COLLABORATIVE RESEARCH: LAST GLACIAL MAXIMUM AND DEGLACIATION CHRONOLOGY FOR THE FOUNDATION ICE STREAM AND SOUTHEAST WEDDELL SEA EMBAYMENT

I. INTRODUCTION: IMPORTANCE OF THE WEDDELL SEA SECTOR OF ANTARCTICA TO UNDERSTANDING GLOBAL SEA-LEVEL CHANGE

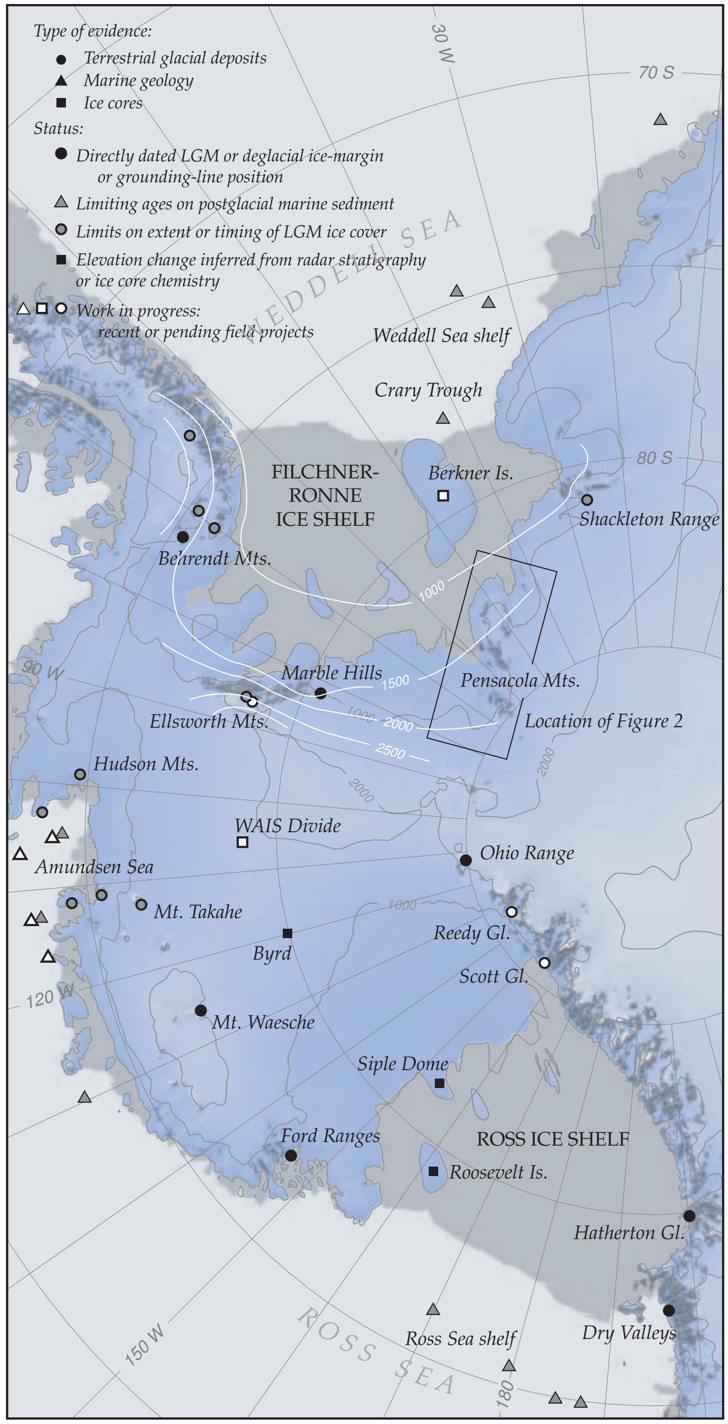
Changes in the size of the Antarctic and Greenland ice sheets have been the primary factor affecting global sea level for the past several thousand years. These ice sheets contain the majority of water on Earth that is not already in the oceans, so they will also be the primary factor driving future sea level change. Research into the late Holocene and future effect of ice sheet changes on sea level has proceeded along two tracks. First, geophysical studies have combined geologic evidence of sea level change with models of Earth deformation to infer the size of past transfers of water between ice sheets and oceans (e.g., Nakada and Lambeck, 1988; Tushingham and Peltier, 1991; Peltier, 2004); second, glaciologists have constructed ice sheet models that, given climate data, can reproduce past changes and predict future changes in ice sheet size and thence in the amount of water in the oceans (e.g., Huybrechts, 2002). In both of these cases, direct geologic evidence of past ice sheet size is critically important. First, past ice sheet configurations inferred from sea level changes alone are generally not unique, and independent evidence is needed to constrain them; Second, ice sheets have a long response time and are not expected to be in equilibrium with the modern climate, so ice sheet models that seek to predict future changes must incorporate an accurate reconstruction of past changes (e.g., Ackert, 2003). This proposal seeks to address a significant weakness in the geologic record of past ice sheet change in Antarctica by locating and dating evidence of past ice-marginal positions in the Pensacola Mountains, at the head of the Weddell Sea embayment, where no such geological evidence now exists.

The most important regions of Antarctica from the perspective of last-glacial-maximum (LGM) to present sea level change are the two marine embayments that separate East and West Antarctica, the Ross (now occupied by the Ross Ice Shelf) and Weddell (occupied by the Filchner-Ronne ice shelf) embayments (Figure 1). Most ice is lost from the Antarctic ice sheets by iceberg calving into the oceans, and calving rates are strongly controlled by water depth, so the main factor responsible for increased Antarctic LGM ice extent was lower sea level. At the LGM, grounded ice extended nearly to the edge of the continental shelf throughout the continent, and the bulk of the change in total ice volume since that time was caused by grounding line retreat from the shelf edge to present grounding-line positions. The largest grounding-line retreats occurred in the Ross and Weddell embayments, so the largest changes in ice volume occurred in these areas.

To date most research efforts have been focused on the Ross Sea region. Marine-geological studies showed that Ross Sea ice was grounded nearly to the continental shelf at the LGM (summarized in Anderson et al., 2002). Subsequent ice sheet reconstructions (e.g., CLIMAP, 1981; Nakada and Lambeck, 1988; Tushingham and Peltier 1991; James and Ivins 1998) inferred, mostly from modeled ice surface profiles terminating at the shelf edge, that ice in the central Ross Sea was approximately 1000 m thicker at the LGM; these reconstructions implied an excess ice volume at the LGM relative to present of at least 25 m sea-level equivalent (SLE) for Antarctica. In addition, many of these reconstructions assumed that Antarctic deglaciation was completed by the early Holocene. Research in the past ten years has significantly changed these ideas in two ways: one, by finding that Ross Sea ice at the LGM was much thinner than originally thought, apparently due to the importance of ice streams in maintaining a low ice surface slope (Conway et al. 1999; Parizek and Alley, 2004; Waddington et al. 2005; Price et al., 2007); two, by finding that deglaciation was still under way well into the Holocene (Conway et al., 1999; Stone et al., 2003).

The realization that LGM Ross Sea ice was not as thick as originally supposed has significantly reduced the possible contribution that Antarctica could have made to post-LGM sea level change. Recent ice sheet reconstructions that take the new results into account infer as little as 10 m SLE of excess LGM ice volume (Ivins and James, 2005). This, in turn, means that the size of other ice sheets must be adjusted upward to accommodate observed sea-level changes. Likewise, the discovery that Ross Sea deglaciation continued

Figure 1. Geological evidence for LGM and Holocene ice extent and elevation changes in the Ross, Weddell, and Amundsen Sea embayments.



The majority of past work has been focused on the margins of the Ross Sea; this is summarized in Conway et al. (1999). Recent work in the Ross embayment has been centered on the southern Transantarctic Mountains (Todd et al., 2005a; Stone et al., 2005; Todd et al., 2006; Ackert et al., 2007). Recent field campaigns have also sought to improve the marine-geological (Larter et al., 2007a,b) and terrestrial (Johnson et al., 2008) record in the Amundsen Sea embayment.

For the Weddell embayment, Bentley and Anderson (1998) and Bentley (1999) summarize the majority of marine and terrestrial evidence for LGM ice extent. The light contours show the suggested LGM ice surface of Bentley and Anderson (1998) and Bentley (1999). Bentley et al. (2006a), Fogwill et al. (2004), and Todd et al (2005b) have reported new glacial-geological observations and exposure-dating results from the southern Antarctic Peninsula, the Shackleton Range, and the Marble Hills, respectively. Current research in this area is focused on the Ellsworth Mountains (Bentley et al., 2006b, 2007) and a recently drilled ice core at Berkner Island (Mulvaney et al., 2008 in press).

The LGM ice extent on the west side of the Antarctic Peninsula is known from a large body of marine-geological research; we have not included it here.

well into the Holocene has forced a re-examination of how much meltwater has been added to the oceans in the Holocene.

There exists much less information about LGM ice extent or the timing of deglaciation in the Weddell embayment. As in the Ross Sea, marine-geological studies of the continental shelf in the outer Weddell Sea show that grounded ice extended nearly to the shelf edge at the LGM (Elverhoi, 1981; Bentley and Anderson, 1998; Anderson et al., 2002). Radiocarbon age control on marine sediments in this region is weak, consisting of radiocarbon dates on the uppermost glaciomarine unit that scatter between 13,000 - 40,000 ^{14}C yr B.P. and often are not in stratigraphic order (Anderson et al., 2002). Until very recently, the only terrestrial glacial-geologic observations relevant to LGM ice sheet thickness were i) a trimline in the Ellsworth Mountains that is in places more than 1000 m above the present ice sheet elevation (Denton et al., 1992); ii) evidence that ice overrode all currently exposed summits in southern Palmer Land (summarized in Bentley and Anderson, 1998); and iii) glacial-geologic observations in the Shackleton Range that appear to limit LGM ice thickening to less than 350 m (Hofle and Buggisch 1993). These observations suggested to Bentley and Anderson (1998) as well as Bentley (1999) that ice in the interior Weddell Embayment was more than 1000 m thicker than present at the LGM (although they noted correctly that there was little age control on the terrestrial deposits, so they could record an ice advance that predated the LGM). This view has largely been adopted in Antarctic ice sheet reconstructions used in global sea-level modeling (CLIMAP, 1981; Denton and Hughes, 2002; Ivins and James, 2005). In recent LGM ice volume reconstructions that include thinner Ross Sea ice (Ivins and James, 2005), this implies that the Weddell Sea sector contained more than 25% of excess Antarctic LGM ice volume.

In another parallel to the development of research in the Ross embayment, however, recent research in the Weddell embayment suggests that existing reconstructions may have seriously overestimated LGM ice thickness. Exposure ages from the Shackleton Range, that provide no evidence of LGM ice cover of the higher summits, confirm earlier glacial-geologic inference of limited thickening (Fogwill et al., 2004). Exposure ages from the Marble Hills (Todd et al., 2005b), at the eastern end of the Ellsworth Mountains, show that the LGM ice surface was well below the high trimline mapped by Denton and others in the Ellsworth Mountains; this trimline appears to record an older glaciation. Recent observations by Bentley and others (2006b, 2007) from elsewhere in the Ellsworth Mountains agree. The question of whether or not deglaciation in the Weddell Sea continued into the Holocene is still unresolved. New exposure ages from the west side of the Antarctic Peninsula indicate that deglaciation of southern Palmer Land was complete by 10,000 yr BP (Bentley et al., 2006a), but the exposure ages from the Marble Hills (Todd et al., 2005b) and the Ellsworth Mountains (Bentley et al., 2007) record Holocene ice surface lowering.

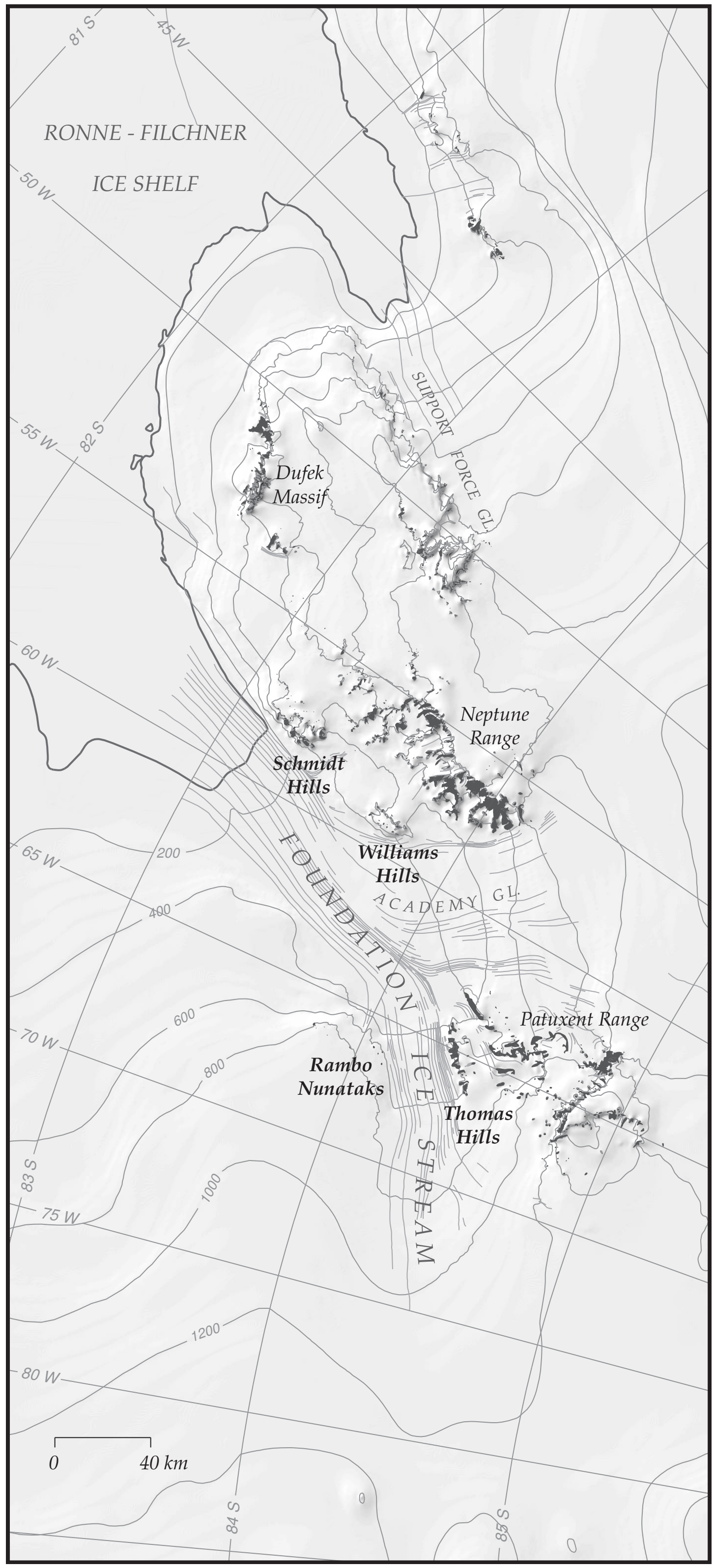
To summarize, new glacial-geologic mapping and age determinations from the fringes of the Weddell Embayment challenge existing LGM ice surface reconstructions. In existing 'thick ice' reconstructions, the Weddell Sea sector accounts for more than 25% of the Antarctic ice volume change between the LGM and the present. A discovery that the ice must have been thinner than supposed would – as recent research in the Ross Sea has done – force a reevaluation of Antarctica's contribution to past sea level changes. Furthermore, the rate and timing of post-LGM ice volume change in the majority of the Weddell embayment east of the Marble Hills is essentially unknown at present. Overall, the uncertainty in ice volume history in this region is the single largest uncertainty in understanding LGM-to-present ice volume change in Antarctica.

II. PROPOSED RESEARCH PROGRAM IN THE PENSACOLA MOUNTAINS

II.A. Proposed field areas. The major challenge in reconstructing Antarctic ice sheet history is that there are few ice-free surfaces that could preserve geologic evidence of ice elevation changes. The significant ice-free areas in the Weddell embayment are the Ellsworth and Shackleton Ranges, at the western and eastern fringes of the embayment, respectively, and the Pensacola Mountains, centered at the head of the embayment (Figure 1). In this project, we propose to reconstruct ice surface elevation changes in the Pensacola Mountains, specifically at a series of nunataks adjacent to the Foundation Ice Stream (Figures 2,3). The Foundation Ice Stream drains ice from East Antarctica and flows into the Ronne-Filchner Ice Shelf. Like the major East Antarctic outlet glaciers that flow through the Transantarctic Mountains into the Ross Sea,

Figure 2. Proposed field areas in the Pensacola Mountains. We propose to focus on four sites where ice-free areas are located close to the margin of the Foundation Ice Stream: the Schmidt Hills, Williams Hills, Thomas Hills, and the Rambo Nunataks. Figure 3 shows air photos of the first three locations.

This map was generated using digital elevation data from the RAMP DEM and vector data from the Antarctic Digital Database; the grounding line of the Foundation Ice Stream (dark line) is that shown in the ADD. Contour interval is 200 m.



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changes in the surface elevation of the Foundation Ice Stream are most likely to be the result of changes in: i) the extent and thickness of grounded ice in the Weddell Sea, and ii) accumulation rate and ice surface elevation in interior East Antarctica. Thus, just as reconstructed surface elevation changes of Transantarctic Mountains glaciers have been used to understand changes in the thickness of Ross Sea ice (e.g., Bockheim et al., 1989; Conway et al., 1999; Todd et al., 2006, 2007), we will reconstruct changes in the surface elevation of the Foundation Ice Stream as a means of understanding ice thickness changes in the Weddell Sea.

II.B. Glacial geologic mapping and exposure dating. The primary method we will use to reconstruct changes in the surface elevation of the Foundation Ice Stream is exposure-dating of glacial erratics stranded above the present ice surface. This method has been successful in many other studies in Antarctica (e.g., Ackert et al., 1999, 2007; Stone et al., 2003; Bentley et al., 2006a), and it depends on two things: first, there must be ice-free areas near the part of the ice sheet whose history we are interested in, and second, glacially transported erratics must be able to accumulate in these areas during ice retreat. If these conditions are met, the exposure ages of erratics collected from a range of elevations can yield a precise reconstruction of the rate and timing of ice surface lowering. The accumulation of erratics in a particular area is favored by several factors: in our experience, the most important ones are proximity to a glacier large enough to carry a significant amount of subglacial and englacial debris from upstream regions, and rock surfaces that slope gently enough that erratics can accumulate as the ice surface lowers.

Reconnaissance air photo survey of the Pensacola Mountains suggests that three groups of nunataks that border the Foundation Ice Stream meet these requirements: the Schmidt Hills, the Williams Hills, and the Thomas Hills (Figures 2,3). These nunataks are close to the ice stream margin and extend up to several hundred meters above the present ice surface. Summit elevations in all three ranges are near 1100 m, which is slightly less than the proposed LGM ice surface elevation in Bentley (1999); if, in fact, the LGM ice surface was significantly lower than proposed, they may not have been completely ice-covered at the LGM. Although these ranges were visited and their bedrock geology was mapped in the 1960's and 1970's (Schmidt, 1978), there is little documentation of their glacial geology. Air photos reveal mostly bare bedrock and talus, and do not show any prominent moraines. However, Schmidt et al. (1978) reported "scattered erratics...on most rock slopes and peaks" at elevations up to 1000 m above the present ice surface. Thus, we anticipate that the glacial geology of these sites will resemble that in the Ford Ranges (Stone et al., 2003; Sugden et al., 2005) or the lower regions of the Reedy and Scott Glaciers (Todd et al., 2006, 2007) where significant moraines or till accumulations are rare to absent, but surfaces are covered by a scatter of glacially transported erratics. Such conditions are favorable for exposure dating, as a) the lack of significant till accumulation makes it more likely that the exposure age of erratics will reflect deglaciation rather than till erosion or cryoturbation, and b) erratics are commonly found perched on bedrock in stable positions rather than on unconsolidated sediment, which increases confidence that they have not moved since emplacement.

An additional set of rock outcrops, the Rambo Nunataks, are located across the Foundation Ice Stream from the Thomas Hills and appear well positioned to accumulate erratics, but air photos show that ice-free areas here are small and steep. We propose to visit these nunataks as well, but believe they are less likely to yield dateable material than the three primary sites.

Thus, this section of the project will involve: i) using glacial-geologic mapping – including observations of glacial erosional features, glacial sediments, and bedrock and erratic lithologies and weathering characteristics – to determine whether our target areas were or were not covered by ice during the LGM; ii) identifying recessional deposits that can be dated; and iii) determining the rate and timing of ice surface lowering by cosmogenic-nuclide exposure dating of these recessional deposits. For the most part we will rely on measurements of ^{10}Be, the cosmogenic nuclide that can be measured most precisely by accelerator mass spectrometry at present, in quartz. We have also budgeted for i) a smaller number of measurements of ^{26}Al in quartz as a check on the ^{10}Be ages, and ii) a smaller number of measurements of cosmogenic ^{3}He in olivine or pyroxene in the event that mafic lithologies are prevalent at any of our sites.

Reviewers of a previous submission of this proposal requested additional information about our field map-

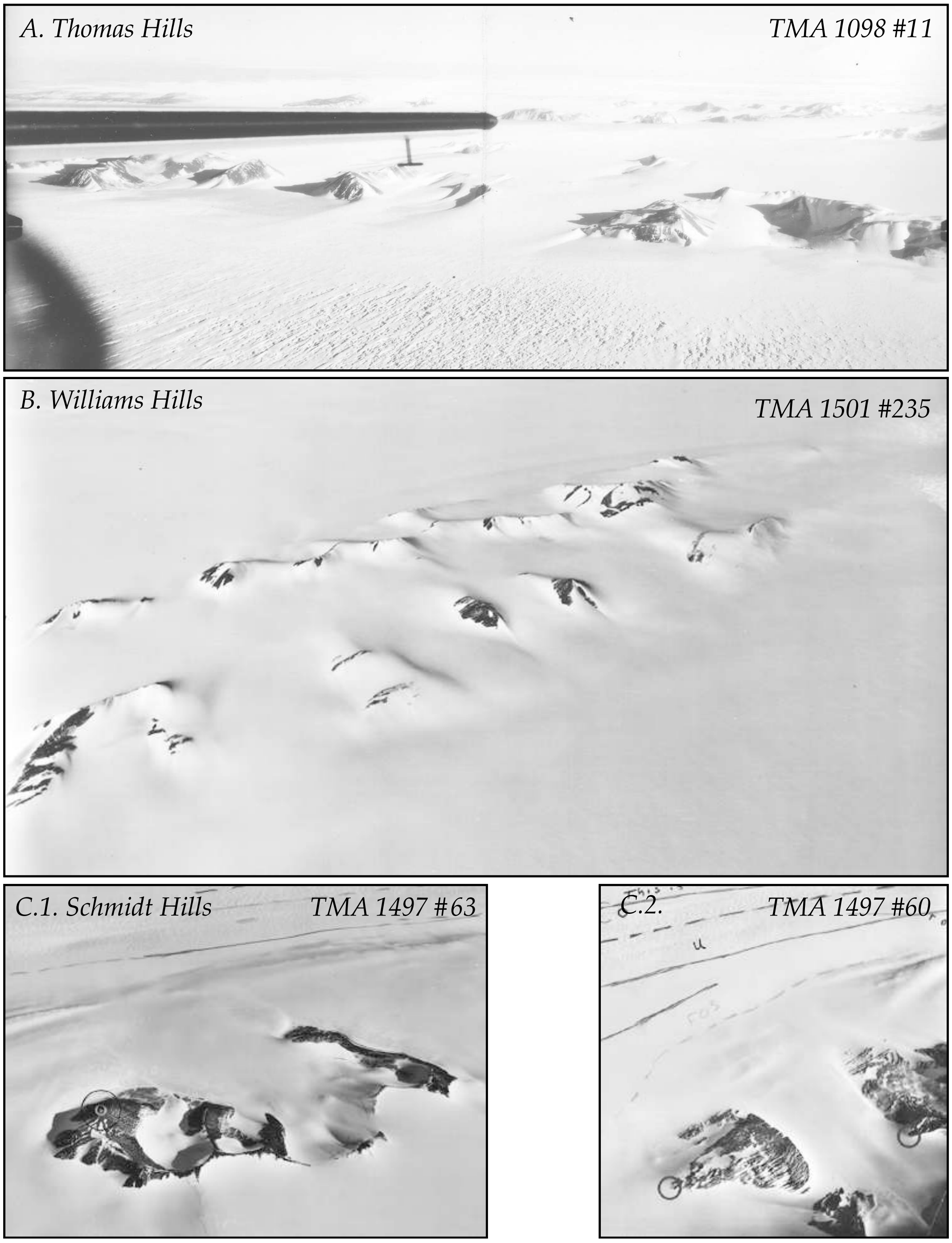

Figure 3. Proposed field areas in the Pensacola Mountains. A., overview of Thomas Hills looking SE from the center of the upper Foundation Ice Stream. B., overview of the Williams Hills looking SE from the lower Foundation Ice Stream. C.1. and C.2., looking NW over nunataks in the Schmidt Hills showing ice-free bedrock surfaces immediately adjacent to the shear margin of the lower Foundation Ice Stream. The penciled marks are from cartographic use of these images: the lines show the ice stream margin, and the circles highlight photogrammetric control points. U.S. Navy images; flight lines and numbers indicated above.

ping and sampling program and whether or not the problem of cosmogenic-nuclide inheritance, common in many Antarctic settings, would affect our results. Here we discuss these two related issues in detail. The key issue here is that rock samples from ice-free areas in Antarctica commonly contain larger cosmogenic-nuclide inventories than can be accounted for by the time since they were most recently exposed by ice retreat (e.g., Sugden et al., 2005). This occurs because much Antarctic ice is frozen to its bed, so subglacial erosion is negligible during periods of ice cover, and the cosmogenic-nuclide inventory of bedrock surfaces can record the integrated effect of many discontinuous periods of exposure. In addition, erratics that are deposited during one ice-free period can remain in place while covered by cold-based ice and re-emerge in subsequent interglaciations; alternatively, they can be re-entrained by overriding ice and subsequently deposited on another nunatak. Our goal in this project is to reconstruct the most recent deglaciation in our field area, so erratics or bedrock surfaces that have a nuclide inventory inherited from previous exposure periods could present a serious complication. However, many previous exposure-dating studies provide clear guidance on how to deal with this potential problem, as follows.

First, previous exposure-dating studies in Antarctica (e.g., Sugden et al., 2005) and elsewhere (e.g., Briner et al. 2003 and references therein) have shown that cosmogenic-nuclide inheritance is common in glaciated bedrock surfaces, and can even occur in situations where bedrock surfaces are located adjacent to major trunk glaciers and show clear evidence of subglacial scouring. We do not propose to sample bedrock surfaces in this project.

Figure 4. Left panel, a high-elevation site in the Ford Ranges showing felsenmeer and weathered bedrock surfaces (Stone et al., 2003; Sugden et al., 2005). 9 out of 10 erratics collected at this site were pre-exposed. Right panel, a nearby low-elevation site showing streamlined forms, grooves, and striations. Out of five erratics collected at this site, none were pre-exposed.

Second, these studies also show that the proportions of "fresh" erratics – whose exposure ages record the most recent deglaciation – and "pre-exposed" ones have a clear relationship to the glacial-geologic context of the site. For example, in the Ford Ranges (Stone et al., 2003; Sugden et al., 2005; Figure 4), erratics collected at low-elevation sites, where bedrock surfaces were striated, polished, and streamlined, were all fresh, showing Holocene ages and a monotonic age-elevation relationship. At higher-elevation sites where bedrock surfaces showed weathered surfaces, felsenmeer, and tafoni, and lacked evidence of subglacial erosion, the majority of erratics (up to 90%) were pre-exposed. In this project, we will take advantage of these observations, and similar observations from other studies, in selecting sample locations. For example, aerial photos of our proposed field site at the Schmidt Hills (Figure 3, C.2) show streamlined bedrock forms at low-elevation sites near the margin of the Foundation Ice Stream; the proportion of pre-exposed erratics at these sites is likely to be small. We expect that at higher-elevation sites, we will observe weathered bedrock surfaces that suggest little subglacial erosion. At these sites, we will sample more erratics in the expectation that a larger proportion of them will be pre-exposed.

Third, the glaciological context of a site also exerts a strong control on the proportion of erratics that show pre-exposure. For example, in the Ford Ranges (Stone et al., 2003), the majority of exposure-dating sites were adjacent to major through-flowing glaciers draining the interior of the ice sheet, and the overall proportion of pre-exposed erratics was relatively low (88% of the erratics analysed in the entire study of Stone et al., 2003 had Holocene exposure ages). In the Marble Hills (Todd et al., 2005b), on the other hand, the exposure-dating site lay well inland, adjacent to relatively locally derived ice draining nearby higher elevations in the Ellsworth Range. At this site, only 38% of erratics analysed had Holocene exposure ages. We attribute this difference to the fact that flowlines terminating at the Marble Hills during the LGM and Holocene probably originated near sometimes-ice-free areas where erratics with prior surface exposure could have been entrained. We conclude from this and similar comparisons that fresh erratics are prevalent, and pre-exposed erratics are rare, at sites located near major trunk glaciers, where flowlines that terminated at the site during past periods of greater ice extent would have originated well upstream in the interior of the ice sheet where ice-free areas are absent. We have selected our proposed field sites in part for this reason, choosing sites as close as possible to the modern Foundation Ice Stream rather in the interior of the Neptune and Patuxent ranges.

Fourth, the results of previous exposure-dating studies that analysed a large number of erratics arranged in elevation transects from single nunataks typically show an array of Holocene exposure ages that define a monotonic age-elevation relationship, and a scatter of older ages that show no such relationship (Figure 5). This is expected if the fresh erratics that record the most recent deglaciation are linked by a common deglaciation history, but pre-exposed erratics may have survived varying durations of ice cover, or been initially exposed at other sites before they were transported to their present location. The fact that these studies analysed a large number of samples in elevation transects from single nunataks or groups of nunataks builds confidence in this interpretation. We will follow this strategy in the present study, with the goal of collecting enough data that we can clearly identify an array of samples that define the most recent deglaciation. Previous work suggests that this requires at least $\sim$10-15 exposure ages in each elevation transect from a particular nunatak or group of nunataks.

Finally, Ackert et al. (2007) used an analytical strategy to screen out pre-exposed erratics. They collected samples from a high elevation, inland site near an ice divide, where bedrock surfaces were deeply weathered and showed little evidence of subglacial erosion. By inference from the observations outlined above, they anticipated that most erratics would be pre-exposed. They used a two-tiered analytical strategy in which they began with relatively rapid and inexpensive, but imprecise, ^{3}He measurements to screen out samples with ages significantly older than the LGM. In agreement with expectations from geomorphic observations, they found that 95% of erratics at this site were pre-exposed. They then made more precise, but more time-consuming and expensive, ^{10}Be measurements only on the resulting pre-screened sample set. In this project, we have used similar geomorphic and glaciological arguments to select sites where pre-exposed erratics are unlikely, so we do not anticipate using this type of screening procedure. However, although this was not our primary purpose in budgeting for ^{3}He measurements in this project, we have so budgeted and have the option to use this strategy if we believe that a large number of erratics at a key site may be pre-exposed.

To summarize, previous Antarctic exposure dating studies provide clear guidance for this study in a) using geomorphic and glaciological observations to select sites with a low proportion of pre-exposed erratics, and b) designing a sampling strategy that allows "fresh" and pre-exposed erratics to be distinguished. We will take full advantage of this guidance in the present project. We have already sought to select sites whose glaciological context suggests a low proportion of pre-exposed erratics. In the field work, we will use a strategy of dense sampling along elevation transects, as well as adjusting the sampling density to reflect the glacial-geologic context of the site, to ensure that the pre-exposed erratics that we do discover can be distinguished from the fresh erratics that record the most recent deglaciation.

Reviewers of a previous proposal also sought more information on the likely precision of exposure-dating of glacial erratics. At present, formal measurement uncertainties for ^{10}Be measurements at the ages and elevations we will encounter in this project are between $\sim$4% (10 ka, 1000 m elevation) and $\sim$15% (500 yr,

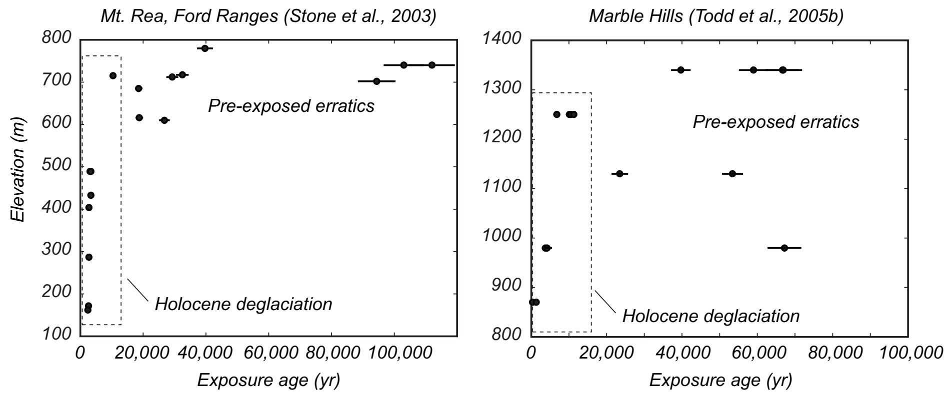

Figure 5. Age-elevation relationships of exposure ages at Mt. Rea, Ford Ranges (Stone et al., 2003) and the Marble Hills (Todd et al., 2005b). In both cases, an array of Holocene ages with a monotonic age-elevation relationship contrasts with a scatter of older ages from pre-exposed erratics.

100 m elevation). Of published Antarctic exposure-dating studies, only Stone et al. (2003) have reported multiple instances of replicate sampling, where adjacent erratics from the same site (within a few meters of each other) were collected and analysed. In five such instances in this study, exposure ages agreed within measurement error, suggesting that geologic uncertainties such as variable surface erosion were less important than measurement errors. We propose to follow a similar strategy in this study to evaluate the relative importance of analytical and geologic uncertainties.

Although the primary dating method we will use is cosmogenic-nuclide exposure dating, it is possible that ice-marginal melt pond deposits may be present at some of our target areas, and these may contain organic material that could provide radiocarbon dates on past ice-marginal positions (e.g., Hall et al. 2005). We have not specifically budgeted for radiocarbon dates; if we find significant radiocarbon-dateable material, we will redirect funds budgeted for exposure dating.

II.C. The last 2000 years of ice retreat: glaciological context of exposure-dating sites. We propose a secondary research focus directed at better understanding the processes that control the location of the ice margin at our field sites, involving targeted exposure dating as well as a small-scale ice-penetrating radar study. Changes in ice-marginal positions – and thus the sequence of exposure ages that we observe – are controlled not only by the regional mass balance of the ice sheet, but also by local changes in the mass balance of snow- and icefields directly adjacent to the exposure-dating sites. In order to accurately reconstruct the regional changes, we need to understand the local effects. Here we describe why this issue may be important, argue that we lack the basic information needed to evaluate how important it is, and propose a strategy to obtain some of this basic information.

First, this issue is critical to understanding latest Holocene to recent ice sheet change. Due to the presence of fringing snowdrifts and icefields fed by local accumulation and wind deposition, the elevation of the ice margin adjacent to nunataks like those that we propose to visit – or that were visited in previous exposure-dating projects – varies locally by tens of meters. The magnitude of ice surface elevation change since the LGM – hundreds of meters of elevation drop over thousands of years – is much greater than this modern local variation in ice-marginal position. In effect, the signal is much larger than the noise. However, when we consider changes in ice sheet elevation at the scale of tens of meters that may have taken place in the past several hundred to ca. 2000 years, the processes controlling the exact location of the present ice margin become critical to interpreting the exposure ages. For example, exposure-dating studies in the Ford Ranges of Marie Byrd Land suggest that Holocene deglaciation may be continuing at present (Stone et al., 2003; Sugden et al., 2005). This is an important claim, because if true it would suggest that modern ice surface lowering and grounding line retreat in West Antarctica might be a continued response to overall Holocene deglaciation (e.g., Conway et al., 1999) rather than a new response to recent climate or

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oceanographic changes (e.g., Rignot and Jacobs, 2002). However, whether Holocene deglaciation is (or is not) ongoing depends very strongly on our understanding of processes controlling the ice-margin position adjacent to exposure-dating sites.

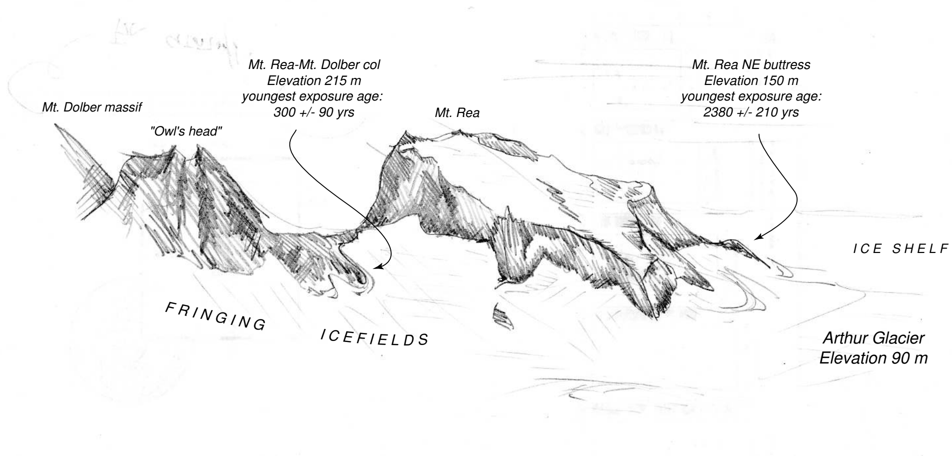

Figure 6. Field sketch looking SW towards the Mt. Rea massif in the Ford Ranges of West Antarctica, showing the relationship of exposure-dating sites, fringing icefields, and the Arthur Glacier.

The results from Mt. Rea (Figure 6) highlight this. Stone et al. (2003) collected samples from the toe of Mt. Rea, where the ice margin is 50 m above the adjacent Arthur Glacier, and from the col between Mt. Rea and Mt. Dolber, where the ice margin is 65 m higher. The lower site is an area of active scouring by wind and is close to the edge of the main glacier; the upper site is at the head of an icefield. The youngest exposure age at the lower-elevation site is 2400 yr; at the higher-elevation site it is 300 yr. Thus, ice surface elevations at these two sites may be decoupled. It is easy to envision a situation where the Arthur Glacier is near equilibrium with present climate and sea level and has changed little in the last 2000 years, but locally fed icefields have thinned in response to a recent climate change. If this were true, the exposure ages of erratics at the head of small icefields would lead us to wrong conclusions about elevation changes at the trunk glacier. The difficulty in understanding whether this scenario is possible at this particular site – or more importantly, at similar sites we propose to visit in this project – is that we have no information about what processes control the elevation of the locally fed icefields. One possibility is that the icefields are composed of glacier ice that was originally part of the nearby through-flowing glacier, but was isolated from the main glacier flow as the surface elevation dropped, and has not yet melted or sublimated. In the Ford Ranges, this appeared to be the case at one site where a snow pit revealed old glacier ice below a thin layer of snow at the margin of a small icefield. In this case, the icefields would be persistent features subject to steady downwasting only. More commonly, local icefields are headed by bergschrunds, implying active ice flow driven by local accumulation. In this case, local icefields might both shrink and grow over time with changes in local accumulation rates or patterns of wind deposition. These two possibilities have significantly different implications for the interpretation of young exposure ages – in the first case, exposure ages close to the present ice margin would reflect overall regional mass balance, albeit with a delay as marginal ice melted; in the second case, they would reflect local climate changes.

Thus, in the present study, we will attempt to collect basic glaciological information about the snow- and icefields adjacent to our exposure dating sites. This will involve digging snow pits and carrying out a high-frequency (50-400 MHz) ice-penetrating radar survey. The radar survey is suggested by the fact that the two possibilities for the origin of fringing icefields predict different internal stratigraphy. Gradually ablating old ice that was once part of an overriding trunk glacier should show internal reflectors that reflect a past flow field. Reflectors may be entirely absent because of large amounts of strain during ice flow, or may be unconformable with the present surface. If the icefields are entirely fed by local accumulation, on the other hand, near-surface reflectors should be conformable and surface-parallel.

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We will also try to address this issue with a targeted exposure-age sampling approach suggested by the example above. We will collect samples from a range of ice-marginal environments – e.g., as close as possible to the ice stream margin vs. separated from the ice stream by snow- and icefields – with the goal of establishing whether there is or is not a systematic difference in their exposure histories that would shed light on the processes controlling the location of the ice margin.

To summarize, in this part of the project we aim to combine our exposure-dating efforts with a study of the glaciological context of our exposure-dating sites. This will shed light on the processes controlling the location of the ice margin, thus potentially improving our reconstruction of late Holocene to present ice sheet changes. We recognize that we have not devoted enough resources – for example, detailed accumulation rate measurements via firn cores – to this part of the project to develop a full characterization of the glaciology and mass balance of all the relevant fringing icefields. In addition, it is possible to think of many other complications, for example the possibility that the location and size of the icefields might have changed with patterns of wind deposition in the past, that would have secondary effects on the internal stratigraphy. However, we view this radar investigation as the most effective way to gather the very basic information, that we now lack, about the glaciological processes controlling the small-scale location of the ice margin.

Finally, reviewers of a previous proposal questioned whether the ambiguities in the interpretation of young exposure ages that we point out here (and perhaps devote an excessive amount of time to in this project description) will affect the overall objectives of this project. We emphasize that our overall objective of reconstructing LGM-through-Holocene ice surface elevation changes is affected very little by this issue. As discussed above, the signal we seek to reconstruct – hundreds of meters of elevation change over thousands of years – is much larger than the noise contributed by small-scale variations in the ice margin elevation. The goal of this secondary focus of the project is to gather information that will improve our ability to address a second issue: the interpretation of very recent exposure ages as a record of much smaller, latest Holocene ice sheet changes. Previous research has already proven the effectiveness of exposure-dating methods for our primary focus on LGM-through-Holocene ice sheet change. Our secondary research focus seeks to gather the basic information needed to expand the usefulness of the method to an additional important question.

II. D. Data synthesis and modeling. Finally, we propose to use an ice-flow model for the Foundation Ice Stream to link together our field observations and exposure-dating results, and use them to evaluate possible LGM and Holocene elevation-change scenarios for the Weddell Sea embayment. We will use a simple, time-dependent flowband model that Claire Todd has already adapted for her current work in relating exposure ages at Reedy Glacier to ice surface elevations in the Ross Sea (Todd et al., 2006, 2007). One challenge in this part of the project is that we lack some of the important input data required for this model. Modern surface elevations are already available from the RAMP DEM (Liu et al., 2001) and the ICESAT missions, and present-day surface velocities have been measured using SAR (Joughin, 2005). On the other hand, the BEDMAP data set contains little information on ice thickness in this region, and heavy crevassing on the ice stream makes ground-based ice thickness measurements unrealistic. Also, we will have to estimate local accumulation rates from continent-wide interpolations. Thus, this part of the project will be directed mainly at establishing in broad terms what LGM and Holocene ice surface elevation scenarios for the Weddell Sea are glaciologically consistent with our exposure age data. This part of the project is particularly important in light of the fact that surface elevation changes at the Foundation Ice Stream may be the result of both downstream changes in the thickness of Weddell Sea ice and upstream changes in ice thickness and accumulation rate in interior East Antarctica. Todd's previous research at the Reedy Glacier, which flows into the Ross Sea embayment in an equivalent position to the Foundation Ice Stream on the opposite side of the continent, has shown that glacier surface elevations there responded to both of these factors in different ways (see the 'Results of Prior Research' section below). We anticipate that this may well be true at the Foundation Ice Stream as well, which makes it important to have available a glaciological model that can be used to explore the expected response to both factors.

III. BROADER IMPACTS: CAREER DEVELOPMENT FOR EARLY-CAREER RESEARCHERS

This part of the project focuses on providing resources and opportunities for Todd and Balco, both early-career scientists, to develop their careers in teaching and research. Todd has recently joined the faculty at Pacific Lutheran University – a small undergraduate-focused college serving primarily students from the Pacific Northwest – where she is developing an undergraduate program in climate change science. This proposal seeks to further her ability to integrate research and teaching, by enabling her to remain involved in global change research at a high level as she develops her teaching expertise. Balco, on the other hand, is a research scientist at a non-profit Earth science research institute. This proposal aims to maintain Balco's involvement with undergraduate and graduate student training and mentoring through collaboration with Todd, Todd's undergraduate students, and Conway's graduate students at the U. of Washington. Through fostering collaboration between scientists focused on both teaching and research, both areas benefit. Successfully bringing the results of global change research into the public arena requires scientists who are both well-trained and deeply involved in research, teaching, and public outreach, and this project aims to help the PI's develop and maintain all of these skills.

We seek to accomplish this as follows. Todd will participate in the fieldwork for this project as well as playing a key role in the data analysis and modeling, and we have also budgeted for her to continue to attend Antarctic research meetings annually; this maintains her involvement in Antarctic research and enhances her ability to incorporate new results into her teaching. We plan that Todd will supervise one or more undergraduates, who will participate in fieldwork and complete individual research projects based on that fieldwork. Balco will assist in the training of both graduate and undergraduate students, both in the field and in laboratory analytical techniques. We have included funds for Balco to travel to the Seattle area, as well as for UW graduate students to travel to BGC, to facilitate this.

IV. RESEARCH PLAN

IV.A. Personnel. The senior personnel of this project are Greg Balco, Claire Todd, and Howard Conway. Greg Balco (Berkeley Geochronology Center) will have primary responsibility for the glacial geology and exposure dating parts of the project. He will i) take the lead in planning the fieldwork, ii) participate in both field seasons, iii) as noted above help to supervise graduate students at the UW who will work on glacial geology, glaciology exposure dating, and ice sheet modeling, and iv) train one or both of these students in cosmogenic-nuclide methods at UW and BGC. Howard Conway (UW) will be responsible for the UW portion of the project. Conway's main responsibilities will be i) to act as a resource for Balco and Todd in planning and carrying out the fieldwork, ii) to participate in the fieldwork as his schedule permits, and iii) to formally supervise the graduate students at UW. Claire Todd (Pacific Lutheran University) will also participate in the glacial geology and exposure dating parts of the project, but does not have full-time access to a cosmogenic-nuclide analysis lab, so will have a secondary role in the analytical work. Her main responsibilities will be i) to participate in the fieldwork, ii) to supervise research by undergraduates, iii) to take the lead in applying the ice-flow model during the data-analysis phase of the project, and iv) to incorporate the project into her teaching and outreach activities.

One graduate student at UW will be involved in all parts of this project. We view the improved integration of exposure-age data with ice-flow modeling as a critical future advance in understanding the LGM-to-present evolution of the Antarctic ice sheet, and we intend that this student's research and training will reflect this combined approach. A second graduate student, whose research involves ice-penetrating radar applications to glaciology, will have primary responsibility for the radar investigation. We have budgeted only partial support for this student and envision that this project will be a secondary part of their overall research.

Undergraduates supervised by Todd will also be involved in this research. They will participate in the fieldwork, and we have requested summer stipends to support undergraduate involvement in analytical work, data analysis, and ice flow modeling.

IV.B. Research timeline.

- *Year 1.* The first project year will involve fieldwork planning and preparation, air photo reconnaissance, and the first field season. The first field season will be focused on the two downstream sites, the Schmidt Hills and the Williams Hills. We have also budgeted some analytical costs for Year 1 to facilitate rapid processing of a few samples as soon as we return from the field; having early results as quickly as possible will help us to plan the second year's fieldwork.
- *Year 2.* The bulk of the analytical costs are budgeted for the second and third project years. The second year will include the second season of fieldwork, analysis of samples collected during the first field season, and initial data analysis and interpretation. The second field season will be focused on the upstream sites at the Thomas Hills and the Rambo Nunataks.
- *Year 3.* The third project year will involve analysis of samples from the second field season, data collation, analysis, and interpretation using the ice-flow model, and presentation of the results.

IV.C. Data availability and archiving. The primary data that result from this project will be a set of exposure ages that constrain ice sheet elevations at past times. This information is important because it serves as target data for ice sheet models that seek to explain past changes, and as initialization data for models that seek to predict future changes. These measurements will be archived and made publicly available at the U. of Washington Cosmogenic Nuclide Lab web site with other similar exposure-age data from past research by UW scientists. Balco has been a leader in standardizing exposure age data reporting and developing software tools to compare exposure-dating studies, and is currently involved in planning a cosmogenic-nuclide database for the EarthChem project; integration of data from this project into larger research questions will benefit from this experience. Finally, once analysis of rock samples is complete, we will seek to archive them at the U.S. Polar Rock Repository.

V. RESULTS FROM PRIOR NSF SUPPORT

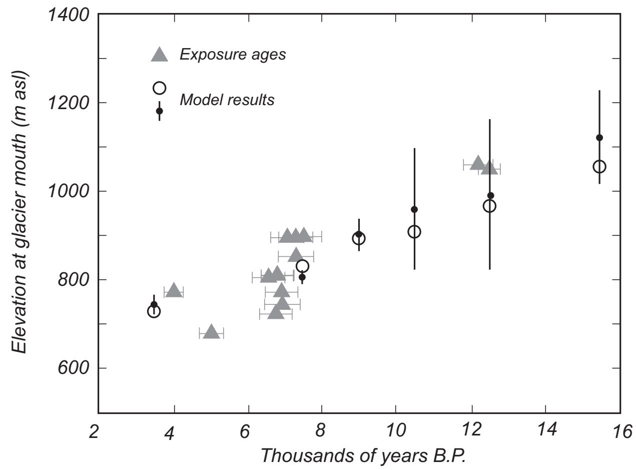
Collaborative Research: History and evolution of the Siple Coast Ice Streams as recorded by former shear margin scars. (Conway, C.F. Raymond, and T.A. Scambos, OPP 9615347; $368,006, 5/00-6/05). We investigated visible scar features in the vicinity of the now stagnant Kamb Ice Stream. Fieldwork included high (100-200 MHz) and low (2-7 MHz) frequency radar profiles, GPS topography and motion measurements, snow pits and 16m cores for estimating the accumulation rate. Results have been presented at meetings and in seven peer-reviewed publications. Highlights include:

- A tributary that used to flow toward Kamb Ice Stream has switched direction and now flows toward Whillans Ice Stream (Conway et al., 2002). Understanding short-term variability of ice stream discharge is needed to evaluate the long-term stability of West Antarctica.
- Radar measurements across four relict ice stream margins show bed reflectivity jumps from low to high values 4-10 kilometers inside the outer most buried crevasses (Catania et al., 2003). This surprising observation is relevant to understanding the controls on ice streams.
- Not all scar features are paleo-ice stream margins. A new type of flat-ice-terrain has been identified (Catania et al., 2005), which opens the possibility that the lower reaches of Kamb Ice Stream were floating in the recent past; the associated scar feature likely represents an old grounding line. Radar and model investigations indicate that the lower reach of the ice stream was floating about 350 years ago; analyses indicate grounding line advance of as much as 100 km just prior to ice-stream stagnation (Catania et al., 2006a, 2006b).
- The spatial pattern of radar-detected internal layers preserved in the now stagnant Kamb Ice Stream were used to show that pre-stagnation velocities in the trunk region exceeded 350 m/yr (Ng and Conway, 2004).

The project supported the PhD thesis research of Ginny Catania; she graduated in November 2005 and now has a research position at the University of Texas. The project also partially supported a research associate (Tony Gades) and an undergraduate student (Hans-Peter Marshall).

Collaborative Research: Late Quaternary History of Reedy Glacier (Although Todd was not the PI of this proposal, it formed the bulk of her Ph.D. dissertation. PI's were Conway, J.O. Stone, and B.L. Hall; OPP-0229314; $370,051, 6/03-6/07). This project focused on cosmogenic ^{10}Be dating of glacial erratics in order to determine the timing of the maximum ice thickness and ice retreat in the southern Transantarctic Mountains. Todd then used these measurements, ice-penetrating radar measurements of ice thickness, and GPS measurements of ice velocity to constrain a numerical glacier flowline model that predicts LGM through Holocene surface profile evolution at Reedy Glacier. Results show a complicated pattern of elevation changes that are related to i) WAIS thinning following grounding line retreat in the Ross Sea, and ii) accumulation rate changes in East Antarctica.

Maximum ice thicknesses at Reedy Glacier occurred at different times and different locations along the glacier. The earliest maximum, ca. 17,500 – 14,000 yr B.P., is recorded by deposits located > 20 - 50 km from the head of the glacier and records increasing thickening downglacier. Exposure ages from nunataks near the mouth of the glacier show that retreat from this maximum was coincident with ice sheet retreat in the western Ross Sea. In contrast, exposure ages from the upper glacier show that maximum ice thickness near the head of the glacier was reached much later, between 9500 and 7500 yr B.P. Results from the flowline model show that these observations are best explained by a reconstruction where: i) the early elevation maximum and retreat therefrom, at mid-glacier and below, is a response to thinning of grounded ice from the WAIS, presumably related to grounding line retreat in the Ross Sea; and ii) the later Holocene maximum at upper glacier sites is a response to increased accumulation rates on the polar plateau consequent on Holocene climate warming.



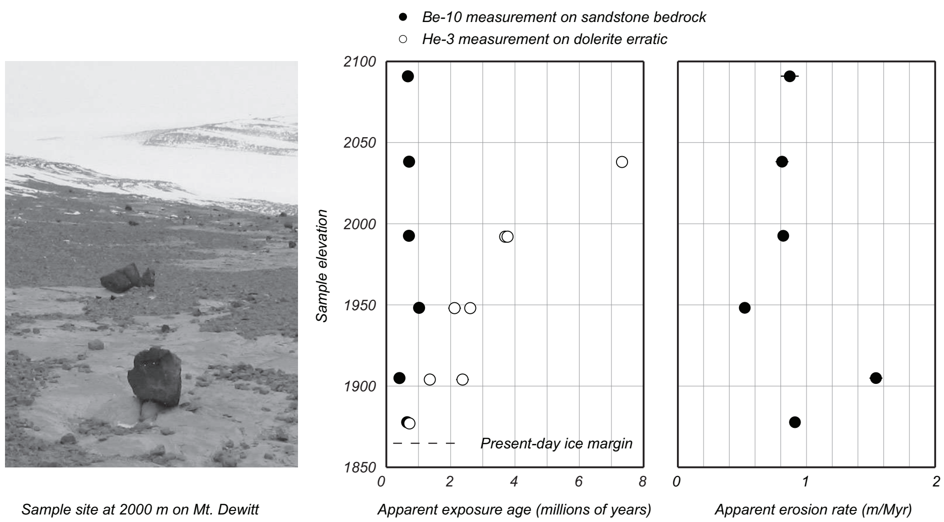
Exposure ages from nunataks at the mouth of Reedy Glacier compared with surface elevations predicted by full flowline model fit to exposure ages from the entire length of the glacier. The exposure-dating samples are from several nunataks within ∼10 km of each other. The two sets of model results were calculated using different model norms and ice surface profile smoothness criteria.

This project formed the bulk of Claire Todd's Ph.D. dissertation and has resulted in a number of conference abstracts (Todd et al., 2005a; Todd et al., 2006; Todd et al., 2007; Stone et al., 2005).

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 a collaboration between Balco and J. Putkonen (UW) directed at applying dating techniques based on multiple cosmogenic nuclides to learn about deposit ages, erosion rates, and landscape evolution in the McMurdo Dry Valleys. Understanding the age of surface deposits in the Dry Valleys is important because these deposits are a potentially rich record of the history of the East Antarctic Ice Sheet; however, applying exposure-dating methods to these deposits is challenging because of the extreme age of some of the deposits, and the fact that even very slow erosion sustained over long periods of time can efface original surfaces. Thus, understanding the age and significance of these deposits is linked to understanding the erosional processes that affect their preservation and modification. We used multiple cosmogenic nuclides with different half-lives, which record events that took place over different spans of time, as well as observations of past and present sediment transport rates, to investigate this. Results include:

- Erosion rates in the Dry Valleys are in fact lower than nearly anywhere else on Earth, but are not zero. Bedrock and regolith surfaces are eroding at 0.25-2.5 m/Myr, which is slow on a global scale, but still sufficient to significantly modify landforms over millions of years. Landscape-forming processes here do not seem to be fundamentally different than elsewhere on Earth, but to occupy one end of a continuum.

- However, erosional processes in the Dry Valleys are unusual compared to similar processes elsewhere. First, extreme differences in resistance to erosion among rock types create similarly large differences in the duration of exposure of closely juxtaposed materials (see figure below) .



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 they lie on have much lower apparent Be-10 exposure ages, that vary little with elevation. This mismatch is best explained by steady bedrock erosion since deposition of the erratics. 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, and suggest that these bedrock surfaces have eroded several meters without fully dislodging the erratics.

- Second, gravity-driven creep is the dominant mode of hillslope sediment transport elsewhere on Earth. In the Dry Valleys, however, surface cosmogenic-nuclide concentrations significantly lower than the geologic age of the sediment show that hillslope surfaces are lowering at 1-2 m/Myr, but cosmogenic-nuclide depth profiles show that penetrative creep is not occurring. Apparently in the absence of water to drive expansion and contraction of soils, hillslope erosion, even on steep slopes, is limited to processes such as granular disintegration and wind that affect only the immediate surface (Putkonen et al., 2008).

- Overall, rates of erosion and surface modification vary greatly on small spatial scales in the Dry Valleys. Surfaces that appear to have remained essentially unmodified for millions of years are adjacent to surfaces that have eroded significantly during that time. This is important in understanding whether the present distribution of surface deposits in the Dry Valleys has depositional significance, or reflects postdepositional erosional processes.

The results of this project are in the process of publication, including to date one peer-reviewed paper (Putkonen et al., 2008) and several meeting abstracts (Balco et al., 2008; Putkonen et al., 2007).

REFERENCES

R.P. Ackert, Jr., 2003. An Ice Sheet Remembers. *Science* 299, p. 57-58.

R. P. Ackert, Jr., D.J. Barclay, H.W. Borns, Jr., P.E. Calkin, M.D. Kurz, J.L. Fastook, E.J. Steig, 1999. Measurements of past ice sheet elevations in interior West Antarctica. *Science* 286, pp. 276-280.

R.P. Ackert, Jr., S. Mukhopadhyay, B. Parizek, H. Borns, 2007. Ice elevation near the West Antarctic Ice Sheet divide during the Last Glaciation. *Geophysical Research Letters* 34, L21506, doi:10.1029/2007GL031412.

J. B. Anderson, S.S. Shipp, A.L. Lowe, J.S. Wellner, A.B. Mosola, 2002. The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review. *Quaternary Science Reviews* 21, pp. 49-70.

Balco G., Putkonen J., Morgan D., Schaefer J., Winckler G., 2008. Bedrock erosion rates in the Antarctic Dry Valleys. Abstracts, 2008 Goldschmidt Conference Abstracts, Vancouver, BC. p. A47.

M.J. Bentley, J.B. Anderson, 1998. Glacial and marine geological evidence for the ice sheet configuration in the Weddell Sea - Antarctic Peninsula region during the Last Glacial Maximum. *Antarctic Science*, v. 10, pp. 309-325.

M.J. Bentley, 1999. Volume of Antarctic ice as the Last Glacial Maximum, and its impact on global sea level change. *Quaternary Science Reviews*, v. 18, pp. 1569-1595.

M.J. Bentley, C.J. Fogwill, P.W. Kubik, D.E. Sugden, 2006a. Geomorphological evidence and cosmogenic $^{10}Be/^{26}Al$ exposure ages for the Last Glacial Maximum and deglaciation of the Antarctic Peninsula Ice Sheet. *Geological Society of America Bulletin*, v. 118, pp. 1149-1159.

M.J. Bentley, C.J. Fogwill, D.E. Sugden, 2006b. Glacial history of the Ellsworth Mountains, Weddell Sea embayment, West Antarctica. Thirteenth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

M.J. Bentley, C.J. Fogwill, A. L. Hubbard, A. Le Brocq, D.E. Sugden, 2007. Glacial history of the Ellsworth Mountains, Weddell Sea embayment, West Antarctica. Fourteenth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

J.G. Bockheim, S.C. Wilson, G.H. Denton, B.G. Anderson, M. Stuiver, 1989. Late Quaternary fluctuations of Hatherton Glacier, Transantarctic Mountains. *Quaternary Research*, v. 31, pp. 229-254.

J.P. Briner, G.H. Miller, P.T. Davis, P.R. Bierman, M. Caffee, 2003. Last Glacial Maximum ice sheet dynamics in Arctic Canada inferred from young erratics perched on ancient tors. *Quaternary Science Reviews* 22, pp. 437-444.

G. Catania, H. Conway, A. Gades, C. Raymond, H. Engelhardt, 2003, Bed reflectivity beneath inactive ice streams in West Antarctica. *Annals of Glaciology* 36, pp. 287-291.

G. Catania, H. Conway, C. Raymond, T. Scambos, 2005. Surface morphology and internal layer stratigraphy in the downstream end of Kamb Ice Stream, West Antarctica. *Journal of Glaciology* 51, pp. 423-431.

G. Catania, T. Scambos, H. Conway, C. Raymond, 2006a. The sequential stagnation of Kamb Ice Stream, West Antarctica. *Geophysical Research Letters* 22, (L14502), doi:10.1029/2006GL026430.

G. Catania, H. Conway, C. Raymond, T. Scambos, 2006b. Evidence for floatation or near-floatation in the mouth of Kamb Ice Stream, West Antarctica prior to stagnation. *Journal of Geophysical Research* 111, F01005, doi:10.1029/2005JF000355.

CLIMAP, 1981. Seasonal reconstruction of the Earth's surface at the last glacial maximum. Geological Society of America, Map and Chart Series C36.

H. Conway, B.L. Hall, G.H. Denton, A.M. Gades, E.D. Waddington, 1999. Past and future grounding line retreat of the West Antarctic Ice Sheet. *Science* 286, pp. 280-283.

H. Conway, G. Catania, C.F. Raymond, A.M.Gades, T.A. Scambos, H. Engelhardt, 2002. Switch of flow direction in an Antarctic ice stream. *Nature* 419, pp. 465-467.

G.H. Denton, J.G. Bockheim, R.H. Rutford, B. Andersen, 1992. Glacial history of the Ellsworth Mountains, West Antarctica. *in* G.F. Webers, C. Craddock, J.F. Splettstoesser, eds., Geology and Paleontology of the Ellsworth Mountains, West Antarctica. Geological Society of America Memoir 170, pp. 403-432.

G. H. Denton, T.J. Hughes, 2002. Reconstructing the Antarctic Ice Sheet at the Last Glacial Maximum. *Quaternary Science Reviews*, v. 21, pp. 193-202.

A. Elverhoi, 1981. Evidence for a late Wisconsinan glaciation of the Weddell Sea. *Nature*, 293, pp. 641-642.

C.J. Fogwill, M.J. Bentley, D.E. Sugden, A.R. Kerr, P.W. Kubik, 2004. Cosmogenic nuclides ^{10}Be and ^{26}Al imply limited Antarctic Ice Sheet thickening and low erosion in the Shackleton Range for >1 m.y. *Geology*, v. 32, pp. 265-268.

B.L. Hall, G.R.M. Bromley, 2005. Relict algal mats at Reedy Glacier: Radiocarbon dating at 86°S. Twelfth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

H.-C. Hofle, W. Buggisch, 1993. Glacial geology and petrography of erratics in the Shackleton Range, Antarctica. *Polarforschung*, v. 63, pp. 183-201.

P. Huybrechts, 2002. Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles. *Quaternary Science Reviews*, v. 21, pp. 203-231.

E.I. Ivins and T.S. James, 2005. Antarctic glacial isostatic adjustment: a new assessment. *Antarctic Science* 17, pp. 541-553.

T.S. James and E.I. Ivins, 1998. Predictions of Antarctic crustal motions driven by present-day ice sheet evolution and by isostatic memory of the Last Glacial Maximum. *Journal of Geophysical Research*, v. 103, pp. 4993-5017.

J.S. Johnson, M.J. Bentley, K. Gohl,2008. First exposure ages from the Amundsen Sea Embayment, West Antarctica: the late Quaternary context for recent thinning of Pine Island, Smith, and Pope Glaciers. *Geology* 36, pp. 223-226.

I. Joughin, J. Bamber, D. MacAyeal, T. Scambos, M. Fahnestock, 2005. Integrating satellite observations with modeling: basal shear stress of the Filchner-Ronne ice streams, Antarctica. Twelfth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

R.D. Larter, K. Gohl, C.-D. Hillenbrand, G. Kuhn, T.J. Deen, R. Dietrich, G. Eagles, J.S. Johnson, R.A. Livermore, F.O. Nitsche, C.J. Pudsey, H.-W. Schenke, J.A. Smith, G. Udintsev, G. Uenzelmann-Neben, 2007a. West Antarctic Ice Sheet change since the last glacial period. *EOS, Transactions, AGU*, v. 88, p. 189.

R.D. Larter, C.-D. Hillenbrand, J.S. Johnson, J.A. Smith, T.J. Deen, A.G.C.Graham, K Gohl, G. Kuhn., 2007b. WAIS wasting in the Amundsen Sea Embayment since the Last Glacial Maximum. Fourteenth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

H. Liu, K. Jezek, B. Li, Z. Zhao, 2001. Radarsat Antarctic Mapping Project digital elevation model version 2. Boulder, CO: National Snow and Ice Data Center. Digital media.

R. Mulvaney, O. Alemany, and P. Possenti, 2008 in press. The Berkner Island Ice Core Drilling Project. *in* F. Wilhelms and J. Fitzpatrick, eds., 6th International Workshop on Ice Drilling Technology. *Annals of Glaciology*, v. 47.

M. Nakada and K. Lambeck, 1988. The melting history of the late Pleistocene Antarctic ice sheet. *Nature*, v. 333, pp. 36-40.

F. Ng, H. Conway, 2004. Fast-flow signature in the stagnated Kamb Ice Stream, West Antarctica. *Geology* 32, pp. 481-484.

B. Parizek, R. Alley, 2004. Ice thickness and isostatic imbalances in the Ross Embayment, West Antarctica: Model results *Global and Planetary Change* 42, pp. 265-278.

W.R. Peltier, 2002. On eustatic sea level history: Last Glacial Maximum to Holocene. *Quaternary Science Reviews*, v. 21, pp. 377-396.

W.R. Peltier, 2004. Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, v. 32, pp. 111-149.

Price S. F., H. Conway, E. D. Waddington (2007), Evidence for late Pleistocene thinning of Siple Dome, West Antarctica. *Journal of Geophysical Research* 112, F03021, doi:10.1029/2006JF000725.

Putkonen J., Rosales M., Turpen N., Morgan D., Balco G., and Donaldson M., 2007. Regolith transport in the Dry Valleys of Antarctica. in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A. K. Cooper and C. R. Raymond et al. USGS Open-File Report 2007-1047, Short Research Paper 103.

Putkonen J., Balco G., Morgan D., 2008. Slow regolith degradation without creep determined by cosmogenic nuclide measurements in Arena Valley, Antarctica. *Quaternary Research* 69, pp. 242-249.

E.J. Rignot and S.S. Jacobs, 2002. Rapid bottom melting widespread near Antarctic Ice Sheet grounding lines. *Science* 296, pp. 2020-2023.

D.L. Schmidt, P.L. Williams, W.H. Nelson, 1978. Geologic map of the Schmidt Hills quadrangle and part of the Gambacorta Peak quadrangle, Pensacola Mountains, Antarctica. U.S. Geological Survey, U.S. Antarctic Research Program Map A-8.

J.O. Stone, G. Balco, D.E. Sugden, M.W. Caffee, L.C. Sass, S.G. Cowdery, C. Siddoway, 2003. Holocene deglaciation of Marie Byrd Land, West Antarctica. *Science* 299, pp. 99-102.

J.O. Stone, C. Todd, H. Conway, B. Hall, G. Bromley, 2005. Grounding-line incursion into the southernmost Ross Sea – a comparison of lower Scott and Reedy Glaciers. Twelfth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

D.E. Sugden, G. Balco, S.G. Cowdery, J.O. Stone, L.C. Sass III, 2005. Selective glacial erosion in the Sarnoff and Allegheny Mountains, Marie Byrd Land, Antarctica. *Geomorphology*, v. 67, pp. 313-334.

C. Todd, J. Stone, H. Conway, G. Bromley, B. Hall, 2005a. Evolution of Reedy Glacier from the last glacial maximum to present. Twelfth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

C. Todd, J. Stone. D. Mann, 2005b. Deglaciation of the southern Ellsworth Mountains, Weddell Sea sector of the West Antarctic Ice Sheet. Twelfth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

C. Todd, E.D. Waddington, M. Koutnik, H. Conway, J.O. Stone, 2006. Rebuilding glacial retreat histories using inverse methods and surface exposure age data. Thirteenth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

C. Todd, E.D. Waddington, M. Koutnik, H. Conway, J.O. Stone, 2007a. Solving for a history of ice thickness in the southern Ross Sea Embayment using inverse methods and surface exposure ages. Fourteenth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

C. Todd, J.O. Stone, G. Bromley, B. Hall, H. Conway, 2007b. Surface-exposure ages from Reedy Glacier, Antarctica. Fourteenth Annual West Antarctic Ice Sheet Workshop: *neptune.gsfc.nasa.gov/wais*

A.M. Tushingham, W.R. Peltier, 1991. ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of postglacial relative sea level change. *Journal of Geophysical Research*, v. 96, pp. 4497-4523.

E.D. Waddington, H. Conway, E.J. Steig, R.B. Alley, E.J. Brook, K.C. Taylor, J.W.C. White, 2005. Decoding the dipstick: Thickness of Siple Dome, West Antarctica, at the Last Glacial Maximum. *Geology*, v. 33, pp. 281-284. (2005)