thus, the major challenge is the inherent inaccessibility of the Antarctic landscape: the only significant regions of Antarctica that are not now covered by ice are below present sea level. To overcome this challenge, we propose to employ an IODP mission-specific platform, specifically, a semiautonomous seabed drill suitable for short coring of crystalline bedrock in formerly glaciated and now submarine fjord bottoms.

In the following sections: i) we explain why understanding Cenozoic glacial erosion in Antarctica is important; ii) we describe how we propose to develop this understanding; and iii) we outline criteria for a drilling program necessary to implement this strategy.

1. The when and how of Cenozoic glacial erosion: why is it important?

Understanding how and when glacial landscapes form is broadly important for two reasons.

First, formation of geomorphic features diagnostic of glaciation, e.g., cirques, U-shaped valleys, and landscapes of selective linear erosion (localized glacial troughs incised into an otherwise low-relief landscape; Sugden, 1978) requires the presence of glaciers. Glaciers, in turn, imply a polar or alpine climate, and in addition the spatial distribution of glacial landforms can provide quantitative information about past temperatures. This reasoning is particularly important for Antarctica, because our present understanding of Cenozoic climate and ice sheet change in Antarctica relies heavily on inference from glacial landforms constrained by very sparse geochronological data (Sugden and Denton, 2004; Sugden et al., 1999; Bo et al., 2009; Rose et al., 2013). For example, recent mapping of the Gamburtsev subglacial mountains in East Antarctica (Rose et al., 2013) revealed landforms that are diagnostic of restricted alpine glaciation and thus inconsistent with formation under the present ice sheet configuration; potentially, determining the age of these landforms would yield direct spatial and temporal constraints on how and when the present ice sheet formed.

Second, glaciers are a key process in mediating between surface climate and landscape evolution in orogenic systems. The erosional effectiveness of glaciers means that changes in the extent of glaciation, due to climate change or tectonic uplift, may significantly and nonlinearly change orogenic mass balance, Figure 1. The landscape of the Antarctic Peninsula comprises a low-relief summit plateau deeply incised by glacial troughs: upland valley heads shown in this photo are occupied by glaciers that terminate in marine fjords. This photo (1967 U.S. Navy aerial photo TMA 2143-292L) looks north from the proposed study area in Gerlache Strait along the spine of the peninsula. With the exception of a few inaccessible cliffs that are too steep for snow and ice to accumulate on, the entire landscape above sea level is ice-covered.
as well as impact global geochemical cycles due to changes in sedimentary and weathering fluxes. Understanding, quantifying, and dating changes in landscape form and relief due to widespread Cenozoic glaciation of mountains worldwide is critically important to evaluating these hypotheses as well as to generally understanding the role of glaciation in the climate-tectonic feedback system (e.g., Yanites et al., 2012 and references therein).

2. Investigating glacial erosion via low-temperature thermochronometry

Our approach to the question of how and when glaciation changes landscape form and mountain relief is to generate direct evidence of topographic change in mountain regions. We do this via geochemical observations that allow us to reconstruct the cooling history of minerals now at the Earth’s surface, and in turn to infer the spatial and temporal distribution of surface erosion responsible for that cooling history. In general, reconstructing past erosion is difficult because the process of erosion, by definition, erases evidence of previous landscape configurations, and indirect proxy records of erosion, such as sediment flux and preservation in adjacent basins, are not specifically diagnostic of topographic change. In contrast, because surface erosion affects the thermal field well below the surface, mineral thermochronometers can retain information about surface topography that no longer exists (e.g., Braun, 2005).

In this project we will primarily use the apatite (U-Th)/He thermochronometer, which is based on the production and diffusion of $^4$He that is produced as a daughter product along the U and Th decay chains, and is mobilized and lost by thermally activated volume diffusion. Thus, the concentration of He relative to its parent U and Th is a function of the cooling history experienced by an apatite as it approached the surface. Apatite (U-Th)/He is the lowest-temperature system commonly used in geological applications. Measurements of the bulk concentration of U, Th, and He in apatite, as well as the spatial distribution of $^4$He determined by the related method of $^4$He/$^3$He thermochronometry (Shuster and Farley, 2004), permit one to reconstruct the cooling history of the apatite in the 30-80 °C range (Farley, 2000; Shuster et al., 2006). This temperature range typically corresponds to a depth range of 1-3 km, which is important because this is shallow enough that the thermal field in this depth range is significantly influenced by
high-relief topography. Thus, apatite (U-Th)/He analysis and $^4\text{He}/^3\text{He}$ thermochronometry can be used to learn about changes in surface topography at a relief scale of ~1 km, over time scales of $\sim 10^5$ to $10^7$ years.

Some of the most dramatic relief on Earth is associated with glacial landscapes, and the development of these landscapes in temperate regions due to Plio-Pleistocene cooling and glaciation is hypothesized to play an important role in the widely discussed question of the global tectonic consequences of this climate change (e.g., Molnar and England, 1990; Whipple et al. 2009). Thus, apatite (U-Th)/He thermochronometry has been extensively applied in temperate glacial landscapes to quantify when and how glacial topography formed (e.g., Shuster et al., 2005; Thomson et al., 2010; Shuster et al., 2011; Valla et al., 2011). Figure 2 shows an example from the study of Shuster et al. (2011) in the Fjordland region of New Zealand; this study used (U-Th)/He and $^4\text{He}/^3\text{He}$ measurements to show i) that the present relief is nearly entirely the result of Pleistocene glacial erosion, and ii) that valley formation took place by headward retreat rather than uniform deepening, which is important in understanding the mechanics of glacial erosion.

To summarize, the apatite (U-Th)/He system is well suited to the scale of topographic relief in alpine glacial landscapes formed by selective linear erosion. Applying this tool to glaciated mountain ranges in temperate latitudes has i) revealed the importance of Pleistocene glaciation in fundamentally changing their form and mass balance, and in addition ii) contributed to understanding the process and mechanics of glacial erosion at the landscape scale.

We know much less about how and when glacial landscapes in polar regions, specifically in Antarctica, formed. With the exception of Miocene glaciation of some north polar regions, significant and widespread glaciation outside Antarctica did not take place until the late Pliocene and Pleistocene. The studies mentioned above show that Plio-Pleistocene cooling and the resulting expansion of alpine glaciers in mountain ranges worldwide was the most significant Cenozoic climate event in reshaping present glacial landscapes outside Antarctica. Antarctica, on the other hand, most likely has a very different history of glaciation dating back to the Eocene. For example, the Antarctic Peninsula, which is the proposed focus area of this study, hosted alpine glaciers as early as 34-37 Ma and a regional ice sheet possibly by 15 Ma (Davies et al. 2011 and refs. therein). Thus, much of the glacial valley relief of present Antarctic landscapes likely well predates the Pleistocene. In fact, Rebesco et al. (2008) pointed out that marine sedimentary evidence implies a decrease in sediment yield from the Antarctic Peninsula after 3 Ma, and attributed this to a reduction in glacial erosion caused by a transition from wet- to frozen-based glaciers during Plio-Pleistocene cooling. In Antarctica (as well as some other subpolar regions; see Thompson et al., 2010), Plio-Pleistocene cooling may have halted, rather than accelerated, landscape modification by glaciers.

To summarize, the history of Antarctic glaciation suggests a significantly different history of landscape formation in Antarctica than in other glaciated regions worldwide, and this hypothesis has important implications for how glaciers mediate climate-landscape interactions over million-year time scales. Our goal in this study is to evaluate this hypothesis by developing a direct thermochronometric record of how and when the exemplary glacial landscape of the Antarctic Peninsula formed.

3. Challenges to this approach in Antarctica and criteria for a sample collection program needed to overcome them

The primary challenge in applying thermochrometric methods to find out when and how the Antarctic landscape formed is that these methods require samples of in-place bedrock from the landscape surface. Studies in temperate glacial landscapes have been possible because these landscapes, while commonly glaciated during the Pleistocene, are ice-free at present and therefore accessible for sampling. In contrast, Antarctica is nearly entirely covered by ice. Furthermore, the locations of highest sensitivity for quantifying the timing of incision are in the areas where incision has been greatest -- the more exhumation, the greater the thermochronometric signal. These locations of deepest incision are at the bottom of the major glacial troughs, which are covered by the thickest ice.
Figure 3. Map of the inner continental shelf on the west side of the north-central Antarctic Peninsula showing the proposed study area, which consists of the glacial valley system extending from currently glaciated valleys on the Peninsula itself, to the north and south around Brabant and Anvers Islands, and onto the outer shelf. Both i) the contrast between deep incised valleys and low-relief surrounding topography, and ii) the presence of overdeepened fjord segments, are diagnostic of valley system formation by glacial erosion. The inset at upper right shows location on the Antarctic continent. The red crosshair symbols highlight proposed sample sites WAP-1 to -11; text at left lists water depths and nearby geographic feature names. Data sources are as follows: bathymetric map, GMRT synthesis bathymetry via GeoMapApp; vector coastline and topographic data, Antarctic Digital Database; shaded relief topography of land areas, Radarsat Antarctic Mapping Project (RAMP) digital elevation model.
Access to bedrock samples at locations now covered by ice would theoretically be possible by drilling through ice and then coring bedrock below the ice. Although designs for such a drill system exist (e.g., the "RAID" drill under development by the US IDPO/IDDO), this approach is not feasible in the near future.

However, there is one part of the Antarctic continent where significant topographic relief, presumably formed by Cenozoic glacial erosion, is ice-free at present. This is the Antarctic continental shelf. Specifically, the glacial valley system of the western Antarctic Peninsula, the focus area of this proposal, extends seaward of present glacier margins as an extensive system of fjords that are occupied by glaciers during glacial maximum conditions when sea level is lower than present. Thus, in this region and potentially others like it around the Antarctic continental margin, the sample locations necessary to accomplish our goals -- bedrock outcrops at the bottom of major glacial troughs -- are covered only by water and not by ice. Seabed drilling, unlike subglacial rock drilling, is feasible with existing technology.

The criteria for a seabed drilling program to obtain the samples needed for this project are as follows. They are based on the fact that thermochronometric methods (specifically (U-Th)/He, but also others) require obtaining pristine mineral grains from unweathered samples of in-place bedrock. Thus, the two criteria for our sample collection program are i) certainty that the sample is part of in-place bedrock, and ii) the ability to penetrate surface debris and weathering to obtain a fresh sample.

Based on our investigation of available drilling systems, we believe that this can be accomplished at lowest cost and complexity using a semiautonomous seabed drill, that is, a self-contained drill designed to collect short bedrock cores that is tethered to a vessel by a power/control cable. For example, an attempt to collect loose bedrock clasts via dredging would not yield any certainty that a sample represented local bedrock rather than glacially transported debris, and also by definition the most likely samples of bedrock to be collected by dredging would be the most weathered and therefore friable. On the other hand, a ship-mounted drill system designed to collect long cores would be much larger and more complex than needed, as thin surface sediment and/or a surface weathered layer could most likely be penetrated in less than 1 meter of core. A semiautonomous seabed drill represents the appropriate intermediate level of complexity.

Although many such drill systems exist, in preparing this proposal we specifically investigated two example systems that would be potentially suited for this work, both owned by the British Geological Survey. The more compact of the two is the BGS “Oriente Rock Drill,” which was designed for collecting oriented cores for paleomagnetic research. It is small, compact and suited for deployment from nearly any oceanographic research ship with an A-frame or CTD winch, but is limited to a total core depth of 0.8 m. It would be suitable for this project if sites where bedrock was directly exposed at the seafloor were assured to exist (see discussion below). However, this penetration depth might not be adequate if bedrock surfaces were covered by thin glacial drift. In this case, a more appropriate system would likely be the BGS “RD1” seabed rockdrill/vibracorer, which is significantly larger with correspondingly greater winch and power requirements, but collects a larger core with total core depth up to 5 m.

4. Rationale for the western Antarctic Peninsula; seafloor characteristics; site selection criteria

Of several potential regions of the Antarctic continental shelf where high-relief glacial valley systems are exposed on the seafloor, this proposal is focused on the western Antarctic Peninsula. This is based on both scientific and logistical reasoning, as follows.

First, the fjord system that extends along the entire west coast of the Peninsula represents one of the most extensive glacial landscapes currently exposed on the continental shelf. In the focus area of this project in the north-central portion of the Peninsula (Figures 1, 3, 4), numerous steep-sided, amphitheater-headed glacial valleys incise a low-relief summit plateau. These valleys coalesce into fjords, which in turn flow into two major submarine troughs that, at times of lower sea level, drain ice flowing north and south around Anvers and Brabant Islands onto the outer shelf (Domack et al., 2005). The contrast between deeply incised and locally overdeepened glacial troughs and a surrounding low-relief landscape both onshore and offshore is a textbook example of a landscape of selective linear erosion diagnostic of
formation by glacial erosion. Thus, clear geomorphic evidence that these valleys are glacial in nature, in addition to some stratigraphic and temporal context for regional exhumation from surrounding basins (e.g., Rebesco et al., 2008) implies that a thermochronometric record of their formation will provide the information about Cenozoic ice sheet change and consequent landscape change that we are interested in.

Second, this region also displays the greatest topographic relief of candidate regions on the Antarctic shelf. Relief between the central plateau of the Peninsula, and mountain summits on islands, near 2000 m above sea level, and fjord bottoms near 1000 m below sea level, is well suited to the properties of the (U-Th)/He system. Generation of relief on this scale implies a significant thermal response that is predicted to be clearly detectable with the methods we propose to use. In addition, in contrast to other regions of Antarctica, there exists previously collected (U-Th)/He data from coastal outcrops in our proposed field area (Guenthner et al., 2010) that provide important information for study design and site selection.

Third, access is feasible. Because of the highly indented and steep-walled nature of the fjord system, many fjords are extensively deglaciated at present and it is possible to access nearly the entire length of some valley systems, from mid-shelf to within a few kilometers of the summit plateau, and including areas of highest summit-to-trough relief, by ship. The majority of the field area consists of sheltered inshore waters, ice conditions during austral summer are manageable, ship operations in this area are frequent and routine, and there is an extensive record of ship-based marine-geological and -biological research in the area.

Figure 4. Topographic relief near the head of Barlari Bay, a fjord just south of the proposed field area in the western Antarctic Peninsula, taken from RVIB Nathaniel B. Palmer during the LARISSA cruise in January 2010. The summit plateau, visible in the background, lies at an elevation of 1500-2000 m and is covered by 100-400m of cold-based glacier ice. The water depth at this location is near 600 m, for a total valley relief of approximately 2 km.
Figure 5. Top panel, shaded-relief image of multibeam bathymetric coverage (from GMRT synthesis bathymetry via GeoMapApp) of northern Gerlache Strait around proposed sample site “WAP-9,” showing extensive areas of rough seafloor, presumably bedrock, displaying orthogonal jointing as well as evidence of glacial streamlining and plucking. The proposed sample site is what appears likely to be the locally deepest bedrock outcrop (1090 m water depth). Bottom panel, geologic map drawn from coastal outcrops (Fleming and Thomson, 1979). Red shading denotes Mesozoic plutonic rocks that are known to contain abundant apatite and that would be the primary target of this study; blue and green shadings denote extrusive volcanics of Jurassic through Tertiary age that are less well studied from this perspective but would likely also be suitable. Note that to improve readability of the map, the shaded areas on the map greatly exceed the true size of ice-free rock outcrops. The center panel is an overlay of the two maps.
Fourth, the seafloor in our proposed field area has been extensively mapped by multibeam sonar (Figures 3, 5). These multibeam data reveal relatively small sedimentary basins surrounded by large areas of rough seafloor displaying high acoustic reflectivity (i.e., acoustic basement indistinguishable from the seafloor), and streamlined forms and orthogonal jointing characteristic of bedrock outcrops in glaciated regions. These features have been uniformly interpreted to indicate that the seafloor in these areas exposes crystalline bedrock, presumably metasedimentary and plutonic rocks visible in adjacent coastal outcrops, either directly or with minimal (that is, order 1 meter or less) cover by glacial drift (e.g., Domack et al., 2005). In addition, geologic mapping of coastal outcrops (Figure 5) indicates that suitable lithologies (preferably granitic plutonic rocks) most likely predominate on the seafloor in this area. Thus, available evidence indicates a high likelihood of suitable bedrock exposure on the seafloor within the two valley systems we have targeted. A potential caveat is the apparent lack of seafloor photos providing positive evidence of bedrock exposure; although extensive seafloor photography has been conducted in this region in support of benthic ecology research, this research is focused on sedimentary basins where soft-sediment seabed conditions support richer benthic faunal communities. Our (relatively limited so far but ongoing) search has not yet located data from any photographic campaigns focused on hard-bottom areas.

Based on these observations, our site selection criteria are as follows. Previous studies of glacial landscapes (e.g., Shuster et al., 2011) indicate that the optimal sample distribution consists of a series of samples collected along the centerline of major glacial troughs, if possible supplemented by elevation transects orthogonal to and extending away from the valley centerline. This criterion sets the overall geographic pattern of proposed sample sites (Figure 3). Within this framework, we propose sites where multibeam data indicate seafloor exposure of bedrock: the deepest portions of fjords and valleys contain accumulations of ponded glaciomarine sediment, so bedrock coring sites would be located on the margins of these basins and on sills that separate the basins (Figures 3, 5). Finally, proposed sample sites are further selected based on proximity to suitable lithologies mapped on land. Overall, we propose two sampling transects along major valley systems from fjord heads to mid-shelf, for a total of approximately 10 sample sites, at some of which we would expect to acquire multiple rock cores within a ca. 1-km radius.

5. List of proponents:

**Greg Balco** Berkeley Geochronology Center, Berkeley CA USA (lead proponent). Glacial geology and geochronology; surface process geochemistry; Antarctic geomorphology and glacial history.

**David Barbeau** University of South Carolina, Columbia SC USA. Tectonics; basin analysis; structure and tectonics of the Antarctic Peninsula and Drake Passage region.

**Matthew Fox** University of California, Berkeley CA USA. Quantitative geomorphology; thermochronometry; numerical modeling of crustal thermal structure applied to interpretation of thermochronometric data.

**Joanne Johnson** British Geological Survey, Cambridge UK. Glacial geology and geochronology; Antarctic glacial history; Antarctic Peninsula bedrock and surficial geology.

**David Shuster** University of California, Berkeley CA USA. Thermochronometry and noble gas geochemistry applied to quantitative geomorphology and surface process studies.

**Pierre Valla** Université de Lausanne, Lausanne, Switzerland. Thermochronometry, geochronology, and numerical modeling applied to quantitative geomorphology and climate-tectonic interactions.
References cited:


