WAIS DIVIDE BASAL SCIENCE AND IMPLEMENTATION PLAN

20 January 2009

John C. Priscu, Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717

Slawek Tulaczyk, Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064, USA

Mark Skidmore, Department of Earth Sciences, Montana State University, Bozeman, MT 59717

Table of Contents

EXECUTIVE SUMMARY

General Scientific Context:

Basal and subglacial studies at the WAIS Divide ice coring site will address several of the top-level scientific goals identified previously by the WAIS Divide science community: (1) determining how the West Antarctic Ice Sheet (WAIS) responded to climate changes in the past, (2) improving models of WAIS contribution to near-future global sea level changes, and (3) understanding microbial life in, and beneath, deep ice. These are long-standing scientific goals with well-established scientific and societal relevance. At the present time the WAIS Divide drilling is planned to cease 25m above the bed, thereby omitting sampling of basal ice and subglacial materials. This document outlines the scientific benefits and technological ramifications of continuing drilling and sampling below the current limit of 25m above the bed at the WAIS divide site.

Location and Setting:

The WAIS Divide drill hole provides an unprecedented opportunity to gain access to deep samples of basal ice, as well as subglacial water and sediments, which will permit unique glaciological, geological, and biogeochemical measurements, including measurements of fundamental transitory geochemical and microbial parameters that have not been analyzed previously in Antarctica. Location of the WAIS Divide drill site in the central part of the ice sheet sets this basal/subglacial sampling site apart from previous similar studies, which focused on settings closer to ice sheet margin with thinner ice cover. Recent radar and seismic investigations performed by teams from Penn State University and CReSIS indicate that: (1) presence of a debris-bearing basal ice layer is expected because basal melting conditions are confined to just a few km upstream of the drill site, (2) the subglacial hydrological system beneath the drill site should have relatively low annual water flux rates, of the order of 1 cubic meter per year per meter width of the ice sheet, (3) the ice base is underlain by a 10-to-15-m-thick layer of sediments, which themselves rest on bedrock.

Recommendations:

We have formulated the following three recommendations based on scientific, technological, and operational considerations.

Minimum Plan - Recovery of a continuous basal ice core from 25 meters above the bed to the bed – Acquisition of a basal ice core represents the least complicated extension of the current WAIS Divide drilling plan because it can be accomplished using the existing drill and with limited environmental impact. Analyses of ice, gas, and particulates from a basal core can be used to meet address glaciological, geological, and biological questions identified in this document.

Limited Subglacial Penetration Plan – Recovery of a continuous basal ice core and ~1m of subglacial sediments – Addition of ~1m of subglacial sediments will significantly extend the range of biological, glaciological, and geological investigations which will benefit from analyses of modern subglacial materials. Any extension of the sampling plan into the subglacial environment poses technological, environmental, and operational challenges, which are related to potential contamination, borehole management, and the need for a new sampling tool needed to recover the short subglacial core. Such sampling tool can be a simple push corer attached to the existing drill.

Full Subglacial Sampling Plan – Recovery of a continuous basal ice core, subglacial water sample, full subglacial sediment thickness, and subglacial bedrock – This plan would require development of several new tools for water sampling, 10-to-15m sediment core, and a few meters of bedrock core. Operational considerations would need to take into account the issue of borehole motion during sampling and management of borehole fluid pressure to avoid fluid injection into the subglacial zone.

SCIENCE OBJECTIVES

Overview and Motivation

Basal and subglacial environments represent a crucial and relatively unstudied transition zone between an ice sheet and underlying geologic substrata. Processes taking place in this zone determine: (i) the rate of ice flux through an ice sheet, (ii) erosional and sedimentary dynamics of an ice sheet, (iii) phylogenetic and metabolic diversity, and (iv) the biogeochemical transformation of materials between an ice sheet and its geologic substrate. Accreted basal ice layers, subglacial water bodies, and subglacial sediments provide records of temporal variations in the rate and magnitude of these different subglacial processes. The scientific need for exploration of subglacial Antarctic environments has been recognized by SCAR through its establishment of the Subglacial Antarctic Lake Environment (SALE) Scientific Research Program. SALE and its predecessor SALEGOS have produced numerous reports highlighting the scientific rationale and technology required to sample these environments (see http://scarsale.tamu.edu/). These reports formed the basis of a recent National Research Council document "Exploration of Antarctic Subglacial Aquatic Environments: Environmental and Scientific Stewardship" (NRC 2007), and subglacial environments were listed as one of the frontiers for polar biological research in an earlier NRC report (NRC 2003). The 2007 NRC report concluded that "It is time for scientific research on subglacial lakes to begin."

Targeted samples of basal ice and subglacial sediments from beneath the West Antarctic ice sheet have been recovered in a limited number of locations, with some additional samples being obtained as a byproduct of ice coring near/through the ice-base interface (Bindschadler et al., 1987; Kamb, 2001; Lanoil et al., in press; see Figure 1). Most of the targeted subglacial sampling took place beneath three ice streams flowing through the Siple Coast region, where the presence of a widespread drape of Tertiary glaciomarine deposits facilitated development of a spatially homogeneous layer of weak, relatively easy to sample, subglacial sediments (Figure 1; Tulaczyk et al., 1998; Studinger et al., 2001; Tulaczyk et al., 2001a, b). Debris-bearing basal ice has been sampled in the late 1960s from beneath the Byrd station, at the bottom of the first borehole drilled to bedrock in Antarctica (Gow et al., 1979) and in 2000 from a single borehole drilled to the bottom of Kamb Ice Stream (Vogel et al., 2005; 2006). The sampling technologies deployed in these cases permitted reliable analysis of subglacial sediments, rock samples, ice matrix, and subglacial water samples only. None of these previous deep basal and subglacial sample acquisitions in West Antarctica were made in the manner permitting unequivocal preservation of transient properties of these materials, e.g., pore water gas chemistry and microorganisms. 16S rRNA gene sequence data and the diversity of bacteria cultured from sediments collected in 2000 from beneath the Kamb Ice Stream revealed surprisingly high cellular densities (~10^7 cell g sediment^{-1}) but low microbial diversity (only 5 phylotypes). Isolates were cold tolerant and the 16S rRNA gene diversity was similar to that found in subglacial alpine and Arctic sediments and water (Lanoil et al., in press). Although the integrity of these samples may have been compromised by the lack of proper handling and storage before

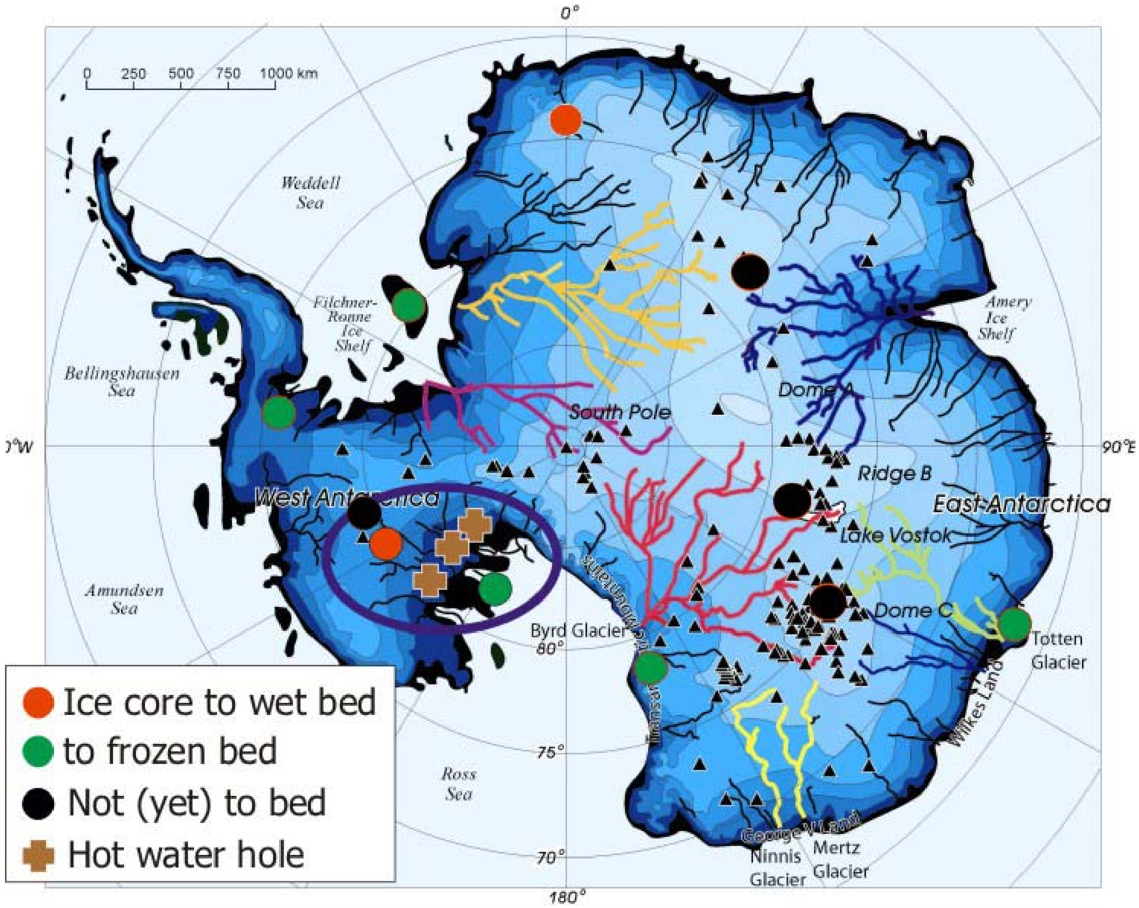

Figure 1. Location of past and current drilling projects in Antarctica that either reached the bedrock or may do so in the near future (compilation courtesy of Dr. S. Vogel).

analyses, they strongly imply that an active bacterial assemblage exists beneath Kamb Ice Stream. If the estimates of abundance are accurate, these environments may constitute one of the most significant unknown ecosystems on Earth and represent a significant pool of bacterial organic carbon not previously considered in global carbon budgets (Priscu and Christner, 2004; Priscu et al., in press).

The WAIS divide ice core site will be the first location where a targeted and well-designed sampling plan of the basal ice and subglacial environment will be implemented. Proper development of this sampling plan will allow the first full suite of integrated physical, chemical and biological analyses to be made that will address a wide range of important scientific questions and test hypotheses concerning the relationships among glaciology, sedimentology, hydrology, biogeochemistry and geomicrobiology. From a purely biological perspective, the WAIS divide basal environment, if sampled properly, will provide (i) fundamental information on adaptation and evolution under extremely cold conditions (e.g. Christner et al., 2008; Bakermans, 2008), (ii) new information relevant to contemporary geomicrobiology in glaciated regions on Earth (e.g. Skidmore et al., 2000, 2005; Mikucki and Priscu, 2007), and (iii) will act as an Earthly analogue in our search for extraterrestrial life (NRC 2005; Jepsen et al., 2007; Priscu et al., 1998; McKay et al., 2005), and (iv) will enhance our understanding of microbial survival during periods of pervasive low-latitude glaciation (e.g., Snowball Earth).

SITE DESCRIPTION AND SCIENTIFIC POTENTIAL

Recent radar investigations by the University of Kansas CReSIS team provide new, important constraints on the spatial distribution of basal conditions at, and in the vicinity of, the WAIS Divide drill site (Claude Laird, personal communication, October 2008; Figures 2 and 3). Their findings show that the drill site lies over a local basal depression, which is several hundred meters deep and has diameter of nearly 10 km (Figure 2). This subglacial depression corresponds to an area of much higher bed reflectivity than the surrounding region (Figure 3). High basal reflectivity typically indicates wet bed whereas low reflectivity is often associated with frozen basal conditions. If such interpretation is applicable here, then the basal thermal regimen switches from freezing to melting just 2-3 km upstream of the drill site (note that ice flow is from upper right towards lower left in Figures 2 and 3). With basal melting rates estimated to be just ~0.5 mm/yr at the drill site (K. Taylor, personal communication), continuity considerations suggest that water through flow rates should be of the order of 1 cubic meter per year per meter width of the ice sheet. Such low subglacial water fluxes may be carried either by Darcian water flow through subglacial sediments and rocks or in a subglacial water film ~0.1 mm in thickness. Combination of a subglacial depression and basal melting around the drill site could be interpreted as conditions, which may lead to formation of a subglacial lake. However, examination of existing radar data does not support such interpretation. This is because radar bed reflections do show evidence of localized roughness (Conway et al., 2003; C. Laird, pers. comm. 2008), which is not consistent with flat nature of radar reflections in radar data collected elsewhere over subglacial lakes.

Active seismic surveys performed at the WAIS Divide drill site by the geophysical team from Penn State University (S. Anandakrishnan, pers. comm., April 2008) provide additional evidence against the presence of a subglacial lake in the WAIS Divide depression. In fact, Dr. Anandakrishan's interpretation is that if there is water layer beneath the drill site, its thickness is below the resolution of the seismic survey, which is <2 m. Seismic data do indicate that the drill site is underlain by 10-15 m of sediments that rest on a high-velocity rock layer, which has a lower bounding reflector at ~150 m depth below the ice base.

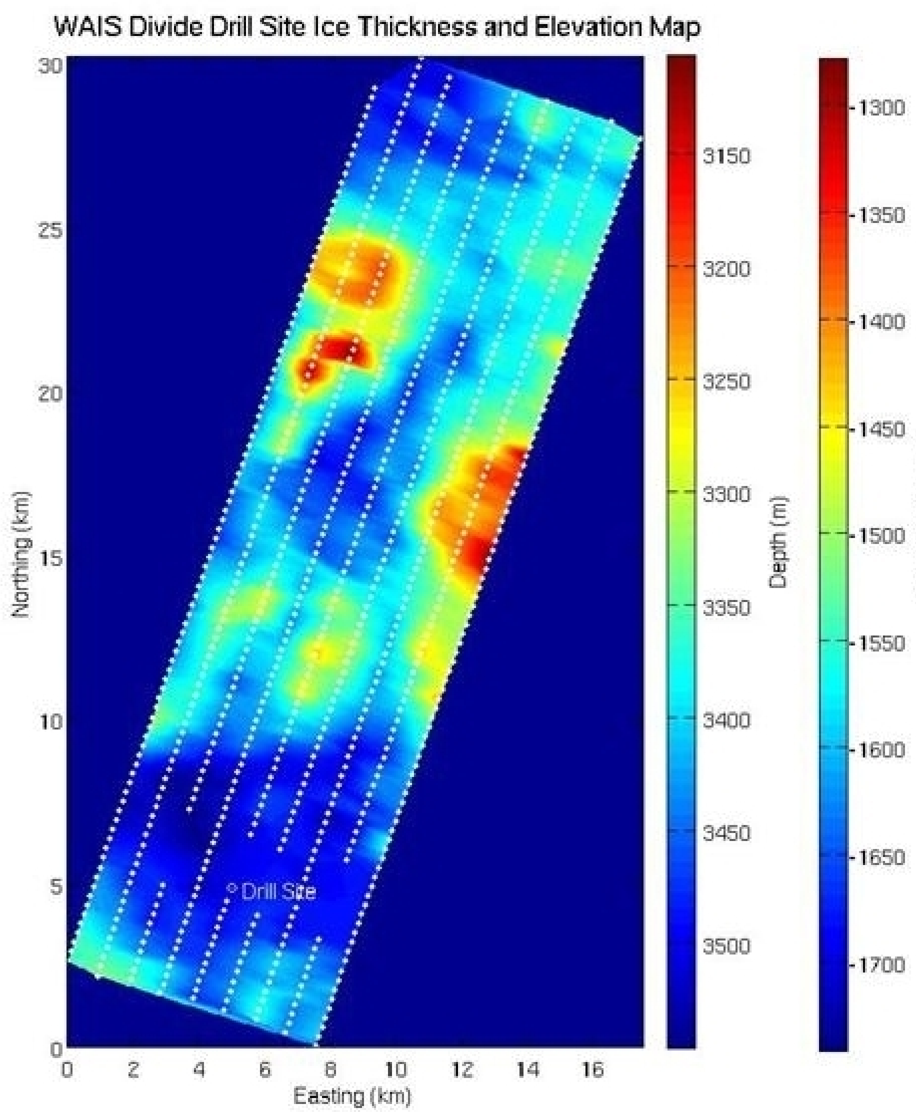

Figure 2. Location of the WAIS divide drill site in the context of regional ice thickness and bed elevation distribution (Figure contributed by Dr. Claude Laird, University of Kansas, based on radar data collected by the CReSIS

This wealth of new geophysical information coming from radar and seismic survey permits us to narrow down the possible range of subglacial conditions that may be encountered during drilling. Originally, we considered four general scenarios for the physical environment at the base of the ice sheet, as shown in Table 1. Based on present information, scenario 1 (Table 1) is the most plausible. Two of the most important remaining unknowns are: (1) the exact thickness of subglacial water layer (water budget calculations suggest nil to <1 mm but direct evidence from seismic only puts the observational constraint at <2m); (2) the consistency of subglacial sediments, which are likely to be more water rich and saturated within a few dm/m of the ice base to more consolidated below that. Sediment strength could vary from nil for liquefied sandy material to the order of 0.1-10MPa for indurated sediments. Technological and operational planning would be greatly aided by further surface or borehole geophysical experiments that will constrain these two fundamental parameters.

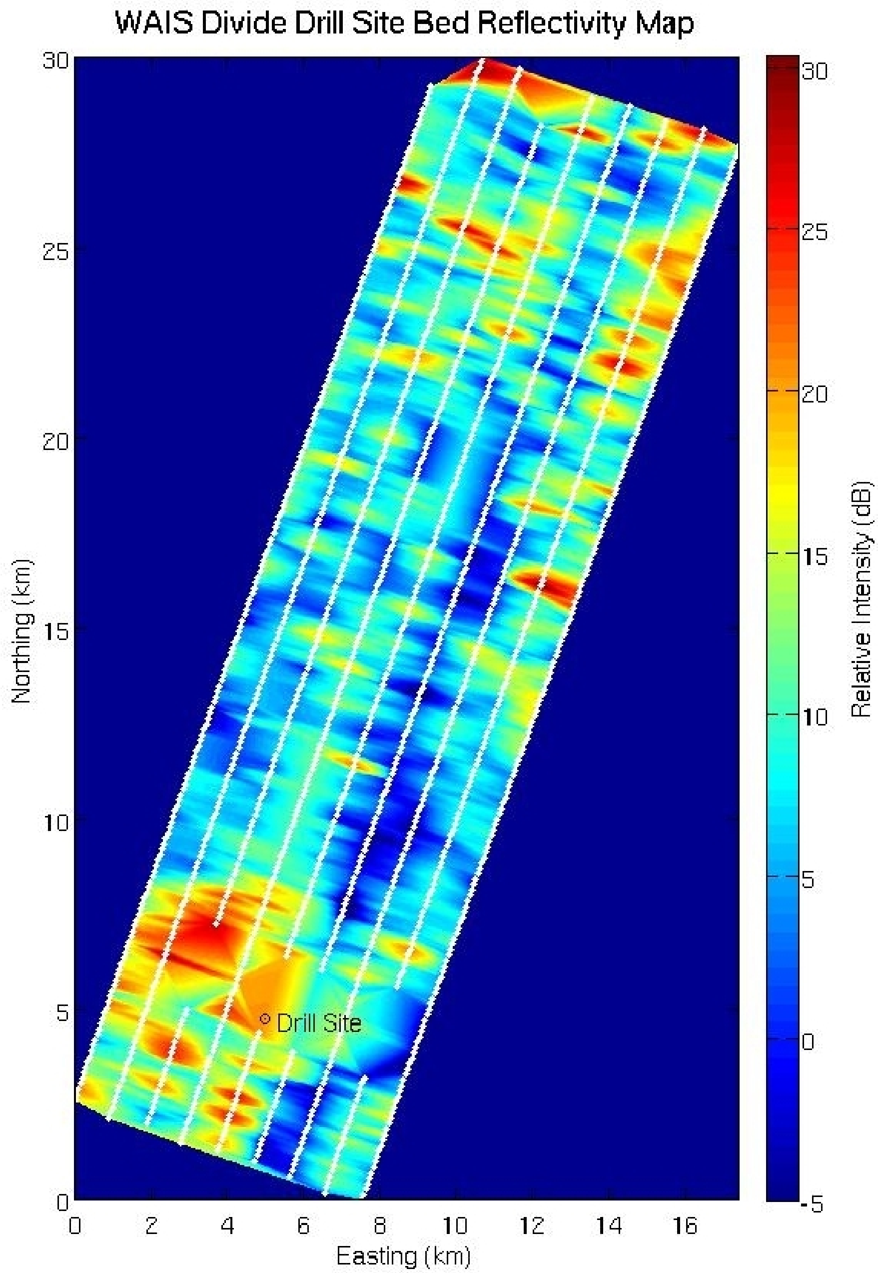

Figure 3. Location of the WAIS divide drill site in the context of regional distribution of bed reflectivity (Figure contributed by Dr. Claude Laird, University of Kansas, based on radar data collected by the CReSIS team). High radar bed reflectivity (red) indicates basal melting whereas low reflectivity suggests frozen bed.

The WAIS Divide project, expected to reach bedrock during the 2011/2012 field season, provides one of the first coordinated scientific and logistic efforts by the US involving glaciologists, geologists, geochemists and biologists. This document presents a science plan, technology requirements, and environmental considerations to guide basal environment research efforts at the WAIS Divide core site.

Basal Ice

Basal ice layers from previous deep boreholes in West Antarctica record interactions with the underlying substrate (e.g. Gow and Williamson, 1976; Gow et al., 1979; Vogel et al., 2006; Christoffersen et al., 2006). Notably the basal ice layers provide information on temporal dynamics of ice and subglacial water flow, understanding of which is crucial to accurate modeling of ice sheet evolution (Russell-Head and Budd, 1979; Vogel et al, 2005). Determination of sediment concentration and distribution in basal ice provides constraints on rates of subglacial erosion and basal sediment transport, which may influence ice sheet dynamics over time scales ranging from tens to millions of years (Alley et al., 2007; Jamieson et al., 2008). Sediments and rock fragments entrained into basal ice provide a unique regional, rather than local, insight since the process of debris entrainment takes place over long time periods at the base of moving ice (Vogel et al., 2003; 2006). In addition, iron nano-particulates incorporated into basal ice may have a significant role in fertilizing the Southern Ocean and facilitating microbial CO_2 uptake in ocean surface waters if basal ice formed in the interior is advected to the ice sheet margin (Raiswell et al., 2008).

Table 1. Possible basal material scenarios at the WAIS Divide drill site

Scenario 1	Scenario 2	Scenario 3	Scenario 4
basal ice	basal ice	basal ice	basal ice
water (<mm thick)	water (cm's thick)	no water	no water
wet sediment (m thick)	no sediment	frozen sediment	no sediment
bedrock	bedrock	bedrock	bedrock

The high sediment content of the debris-rich basal layers appears to be a nutrient and carbon source for microorganisms (Skidmore et al., 2000; Sheridan et al., 2003; Miteva et al., 2004). This contention has been corroborated by the gas composition of the basal ice from ice cores which imply in situ biogenic production (e.g., N_2O, CH_4, CO_2; Campen et al., 2003; Souchez et al., 1995; Tung et al, 2005; Tison et al., 1998). Interconnected liquid veins along three-grain boundaries in ice have been suggested as a habitat suitable for microbial activity in glacial ice (Price, 2000; Mader et al., 2006) and microbial activity in laboratory ice has been demonstrated to occur at temperatures as low at -32^{o}C Miteva et al. (2007). Collectively, these data indicate that the basal ice zone is an active microbial habitat due to the relatively warm temperatures > -5°C, the availability of thermodynamically favorable redox couples required to support biological metabolism, and the presence of silt and clay sized particles (cf. GISP2; GRIP) that may provide a nutrient source for the microbes (Tung et al., 2006). Basal ice can also provide important information on the microbiology and associated biogeochemical processes underlying the subglacial environment (e.g., Priscu et al., 1999; Skidmore et al., 2000; Christner et al., 2006).

Basal water

Basal waters from beneath the Antarctic Ice sheet have rarely been sampled directly. Water samples were collected by Kamb and colleagues from beneath the Kamb Ice Stream, in 2000, however the sampling was opportunistic from the top of the coring apparatus and no specific precautions were taken to minimize biological and geochemical contamination. The opportunistic nature of the samples limited the number and type of biological and geochemical analyses that could be performed on the samples (Vogel et al., 2008; Lanoil et al., in press). The biogeochemical and microbiological composition of surficial waters of subglacial Lake Vostok have been inferred from the accreted ice at the base of the Vostok ice core (e.g. Priscu et al., 1999; Karl et al., 1999; Christner et al., 2006; Priscu et al., 2007). Sampling of basal water from beneath the WAIS divide core would provide the first direct samples of sub-ice sheet waters where precautions have been taken to maintain their integrity and minimize contamination of both the samples and the surrounding environment.

Information on the hydrological characteristics of the subglacial water will be essential for calculation of the mass balance of subglacial materials and the supply rate of essential nutrients and removal of metabolic wastes to support microbial activity. The hydraulic turnover (i.e., flushing time) can be addressed by measuring helium 4/3, neon 21/20, and argon 40/36 ratios in the basal water, because the heavier isotope is radiogenically produced in sediments and should accumulate at a known rate beneath an ice sheet if flow rates are low in the sub-ice hydrological system (e.g. Poreda et al., 2004). The melting rate, inferred from the measured basal heat flux and ice flow modeling, gives the input of atmospheric gases to the system. The degree to which these ratios in the subglacial waters are atmospheric gives the effective flushing efficiency of the system, or the connectivity to the outside environment. The absolute gas abundance (pressure) of nitrogen and argon-36 also gives an indicator of the flushing time, because these gases are dominantly being delivered by melt and removed by hydrological flow, and at steady state these fluxes must be equal.

The dissolved and particulate matter chemistry in concert with dissolved reactive gases will also provide information on basal water origins, hydrological conditions, and biogeochemical weathering processes (Tranter et al., 2005). Chloride (Cl^-) is a geochemically and microbially conservative element whose sources are ice melt and subglacial porewater, assuming that halite is absent in the subglacial sediments/bedrock. Ice melt would generate low Cl^- concentrations (~ 8 µM; Kreutz et al., 1998) whereas ancient seawater would have orders of magnitude higher Cl^- concentrations (~ 468,000 µM; Holland, 1978). Thus Cl^- concentrations would provide a first order constraint on the proportions of ice melt and ancient seawater than contribute to the subglacial water. The major anion and cation composition of the waters will provide information the types and proportions of mineral weathering in the subglacial environment (Skidmore and Sharp, 1999; Anderson et al., 2000; Tranter et al., 2002) and the isotopic composition of certain anions e.g. SO_4^{2-}, NO_3^- and HCO_3^- will provide information on the source materials for these dissolved constituents. For example the $\delta^{34}S$-SO_4^{-2} is significantly different if pyrite is the source vs. gypsum/anhydrite (Bottrell and Tranter, 2002; Skidmore et al., 2005) and if the major SO_4^{-2} source is pyrite oxidation then the $\delta^{18}O$-SO_4^{-2} is diagnostic for oxidation of pyrite under aerobic vs. anaerobic conditions (Bottrell and Tranter, 2002).

The oxidation state of subglacial fluid is also an important variable that is governed by metabolic activity and the flux of gases to the fluid itself (Skidmore et al., 2000). For example molecular oxygen is constantly delivered during melting of the overlying ice sheet, whereas reduced gases (e.g., H_2, CH_4, H_2S) may be delivered from the subglacial sediments and/or bedrock (Wadham et al., 2008). It will be important to determine which flux dominates, and what role these gases have on microbial activity and conversely, how microbial metabolism influences these gases. Calculations based on gas supply from the overlying ice sheet to Lake Vostok indicate that dissolved oxygen levels within the subglacial lake exceed those in the surface ocean by 50-fold, a situation that could influence biological activity in the surface waters of the lake (McKay et al., 2003). Further calculations for the Vostok system showed that, once this oxygen concentration is reached, the remaining oxygen originating from the melting ice sheet should form clathrates. Based on the hydraulic retention time of the Vostok basin, McKay et al. estimated that 30% of the water in the lake may be associated with the icy cages of the clathrates.

The presence of liquid water has been shown to be the key to life on our planet: where there is free water there is biological activity (Priscu et al., 1998; 1999; Karl et al., 1999; Price, 2000). The basal environment beneath the WAIS Divide site is likely to have started as a marine environment that was covered by ice, and has been effectively isolated from the rest of Earth's biosphere for more than 100,000 years. An integrated investigation of the phylogenetic and metabolic diversity of the microbial assemblage and its role in biogeochemical processes in this basal water layer has never been accomplished. Such a study will yield new information on the structure and function of these novel subglacial systems. Investigations of the subglacial paleomarine environments beneath the West Antarctic Ice Sheet will complement ongoing research on subglacial environments beneath the East Antarctic ice sheet (e.g., Lake Vostok), which is not of paleomarine origin.

Subglacial Sediments

The base of an ice sheet or glacier is, typically, underlain by a layer of subglacial till; sedimentary material that has been transported during ice motion. Such a till layer is frequently decimeters to meters thick. Similar to sediments entrained into basal ice, the composition of subglacial till is representative of the regional geologic setting upstream of a given sampling site. For instance, analyses of data from North America indicated that coarse size fractions in subglacial sediments are typically derived from materials located within 1 to 10 km of a sampling site whereas the mud fraction may come from as far away as 100 to 1000 km (Clark, 1987). The geologic setting of the WAIS ice coring site is inferred from regional aerogeophysical surveys, and it may belong to a relatively young subglacial volcanic province (Behrendt et al., 1994; Blankenship et al., 2001; Studinger, 2001). The presence of active subglacial volcanism or geothermal activity has important implications not only to interpretations of the geologic history of the region, but also to the issue of ice stream stability, as it is expected that volcanic eruptions and the associated increased subglacial water production may destabilize parts of the ice sheet (Blankenship et al., 1993; Corr and Vaughan, 2008; Vogel, 2008). The WAIS core site is located on a flank of the Bentley Subglacial Trench and within the region of high amplitude aeromagnetic anomalies that have been used to argue for the subglacial presence of relatively young basaltic volcanic centers. Analysis of subglacial sediment provenance combined with isotopic dating of any volcanic rock fragments will provide important constraints on the intriguing possibility that the West Antarctic ice sheet has experienced significant interactions with active subglacial volcanism. Volcanic CO_2 has a $\delta^{13}C$ value of – 2 to -6 ‰, compared to microbial CO_2 with a $\delta^{13}C$ value of ~ – 25 ‰ (Faure and Mensing, 2006). Similarly for CH_4, geogenic methane has $\delta^{13}C$ values from -15 to -40 ‰ whereas biogenic methane has $\delta^{13}C$ values of < -50 ‰ (Whiticar et al., 1986; Clark and Fritz, 1997). Thus, the measurement of selected noble gases in concert with measurements of the CO_2/N_2 ratio, $\delta^{13}C$-CO_2, $\delta^{13}C$-CH_4 and $\delta^{13}C$-HCO_3^- of the sediment porewaters will also provide novel information on the importance of volcanic activity in the vicinity of the drilling WAIS Divide site.

Geotechnical and hydrological properties of the subglacial material from beneath the WAIS Divide core site represent data that are needed to develop reliable parameterizations of subglacial mechanical and hydrologic processes important in quantitative modeling of ice flow and its variability (e.g. Johnson and Fastook, 2002; Bougamont et al., 2003). The stable isotopic composition of pore water may provide data that will enable reconstruction of the subglacial hydrological history at the site over timescales of decades to centuries (Vogel and Tulaczyk, 2008). This is because a subglacial sediment layer acts as a diffusive column and vertical variations in the stable isotopic composition of pore water can be interpreted in terms of temporal variations of water composition at the ice-base interface. Studies of subglacial sediment stratigraphy may also reveal the history of changes in subglacial physical and chemical conditions. Finally, analyses of microfossils and cosmogenic beryllium in subglacial sediments will provide a key constraint on the timing of the last major deglaciation of the area (Scherer et al., 1998). This data is important since there is a dearth of data quantifying the extent to which the West Antarctic ice sheet retreated during past interglacials.

Diatoms and other microfossils recovered to date from beneath the WAIS have proven to be powerful tracers of ice sheet history (Scherer et al., 1998; 2008) and subglacial sedimentary processes (Scherer et al., 2004; Scherer, 2005; Sjunneskog and Scherer, 2005; Sjunneskog et al., 2007). Both marine and non-marine diatoms and diatomaceous clasts have been recovered from all sediment samples recovered from beneath the WAIS and Ross Ice Shelf to date, including sediments from beneath the Whillans and Kamb ice streams (Scherer, 1989a, 1989b; Scherer, 1991; Tulaczyk et al., 1998; 2001a, b; Scherer, 2003; Scherer et al., 1998) and Crary Ice Rise (Scherer, 1992; Scherer et al., 1988). Rare microfossils, excluding diatoms, have been recovered from basal material recovered from the Byrd ice core (Scherer, 1992). Abundant and diverse diatoms have been recovered from short sediment cores extracted from beneath the southern margin of the Ross Ice Shelf at Site J-9 (Harwood and Scherer, 1988; Harwood et al., 1989; Scherer, 1992), and ANDRILL recovered a long and remarkable stratigraphic record of Pliocene and Pleistocene diatoms from beneath the northwestern corner of the Ross Ice Shelf (Scherer et al., 2007). Sediments beneath WAIS Divide are expected to include glacially transported microfossils representing both terrestrial and marine sources, with ages spanning the Cenozoic, plus older palynomorphs and other biogenic traces. Diatoms are fragile particles, and their preservation in subglacial sediment provides insight into physical sediment transport processes, as demonstrated by laboratory experiments (Scherer et al., 2004; Scherer, 2005).

Microbial analysis of subglacial sediments collected from beneath the Kamb Ice Stream revealed the presence of a relatively simple bacterial assemblage containing both heterotrophs and chemolithoautotrophs (Lanoil et al., in press). Gene sequence data implied the presence of iron- and sulfide-oxidizing bacteria, i.e. the neutrophilic iron-oxidizers *Gallionella* and the acidiphilic iron- or sulfur-oxidizer *Thiobacillus*. Biologically-driven sulfide oxidation has been proposed as a significant source of sulfate flux at the Bench Glacier in Alaska, an environment with a similar microbial community composition (Skidmore et al., 2005), and is a proposed energy source for the Lake Vostok and Taylor Glacier (Antarctic) microbial communities (Christner et al., 2006; Mikucki and Priscu, 2007). Chemically driven metabolism, coupled with autotrophic carbon dioxide fixation, could explain the energetic basis of subglacial bacteria and their persistence over the long time periods of direct isolation from the atmosphere. Subglacial chemolithoautotrophic metabolism can also provide a source of organic carbon to support subglacial heterotrophic activity supporting an emerging theme that consortia of microorganisms with complementary metabolisms are required to support ecosystems in extreme environments (e.g. Paerl and Priscu, 1998). Lanoil et al. (in press) showed that the basal sediments beneath the Kamb Ice Stream contained 0.5 to 1.5 wt % organic carbon, but the composition of the carbon and thus its potential source was not measured.

Priscu et al. (2008) have argued that, due to the presence of water-saturated sediments at the base of the ice sheet, the subglacial environment of Antarctica should be considered the Earth's largest wetland, with a subglacial aquifer containing between 10^4 and 10^6 km^3 of groundwater. Based on their calculations and the in situ cell abundance reported by Lanoil et al. (in press), they estimate the Antarctic subglacial sediments and the associated aquifer contain ~10^{29} prokaryotic cells. This prokaryotic abundance is more than 1000 times greater than the prokaryotic abundance estimated for all surface freshwaters (lakes and rivers) combined (Whitman et al., 1998). These seminal estimates must be refined by further sampling of the subglacial environment and better estimation of the extent of water-saturated sediments at the base of the Antarctic ice sheets; however, they clearly indicate that Antarctica contains a significant and previously unrecognized reservoir of prokaryotic carbon that should be considered when addressing issues concerning global carbon dynamics and subglacial weathering processes (Sharp et al., 1999; Skidmore et al., 2000; Tranter et al., 2002; Wadham et al., 2008).

Bedrock

The WAIS divide coring site is located in a geologically intriguing setting close to the Bentley Subglacial Trench, the deepest part of the Byrd Subglacial Basin, which at ~2,540 m below sea level represents the deepest depression within any interior part of Earth's continental crust (Figure 4). The origin of such a large depression may be related to the Mesozoic-Cenozoic extensional history of the West Antarctic Rift System (Behrendt et al., 1994). In addition to its geologic significance, the presence of such a significant depression below sea level beneath the main body of the WAIS makes this ice sheet susceptible to rapid collapse if ice sheet retreat allows marine incursion into the region due to marine ice sheet instability (Hughes, 1975; Thomas, 1980). Studies of bedrock samples, and subglacial/basal sediment samples, will improve our understanding of the origin and temporal evolution of bathymetry in this crucial part of West Antarctica. Such information will further advance the existing knowledge of Antarctic ice sheet and climate evolution, which may have been significantly modulated by temporal evolution of Antarctic bathymetry and elevation distribution (DeConto and Pollard, 2003). Geochemical, petrological, and geochronologic analysis of subglacial rock fragments from WAIS divide will provide data to significantly improve our understanding of the spatial structure and temporal evolution of West Antarctic crust and lithosphere. Of particular value will be correlations of subglacial materials to already known equivalents from sparse outcrops provided by nunataks in the ice sheet interior and coastal ranges of West Antarctica (Pankhurst et al., 1998; Elliot and Fanning, 2008).

Recent preliminary reports from active seismic surveys performed at the WAIS drill site by the Penn State geophysical team suggests that the drill site may be underlain by a 10 to 15 m of subglacial sediments resting on a ~150 m layer of high density rocks (S. Anandakrishnan, pers. comm., 2008). The high density of this rock layer, calculated from its seismic properties indicates igneous origin. This opens the possibility that there is a layer of volcanic (perhaps basaltic?) rocks underneath the drill site. If this is the case, it may be possible to directly sample, date, and analyze in detail subglacial volcanics whose presence has been thus far inferred from indirect geophysical data or small rock fragments (Behrendt et al., 1994; Vogel et al., 2006). If possible, acquisition of bedrock, or sediment core should be followed by measurements of subglacial temperature gradients to determine in situ the geothermal flux rate, which is of

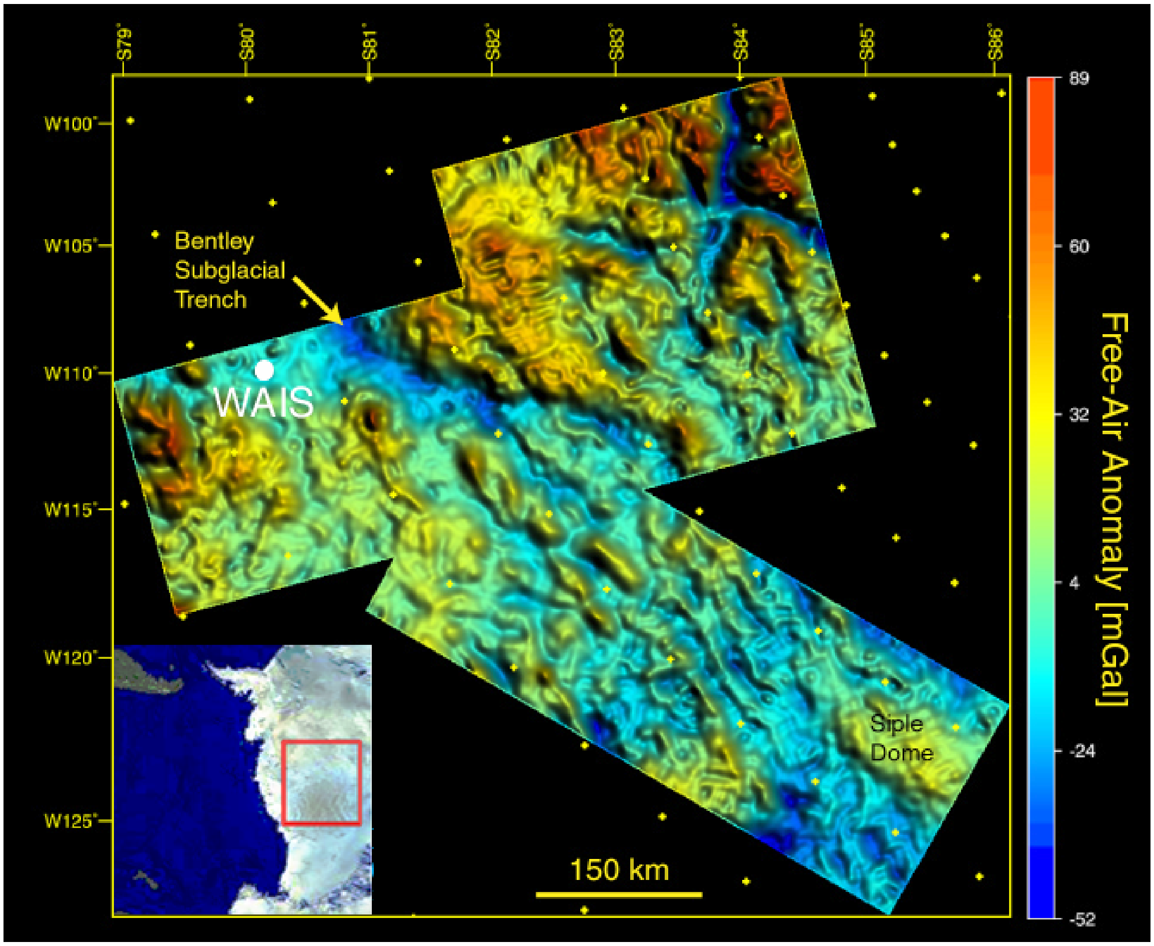

Figure 4. Location of the WAIS Divide drill site (white circle labeled 'WAIS') overlain on a background map of Free-Air Gravity Anomaly. The drill site is located in the vicinity of Bentley Subglacial Trench in an area where the amplitude of gravity anomalies is relatively low (Bell et al., 1999). The inset in lower left shows a satellite image of West Antarctica with the red box indicating location of the main figure. Note that the inset has been rotated so that North is to the left to maintain consistency with the orientation of the main figure itself.

fundamental importance to geophysical and glaciological interpretations but is currently unconstrained in the interior of West Antarctica.

Viable microorganisms have been recovered 1.6 km beneath the sea floor (Roussel et al., 2008), 3.2 to 5 km in South African diamond mines (Lin et al., 2006), 2.3 km below the Earth's surface in sedimentary rocks, and at depths of 5.3 km in deep basaltic aquifers (Pedersen, 2000). These studies reveal that active microbial populations can thrive in deep subsurface environments, including bedrock. Roussel et al. (2008) estimated that the sub-sea floor ecosystem may contain two-thirds of Earth's total prokaryotic biomass. Many of the microorganisms found in these environments are thermophilic Archaea that can derive their energy from reduced chemicals and can grow in the elevated temperatures that persist at these depths. Bulat et al. (2004), studying the accretion ice over Lake Vostok, used He 3/4 data and the presence of gene sequences representing thermophiles to contend that reduced compounds and associated bacteria are advected into the liquid water column through seismo-tectonic

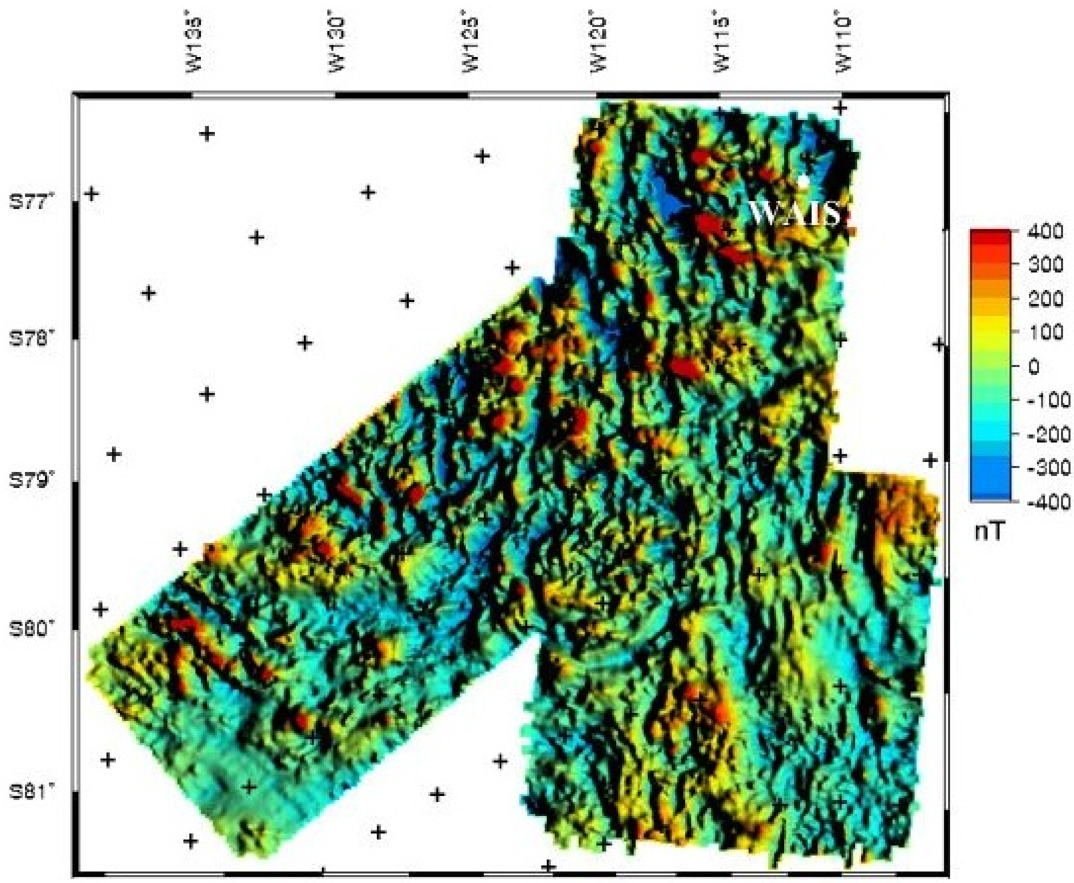

Figure 5. The WAIS Divide drillsite (white circle and label in the upper left) is located in the vicinity of high-amplitude aeromagnetic anomalies which have been interpreted as potential Late Cenozoic volcanic centers (Behrendt et al., 2007). Note that the shape of the survey area is the same as in Figure 4 but orientation differs by 90 degrees.

fissures in the floor of Lake Vostok. These studies provide indirect evidence that active microorganisms can thrive in deep bedrock beneath the East Antarctic Ice Sheet. A systematic microbiological study of the subglacial bedrock at the WAIS Divide core site will provide important information on this novel microbial ecosystem and define its potential importance relative to the basal ice microbial community and the microbial communities in subglacial waters and sediments if those components are present in the basal environment at the WAIS divide site.

Other important questions that can be addressed by bedrock sampling include: (1) the flux of methane from the solid earth beneath the ice sheet; (2) if methane hydrates are present, could they play a role in the collapse of the ice sheet? ; (3) Is there oil under the ice sheet? Measurements of key hydrocarbons (e.g., octane, benzene, toluene) could provide indirect information to address this latter question.

RESEARCH THEMES TO BE ADDRESSED

Overarching themes:

1. The WAIS Divide basal environment is a dynamic ecosystem comprised of four components; basal ice, water, sediment and bedrock that exchange material and energy on differing timeframes. The four components are inhabited by distinct microbial communities dictated by the geochemical and hydrological conditions specific to each component.

2. Geologic materials located beneath the drill site provide archives of past changes in ice sheet extent and dynamics that will elucidate the role of the West Antarctic ice sheet in Antarctic climate evolution.

3. Glaciological investigations of the WAIS divide drill site will improve the ability of ice sheet models to predict how fast West Antarctic ice sheet may collapse if it becomes unstable.

<u>Specific questions:</u>

Glaciological

1. Is there evidence for deglaciation of the interior of West Antarctica during previous interglacial climate stages?
2. What are the modern hydrological and mechanical conditions beneath the central ice reservoir of WAIS and how should they be represented in ice sheet models aimed at predicting future sea level changes?
3. Did these conditions vary over decadal to millennial timescales?
4. Is the basal ice weak and thick and does it play an important role in accommodating ice motion?

5. What are the physical and chemical characteristics of the subglacial hydrological system beneath the WAIS Divide drill site and what role does it play in the ice-sheet wide water drainage system?

Geological

1. What are the rates of subglacial erosion, debris entrainment, and transport in the central part of WAIS and how do they contribute to coupled ice-sediment flow within the ice sheet and to long-term evolution of subglacial topography?
2. Is there evidence for Late Cenozoic subglacial volcanic, geothermal, or hydrothermal activity?
3. What is the history of Cenozoic exhumation rates and extension in the central West Antarctica and to what extent geodynamic processes contributed to creation of deep subglacial troughs in the region?
4. How did the crustal structure of central West Antarctica evolve in the context of broader plate tectonic history of the Antarctic continent?

Geochemical

1. What proportion of the water in the subglacial environments (basal water, subglacial sediments and bedrock) is glacial melt vs. ancient seawater?
2. Does the aqueous geochemistry of the subglacial environments (basal ice, subglacial water, subglacial sediments and bedrock) reflect in situ physical, chemical (abiotic) and biotic processes?
3. Does the mineralogical composition of various size fractions in the basal ice and subglacial sediments reveal differences in transport regimes/rates?
4. Is there evidence for microbial alteration of mineral surfaces in basal ice, subglacial sediments and bedrock samples?

Biological

1. Are basal ice, liquid water, subglacial sediments and bedrock inhabited by distinct prokaryotic assemblages dictated by the geochemical and hydrological conditions specific to each site?
2. Is subglacial heterotrophic microbial metabolism present and limited by nutrient availability?
2. Is heterotrophic subglacial microbial productivity and respiration cold-adapted?
3. Does chemoautotrophy provide a source of reduced carbon to the subglacial environment? If so, is it sufficient to sustain heterotrophic activity?
4. Does subglacial weathering of sediments generate inorganic redox couples that can support chemolithotrophic metabolism?

6. Do prokaryotic assemblages mediate subglacial biogeochemical transformations of C, N and S?

SAMPLES REQUIRED TO ADDRESS THE SCIENTIFIC QUESTIONS

It has to be recognized that either by design or by accident the recovery of basal and subglacial materials may not be as complete as outlined in Table 2. Hence, it is important to consider the potential trade-offs between depth of sample recovery and expected scientific payoffs.

Basal Ice -- In the case of basal ice recovery being limited to the order of ~0.1 m, the

Table 2. Samples that need to be recovered to meet the science requirements, (assuming the specific basal materials are present beneath the ice)

Basal ice	Water	Sediment	Bedrock
Intact 12 cm diameter core for the bottom 25 m to the bed	20 liters: Aseptic/clean sampling for microbiology and geochemistry	➢ Core with 2inch minimum diameter representing the upper 1-10 m of sediment ➢ Intact, undisturbed, oriented core preferred ➢ Aseptic/clean sampling for microbiology and geochemistry	➢ Core with 1.5 inch diameter minimum (3.5 inch or more optimum) representing the upper 1-10 m of bedrock. ➢ Unfractured, oriented core preferred ➢ Aseptic/clean sampling for microbiology and interstitial geochemistry ➢ Limited frictional heating during coring

scientific payoff would be highly limited, mostly to selected microbiology and biochemistry science questions. Recovery of meters to ~25m of basal ice will enable many more scientific studies, including those focusing on glaciological issues concerned with past changes in subglacial hydrology, freezing rates, sediment erosion rates and basal deformation. However, investigations of basal processes pertaining to possible future ice-sheet collapse scenarios would not be possible unless a core of subglacial sediments is also obtained. We expect that some geologic materials in the form of entrained debris can be recovered from a (nearly) complete basal ice core but focused investigations of the time when the site was last deglaciated will likely not be possible. Similarly, characterization of subglacial geology and geochronology would be possible but limited in scope due to sample size limitations. Microbiological and biochemical analyses would be possible and insights into subglacial microbial habitats will likely be gained since we expect that the basal ice incorporates microbes and biochemical compounds from the subglacial environment (e.g. Skidmore et al., 2000). However, the likelihood of high visibility publications documenting subglacial microbial habitats beneath the center of the West Antarctic ice sheet will be highly diminished without direct subglacial sampling.

Water – Recovery of 1L of water would be sufficient to conduct a range of aqueous geochemical analyses including δD and $\delta^{18}O$, major and trace elements, nutrient analyses and redox state of ions in the water, via voltametry. A thorough geochemical and microbial characterization of waters from an Icelandic subglacial lake (from beneath a 300m thick ice cap) has been done with a 0.4 L sample (Gaidos et al., in press). All aqueous samples will require filtration and the microbial cells and sediment trapped on the filters can be utilized for microbial analyses e.g. for cell counts. It may also be possible to measure dissolved gases from a 1L sample but this would likely depend on the concentration of these gases. Basic characterization of the cell concentration and the viability of these cells, both live dead and actively respiring cells in the waters would be possible with a 1L sample. However, if there is low biomass in the subglacial waters, e.g. $10^2 - 10^3$ ml^{-1}, as in deep Antarctic glacial ice, Christner et al., (2006) as opposed to the ~10^5 ml^{-1} in the Gaidos et al. (in press) study, a larger volume sample e.g. 10L would result in more robust analyses.

Subglacial sediments – Recovery of just ~1m of sediments will increase significantly the glaciologic, geologic, geochemical, and biological paybacks, as compared to recovery of basal ice alone. Investigations of sediment strength, composition, and geotechnical properties will elucidate the likelihood inception of fast ice flow in the ice sheet interior in the event of ice sheet collapse. Analyses of microfossils and cosmogenic isotopes may allow determination of the time when this site was last deglaciated. There will be sufficient geologic material for basic geochemical, geochronologic, and mineralogic/petrologic analyses to check for presence of recent subglacial volcanics and to correlate regional subglacial geology with known subaerial outcrops. These samples will likely suffice to perform low-temperature thermochronologic investigations on detrital grains to elucidate Cenozoic thermal evolution of the area and its role in development of subglacial bathymetry.

Subglacial sediments are likely to be a significant microbial habitat due to available chemical energy sources. These measurements would provide the first direct analyses of microbial populations from beneath the WAIS that will be collected and stored using the necessary precautions appropriate for microbial analyses. This data will be highly informative in evaluating the complexity of the subglacial microbial biome and its potential size. Further, an improved understanding of this microbial community may have important implications for understanding microbial survival and activity due to periods in Earth's history when there was pervasive low latitude glaciation ("Snowball Earth"). One meter of sediment core would provide significant material for both microbial and geochemical investigations. Solid phase geochemical analyses are described above. There would be sufficient porewater to conduct a range of aqueous geochemical analyses and microbial analyses as described above in the water section. Additional microbial analyses such as cell counts, microbial activity measurements and for microbial diversity e.g. (16S rRNA gene sequence) could be undertaken on cells extracted from the sediments.

The value of recovering subglacial sediment cores longer than ~1m will depends on subglacial stratigraphy, which is at present unknown. If the 10-15-m-thick sediment layer indicated by seismic surveys represents an accumulation of subglacial till, the value of getting more material is limited for glaciological and geologic investigations. However if a significant redox gradient is present in the till this would be highly significant and useful for microbial analyses as one would expect to find different microbial communities down core as redox conditions change, as is observed in sediment cores from lacustrine and marine settings. However, if the disturbed, subglacial till portion of this sequence is limited to just its upper part, obtaining undisturbed section of subglacial sediments could be of tremendous scientific value, if that section represents an interesting time period, which can be dated and analyzed to constrain preglacial/interglacial paleoclimatic conditions (e.g. Pleistocene/Pliocene/Miocene marine sediments or Eocene/older marine sediments). Unfortunately, subglacial tills can be easily as thin as ~0.1m or as thick as ~10 m, so it is impossible to know a priori whether undisturbed sediments are present at the drill site. It is also impossible to know their age or whether they can be dated. It would be highly valuable if additional geophysical analyses can be conducted to resolve at least some of these uncertainties.

Bedrock – Collection of sediment cores all the way to the bedrock could enable dating when central West Antarctica submerged below sea level, if datable transgressive sediments are present. Acquisition of a bedrock core would be valuable for paleomagnetic studies, to potentially help resolve the contribution of West Antarctic crustal extension to the existing uncertainties in reconstruction of global plate tectonic positions. It is uncertain if sediments overlying the bedrock will reflect its composition or if the bedrock has been simply blanketed by sediments sourced elsewhere. If the latter is the case, obtaining even a short bedrock core (~1m) would greatly enhance the ability of meeting geologic objectives listed above.

SCIENTIFIC REQUIREMENTS FOR DRILLING EQUIPMENT THAT WILL BE USED TO COLLECT THE SAMPLES

Basal ice

The same drill can be used as for the main body of the ice core, however, the drilling head may require modification for the “soft ice” likely to be encountered in the basal zone. Measurements of the ice temperature at ~ 3,400 m when drilling reaches this depth would be helpful in guiding this aspect of the drilling. Scientists should work with ICDS to develop the appropriate technology.

Basal water

Previous ice core drilling projects, e.g. Byrd, NGRIP that encountered basal water allowed the water to freeze in the borehole. At NGRIP this refrozen ice was redrilled, however, analysis of the refrozen ice using NMR in the Priscu Laboratory found drilling fluid throughout the core (cross sections revealed ethanol in the range of 0.1-20 mM, numerous ethylene glycol peaks and peaks in the aromatic/amine and hydrocarbon region) indicating significant mixing with the overlying drill fluid during water movement up borehole and during the refreezing process. It is noted that the rise of water in the NGRIP borehole was not controlled and a more controlled approach may yield less mixing, however this is still not the optimal sampling approach for basal waters. See below for a sampling strategy involving a packer/balloon sampler.

Packer and balloon sampler for basal water

The following idea was provided by Jeff Severinghaus (personal comm. 2008) for water sampling.

> *"Perhaps one could lower a packer attached to the bottom of a modified drill barrel, (it could be deployed) when it is thought that the drill is nearing the bed, to keep the sonde from seeing any water and getting stuck. The packer would have a mechanical shaft feed-through to allow continued drilling/coring below the packer. A detachable ("expendable") coring device would be attached below, so that if it froze in it would not be such a loss as losing the whole sonde. The hole would be underpressured. Sensors would monitor pressure on both sides of the packer and a sensor on the drill head would monitor for the presence of water. If no water is detected, the packer would be deflated at the end of a run and core would be retrieved as normally done. When water is detected, and the pressure below the packer suddenly rises, a basal water sampler intake tube machined into the side of the core barrel could be activated, trapping a sample. A separate flexible but confined reservoir (a balloon in a cage) above the packer, connected to a tube penetrating the packer, would allow a restricted amount of fluid to rush up into the balloon, allowing water to rise up far enough to prevent contamination of the bed. Then, the pressure compensation of the whole borehole could be increased until the measured pressure differential across the packer is nil. Then the packer could be deflated, without having water rush up around the drill, and the drill and sample withdrawn to the surface. Later the hole could be gradually undercompensated to make the water level rise high enough that long-term contamination of the bed is unlikely. Presumably this water would freeze in place over time.*

> *This plan would achieve the twin goals of not losing the drill and not contaminating the bed. It still might mix in a little drill fluid with the water sample, however. But water is denser than drill fluid, so if the intake were located at the very bottom of the drill head one might get lucky and sample pure water. One would be helped by the fact that the water rushing in would only be able to go up as far as the packer, so there might be less turbulent mixing than in the case at NGRIP, where the water rushed in many meters."*

The Russian Antarctic Expedition (RAE) has proposed a similar plan to sample the water from Lake Vostok (V. Lukin, pers comm). Ideally the water will be collected from the basal environment using a sterilized sampler to minimize microbial and geochemical contamination of the basal water. Following Jeff's idea "the balloon" could be manufactured of Tyvek, which is largely chemically and biologically inert. Balloon dimensions of 10 cm "diameter" and 3 m height provide a nominal volume of ~ 23 L. However, as noted earlier this will be the first "clean" sample of basal water from beneath the Antarctic Ice Sheet, thus a few liters of this water would be of significant interest. During the rise to the surface the water sample in the balloon would undoubtedly freeze. The headspace to the balloon would be evacuated at the surface into a gas sampler for gas analysis and any residual drill fluid. It would be advantageous to conduct gas analyses in the field at the drill site. The balloon could then be opened in a laminar flow hood and sectioned for gas, aqueous and microbial samples as for an ice core. Scientists should work with ICDS to examine the feasibility of this technology.

Basal sediment and rock coring

Coring and drilling technologies for acquisition of sediment and bedrock cores are relatively mature and options specific to the WAIS Divide sampling of subglacial material have been discussed at a recent workshop (Vogel et al., in preparation). Operational difficulties may arise from variable consistency of subglacial sediments as well as the presence of flowing and potentially thick water layer at the ice base. Sampling of sediments and rocks for geochemical and biological analysis should follow the same standards of cleanliness as those established for water sampling. Adding microspheres (1 μm diameter) to the core barrel for the sediment coring as is done for Ocean Drilling Project (ODP) sediment cores (ref) would provide a measure of any solid phase penetration from the core exterior to evaluate potential microbial contamination. Acquisition of materials for geologic analyses is less sensitive to conditions during drilling and core recovery. However, since there will be a single sediment/bedrock core used for the geological, geochemical and biological analyses, the coring should induce a minimal amount of frictional heating in order to maintain the sample at close to ambient temperatures ~ < 10^{o}C.

FIELD PLAN, SCHEDULING AND CONFLICT AVOIDANCE WITH BOREHOLE LOGGING

The outline included here follows that from the "Replicate Coring and Borehole Logging Science and Implementation Plan**" and has been prepared** following discussions with the authors' of that plan.

Basal ice sampling is planned for January 2012, based on the current drilling schedule at WAIS divide. Basal waters, sediment and bedrock would ideally be sampled later that same season, assuming that no significant technical problems are encountered.

The timeline for the field component of the research is as follows:

February 2011:	Drilling at WAIS Divide reaches (3465 m) approximate boundary of glacier ice and basal ice. Deformation/temperature/sonic velocity borehole logging activities begin following drilling (1st borehole logging season).
Nov. 2011-Feb. 2012:	Basal ice coring to the bed (~3685m), followed by subglacial water, sediment and bedrock sampling. Deformation/temperature/sonic velocity borehole logging activities occur early season prior to drilling. (2nd borehole logging season).
Nov. 2012	Basal sampling is complete. Borehole temperature logging at WAIS, prior to thermal disturbance of borehole by replicate coring. Optical and deformation logging, prior to disturbance of borehole wall by replicate coring (3rd borehole logging season).

ADVISING THE U.S. SCIENCE COMMUNITY ABOUT BASAL RESEARCH AT THE WAIS DIVIDE SITE

A "dear colleague" letter should be posted on the NSF-OPP website informing scientists of the planned sampling strategy and the request for an environmental permit. Other venues for the dear colleague letter include the Texas A&M University Polar Science Programs email notification system called "ANtarctic Science WEb Resource" (ANSWER).

CURATION AND ALLOCATION OF WAIS DIVIDE BASAL SAMPLES

Sample allocation of basal ice samples from the ice core would be determined by the WAIS divide steering committee and the ICWG sample allocation committee. Specific sample allocation would also be based on the science objectives of funded projects and their requirements. A proportion of the core, (the specific amount would be determined by the science requirements of existing funded projects) would be archived at NICL, presuming it is still in operation in 2012.

ENVIRONMENTAL CONSIDERATIONS

The issue of environmental stewardship for the exploration of subglacial environments is important to many parties. No standard protocols have been established for minimizing contamination of subglacial environments, although general guidelines concerning environmental stewardship are provided in the Antarctic Treaty. The Treaty Protocol conditionally supports the exploration of subglacial research and accepted it as a legitimate activity. The fundamental responsibility of all parties subject to the Antarctic Treaty is to maintain the best possible environmental stewardship for all activities, while appreciating that some impacts are acceptable in pursuit of scientific understanding and that these should be mitigated to the extent practicable.

In an attempt to provide guidelines for subglacial lake exploration the U.S. National Science Foundation requested guidance from the U.S. National Academies to suggest a set of environmental and scientific protection standards needed to responsibly explore the subglacial lake environments found under continental-scale ice sheets. In response, the National Research Council of the National Academies created the Committee on the Principles of Environmental and Scientific Stewardship for the Exploration and Study of Subglacial Environments (NRC 2007). The NRC committee was asked to:

- Define levels of "cleanliness" for equipment or devices entering subglacial aquatic environments
- Develop a sound scientific basis for contamination standards recognizing that different stages of exploration may be subject to differing levels of environmental concern
- Recommend the next steps needed to define an overall exploration strategy.
- Consider existing technology with respect to contamination and to highlight potential needs for technological development
- Identify additional scientific studies that are needed to reduce contamination
- To assess whether it is scientifically beneficial to proceed with exploration now versus later; and
- To identify potential targets among the many Antarctic subglacial aquatic environments.

Although tasked specifically to focus on subglacial lakes, the NRC Committee immediately recognized that subglacial lakes may be hydrologically connected through rivers or films of water beneath the ice sheet within distinct drainage basins. The

Committee therefore concluded that all "wet" subglacial environments were within their charge.

The NRC Committee made 13 specific recommendations, all in support of moving forward on efforts to eventually sample, in an integrated fashion, Antarctic subglacial environments. Their first recommendation, which set the stage for all ensuing recommendations, is: "Direct exploration of subglacial aquatic environment is required if we are to understand these unique systems. Exploration of subglacial aquatic environments should proceed and take a conservative approach to stewardship and management while encouraging field research". Despite strong support for subglacial research, their recognized that many fundamental questions remained to be answered about these unique environments. Accordingly, the management of subglacial field research requires responsible environmental stewardship while allowing field work to proceed in accordance with the Antarctic Treaty.

This study was perceived by many as "U.S. centric", despite the fact that the NRC Committee was international. In response to these claims, the SCAR Subglacial Antarctic Lake Exploration (SALE) Scientific Program Group requested that SCAR develop an international code-of-conduct for the Exploration and Research of Subglacial Aquatic Environments. The recommendation was recently approved by the Delegates at XX SCAR. SCAR is now organizing an 8 member international and multidisciplinary Action Group (AG) to address the following terms of reference:

- Review previous SCAR codes of conduct, the process utilized to arrive at consensus, and develop a Code of Conduct format and content consistent with previous documents.

- Define the range of activities required for subglacial Antarctic exploration (SAE) exploration and research in light of the scientific interest of the life sciences, geosciences and physical sciences including:

    - remote surveying techniques;
    - entry/drilling technologies;
    - sampling devices of all types;
    - emplacement of instruments, sensors and observatories of all types;
    - in situ experiments;
    - recovery of artifact-free samples;
    - disturbance-free recovery of samples;
    - logistical access to remote locations;
    - on-site drilling and laboratory facilities;
    - equipment sterilization/cleaning technologies; and
    - others as identified by the AG.

- Develop guiding principles for SAE exploration and research based on best practices and the most likely sources and types of contamination, the efficacy of methods to reduce or eliminate contamination, definitions of acceptable standards of "cleanliness", demonstration of compliance with "cleanliness" standards, variable desired levels of "cleanliness" among activities, and the ability of current technologies to meet "cleanliness" standards by considering:
    - all relevant literature (i.e., planetary protection measures), applicable ATS environmental policies and procedures, expert advice, and any other sources of information and
    - paying special attention to SALE reports and the US National Academies report on environmental stewardship of SAE.

- Complete a work plan, budget and schedule to:
    - provide a draft of the Code of Conduct to be presented to the SCAR Executive Committee meeting in 2009,
    - ensure wide community comment and input including consultation and review by appropriate ATS entities such as COMNAP, and
    - based on community input, reviews by the relevant ATS entities and the SCAR Executive Committee, revise the draft Code of Conduct and communicate its deliberations and recommendations to SCAR SCATS in time to prepare an Information Paper for the ATCM/CEP in 2010.

Clearly, environmental considerations for subglacial environment exploration is moving forward, but currently no standards exist and it remains up to the national programs to define and be satisfied with their level of environmental stewardship.

The NRC (2007) report indicated that any introduction of contaminants (biotic and abiotic) to the subglacial environment be at levels at or below those that presently exist. Unfortunately, we have very little data on conditions that exist beneath the WAIS Divide site. From the biological work done on the Vostok (Priscu et al. 1999, Christner et al. 2006) and the shallow (70-130 m) WAIS Divide ice cores, we know that bacteria in the ice sheet have densities of 10-1000 cells g^{-1} ice. A single subglacial sediment sample from beneath the Kamb Ice Stream revealed bacterial densities of ~ 10^7 cells g^{-1} sediment, which may be an overestimate by 1-2 orders of magnitude owing to warmer storage conditions than those in situ for certain time periods prior to analysis (Lanoil et al. in press). It seems prudent that the WAIS Divide project monitor bacterial densities in the basal ice and drilling fluid as the bed is approached to provide us with the best estimates of background biological contamination. Data from the basal ice and drilling fluid will likely be an underestimate of bacterial densities that occur in actual subglacial sediments based on the Lanoil et al. measurements under the Kamb Ice Stream and those typically found in sediments of lake ecosystems (sediments are typically "hotspots" for microbial activity). Clone libraries of 16S rRNA gene sequences could also be made from drilling fluid and basal ice to determine if phylotypes in these environments are similar to those in the actual subglacial sediments. In addition to microbial measurements, measurements of drilling fluid signatures (e.g., fluorescence, GC-MS, NMR) should be made in any subglacial samples collected (water, sediment or bedrock) to determine the extent to which drilling fluid entered the subglacial environment. These data will be useful not only to determine potential levels of environmental contamination, but will provide scientists with background information which can be used to examine the extent of contamination they have to deal with when processing their samples. Such information will provide a useful starting point for decontamination protocols that will be employed back in the US (e.g. Christner et al. 2005).

Until we see the code-of-conduct produced by SCAR on Antarctic subglacial environment exploration, we can expect that a permit either via an Initial Environmental Evaluation (IEE) and an Environmental Assessment (EA) as a combined environmental document, or a Comprehensive Environmental Impact Evaluation (CEE) will be required to drill the final 25 m of ice to the bed and for any basal sampling (water/sediments/bedrock). An outline of protocols for environmental assessment of subglacial environments is provided in a recent NRC report (NRC, 2007) and should be consulted as appropriate for basal sampling at the WAIS divide site.

The initial IEE/EA for the WAIS divide project in June 2005 raised the possibility of an inadvertent connection to the bed in the main drilling phase, if the radar information on ice thickness was in error. It was noted that this was an "*unlikely possibility but it cannot be excluded.*" In that case a potential release of 1,500 L of drilling fluid, equivalent to draining a ~ 45 m high column in a 20 cm diameter hole, was evaluated. It should be noted that the likelihood of release of drilling fluid into the environment during basal sampling is greater than in the initial drilling phase. Consequently, an evaluation should be made of the possible release of a volume of borehole fluid greater than 1,500 L, as was undertaken for the initial IEE/EA

A prudent approach to examine the potential consequences of a release of drilling fluid into the subglacial environment would involve advective transport modeling of a drilling fluid plume using STOMP (Subsurface Transport Over Multiple Phases) which is parameterized for LNAPL (White and Oostrem, 2000; 2006). However, the toxicity of the drilling fluid mixture to microorganisms and its lithologic reactivity has not been thoroughly tested though the kerosene-based fluid in the Vostok borehole has been show to support the growth of hydrocarbon degrading microorganisms (Alekhina et al., 2007). A suite of laboratory experiments at *in situ* sub-ice sheet temperatures and pressures examining the interactions of drill fluids with subglacial tills and cold tolerant microbial isolates would aid in evaluating the biogeochemical impact of a drill fluid release on the subglacial environment.

REFERENCES

NRC. 2003. Frontiers in Polar Biology in the Genomic Era. The National Academies Press, Washington D.C. 166 p. Authors: Detrich, H.W., J.W. Deming, C. Fraser, J.T. Holibaugh, W.M. Mohn, J.C. Priscu, G.N. Somero, M.F. Thomashow and D. H. Wall.

NRC. 2005. Prevention of the Forward Contamination of Mars. The National Academies Press, Washington D.C. 167 p. Authors: Chyba C.F., S. Clifford, A. Delamere, M.S. Favero, E.J. Mathur, J.C. Niehoff , G.G. Ori, D.A. Paige, A. Pearson, J.C. Priscu, M.S. Race, M.L. Sogin and C. Tacaks-Vesbach.

NRC. 2007. Exploration of Antarctic Subglacial Aquatic Environments: Environmental and Scientific Stewardship. The National Academies Press, Washington D.C. 166 p. Authors: Hobbie J.E., A. Baker, G. Clarke, P.T. Doran, D. Karl, B. Methe, H. Miller, S.B. Mukasa, M. Race, W. Vincent, D. Walton and J. White.

Alekhina, I.A., D. Marie, J.R. Petit, V.V. Lukin, V.M. Zubkov and S.A. Bulat. 2007. Molecular analysis of bacterial diversity in kerosene-based drilling fluid from the deep ice borehole at Vostok, East Antarctica. FEMS Microbiology Ecology. 59: 289–299.

Alley, R.B., S. Anandakrishnan, T.K. Dupont, B.R. Parizek and D. Pollard. 2007. Effect of sedimentation on ice-sheet grounding-line stability. Science. 315:1838-1841. doi:10.1126/science,1138396.

Anderson, S.P., J.I. Drever, C.D. Frost and P. Holden. 2000. Chemical weathering in the foreland of a retreating glacier. Geochimica et Cosmochimica Acta. 64:1173-1189.

Bakermans, C. 2008. Limits for microbial life at subzero temperatures, p. 17-28. In: Margesin R., F. Schinner, J.-C. Marx and C. Gerday (eds.), Psychrophiles: from Biodiversity to Biotechnology. Springer-Verlag, Berlin.

Behrendt, J.C., D.D. Blankenship, C.A. Finn, R.E. Bell, R.E. Sweeney, S.M. Hodge and J.M. Brozena. 1994. Casertz Aeromagnetic Data Reveal Late Cenozoic Flood Basalts (Questionable) in the West Antarctic Rift System. Geology. 22:527-530

Bell, R.E., V.A. Childers, R.A. Arko, D.D. Blankenship and J.M. Brozena. 1999. Airborne gravity and precise positioning for geologic applications: Journal of Geophysical Research-Solid Earth. 104:15281-15292.

Bell, R.E., M. Studinger, C.A. Shuman, M.A. Fahnestock and I. Joughin. 2007. Large subglacial lakes in East Antarctica at the onset of fast-flowing ice streams. Nature. 445: 904-907.

Bindschadler, R.A., S.N. Stephenson, D.R. Macayeal and S. Shabtaie. 1987. Ice Dynamics at the Mouth of Ice Stream-B, Antarctica. Journal of Geophysical Research-Solid Earth and Planets. 92:8885-8894.

Blankenship, D., D.L. Morse, C.A. Finn, R.E. Bell, M.E. Peters, D. Kempf, S.M. Hodge, M. Studinger, J.C. Behrendt and J.M. Brozena. 2001. Geologic controls on the initiation of rapid basal motion for West Antarctic ice streams, p. 123-136. In: R.B. Alley and R. Bindschadler (eds.), The West Antarctic ice sheet: behavior and environment, Volume 77, Antarctic Research Series. Washington D.C., AGU.

Blankenship, D.D., R.E. Bell, S.M. Hodge, J.M. Brozena, J.C. Behrendt and C.A. Finn. 1993. Active Volcanism beneath the West Antarctic Ice-Sheet and Implications for Ice-Sheet Stability. Nature. 361:526-529.

Bottrell, S. and M. Tranter. 2002. Sulphide oxidation under partially anoxic conditions at the bed of the Haut Glacier d'Arolla, Switzerland. Hydrological Processes. 16:2363-2368.

Bougamont, M., S. Tulaczyk and I. Joughin. 2003. Response of subglacial sediments to basal freeze-on 2. Application in numerical modeling of the recent stoppage of Ice Stream C, West Antarctica. Journal of Geophysical Research-Solid Earth. 108.

Bulat, S.A., I.A. Alekhina, M. Blot, J.-R. Petit, M. de Angelis, D. Wagenbach, V.Y. Lipenkov, L.P. Vasilyeva, D.M. Wloch, D. Raynaud and V.V. Lukin. 2004. DNA signature of thermophilic bacteria from the aged accretion ice of Lake Vostok, Antarctica: implications for searching for life in extreme icy environments. International Journal of Astrobiology. 3:1–12.

Campen, R.K., T. Sowers and R.B. Alley. 2003. Evidence of microbial consortia metabolizing within a low-latitude mountain glacier. Geology. 31:231-234.

Christner, B.C., G. Royston-Bishop, C.F. Foreman, B.R. Arnold, M. Tranter, K.A. Welch, W. B. Lyons, A.I. Tsapin, M. Studinger and J.C. Priscu. 2006. Limnological conditions in Subglacial Lake Vostok, Antarctica. Limnology and Oceanography. 51:2485-2501.

Christner, B.C., M. L. Skidmore, J.C. Priscu, M. Tranter and C.M. Foreman. 2008. Bacteria in Subglacial Environments, p. 51-71. In: R. Margesin, F. Schinner, J.-C. Marx and C. Gerday (eds.), Psychrophiles: from Biodiversity to Biotechnology. Springer-Verlag, Berlin.

Christoffersen, P., S. Tulaczyk, F.D. Carsey and A.E. Behar. 2006. A quantitative framework for interpretation of basal ice facies formed by ice accretion over subglacial sediment. Journal of Geophysical Research-Earth Surface. 111.

Clark, P.U. 1987. Subglacial sediment dispersal and till composition. Journal of Geology. 95:527-541.

Clark, I. and P. Fritz. 1997. Environmental Isotopes in Hydrogeology. CRC Press, Boca Raton, FL, USA.

Corr, H.F.J. and D.G. Vaughan. 2008. A recent volcanic eruption beneath the West Antarctic ice sheet. Nature Geoscience. 1:122-125.

DeConto, R.M. and D. Pollard. 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO2. Nature. 421: 245-249.

Elliot, D.H. and C.M. Fanning. 2008. Detrital zircons from upper Permian and lower Triassic Victoria Group sandstones, Shackleton Glacier region, Antarctica: Evidence for multiple sources along the Gondwana plate margin. Gondwana Research. 13: 259-274.

Faure, G. and T.M. Mensing. 2006. Isotopes: Principles and Applications. John Wiley and Sons, Hoboken, NJ, USA.

Fricker, H.A., T. Scambos, R. Bindschadler and L. Padman. 2007. An active subglacial water system in West Antarctica mapped from space. Science. 315:1544 -1548.

Gaidos, E., V. Marteinsson, T. Thorsteinsson, T. Jóhannesson,Á.R Rafnsson, A. Stefánsson, B. Glazer, B. Lanoil, M. Skidmore, S.K. Han, M. Miller, A. Rusch and W. Foo, (in press) An oligarchic microbial assemblage in the anoxic bottom waters of a volcanic subglacial lake. ISME Journal: Multidisciplinary Journal of Microbial Ecology.

Gow, A.J., S. Epstein and W. Sheehy. 1979. On the origin of stratified debris in ice cores from the bottom of the Antarctic ice sheet. Journal of Glaciology. 23:185-192.

Gow, A.J. and T. Williamson. 1976. Rheological implications of internal structure and crystal fabrics of West Antarctic Ice Sheet as revealed by deep core drilling at Byrd Station. Geological Society of America Bulletin. 87:1665-1677

Gray, L., I. Joughin, S. Tulaczyk, V.B. Spikes, R. Bindschadler and K. Jezek. 2005. Evidence for subglacial water transport in the West Antarctic Ice Sheet through three-dimensional satellite radar interferometry. Geophysical Research Letters. 32:L03501.

Harwood, D.M., R.P. Scherer and P.N. Webb. 1989. Multiple Miocene Marine Productivity Events in West Antarctica as Recorded in Upper Miocene Sediments beneath the Ross Ice Shelf (Site J-9). Marine Micropaleontology. 15: 91-115.

Harwood, D.M. and R.P. Scherer. 1988. Diatom biostratigraphy and paleoenvironmental significance of reworked Miocene diatomaceous clasts in sediments from RISP Site J-9. Antarctic Journal of the United States. 23:31-34.

Holland, H.D. 1978. The Chemistry of the Atmosphere and Oceans. Wiley and Sons, New York.

Hughes, T. 1975. West Antarctic Ice Sheet - Instability, Disintegration, and Initiation of Ice Ages. Reviews of Geophysics. 13: 502-526.

Jamieson, S.S.R., N.R.J. Hulton and M. Hagdorn. 2008. Modelling landscape evolution under ice sheets. Geomorphology. 97: 91-108.

Johnson, J. and J.L. Fastook. 2002. Northern Hemisphere glaciation and its sensitivity to basal melt water. Quaternary International. 95-6:65-74

Jepsen, S.M, J.C. Priscu, R.E. Grimm and M.A. Bullock. 2007. The Potential for Lithoautotrophic Life on Mars: Application to Shallow Interfacial-Water Environments. Astrobiology. 7:342-354.

Kamb, B. 2001. Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion, p. 157-200. In: R.B. Alley and R. Bindschadler (eds.), The West Antarctic ice sheet: behavior and environment, Volume 77, Antarctic Research Series. American Geophysical Union , Washington, DC.

Karl, D.M., D.F. Bird, K. Bjorkman, T. Houlihan, R. Shackelford and L. Tupas. 1999. Microorganisms in the accreted ice of Lake Vostok, Antarctica. Science. 286:2144-2147.

Kreutz, K.J., P.A. Mayewski, S.I. Whitlow and M.S. Twickler. 1998. Limited migration of soluble ionic species in a Siple Dome, Antarctica, ice core. Annals of Glaciology. 27:371-377.

Lanoil, B., M. Skidmore, J.C. Priscu, S.-K. Han, W. Foo, S.W. Vogel, S. Tulaczyk and H. Engelhardt. In press. Bacteria beneath the West Antarctic Ice Sheet. Environmental Microbiology.

Lin, L., P. Wang, D. Rumble, J. Lippmann-Pipke, E. Boice, L.M. Pratt, B. Sherwood-Lollar, E. L. Brodie, T.C. Hazen, G.L. Andersen, T.Z. DeSantis, D.P. Moser, D. Kershaw and T.C. Onstott. 2006. Long-Term Sustainability of a High-Energy, Low-Diversity Crustal Biome. Science. 31:479-482.

Mader, H., M. Pettitt, J. Wadham, E. Wolff and R.J. Parkes. 2006. Subsurface ice as a microbial habitat Geology. 34:169-172.

McKay, C.P., D.T. Andersen, W.H. Pollard, J.L. Heldmann, P.T. Doran, C.H. Fritsen and J.C. Priscu. 2005. Polar Lakes, Streams, and Springs as Analogs for the Hydrological Cycle on Mars, p. 219-233. In: T. Tokano (ed.), Water on Mars and Life (Advances in Astrobiology and Biogeophysics). Springer-Verlag, Berlin, Heidelberg.

McKay, C.P., K.P. Hand, P.T. Doran, D.T. Anderson and J.C. Priscu. 2003. Clathrate formation and the fate of noble and biologically useful gases in Lake Vostok, Antarctica. Geophysical Research Letters. 30:1702. doi:10.1029/2003GL017490

Mikucki, J., and J.C. Priscu. 2007. Bacterial Diversity Associated with Blood Falls, a Subglacial Outflow from the Taylor Glacier, Antarctica. Applied and Environmental Microbiology. 73:4029-4039.

Miteva, V.I., P.P. Sheridan and J.E. Brenchley. 2004. Phylogenetic and Physiological Diversity of Microorganisms Isolated from a Deep Greenland Glacier Ice Core. Applied and Environmental Microbiology. 70:202-213.

Miteva, V., T. Sowers and J. Brenchley. 2007. Production of N_2O by ammonia oxidizing bacteria at subfreezing temperatures as a model for assessing the N_2O anolmalies in the Vostok Ice Core. Geomicrobiology Journal. 24:451-459.

Paerl, H.W. and J.C. Priscu. 1998. Microbial phototrophic, heterotrophic and diazotrophic activities associated with aggregates in the permanent ice cover of Lake Bonney, Antarctica. Microbial Ecology. 36:221-230.

Pankhurst, R.J., S.D. Weaver, J.D. Bradshaw, B.C. Storey, and T.R. Ireland. 1998. Geochronology and geochemistry of pre-Jurassic superterranes in Marie Byrd Land. West Antarctica, Journal of Geophysical Research – Solid Earth. 103:2529-2547.

Pedersen, K. 2000. Exploration of deep intraterrestrial microbial life: current perspectives. FEMS Microbiology Letters. 185:9-16.

Poreda, R.J., A.G. Hunt, W.B. Lyons and K.A.Welch. 2004. The helium isotopic chemistry of Lake Bonney, Taylor Valley, Antarctica: Timing of late Holocene climate change in Antarctica. Aquatic Geochemistry. 10: 353–371.

Price, P.B. 2000. A habitat for psychrophiles in deep Antarctic ice. Proceedings of the National Academy of Science. 97:1247-1251.

Priscu, J.C. and B. Christner. 2004. Earth's Icy Biosphere, p. 130-145. In: A.T. Bull (ed.), Microbial Diversity and Prospecting. ASM Press, Washington, D.C.

Priscu, J.C., E.E. Adams, W. Berry Lyons, M.A. Voytek, D.W. Mogk, R.L. Brown, C.P. McKay, C.D. Takacs, K.A. Welch, C.F. Wolf, J.D. Kirshtein and R. Avci. 1999. Geomicrobiology of subglacial ice above Lake Vostok, Antarctica. Science. 286:2141-2144.

Priscu, J.C., B.C. Christner, C.M. Foreman and G. Royston-Bishop. 2007. Biological Material in Ice Cores, p. 1156-1166. In: S.A. Elias (ed. in chief), Encyclopedia of Quaternary Sciences, Volume 2. Elsevier B.V., UK.

Priscu, J.C., C.H. Fritsen, E.E. Adams, S.J. Giovannoni, H.W. Paerl, C.P. McKay, P.T. Doran, D.A. Gordon, B.D. Lanoil and J.L. Pinckney. 1998. Perennial Antarctic Lake Ice: An Oasis for Life in a Polar Desert. Science. 280:2095-2098.

Priscu, J.C., S. Tulaczyk, M. Studinger, M.C. Kennicutt, B.C. Christner and C.M. Foreman. 2008. Antarctic Subglacial Water: Origin, Evolution and Ecology. In: J. Laybourn-Parry and W. Vincent (eds.), High Latitude Lakes and Rivers. Oxford University Press.

Raiswell, R., L.G. Benning, L. Davidson and M. Tranter. 2008. Nanoparticulate bioavailable iron minerals in icebergs and glaciers. Mineralogical Magazine. 72: 345–348.

Roussel, E.G., M. Cambon Bonavita, J. Querellou, B.A. Cragg, G. Webster, D. Prieur and R. J. Parkes. 2008. Extending the Sub–Sea-Floor Biosphere. Science. 320: 1046.

Russell-Head, D.H. and W.F. Budd. 1979. Ice sheet flow properties from combined borehole shear and ice core studies. Journal of Glaciology. 24:117-130.

Scherer, R.P., D.M. Harwood, S.E. Ishman and P.-N.Webb. 1988. Micropaleontological analysis of sediments from the Crary Ice Rise, Ross Ice Shelf. Antarctic Journal of the United States, 23:34-36.

Scherer, R.P. 1989a. Microfossil assemblages in "deforming till" from Upstream B, West Antarctica: implications for ice stream flow models. Antarctic Journal of the United States. 24:54-55.

Scherer, R.P. 1989b. Paleoenvironments of the West Antarctic interior: microfossil study of sediments below Upstream B. Antarctic Journal of the United States. 24: 56-57.

Scherer, R.P. 1991. Quaternary and Tertiary microfossils from beneath Ice Stream B - Evidence for a dynamic West Antarctic Ice Sheet history. Global and Planetary Change. 90:395-412.

Scherer, R.P. 1992. Diatom paleoproductivity and sediment transport in West Antarctic basins and the Neogene History of the West Antarctic Ice Sheet. Pd.D. Dissertation, The Ohio State University, Columbus, Ohio.

Scherer, R.P., A. Aldahan, S. Tulaczyk, G. Possnert, H. Engelhardt and B. Kamb. 1998. Pleistocene collapse of the West Antarctic ice sheet. Science. 281:82-85.

Scherer, R.P. 2003. Quaternary interglacials and the West Antarctic Ice Sheet, p. 103-112. In: A. Droxler and R. Poore (eds.), Earth's Climate and Orbital Eccentricity: The Marine Isotope Stage 11 Question, AGU Geophysical Monograph # 137. Washington, D.C.

Scherer, R.P., C.M. Sjunneskog, N.R. Iverson and T.S. Hooyer. 2004. Assessing subglacial processes from diatom fragmentation patterns. Geology. 32:557-560.

Scherer, R.P. 2005. Frustules to fragments, diatoms to dust: How degradation of microfossil shape and microstructures can teach us how ice sheets work. Journal of Nanoscience and Nanotechnology. 5:96-99.

Scherer, R., M. Hannah, P. Maffioli, D. Persico, C. Sjunneskog, P. Strong, M. Taviani. 2007. Palaeontologic characterization and analysis of ANDRILL core AND_1b. Terra Antartica. 15:223-254.

Scherer, R.P., S. Bohaty, R. Dunbar, O. Esper, J. Flores, R. Gersonde, D. Harwood, A. Roberts and M. Taviani. 2008. Antarctic records of precession-paced insolation-driven warming during early Pleistocene Marine Isotope Stage 31. Geophysical Research Letters. 35.

Sharp, M., J. Parkes, B. Cragg, I.J. Fairchild, H. Lamb and M. Tranter. 1999. Widespread bacterial populations at glacier beds and their relationship to rock weathering and carbon cycling. Geology. 27:107-110.

Sheridan, P.P., V.I. Miteva and J.E. Brenchley. 2003. Phylogenetic Analysis of Anaerobic Psychrophilic Enrichment Cultures Obtained from a Greenland Glacier Ice Core. Applied and Environmental Microbiology. 69:2153-2160.

Sjunneskog, C., R. Scherer, A. Aldahan and G. Possnert. 2007. Be-10 in glacial marine sediment of the Ross Sea, Antarctica, a potential tracer of depositional environment and sediment chronology. Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms. 259:576-583.

Sjunneskog, C. and R.P. Scherer. 2005. Mixed diatom assemblages in glacigenic sediment from the central Ross Sea, Antarctica. Palaeogeography Palaeoclimatology Palaeoecology. 218:287-300.

Skidmore, M., S.P. Anderson, M. Sharp, J. Foght and B.D. Lanoil. 2005. Comparison of microbial community compositions of two subglacial environments reveals a possible role for microbes in chemical weathering processes. Applied and Environmental Microbiology. 71:6986-6997.

Skidmore, M.L., J.M. Foght and M.J. Sharp. 2000. Microbial life beneath a high Arctic glacier. Applied and Environmental Microbiology. 66:3214-3220.

Skidmore, M.L. and M.J. Sharp. 1999. Drainage behaviour of a high Arctic polythermal glacier. Annals of Glaciology. 28:209-215.

Souchez, R., M. Lemmens and J. Chappellaz. 1995. Flow-induced mixing in the GRIP basal ice deduced from the CO_2 and CH_4 records. Geophysical Research Letters. 22:41-44.

Studinger, M., R.E. Bell, D.D. Blankenship, C.A. Finn, R.A. Arko, D.L. Morse and I. Joughin. 2001. Subglacial sediments: A regional geological template for ice flow in West Antarctica. Geophysical Research Letters. 28:3493-3496.

Thomas, R.H. 1980. Climatic warming of the West Antarctic Ice Sheet. Nature. 287:759-760.

Truffer, M. and M. Fahnestock. 2007. Rethinking ice sheet time scales. Science. 315:1508-1510.

Tison, J.-L., R. Souchez, E.W. Wolff, J.C. Moore, M.R. Legrand and M. de Angelis. 1998. Is a preglacial biota responsible for enhanced dielectric response in basal ice from the GRIP ice core? Journal of Geophysical Research. 103:18885-18894.

Tranter, M., M.J. Sharp, H.R. Lamb, G.H. Brown, B.P. Hubbard and I.C. Willis. 2002. Geochemical weathering at the bed of Haut Glacier d'Arolla, Switzerland - a new model. Hydrological Processes. 16:959-993.

Tranter, M., M. Skidmore and J. Wadham. 2005. Hydrological controls on microbial communities in subglacial environments. Hydrological Processes. 19:995-998.

Tulaczyk, S., B. Kamb, R.P. Scherer and H.F. Engelhardt. 1998. Sedimentary processes at the base of a West Antarctic ice stream: Constraints from textural and compositional properties of subglacial debris. Journal of Sedimentary Research. 68:487-496.

Tulaczyk, S., B. Kamb and H.F. Engelhardt. 2001a. Estimates of effective stress beneath a modern West Antarctic ice stream from till preconsolidation and void ratio. Boreas. 30:101-114.

Tulaczyk, S.M., R.P. Scherer and C.D. Clark. 2001b. A ploughing model for the origin of weak tills beneath ice streams: a qualitative treatment. Quaternary International. 86:59-70.

Tung, H.C., N.E. Bramall and P.B. Price. 2005. Microbial origin of excess methane in glacial ice and implications for life on Mars. Proceedings of the National Academy of Sciences. 102:18292-18296.

Tung, H.C., P.B. Price, N.E. Bramall and G. Vrdoljak. 2006. Microorganisms metabolizing on clay grains in 3-km-deep Greenland basal ice. Astrobiology. 6:69-86.

Vogel, S.W., Tulaczyk, S., and Joughin, I.R., 2003, Distribution of basal melting and freezing beneath tributaries of Ice Stream C: implication for the Holocene decay of the West Antarctic ice sheet, Annals of Glaciology, Vol 36, Volume 36: Annals of Glaciology, p. 273-282.

Vogel, S.W., S. Tulaczyk, B. Kamb, H. Engelhardt, F.D. Carsey, A.E. Behar, A.L. Lane and I. Joughin. 2005. Subglacial conditions during and after stoppage of an Antarctic Ice Stream: Is reactivation imminent? Geophysical Research Letters. 32.

Vogel, S.W., S. Tulaczyk, S. Carter, P. Renne, B. Turrin and A. Grunow, A. 2006. Geologic constraints on the existence and distribution of West Antarctic subglacial volcanism. Geophysical Research Letters. 33.

Vogel, S.W. 2008. Cryosphere: Fire and ice. Nature Geoscience. 1:91-92.

Vogel, S.W. and S.Tulaczyk. 2008. Porewater Geochemistry. In: M. Pompilio, N.D., C. Gebhardt, D. Helling, G. Kuhn, P. Kyle, R. Mckay, F.Talarico, S. Tulaczyk, S.W. Vogel and T. Wilch (eds.), Chapter 6 - Petrology and geochemistry. In: T.R. Naish, R. D. Powell, R. H. Levy and the ANDRILL-MIS Science Team, Initial Science Results from AND-B, ANDRILL McMurdo Ice Shelf Project, Antarctica, Terra Antarctica, v. 14, Terra Antarctica: Siena, Museo Nazionale dell'Antartide.

Vogel, S.W., S. Tulaczyk and B. Lanoil. 2008. Chemistry of an antarctic subglacial environment: The role of subglacial geochemical processes in global biogeochemical cycles and quantifying subglacial hydrological processes. Geochimica Et Cosmochimica Acta. 72:A987-A987.

Wadham, J., M. Tranter, S. Tulaczyk and M.J. Sharp. 2008. Subglacial methanogenesis: A potential climatic amplifier? Global Biogeochemical Cycles. 22:doi:10.1029/2007GB002951.

White, M.D. and M. Oostrom. 2000. STOMP Subsurface Transport Over Multiple Phase: Theory Guide PNNL-11216 (UC-2010). Pacific Northwest National Laboratory.

White, M. D. and M. Oostrom. 2006. STOMP Subsurface Transport Over Multiple Phase: User's Guide PNNL-15782 (UC-2010). Pacific Northwest National Laboratory.

Whiticar, M.J., E. Faber and M. Schoell. 1986. Biogenic methane formation in marine and freshwater environments: CO_2 reduction vs. acetate fermentation - Isotope evidence. Geochimica et Cosmochimica Acta. 50:693-709.

Whitman, W.B., D.C. Coleman and W.J. Wiebe. 1998. Prokayotes: the unseen majority. Proceedings of the National Academy of Sciences, USA. 95:6578–6583.

Wingham, D.J., M.J. Siegert, A. Shepherd and A.S. Muir. 2006. Rapid discharge connects Antarctic subglacial lakes. Nature. 440:1033-1036.