RESULTS OF PRIOR NSF SUPPORT

Anandakrishnan NSF-OPP-0229659 – Tidal Modulation of Ice Stream Motion, $363,834 (May 2003-April 2006): GPS and seismic monitoring: This work focused on observations to better characterize the surprising discovery of tidal modulation of ice-stream flow. In collaboration with NASA, Penn State University participated in collecting and analyzing velocity and tidal data collected on the Siple Coast ice streams. We have established that Whillans Ice Stream alone exhibits stick-slip motion and that on all of the ice streams tidal modulation of velocity decays upstream. The seismicity of the ice streams is strongly modulated by the tidal cycle (both diurnal and surprisingly, the spring-neap cycle as well). Discoveries include the sediment wedge at the grounding zone. Publications resulting from this award: Joughin et al. (2005), Horgan and Anandakrishnan (2006), Alley et al. (2007), Anandakrishnan et al. (2007).

Fricker NSF-OPP-0337838: Monitoring an Active Rift System at the front of Amery Ice Shelf (AIS) $465,834 (May 2004-April 2008). A collaborative project between SIO and the Australian Antarctic Division, the study focused on deploying a combination of short-period seismometers and GPS receivers around the tip of a rift on the AIS where an iceberg calving event is imminent, combined with analysis of satellite imagery. The Award provided support for one GSR (Jeremy Bassis) for three years, one technician to participate in the 2004-05 and 2006-07 seasons, one new postdoc (James Behrens, 2005-06; 2006-07), one MS Student (Marianne Okal, 2005-06), three undergraduate students and one high school student. We also initiated a successful Schools outreach program called "Breaking the Ice" in collaboration with Jeff Severinghaus and the SDCOE, which offered a site visit to SIO to learn about different aspects of Antarctic research. Key developments and findings: (1) rift propagation is episodic and not triggered by winds or tides (Bassis et al., 2005); (2) rift propagation is seasonal (Fricker et al., 2005a); (3) icequake event locations form a cluster along the rift axis; (3) size-frequency distribution of icequakes follows a power law; (4) measurement of mélange thickness inside rifts showed that it accounted for ~30% of the total ice shelf thickness (Fricker et al., 2005b).

Jacobel NSF-OPP-9814574 Radar Studies of Internal Stratigraphy and Bedrock Topography along the US-ITASE Traverse, $392,373 (April 1, 1999 – May 31, 2005). St. Olaf College was responsible for the deep radar sounding along the US-ITASE traverse route and near the ice core drilling sites with the objective of characterizing the bed topography and ice internal stratigraphy. Eight undergraduate students were involved in the project and presented work at research symposia. Postdoc Brian Welch was supported in part by the project and part with teaching responsibilities at St. Olaf College. Both investigators have contributed to outreach at local and national levels. Key results: (1) A new deep radar sounder was developed to produce maps of bed topography and internal stratigraphy with unprecedented detail (Welch and Jacobel, 2003); (2) discovery of a unique internal layer seen throughout WAIS at ~17.5 ky (Jacobel and Welch, 2005); (3) characterized a potential deep ice core drilling site at Hercules Dome (Jacobel et al., 2005); (4) discovered a region of wind scour over steep basal topography (Welch and Jacobel, 2006); discovered distorted englacial stratigraphy related to flow anomalies in the region of Byrd Station, probably indicative of changes in the flow of the WAIS at the end of the LGM (Siegert et al., 2005).

Lanoil NSF-OPP-0314293: SGER: Microorganisms in sub-ice sediments from the Western Antarctic Ice Sheet, Ice Stream C, $75,000 (2/15/03-2/25/04) This project focused on characterization of geochemistry and geomicrobiology of sediment samples from beneath the Kamb Ice Stream. Primary findings from this study include: the presence of an abundant microbial community closely related to those found in other subglacial systems, with indications of chemolithoautotrophic sulfide and/or iron oxidation as the primary carbon and energy source. (Lanoil et al., submitted); geochemical indications that weathering in this environment is at least partially biotic (Lanoil et al., submitted); the wet sediments beneath the Antarctic ice sheets host a microbial community that rivals surface soils in cell abundance (Priscu et al., in press). This work supported a postdoctoral scholar (M. Skidmore), a technician (W. Foo, now a graduate student in the Lanoil laboratory), and two female undergraduate researchers. Data from this project has been presented in four oral and poster presentations at national or international meetings and 6 departmental seminars.

Mikucki NSF-OPP0631494: Collaborative Research: IPY- Plankton Dynamics in the McMurdo Dry Valley Lakes During the Transition to Polar Night (Priscu is lead PI). $231,607 (2007-2009). The project will study lakes within the Taylor Valley during the transition from 24h sunlight to polar night to test the overarching hypothesis that the onset of darkness induces a cascade of physiological changes that alters the functional roles of autotrophic and heterotrophic microplankton within the lakes. This IPY award has been funded and data collection will begin during the 07-08 Antarctic field season.

Mitchell has never been a PI or co-PI on an NSF grant.

Powell NSF-OPP-0342484: (NIU budget is a UNL Subaward 25-0550-0001-005) Collaborative Research: ANDRILL – Investigating Antarctica's role in Cenozoic global environmental change. The ANDRILL Program successfully recovered a 1285m-long succession of cyclic glacimarine sediment with interbedded volcanic deposits, in its first season of drilling from the McMurdo Ice Shelf (MIS). The MIS drillcore represents the longest and most complete (98% recovery) geological record from the Antarctic continental margin to date, and will provide a key reference record of climate and ice sheet variability through the Late Neogene. Repetitive vertical successions of facies imply at least 60 fluctuations, of probable Milankovitch-duration, between subglacial, ice proximal and ice distal open marine environments. These have been grouped into 3 types of facies cycles that correspond to glacial-interglacial variability during climatically distinct periods of the Late Neogene: (1) Cold polar climate and ice (Late Miocene, ~13-10Ma & Pleistocene, ~1-0Ma). (2) Relatively warmer climate, polythermal ice and interglacials dominated by pelagic diatomites (Pliocene, ~5-2Ma). (3) Warmer climate, polythermal ice with interglacials dominated by hemipelagites (early-Late Miocene, ~9-6Ma). A ~90m-thick Early Pliocene interval of diatomite shows no apparent glacial cyclicity and represents an extended period of ice-free conditions indicative of a reduced West Antarctic Ice Sheet (WAIS). Spectacular Late Pliocene (~2.6-2.2 Ma) glacial-interglacial cycles characterized by abrupt alternations between subglacial/ice-proximal facies and open marine diatomites imply significant WAIS dynamism, and contribution to global ice volume changes coeval with the initiation of Northern Hemisphere glaciations. A ~4m-thick interval of diatomaceous mudstone in the Middle Pleistocene also represents warm-interglacial ice-free conditions. Intriguingly, the last 1Ma is dominated by glacial deposits interrupted by periodic, small-scale retreats of the grounding line. At this time 2 abstracts were presented at EGU, 2 will be presented at INQUA, 13 abstracts have been submitted to ISAES, an Eos article is in preparation as are others for Nature/ Science, Geology, GRL, etc.

Priscu-NSF-MCB/OPP 0237335 Microbial Diversity and Function in the Permanently Ice-Covered Lakes of the McMurdo Dry Valleys, Antarctica, $344,085 (2003-2008). Please refer to the following websites (http://www.homepage.montana.edu/~lkbonney/; http://www.mcmlter.org/; http://mcm-dvlakesmo.montana.edu/) for progress and outreach. Results from this project have shown that: (1) Contemporary metabolic activity and biodiversity fueled by ancient nutrient pools associated with the past climate regime in the McMurdo Dry Valleys (MCM); (2) the MCM are in a decadal cooling trend that has dramatically influenced all ecosystem processes; (3) subglacial Lake Vostok harbors a unique microbial assemblage consisting of chemolithoautotrophs feeding on iron and sulfur minerals, and heterotrophs living off of the new carbon produced by the chemolithotautorophs; (4) the limits of life in highly saline habitats within the MCM is limited by free water (most of the water is bound as mineral hydrate); (5) the permanent lake ice on the MCM lakes harbors is an oasis for life in what would otherwise appear to be an uninhabitable environment; (6) the subglacial environment beneath the Taylor Glacier is anoxic and saline, and contains microorganisms capable of living on iron and sulfur compounds under these conditions; (7) subglacial environments within the MCM have a significant geochemical and biological influence on downsteam hydraulic environments; (8) subglacial environments beneath the Antarctic ice sheet possesses a large pool of previously unrecognized bacterial carbon that rivals those of surface environments on Earth.

Tulaczyk NSF-OPP-0338295 Collaborative Research – Is Kamb Ice Stream Restarting? Glaciological Investigations of the Bulge-Trunk Transition on Kamb Ice Stream, West Antarctica $240,375 (May 1 2004-April 30 2008). UCSC was the lead institution on this collaborative grant. Field activities included deployment of five continuously recording GPS receivers on a suspected subglacial lake (Gray et al., 2005) and campaign-style GPS measurements of ice velocity changes in ~300 locations on Kamb Ice Stream in combination with deep radar surveys by St. Olaf College team. The award provided partial support for one postdoc (Dr. Ginny Catania, now Research Associate at the University of Texas), one doctoral student (Dr. Ian Howat, now Assistant Professor at the Ohio State University), one M.Sc. student (Camas Tung, anticipated graduation Fall 2007) and two REU students (Jeanette Ninyo and Zachary Osafo-Mensah). As part of media outreach the UCSC PI was interviewed by Gabriella Walker about subglacial dynamics of Antarctica and cited by her in two articles published for the 2580 issue of the New Scientist (11/29/2006.) Preliminary findings from this project are: (1) the 'ice bulge' on Kamb Ice Stream is experiencing spatially variable velocity changes, ranging from continuing slow down to local acceleration; (2) force budget calculations indicate that there is significant transfer of stress to the bed at the leading edge of the ice bulge, which may promote basal melting and bed re-lubrication (e.g. Vogel et al., 2005); (3) the suspected subglacial lake discovered beneath Kamb Ice Stream by Gray et al. (2005) has been gaining water during the GPS observation period (12/2004 to 12/2005); (4) internal ice folds in ice streams and mega-scale glacial lineations share the same range of elongation ratios and we hypothesize that these features have linked origin (Tulaczyk et al., in review).

Vogel: Deciphering climatic changes and ice sheet evolution from carbonate stratigraphy (subcontract to NSF-OPP-0342484 (UNL Subaward 25-0550-0001-005); Collaborative Research: Investigating Antarctica's role in Cenozoic global environmental change; ANDRILL MIS Science Team member, $101,466 (2007-2009). The study focuses on geochemical tracers in authogenic carbonate deposits and porewater from AND 001 cores to reconstruct and constrain glacial and subglacial environmental changes over the past 10 Ma. As part of the ANDRILL on-ice science team Vogel implemented ODP style porewater extraction & Rhizon sampling, and conducted on-ice and off ice geochemical measurements. The porewater geochemistry profile of the AND 001 core shows in the upper part a commonly observed decrease in concentrations with depth due to consumption by diagenesis. Overprinted on this natural consumption is a concentration increase with peaks between 200 mbsf and 668 mbsf (Vogel & Tulaczyk, in press a, b). Carbonate deposits are used to contribute to a better understanding of paleo climatic and paleo environmental conditions in the McMurdo Sound area. Preliminary results show isotopically light carbonate cements to be associated with glacial periods while ^{18}O enriched carbonate cements correlate well with warmer climatic conditions like Marine Isotope Stage 31 (Vogel, in press). Heavy carbonate cementation also correlate with subglacial grounding zone deposits.

1. INTRODUCTION

Recent discoveries in West Antarctica have focused scientific attention on the importance of understanding ice sheet interactions with water, either at the basal boundary where ice streams come in contact with active subglacial hydrologic systems (Gray et al. 2005; Fricker et al. 2007) or at marine margins where the ice sheet is exposed to forcing from the global ocean (Anandakrishnan et al. 2007; Alley et al. 2007). Water and wet sediments beneath ice streams play an important role in determining the rate of ice discharge into the ocean (MacAyeal 1992; Fricker et al. 2007; Sergienko et al. submitted; Truffer and Fahnestock 2007). Thermal ocean forcing may represent a key mechanism for destabilizing the West Antarctic Ice Sheet (WAIS), thereby increasing its contribution to global sea level rise (Mercer 1978; Oppenheimer 1998; Rignot and Jacobs 2002; Shepherd et al. 2004) and potentially altering global ocean and atmospheric circulation, and lowering the currently high southern ocean productivity (Sarmiento et al. 2004). At the same time, recent biologic investigations of Antarctic subglacial environments show that they provide a significant habitat for life and source of bacterial carbon in a setting that was previously thought to be inhospitable (Priscu et al. 2004, in press; Mikucki et al. 2004; Lanoil et al. submitted). Just as ice streaming is dependent on availability and dynamics of subglacial water and wet sediments, subglacial microbial ecosystems rely on these two physical settings for supply of water, nutrients, and energy sources (Tranter et al. 2005). This common interest in subglacial materials and processes provides the foundation for the proposed integrative study, which brings together glaciologists, biologists, and geologists.

We propose to survey several distinct, but interconnected, subglacial environments using a combination of physical, chemical, geological and biogeochemical/genomic measurements **to test the overarching hypothesis that glaciological, sedimentological, and biochemical processes combine in the grounding zone to stabilize the ice sheet and to control the structure and function of microorganisms inhabiting the associated subglacial environments**. This hypothesis will be addressed through a collaborative, interdisciplinary research project (Whillans Ice Stream Subglacial Access Research Drilling (WISSARD)) aimed at answering key questions directly relevant to: (1) marine ice sheet stability, (2) subglacial hydrologic and sedimentological dynamics and (3) biotic ecosystems in Antarctic subglacial zones. The proposed geophysical surveys and borehole investigations will be performed on the lower portion of the Whillans Ice Stream (WIS, Figure 1), where three critical subglacial environments can be investigated within a relatively small area: (1) sub-ice-shelf cavity, (2) wet subglacial sediments including the grounding-zone wedge and (3) a subglacial lake. One of the largest lakes, Subglacial Lake Engelhardt (SLE), lies just 10 km upstream from the grounding line with the Ross Ice Shelf (RIS), and drains across the grounding line into the sub-ice-shelf cavity (Fricker et al., 2007). Although horizontally extensive, this lake may be relatively shallow, but was deeper than ~9 m just prior to the last drainage event (Fricker et al. 2007), since previous compilations of bed topography data did not show a large depression there (Lythe and Vaughan, 2000). Just 60 km away, a sedimentary, grounding-zone wedge (GZW) was discovered in the transition zone where ice from WIS goes afloat and becomes part of the Ross Ice Shelf (Anandakrishnan et al., 2007). The GZW is interpreted as a depositional feature that has a stabilizing influence on the lateral position of the grounding line against rising sea level (Alley et al,. 2007). Recent studies have also revealed abundant, active microbial communities in sediments from beneath the nearby Kamb Ice Stream, with indirect biogeochemical evidence that these communities are widespread in wet subglacial sediments throughout the region (Lanoil et al. submitted). If the estimates of abundance are accurate, subglacial water and wet sediments may constitute one of the most significant unexplored ecosystems on Earth (Priscu et

Common abbreviations: GZ= Grounding Zone, GZW= Grounding Zone Wedge, SLE= Subglacial Lake Engelhardt, WIS= Whillans Ice Stream, ROV= Remotely Operated Vehicle, RIS= Ross Ice Shelf

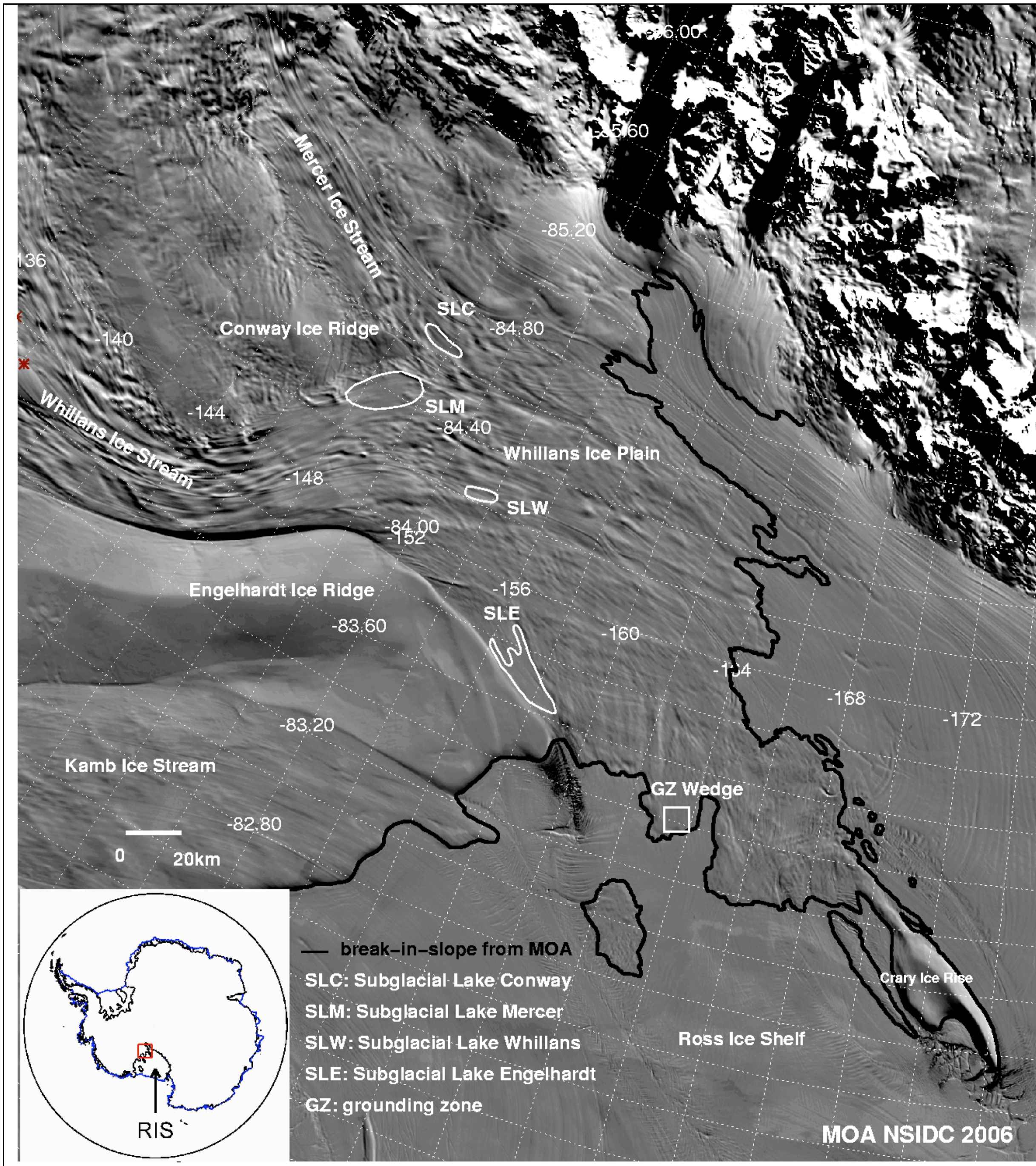

Figure 1: Satellite image of field area showing the grounding-zone wedge identified by Anandakrishnan et al. (2007) and the main subglacial lakes identified by Fricker et al. (2007). Background is the MODIS Mosaic of Antarctica (MOA) from NSIDC (Scambos et al., 2007).

Subglacial lakes and grounding zones (GZs) of ice streams have been identified as high priority targets for scientific investigations by US and international research communities (e.g., SCAR-SALE, http://salepo.tamu.edu; NRC 2007; FASTDRILL, http://www.es.ucsc.edu/~tulaczyk /fastdrill.htm). The proposed preliminary field plan focuses on a transect between SLE and the grounding zone that will allow us to profile and sample three very different but glaciologically, sedimentologically and biologically inter-related environments (Figure 2). Final site selection will

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depend on science, safety considerations and accessibility criteria (e.g. crevasses), and will be based on radar and seismic data that will be collected by the WISSARD surface geophysics team (PSU and St. Olaf) in Years 1 and 2, in combination with satellite imagery (see letter of support from Ted Scambos). These surveys will also elucidate the regional sedimentary and hydrologic structure of the bed, constrain long-term history of ice flow across SLE and GZW, and provide spatial context for interpretation of borehole findings. The boreholes will be used to: (1) investigate sediments, subglacial water discharge, and basal ice at the seaward side of the GZW and within nearby sub-ice-shelf cavity using a multi-sensor Remotely Operated Vehicle (ROV); (2) measure subglacial physical and chemical conditions and determine their temporal variability; (3) collect samples of subglacial water, sediments, and basal ice for biological, geochemical, glaciological and sedimentological analyses.

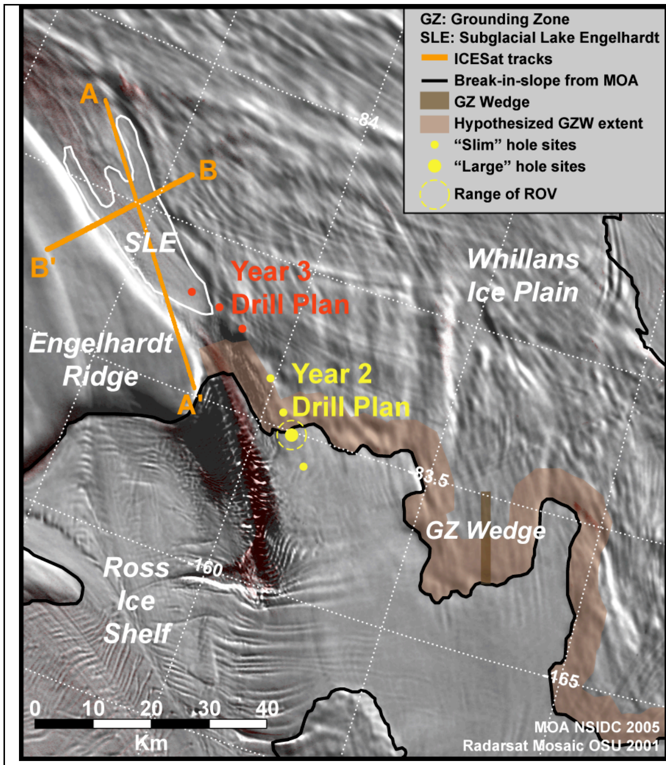

Figure 2: Detailed view of the proposed study area showing SLE and the location (dark brown line) where Anandakrishnan et al. (2007) documented the GZW. MOA shows a break in surface slope (black line) which Horgan and Anandakrishnan (2006) also mapped out suggesting widespread presence of the GZW (light brown shading). Geophysical surveys will verify the spatial extent of the GZW between the original site of Anandakrishnan et al. (2007) and SLE (Year 1) and will map out SLE basin geometry as well as examine regional basal and englacial conditions (Years 2-3). Since satellite images indicate that crevasses may become a concern along the boundary separating ice from Engelhardt Ridge and ice from WIS, aerial reconnaissance will precede our surveys, and the geophysics team will also detect crevasses in the field. Approximate drilling sites for Years 2-3 are indicated but may be modified by geophysics results.

The proximity of SLE to the WIS GZ provides an opportunity to investigate a range of subglacial environments and processes within the framework of a single project in an area that is relatively accessible from McMurdo Station and has ice thickness of only 600-800 m. For comparison, ice thicknesses over Subglacial Lake Vostok and Subglacial Lake Ellsworth, two eminent future targets for subglacial access drilling, are ~4km and ~3km, respectively (Studinger et al. 2003; Siegert et al. 2004). There are scientific and practical advantages to joint research on high-value drilling targets occurring in close proximity. The same logistical arrangements, technological tools, and scientific skill sets can be used to study the individual environments as well as their interconnectivity. An interdisciplinary, drilling-based scientific investigation of an integrated Antarctic system, such as WISSARD, requires significant logistical and financial resources. However, by joining forces in the proposed four-year project, the WISSARD team will be able to exploit logistical economies of scale and scientific synergies to deliver to the scientific community datasets and intellectual advances that would otherwise be difficult, if not impossible, to generate if the same PIs were to pursue a number of separate, smaller projects. The large, interdisciplinary nature of WISSARD will also facilitate increased media visibility and exposure to the general public.

2. BACKGROUND AND MOTIVATION

2.1. Ice Sheet Dynamics and Stability

The recent IPCC report (Lemke et al. 2007) recognized that the greatest uncertainties in assessing global sea level rise in the near future stem from a poor understanding of internal ice sheet dynamics and ice sheet vulnerability to oceanic and atmospheric warming. Complete disappearance of the WAIS alone would contribute ~5 m to global sea level rise, making WAIS a focus of scientific concern due to its potential susceptibility to internal or ocean-driven instability (Mercer 1978; Meier 1993; Oppenheimer 1998). Observations of unstable behavior in a number of coastal sections of WAIS lend some credence to such concerns (e.g. Rignot and Thomas 2002; de Angelis and Skvarca 2003). However, the key processes at the basal ice sheet boundary and at the ice-ocean interface that govern the rate of ice loss to the ocean are still insufficiently understood to be reliably incorporated into ice sheet models and assessments of future sea-level rise (Vaughan and Arthern 2007). Collectively, new observations force us to rethink the timescales on which ice streams change (Truffer and Fahnestock 2007). Examples from WAIS include variations in ice stream motion on a sub-daily basis (Bindschadler et al. 2003), variations in subglacial hydrology on at least a triennial basis (Fricker et al. 2007) and decadal to century scale variability in the availability of subglacial water (Vogel et al. 2005). A report from the recent Workshop on Ice Sheet Modeling (Oppenheimer 2007) identified four specific processes that must be incorporated into models for reliable predictions of future ice sheet changes: i) basal processes associated with ice streams; ii) interaction of the ice sheets with the ocean; iii) flow of water at the surface, within and beneath the ice; and iv) iceberg calving. The lower part of WIS, targeted by the proposed study, provides a dynamic system for investigating the first three of these processes, especially the control of subglacial hydrological and sedimentary processes on the rate of ice discharge to the ocean. This area has been shown to have an active, highly variable subglacial drainage system with a large water flux (Fricker et al. 2007), recent grounding line migration (Bindschadler and Vornberger 1998), and rapid changes in ice velocity (Bindschadler et al. 2003; Joughin et al. 2005). Observations and measurements are needed to constrain sedimentary conceptual models (e.g., Powell and Alley 1997) and quantitative models (Alley et al. 2007) models that link flux and accumulation of sedimentary material beneath ice streams to GZ instability. Direct measurements from the GZ will verify and improve hypothesized models for the migration of modern grounding zones of WAIS by improving our understanding of its recent history and future vulnerability. This line of work will also benefit ongoing efforts to survey and interpret widespread and voluminous sedimentary sequences formed during Late Cenozoic expansions of marine ice sheets and ice streams onto continental shelves (e.g. Domack et al. 1999; Sejrup et al. 2000; O'Cofaigh et al. 2005). Interpretations of these older sedimentary records indicate that marine ice steams are major geologic agents, capable of eroding and transporting sediments at rates comparable to those of the largest rivers, such as Amazon (Nygard et al. 2007).

2.2. Life in Icy Environments

Discoveries of microbial life forms in glacial ice, Lake Vostok accretion ice, and subglacial sediments indicate that the ice-covered Antarctic continent is not a lifeless polar desert (Priscu et al. 1999; Christner et al. 2006; Lanoil et al. submitted). Recent estimates of bacterial abundance in and under the Antarctic ice sheet have revealed the presence of a previously unrecognized carbon pool that rivals that of other global carbon reservoirs (Priscu and Christner 2004). Priscu et al. (2007) recently estimated the volume of groundwater beneath the Antarctic ice sheet to be ~10^6 km^3. Using bacterial estimates of 10^7 g^{-1} collected from beneath the Kamb Ice Stream, these authors further estimated that Antarctic subglacial sediments harbor ~10^{28}

bacterial cells, which equates to 1.2 PgC (Pg=petagram), approaching that found in surface soils on Earth. A study of the degree of similarity among small subunit ribosomal DNA sequence data from bacteria in icy environments across our planet reveals that many the organisms are being selected for by the icy habitat (Priscu et al. 2007). Measurements of microbially mediated geochemical transformations in subglacial environments indicate that this metabolism plays a role in subglacial chemical weathering (Skidmore et al. 2005; Tranter et al. 2005). These seminal studies reveal that the subglacial environment is an enormous and extremely understudied ecosystem that has potentially critical impacts on our understanding of global biogeochemical cycles, astrobiology, and the biodiversity of cold, dark environments.

To date, no studies of microbial community composition in subglacial environments of modern ice sheets have been conducted at sites remote from the ice margin. Closest to our proposed study area is the J9 site of the RIS Drilling Project that yielded sediment samples from the bottom of marine ice-shelf cavity and showed microbial cell abundances and activity approximating those of the deep sea (Azam, 1979). This partially contradicts data from a study on water flowing from beneath the RIS, which revealed no measurable ammonium oxidizer activity and low to undetectable heterotrophic activity (Priscu et al. 1990). Other recent studies indicate the presence of sufficient biological activity to support benthic communities beneath ice shelves floating on seawater (Riddle et al. 2007; Domack, et al. 2005); however the source of nutrients and energy for the communities is unknown. Clearly, there is a need to examine microbial processes beneath large ice shelves, particularly given the possibility that sub-ice-shelf conditions may change under global warming scenarios.

The proposed project will allow us to sample the biology of important habitats located along a subglacial hydraulic gradient: subglacial lake water, subglacial lake sediments, GZW sediments, and GZ seawater. The study of life associated with our planet's ice sheets, will provide fundamental information on adaptation and evolution under extremely cold conditions (e.g. Christner et al. 2007; Mikucki and Priscu 2007). Our proposed work will also yield new information relevant to contemporary geomicrobiology in glaciated regions on Earth, will act as an Earthly analogue in search for extraterrestrial life, and will enhance understanding of microbial survival during periods of pervasive low-latitude glaciation (e.g., Snowball Earth) (e.g., Priscu et al. 1998; McKay et al. 2005, Jepsen et al. 2007).

3. HYPOTHESES

Overarching hypothesis: Dynamic glaciological, sedimentological, and biochemical processes act synergistically to stabilize the ice sheet and control the structure and function of microorganisms inhabiting the Whillans subglacial environment.

We realize that both discovery and hypothesis-driven science will be required if we are to be successful in reaching our science goals. The discovery-based science will allow us to draw further hypotheses as the research progresses. Our specific hypotheses and a sketch of the overall objectives are presented below, with details in the following section.

Specific hypotheses:

Hypothesis 1: Both SLE and the GZW are relatively stable (centuries to millennia) features, but with large temporal and spatial variability on shorter time scales. Both the "stable" and "variable" aspects of these features have implications for ice-sheet stability, including controlling the position of the grounding zone and influencing the flow speed of WIS.

Hypothesis 2: The marine ice-shelf cavity provides both accommodation space for prograding depositional sediment sequences that can (a) stabilize the ice stream grounding zone (b) allow circulation of warmer Ross Sea waters, which can rapidly melt the ice shelf, and (c) allow for an exchange of microbial communities between the Ross Sea and the grounding zone of WIS.

Hypothesis 3: All subglacial environments will harbor a low diversity consortium of viable autotrophs and heterotrophs.

Hypothesis 4: Biologically-mediated weathering is an important mechanism of subglacial geochemical transformations.

Hypothesis 5: There will be a direct and statistically significant relationship between geochemical conditions and microbial community structure and function in each of the major subglacial environments; namely, SLE, the GZW, and the sub ice shelf cavity.

4. OBJECTIVES

1 [Addresses Hypothesis 1]. We will map the extent and structure of Subglacial Lake Engelhardt, the Grounding Zone Wedge, the geometry of the Ross Ice Shelf cavity, and the drainage pathways from SLE to RIS using radar and seismic surveys. The flow and water-storage variability of SLE and WIS drainage system will be constrained with GPS surveys. Samples of subglacial water and sediment, as well as basal ice cores, will be analyzed to derive a historical record of variability in water and sediment transport within SLE and GZW as well as neighboring subglacial regions.

2 [Addresses Hypothesis 2]. We will determine high-resolution seismic stratigraphy of the GZW using combination of ROV sonar and sub-bottom profiler and surface seismic. ROV camera and sonar observations will be used to establish what modern sedimentary processes dominate the seaward edge of the GZW and bottom of neighboring marine ice-shelf cavity. We will measure seawater properties (temperature, salinity, stable isotopes, He isotopes, etc.) to estimate subglacial water input into RIS cavity and calculate basal melting/freezing rates beneath RIS. These rates will be also constrained locally by emplacement of markers into basal ice with ROV and visual ROV observations of basal ice. We will extract sediment cores and water samples in boreholes in RIS, GZW and SLE in order to study microbial diversity in varying glaciological settings; in addition, water/microbe sampling from ROV will measure areal distribution and verify if borehole disturbance may be biasing results.

3 [Addresses Hypothesis 3]. We will phylogenetically catalog prokaryotes, Bacteria and Archaea, in the water and sediments of SLE, and wet sediments and water associated with the sub-ice cavity at the grounding line using ARISA fingerprinting of bacteria and DGGE of Archaea, and construct 16S rRNA gene clone libraries on selected samples allowing us to compare phylotypes with those deposited in public databases.

4 [Addresses Hypothesis 3]. We will measure the density and physiological state of natural microbial assemblages within selected subglacial habitats.

5 [Addresses Hypotheses 4, 5 and 6]. We will characterize the subglacial geochemistry to define hydrological fluxes, biogeochemical weathering mechanisms and provide boundary conditions for phylogenetic determinations and functional gene measurements across distinct subglacial habitats.

6 [addresses Hypothesis 5]. We will use phylogenetic and geochemical data to guide isolation and characterization of prokaryotes that show complementary metabolisms for key nutrient cycles (C, N, S).

5. SIGNIFICANCE OF THE PROPOSED RESEARCH

Various aspects of the significance of the proposed research are mentioned throughout this proposal. Key aspects of the project's significance are summarized below:

5.1 Ice dynamics

1. The GZ is the transition region between a grounded ice sheet and the floating RIS. It represents a critical gateway for loss of ice flowing off the continent into the ocean. The balance of forces controlling ice flow changes rapidly as the ice first begins to float. Additionally, GZ ice dynamics may be destabilized by rapid basal melt due to influx of warm seawater (Rignot and Jacobs 2002). On the other hand, accumulation of a sedimentary GZW may stabilize position of a GZ (Alley et al. 2007). Hence, the GZ may migrate up or downstream in response to changes in sea level, seawater temperature, ice thickness, and sediment influx and is an important indicator of the dynamic state of an ice stream and ice sheet. The proposed study will be first to constrain the complex interaction of glaciological, sedimentary, and oceanographic processes at any ice sheet GZ location. We will use our field results to constrain existing quantitative models of GZ in/stability and propose new ones, if needed.

2. Flow rates of grounded ice control how much ice is evacuated from the WAIS. In concert with model results (Sergienko et al., submitted) and results elsewhere (Bell et al., 2007) we expect that when the SLE is filled, the water acts as lubricant under the ice stream leading to a speed-up, and when it is drained the flow rates decrease. The ICESat results and hydrostatic pressure map of Fricker et al. (2007) suggested that SLE is isolated from the other WIS subglacial lakes. More-recent ICESat data suggest that the lake is filling again, at a rate of ~1m per year (Figure 3). Monitoring the increase in lake levels will help to accurately predict the timing of the next flooding event (which we currently estimate to start in 2016). Measuring the bathymetry of SLE and quantifying the hydrology of the study region will enable a new level of quantitative understanding of hydrological processes beneath ice streams and their linkage to ice sheet dynamics and mass balance.

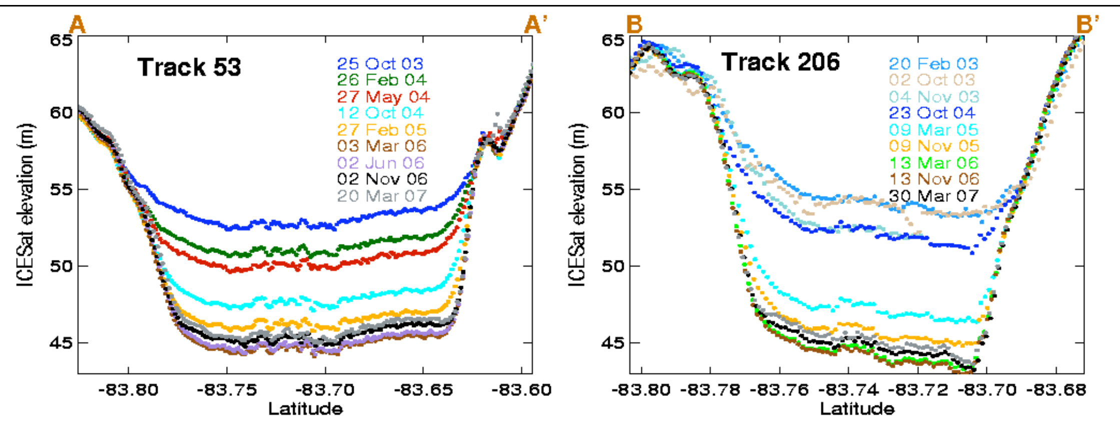

Figure 3: ICESat profiles along and across SLE (see orange lines in Figure 2 for track locations) showing recent filling of the lake (between November 06 and March 07).

3. Instrumental glaciological measurements relevant to ice sheet dynamics and stability are spatially limited, focused primarily on surface glaciology, and mostly cover just the last several decades. To assess the future mass balance of WAIS we need to understand not only the processes controlling ice sheet dynamics now, and their rates, but also how these processes and rates change over longer time scales, such as centuries to millennia. The sedimentary cores and basal ice cores that will be collected and analyzed as part of WISSARD will provide unprecedented insight into temporal evolution of environments and processes. These observations will help generalize previous glaciological results from WIS GZ and other ice sheet margins to develop physically-based parametrizations of key subglacial processes which should be included in numerical ice stream and ice sheet models.

5.2 Biological Diversity and Function

1. The work on molecular phylogeny will yield the first catalog of prokaryotic diversity from a hydrologically linked subglacial environment. Preliminary molecular phylogeny data indicate that novel microorganisms exist within subglacial systems, and we predict that the more detailed studies described here will yield significant insight into the structure of subglacial prokaryotic communities. This discovery-based approach will allow us to formulate additional hypotheses that can be tested experimentally within the context of future proposals.

2. Prokaryotic diversity data will be used to address such ecologically challenging issues as diversity-productivity relationships, and the relationship between diversity and biogeochemistry. The results will expand our knowledge of microbial biogeography to a high latitude subglacial system (Madigan et al. 2000, Ben-Ari 2002, Chase and Leibold 2002).

3. Our study is the first to address the subglacial biogeochemistry of three vital elements (C,N,S) and determine their role in subglacial weathering processes.

4. A recent *Scientific American* article by Gibbs (2001) estimated that there are over one million species of *Bacteria* and *Archaea*. Of these, only about 4,000 have been described and only about half of the forty or so identified phyla have cultured representatives. The proposed study will greatly expand systematic descriptions of polar microorganisms and will provide the first in-depth estimate of biodiversity in a novel subglacial system.

5. Our results will expand what is known about microbial biogeography to relatively understudied high latitude systems (Ben-Ari 2002, Chase and Leibold 2002).

6. A recent NRC report (NRC 2007) specifically stated “It is time for scientific research on subglacial lakes to begin”. We follow recommendations within the report concerning multidisciplinary studies and address important questions within the report concerning linkages among hydraulic connectivity, ice sheet dynamics, sediment characteristics and biological diversity and function.

7. The diverse backgrounds of investigators on our project represent fields that have not often worked together in the past (glaciologists, geochemists, hydrologists, microbial ecologists, molecular biologists). Our interdisciplinary approach will serve as a model for a broader integration of geophysics, glaciology and geomicrobiology.

6. RESEARCH PLAN

6.1 Research Schedule

We propose to launch our field campaign in the 2008-09 Antarctic field season. If funded, the project will encompass three field seasons with tasks distributed as shown in Table 1. Table 1 also shows the individuals responsible for addressing specific objectives detailed in our workplan (Sections 6.2-6.4). We have contacted key personnel at NSF-OPP and Ice Core Drilling Services (see letter of support from ICDS) regarding our proposal ideas and logistics plan to ensure coordination of all scientific and logistical efforts. The overarching theme of the proposal will be addressed by a collaborative team of scientists, each of whom is an expert on certain aspects of the project. The lead PI is Slawek Tulaczyk of UCSC who will manage the project. Other PIs are: Sridhar Anandakrishnan (PSU); Helen Amanda Fricker (SIO); Bob

Jacobal (SOC); Ross Powell (NIU); John Priscu (MSU) and Brian Lanoil (UCR). CoPIs are: Stefan Vogel (NIU); Brian Welch (SOC); Jill Mikucki (HU); Andrew Mitchell (MSU), all of whom are early career scientists.

Table 1. Monthly planner showing research schedule for each component of the project. Key: ST: Tulaczyk, SAK: Anandakrishnan, RJ: Jacobel, BW: Brian Welch, HAF: Fricker, RDP: Powell, SV: Vogel, JP: Priscu, BL: Brian Lanoil, JAM: Jill Mikucki, AM: Mitchell, MIS: McMurdo Ice Shelf, GZW: Grounding Zone Whillans ice stream, SLE: Subglacial Lake Engelhardt.

2008/09	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
	Education & Outreach, Data Archiving, (All)											
	Preparation GZW Geophysics Survey (SAK, RJ, BW, HAF)							GZW Survey (SAK,RJ, BW, HAF)			Geophysics Data Analysis	
	Satellite Image Analysis (HAF)											
	MIS Fieldwork Prepartion (AM, BL, JAM,JP, RDP, SV, ST)								MIS Field-work (BL,RDP (ST,SV)			
	ROV-Hot Water Drill System Integration (RDP, SV)											
	Develop Clean Sampling Protocols (BL,JAM, AM,JP)											
2009/10	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
	Education & Outreach, Data Archiving, (All)											
	Preparation SLE Geophysics Survey (SAK, RJ, BW, HAF)							SLE Survey (SAK,BW,RJ)		SLE - Geophysics Data Analysis		
	Geophysics Data Satellite Image Analysis (SAK, RJ, BW, HAF)											
	GZW Antarctic Fieldwork Preparation [All]							GZW Fieldwork (AM,BL,HAF,JAM,JP, RDP,ST,SV)				
	MIS Data & Sample Processing (RDP, ST, SV)											
	Geochemistry & Weathering Experiments (AM,JAM,SV)											
	Molecular Analysis & Microbial Physiology (AM,BL,JAM,JP)											
	Prepare Publications (All)											
2010/11	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
	Education & Outreach, Data Archiving, (All)											
	Preparation GZW/SLE Geophysics Survey (SAK, RJ, BW, HAF)							SLE Survey (SAK,BW,RJ)		SLE - Geophysics Data Analysis		
	Geophysics Data Satellite Image Analysis (SAK, RJ, BW, HAF)											
	SLE Antarctic Fieldwork Preparation [All]							SLE Fieldwork (AM,BL,HAF,JAM,JP, RDP,ST,SV)				
	GZW Data & Sample Processing (HAF,RDP, ST, SV)											
	Geochemistry & Weathering Experiments (AM,JAM,SV)											
	Molecular Analysis & Microbial Physiology (AM,BL,JAM,JP)											
	Prepare Publications (All)											
2011/12	**Apr**	**Mai**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
	E/O, Data Archiving, (All)											
	Geophysics Data Satellite Image Analysis (SAK, RJ, BW, HAF)							Prepare data for final archive (all)				
	SLE Data & Sample Processing (HAF,RDP, ST, SV)											
	Geochemistry & Weathering Experiments (AM,JAM,SV)											
	Molecular Analysis & Microbial Physiology (AM,BL,JAM,JP)											
	Prepare Publications (All)											

6.2 Surface Geophysics

GPS and remote sensing (lead PI: Fricker). Post-processed position data from geodetic GPS receivers provide detailed record of ice flow at a given location, and have been used to monitor short time-scale variations in ice stream flow rates upstream of the grounding line (e.g. Anandakrishnan et al. 2003; Bindschadler et al. 2003; Gundmunsson, 2006). We will install GPS receivers next to each borehole site to monitor short time-scale changes in ice flow rates in response to i) changing water levels in the lake and ii) tidal motion from the sub-ice-shelf cavity. We will also install three geodetic GPS receivers (one at each ICESat ground track crossover) on SLE and five additional receivers at other non-lake sites on the ice stream (including one on Engelhardt Ice Ridge for static control) in Year 1 and leave them operating for all three years of the proposed project. As well as providing information on ice flow and lake levels, these data will also provide ground-truthing for the ongoing ICESat measurements. HAF is an ICESat Science Team member and is funded through NASA to monitor changes in the WIS lakes as data are acquired. Supporting MODIS satellite image data for this region will be provided by Ted Scambos of NSIDC (see letter of support).

Radar (lead PI: Jacobel). Ground-based radio echo-sounding surveys will chart the englacial stratigraphy and ice-bed interface in the vicinity of the boreholes and the overall subglacial lake basin and outlet conduit. The field methods will consist of 3D local survey grids at the drill sites, a coarse profile grid over the entire lake, profiles across the outlet conduit, and common-midpoint profile (CMP) profiles (e.g., Welch and Jacobel 2005; Jacobel et al. 2005; Pettersson et al. 2006. These data will establish gross ice thickness and ice layering, needed for ice dynamics modeling as well as identifying important glaciological boundaries (e.g., lake to ice-stream; ice-stream to ice-shelf, etc). Wherever possible, the profiles will be collected at 3, 5 MHz, and 10 MHz (with resolution of a few 10s of meters) to optimize penetration into sediments in the manner of Anandakrishnan et al. (2007), as well as to maximize spatial resolution within the bandwidth of the receiver. We will characterize the geometry of the outlet conduit from SLE to the RIS if the surface conditions prove safe in the region. Repeat surveys of selected profile lines and CMP sites during each subsequent field season will establish the scale of changes to the subglacial geometry and reflectivity.

Seismics (lead PI: Anandakrishnan). We propose to conduct seismic reflection imaging along longitudinal and lateral transects at both camps and along a transect between them that will result in representative images of the lake bathymetry, sub-lake sedimentary strata, the GZ wedge, and the ice shelf cavity and sub-cavity. Along each of these transects we will employ seismic reflection profiling to image subglacial till-layer and sub-till sedimentary strata and perform compressional- and shear-wave reflection studies at selected sites to estimate subglacial sediment properties. One technique used in the oil- and gas-exploration sector, which we have pioneered for glacier applications, is measurement of the change in reflection amplitude as a function of incidence angle (Anandakrishnan et al. 2003; Peters et al. 2006; Peters et al. 2007). This technique is coming into widespread use in the exploration industry and is very powerful in identifying changes in fluid properties at the reflecting interface.

Numerous prior studies (e.g., Blankenship et al. 1987; Rooney et al. 1991; Smith 1997) have demonstrated the value of high-resolution seismic reflection experiments over the ice-covered regions of Antarctica, which can be used to characterize regional glacial and subglacial conditions at scales ranging from m to km. At each of the sites we will profile two intersecting lines, each 5-7 km long for a total of about 25 km overall for the season. From prior experience we know that we can drill the shotholes at one of the sites in three days and profile the two lines in three days. We propose to space the shot holes (hot water drilled to 20 m depths) at 200 m along our profile lines in order to shoot a CMP profile with a subsurface CMP spacing of 5 m. Thus, features with amplitudes of a few meters and wavelengths of ~20 m will be resolved; point features will appear as diffraction hyperbolae. Based on our previous experience, subglacial layers 2 m or thicker in the upper 100 m of the bed will be resolved and water depths or sedimentary basins of up to a kilometer thick can be imaged.

To estimate the till-layer porosity, water pressure and acoustic impedance, we will collect both compressional- and shear-wave data (Blankenship et al. 1987; Blankenship 1989) along our profiles. In order to determine (and account for) the large anisotropy within the ice sheet, we propose to shoot orthogonal surveys in which the travel-time anisotropy can be inverted for fabric (e.g., Blankenship and Bentley 1987). These experiments will provide data on both the till layer (and differences in the till between the various regions) and will determine the ice fabric (from anisotropy) in the various regions. Finally, we will shoot a number of short-refraction experiments to determine the depth-density profile within the firn along our line.

6.3. Underwater Geophysics and Oceanographic Measurements (lead PIs: Powell and Vogel)

We will deploy an ice borehole ROV equipped with, among other instrumentation (see NIU facilities page), a multi-beam sea floor imager and high-resolution acoustic sounder. In addition to spatial mapping of GZ sedimentary structures at high spatial and vertical resolution live stream video imaging will allow visual and direct observation of sedimentary processes across the GZ. The onboard sampling capabilities for ice, water and sediment samples allow targeted glaciological, geological and biological investigation based on real time visual observations of sub ice processes and features or physical (temperature probe, shear vane, acoustic doppler current meter, laser particle sizer) or geochemical (CTD, pH, Redox, O_2, H_2S, H_2, N_2O,) measurements.

6.4 Subglacial Hydrology (lead PI: Vogel and Tulaczyk)

Subglacial hydrological processes in the downstream area of WIS and across its GZ will be made using direct borehole measurements of subglacial water flow, the hydropotential surface, water temperature, pressure and salinity. Since borehole measurements only provide point measurements in a spatially heterogeneous subglacial hydrological system and artificial dye tracer experiments in Antarctica are not ecologically sound, we will measure natural biogeochemical tracers including ^{18}O, D and He isotopes (see enclosed letter of support from John Lupton, NOAA). Solute concentration, water isotopes, and He data have long been used as tracers for quantifying the contribution of melt water to ocean water masses (e.g., Hohmann et al. (2002); Jacobs et al. (1985); Rodehacke et al. 2007). In-situ measurements of pH, Redox, O_2, H_2S, H_2, N_2O and temperature, using both an ROV and borehole deployable sediment profiler (NOAA funded NIU development using www.unisense.com sensors) will provide information on spatial variability to help assess sampling-induced chemical changes (e.g. degassing and temperature change) and borehole-penetration related disturbances (see enclosed letter of support from Tim Short, SRI). A containerized geochemical, microbiological field laboratory provides clean (class 100) on-site sample handling and analytical capabilities.

Tulaczyk will perform measurements of subglacial water pressure fluctuations in SLE and over the GZW using two subglacial water pressure transducers, which will be constructed for this project (see enclosed letter of support from Erik Blake of Icefield Instruments). These records will be compared to Fricker's GPS records of vertical and horizontal ice motion to verify if subglacial water dynamics influences ice flow rates in the study area. Physical nature of subglacial drainage systems will also be investigated using breakout curves obtained from shallow water pressure transducers at the time of borehole penetration through ice base. Magnitude and time constant of water pressure equilibration in a borehole allow estimates of basic hydrological parameters of the subglacial drainage system, such as its transmissivity.

6.5. Basal Freezing and Sediment Transport (lead PI: Tulaczyk)

Model-based calculations of basal thermal energy balance in the proposed study region indicate significant basal freezing of several mm per year (Joughin et al. 2004). Knowledge of freezing rates is important to the success of this project because frozen-on basal ice provides a unique archive of past subglacial water dynamics and related ice dynamics (Vogel et al. 2005). In addition, freezing may incorporate microbes from the subglacial environment, preserve them in water-filled openings between ice crystals and transfer them relatively quickly from the subglacial environment to the RIS ice-shelf cavity. Finally, frozen-on basal ice may contain significant debris (Vogel et al. 2005), which will help enlarge the GZW. Direct measurements of englacial temperature profiles in three boreholes (over SLE, GZW, and ice-shelf cavity) will constrain basal temperatures and conductive heat losses. Measurements of subglacial till strength will enable calculation of shear heating because ice sliding velocity is known (Joughin et al. 2005).

6.6 Subglacial Microbiology

Subglacial hydrology and bedrock lithology control electron acceptor and donor supply for microbial growth and therefore should impart a strong influence on subglacial microbial community structure and function (Tranter et al, 2005, Mikucki and Priscu, 2007). The biological, geochemical and molecular measurements proposed here, in conjunction with the geophysical analysis of ice dynamics, will allow us to define the links between subglacial hydrology and microbial community structure. We propose to characterize the geochemistry, biological activity, and microbial diversity of ice, water, and sediment samples from the subglacial environments and to characterize the in situ metabolic processing of C, S and N using isotope geochemistry and functional gene analysis. Long term weathering experiments will confirm our in situ measurements.

Contamination issues (lead PI: Lanoil). All of the geomicrobiologists on this proposal have worked on subglacial environments and realize the importance of sterile techniques, decontamination, and contamination detection (Priscu et al., 1999 Christner et al. 2005 Skidmore et al. 2005). We will work with ICDS to develop a large volume microfiltration (<0.45 µm) and UV treatment system to continuously decontaminate the borehole water to reduce the number of viable microorganisms to reach the NRC target of ~ 100 cell ml^{-1} (NRC, 2007). The drilling water will also be maintained at a temperature >90 ^{o}C, which will significantly reduce the number of viable cells within the drilling fluid (Gaidos, 2004). We will monitor DNA containing bacterial numbers and determine the phylotypes present using techniques described below within the drilling fluid to determine potential background "contamination". The efficacy of these approaches will be tested in year one by the Lanoil laboratory. All biology experiments and sample manipulations will be conducted within a class 100 laminar flow hood equipped with a germicidal UV-C lamp that eliminates 99.99% of atmospheric particles <0.3 µm.

6.6.1 Biogeochemical Characterization

Geochemical measurements of subglacial waters and sediments (Lead PIs: Mitchell, Priscu and Vogel). The complete absence of light within our subglacial study sites implies that energy requirements for new organic carbon production will be satisfied by chemolithotrophy, with electron transport to and from inorganic material, as dissolved ions or solid phase minerals. These compounds can be derived from subglacial ice-melt or from the underlying substrate via microbially mediated mineral dissolution (Hodson et al. 2007) strongly suggesting a direct link between microbial activity and subglacial biogeochemical weathering and hydrology. Consequently, to understand subglacial microbiological diversity and activity, the geochemical environment must be accurately defined in SLE, the boundary zone wedge, and the sub-ice shelf cavity. We propose to measure the following biological labile inorganic and organic components (e.g., Mitchell et al, 2001; 2006;): dissolved and particulate organic carbon (DOC, POC) and nitrogen (DON, PON), NO_3^-, NO_2^-, NH_4^+, soluble reactive P, Fe^{2+}, Mn^{2+}, Ca^{2+}, Mg^{2+}, K^+, Na^+, SO_4^{2-}, O_2 (aq), pH and redox potential. These analytes will be measured in the analytical laboratory at McMurdo Station using standard methods employed by the McMurdo Dry Valley LTER project (www.mcmlter.org). Total dissolved Fe and Mn will be measured on return to MSU by ICP-MS. These data will provide geochemical boundary conditions for all geomicrobiological studies described below and when combined with the obtained phylogentic information from extracted 16S rRNA gene sequences, and functional genes for C, N and S cycling will, for the first time, determine the linkages between microbial community structure and biogeochemical weathering mechanisms in distinct subglacial environments.

Cell enumeration and viability (lead PIs: Priscu, Mitchell and Mikucki). Standard cell counts will be made using SYBR Gold nucleic acid stain (Invitrogen) as outlined by Lisle and Priscu (2004). Cell viability (living vs. dead) will be examined using cytoplasmic respiration potential by reduction of cyanoditolyl-tetrazolium chloride (CTC) (Smith and Priscu 1993, Pyle et al.1995) and with the dual channel nucleic acid stains propidium iodide/Syto 9 (Molecular Probes, Inc; Haugland 1992) to examine membrane integrity. All of these approaches allow microscopic visualization of cells. Hence, we will be able to correlate the degree of viability with cellular attachment to non-living particles and to each other, thereby providing insights into potential consortial relationships.

Microbial Diversity (lead PI: Lanoil). Several studies have indicated the presence of similar communities in subglacial sediments from around the world (Foght et al., 2004; Skidmore et al., 2005; Priscu et al. 2007; Lanoil et al., submitted). Thus, we predict a similar community composition in wet subglacial and Lake Engelhardt sediments. However, the composition of other samples (SLE water, GZ wedge sediments, and water and marine sediments from the sub-ice shelf cavity) will have a more unpredictable community composition. Since the sub-ice shelf cavity is connected to marine open waters, the microbial community in these waters and sediments is likely similar to that observed for other deep Antarctic marine water and sediments, respectively (e.g., Murray et al., 1999; Bowman et al., 2003; Bowman and McCuaig, 2003) or those detected in marine influenced subglacial systems (Mikucki and Priscu, 2007). The GZ wedge sediments are likely to be a mixture of communities as this region is where the microbes transported from the subglacial hydraulic system enter into the sub-ice shelf cavity. To test these hypotheses, we will examine 16S rRNA genes from these samples using DNA fingerprinting methods to guide us in selection of samples for more detailed analysis with clone libraries. Such an approach is widely used and has been used successfully by us with subglacial and sub-ice samples (Cary et al., 2004; Skidmore et al., 2005; Foo and Lanoil, submitted).

For DNA fingerprinting of the bacterial community, we will use the ARISA method [Automated rDNA Intergenic Spacer Analysis; (Fisher and Triplett, 1999; Brown and Fuhrman, 2005)] for bacterial diversity and 16S rRNA gene DGGE for analysis of the diversity of the Archaeal community (Muyzer et al., 1993; Foo and Lanoil, submitted). Fingerprinting data will be used in conjunction with geochemical and activity data to determine the correlations between biogeochemistry and microbial community composition. rRNA gene libraries will be made from selected samples to place this data in a phylogenetic context.

Substrate Incorporation (lead PI: Priscu). Very little information exists on the physiology of microbes in subglacial environments. Substrate utilization profiles for the natural assemblages will be generated using radio-labeled substrates (e.g., $^{14}CO_2$, ^{14}C-acetate, ^{14}C-glucose, ^{3}H-leucine, ^{3}H-thymidine). Importantly, the results will allow us to assess the contribution of chemoautotrophy and heterotrophy to subglacial carbon cycling. Chemoautotrophic activity will be estimated in time-course experiments allowing us to estimate potential rates of CO_2 incorporation. Metabolic rates at *in situ* temperatures will be calculated as described by Takacs and Priscu (1998). Heterotrophic activity will be measured as ^{14}C-acetate, ^{14}C-glucose, ^{3}H-leucine, ^{3}H-thymidine respiration or incorporation into cellular biomass as described by Christner et al. (2006) and Foreman et al. (2007). Differences in incorporation vs. respiration will indicate whether the cells are actively growing or simply using the substrate for maintenance metabolism.

6.6.2 Subglacial Transformations of the Carbon, Sulfur and Nitrogen

No detailed information exists on biological elemental cycling in subglacial environments, despite suggestions that bacterial transformations of key elements in these environments may have global significance (e.g., Sharp, 1999, Skidmore et al. 2000, Mikucki et al., 2004, Priscu et al. 2007). The experiments outlined in this section will provide the first data on biogeochemical transformations of the globally important elements C, S and N within a subglacial lake and its outflow to the sea. Traditional microbiology, isotopic geochemistry and analysis of specific functional genes which mediate the cycling of C, S and N will be used to investigate microbial transformations of these elements. Combining isotopic geochemical measurements of relevant metabolic substrates (i.e. DIC, SO_4^{2-}, H_2S) will also us to draw strong inference between gene expression and actual bioenergetic transformations in situ.

Subglacial carbon metabolism (lead PIs: Lanoil and Mikucki). The isotopic composition of dissolved inorganic carbon (DIC) will be measured for $\partial^{13}C_{DIC}$ and $\Delta^{14}C_{DIC}$. The extent to which the carbon isotopic composition of DIC ($\partial^{13}C_{DIC}$) is depleted from that of glacier ice (~-1‰) or seawater (0‰) will reflect the metabolic processes operating on the subglacial carbon pool (e.g., (Whiticar and Faber, 1986). $\Delta^{14}C_{DIC}$ measurements will indicate the extent of isolation of the subglacial environment from the surface. We expect the isolation to vary significantly from the sub-ice cavity (low isolation) to Lake Engelhardt (high isolation).

We hypothesize that chemoautotrophic CO_2-fixation (as dissolved HCO_3^- or CO_3^{2-}) provides a source of new carbon to the subglacial system. We will use the following primers for the genes of the major enzymes in these chemoautotrophic pathways: ATP citrate lyase beta subunit (aclBA) of the rTCA cycle, RubisCO form I (cbbL) and form II (cbbM) of the Calvin-Benson cycle, both forms of the pyruvate:ferredoxin oxidoreductase gene (por and nifJ) of the acetyl-CoA pathway (Campbell et al., 2003 and Campbell and Cary, 2004), and the propionyl-CoA synthetase gene (Acc) of the 3-HPP pathway (Hugler et al., 2002).

Subglacial sulfur metabolism (lead PI: Mikucki). Microbial mediated processes such as sulfate reduction, sulfide oxidation and sulfur disproportionation will fractionate the isotopic composition of S and O of sulfate relative to H_2S in distinct patterns (Blake et al., 2006). For example, sulfate will become enriched in both $\partial^{34}S$ and $\partial^{18}O$ as sulfate reduction proceeds in subglacial sediments (Wadham et al., 2004). Alternatively, sulfate highly depleted in $\partial^{18}O$ is indicative of sulfate oxidation under anoxic conditions (Bottrel and Tranter, 2002) where the sulfate oxygen is derived from glacier water (which is typically highly depleted in $\partial^{18}O$; <-35‰).

We will measure the stable isotope ratios of dissolved SO_4^{2-}, H_2S and H_2O ($\partial^{18}O_{Sulfate}$, $\partial^{34}S_{Sulfate}$, $\partial^{34}S_{sulfide}$, $\partial^{18}O_{water}$) to provide information about specific biogeochemical pathways of S in the WIS subglacial samples. Results from our isotopic measurements will direct our functional gene analyses. For example, the key energy conserving step of SO_4^{2-} respiration is catalyzed by the enzyme dissimilatory sulfite reductase (DSR) (Odom et al., 1984) and primers exist that target this gene in natural samples (Wagner et al., 1998).

Subglacial nitrogen metabolism (lead PI: Mitchell). Studies on alpine and polar subglacial environments have shown significant differences in the concentration of dissolved N species along hydrological flow paths (e.g., Mitchell et al., 2001, Tranter et al., 2002, Skidmore et al., 2000). We will use primers to detect the presence of specific functional genes which control N cycling, including denitrification (nitrate reductase; nirK, nirS) (Braker et al., 2000; Prieme et al., 2002) and ammonia oxidation (ammonia monooxygenase; amoA) (Kowalchuk et al., 2001). These molecular data will be combined with direct measurement of NO_3^-, NO_2^-, and NH_4^+ concentrations from these habitats to draw inferences between gene expression and bioenergetic transformation of these N species.

Geochemical weathering and isolation of biogeochemically relevant organisms (lead PIs: Mitchell, Mikucki and Priscu). Biogeochemical weathering has been suggested to be important in alpine and arctic subglacial environments (Skidmore et al., 2000) but the importance of this process beneath our planet's ice sheets has never been examined. We propose experimental incubations of water and sediment mixtures incubated at simulated *in situ* conditions. Each bottle will be sampled monthly over a year or longer for solution chemistry composition (NO_3^-, NH_4^+, SO_4^{2-}, Ca^{2+}, Na^+ and K^+; Fe^{2+}; Fe^{3+}; Mn^{2+}) and CO_2 and CH_4 in the headspace. Changes in aqueous and gas chemistry relative to killed controls will indicate the significance of biotic vs. abiotic subglacial weathering. Incubations that demonstrate a change in geochemical properties (e.g. evolution of SO_4^{2-}, Mn^{2+}, Fe^{2+}, NO_3-, or CH_4) will be selected for enrichment cultivation and molecular analyses in order to identify the specific organisms that may play a role in subglacial chemical weathering processes.

7. BROADER IMPACTS

7.1. Societal Relevance

Global warming and sea level rise are of high societal relevance and have received increased attention recently, and over the past year in particular. Understanding subglacial water systems and GZs are critical for improving ice sheet models so that reliable predictions of future sea-level rise can be made. Subglacial environments are important unexplored ecosystems that provide Earthly analogs to putative ecologies on other icy planetary bodies (e.g. Mars, Europa, Enceladas). Subglacial chemistry and biology plays a currently unknown but potentially critical role in global biogeochemical cycles and therefore is a not yet quantified component of the global climate system.

7.2 Science Resource Development

WISSARD will provide the US science community (after an 8 year hiatus) the renewed capability to access and study subglacial environments. We anticipate a significant number of publications from our findings in high impact scientific journals. WISSARD will build the foundation for infrastructure that will support future subglacial research projects. Development of such infrastructure is strongly supported by the scientific community at large as evidenced by extensive participation in workshops such as FASTDRILL, SEAP, SALE, Lake Ellsworth Consortium Workshops, etc (see letters of support from Kennicutt and Siegert). WISSARD will be the first to pioneer an approach implementing recommendations from the National Research Council committee on Principles of Environmental Stewardship for the Exploration and Study of Subglacial Environments (NRC, 2007). We will work together with ICDS to develop and test clean drilling and sampling technology for this and future subglacial research. The tools proposed in WISSARD represents a significant advance in polar sampling strategy by incorporating the use of complex ROV/AUV technology under glacial ice (see enclosed letter from DOER: this technology will be available for use in other subglacial environments. The test of the ROV and clean drilling technology at the former ANDRILL MIS site in year 1 will provide supplementary data regarding environmental impacts of geological drilling in a subglacial environment. Dr. Jemma Wadham (see enclosed letter of intent) is interested in testing her new 'Cryoegg' technology funded by UK NERC grant and will apply for new NERC funds with the explicit aim of participating in WISSARD. JPL/NASA PI, Dr. Alberto Behar (see enclosed letter of intent and CV) plans to deploy his deep borehole camera in narrow-diameter WISSARD boreholes to provide visual observations from Subglacial Lake Engelhardt (2009-10) and other localities where the ROV, with its cameras, will not be deployed. The NASA Cryospheric Program Manager, Dr. Seelye Martin encouraged Dr. Behar to submit a proposal this summer to his program to fund JPL participation in WISSARD.

This project may also provide important insights to marine biologists regarding the extent and diversity of benthic and pelagic communities at the grounding zone; such observations and samples will complement prior work showing abundant and diverse communities beneath the Ross and Amery ice sheets (Lipps et al., 1979, Bruchhausen et al. 1979, Azam et al., 1979, Riddle et al. 2007). Finally, measurements of hydrological and oceanographic properties such as salinity, temperature and current profiles across the grounding zone will provide the scientific community with high quality datasets for incorporation in future studies.

7.3 Education and Outreach (E/O)

There are four core E/O objectives for WISSARD that are detailed below.

1. Increasing student participation in polar research. One of the primary goals of WISSARD is to increase undergraduate and graduate student involvement and training in polar research: all WISSARD PIs are dedicated to this goal and we have included support for 10 graduate and 12 undergraduate students. These students will play a central role instrument and software development, field work, data analyses and outreach programs. St. Olaf College students will present their results at professional meetings and the Pew Forum for Undergraduate Research. UCR is a minority serving institution (30% of undergraduates from minority groups) and will include underrepresented minorities in research. At MSU, Priscu has been actively involved with the Montana American Indian Research Opportunities (AIRO; www.montana.edu/~wwwai) program and will sponsor a Native American student during this project. He also participates in the Big Sky Institute's Science and Society Graduate Fellows Program (www.bsi.montana.edu), Montana watercourse program, Montana Globe Program (www.globe.gov) and the Microbial Life Education Program (serc.carleton.edu/microbelife/microbservatories/mcmurdo.html).

2. Involving young investigators to the polar sciences. Our project will include promising early career investigators in polar research (co-PIs Andrew Mitchell, Jill Mikucki, Stefan Vogel, and Brian Welch) to carry the legacy of subglacial research into the future.

3. Promotion of K-12 teaching and learning programs. NIU: Two educators, Betty Trummel and Louise Huffman, experienced in Antarctic research through ARISE, ANDRILL and the IPY education program, live locally and will be actively involved with WISSARD. **SIO**: We will build on our previous E/O endeavors (see Results of Prior NSF support) by introducing a formal E/O middle school program facilitated through the San Diego County Office for Education (SDCOE; see letter of support) and hosted at the SIO Visualization Center (see letter of support). SDCOE will ensure our program meets the California Earth and Physical Science Standards and help us with our goal of targeting under-represented schools, e.g. the Monarch school which provides for homeless and at-risk children (www.monarchschools.org). Through our partnership with SDCOE, a science educator will participate in every school visit, thereby increasing the educational impact on each student, and training the WISSARD scientists to be more effective at articulating their science to this audience. **MSU:** Mikucki and Priscu recently developed a NSTA approved high school AP Biology curriculum on Antarctic microbiology called "Living Ice" that is currently being used in schools across the U.S. (mcm-dvlakesmo.montana.edu/images/Data/Living%20Ice.pdf; www.montana.edu/news/1077832392.html). The proposed research will provide us with information that will be used to keep this curriculum current. Mikucki has developed *"RedParka: Poles apart? Exploring ecosystem dynamics on a local and global scale"* with a local middle school teacher, Leslie Cassano. 'RedParka' is a 7th grade resource unit designed to excite students about polar research, hydrology, cold environment microbiology, astrobiology and the links between human activity and climate change. RedParka contains lesson plans, data resources and an electronic field journal housed on a webpage hosted by Harvard University (www.redparka.fas.harvard.edu). Mikucki and Cassano will continue to add data, lessons plans and journal entries to this resource as a part of the WISSARD project.

4 Reaching a larger audience through public exhibits, web-based materials and media SIO: We will send material about our project (videos, images, etc.) to the Birch Aquarium at Scripps to display as part of their new exhibit "Feeling the Heat: the Climate Challenge" which was opened in May 2007 by Senator Al Gore and will run for 3 years. The Birch Aquarium receives 500,000 visitors per year. We regularly communicate with Nigella Harforth and Cheryl Peach at the Aquarium who are interested in all things polar, both are keen to include our new research in their exhibit (see letter of support). HAF will give a public lecture at the Aquarium on Antarctic subglacial lakes in September 2007. **NIU:** We will work with Trummel from the Field Museum of Natural History and Huffman from the Museum of Science and Technology to integrate both our field program activities and results of our research into each museum's activities. **Websites:** We will initiate a WISSARD website similar to the one developed for the SIO rifting project (http://loose-tooth.ucsd.edu). Movies that explain our research will be created and posted on popular websites such as YouTube using "action" shots taken in the field. Priscu maintains two websites that provide important information on the societal components of polar research (www.homepage.montana.edu/~lkbonney; mcm-dvlakesmo.montana.edu). **Media:** The public interest for our research is documented in the dramatic media attention that the Fricker et al. (2007) Science paper received reporting the discovery of these lakes. NOVA and National Geographic have expressed interest in producing a scientific program collaboratively with WISSARD for a general public audience. David Monk (videographer and producer), Brave New Pictures, has contacted NIU PIs about producing a feature length film that documents the WISSARD project (see letter of support).

7.4 Data archiving

All data collected by this project will be archived at National Snow and Ice Data Center (NSIDC) and National Geophysical Data Center. GPS data will be archived by UNAVCO. Radar interpretations (ice thickness, surface elevation, basal reflectivity) will be posted at NSIDC. Raw data files will be available on request through NSIDC. Molecular sequence data generated from this work will be submitted to GenBank, a public, web-based database of genomic data (http://www.ncbi.nlm.nih.gov/). Isolates will be submitted to the American Type Culture Collection (ATCC) for public use. Geochemistry data will be placed on a dedicated web site after 1 year of restricted access to allow graduate students and PI's to publish their findings.