THE WEST ANTARCTIC ICE SHEET INITIATIVE

A Multidisciplinary Study of Rapid Climate Change and Future Sea Level

2005 WAIS Workshop Agenda

Wednesday, September 28, 2005		
2:00 to 6:00	Registration	Floyd
7:00	Pizza, beer and snacks (cottage #1)	Bindschadler
Thursday September 29, 2005		
8:00	CONTINENTAL BREAKFAST	
8:00	Registration	Floyd
8:30	Welcome and Agenda Review	Bindschadler
8:45	NSF Remarks	Palais/Borg
	Session #1. **Ice Coring**	
9:15	US ITASE Phase 2 Taylor Dome - South Pole Update and Opportunities [PPT]	Mayewski
9:30	Signals of climate change and the Southern Annular Mode in Antarctic stable isotope records [Abstract] [PPT]	Schneider
9:45	A new Deep Ice Sheet Coring (DISC) drill for coring to the bed at the WAIS Divide site [Abstract] [PPT]	Bentley
10:00	ASEP-Coring [Abstract] [PPT]	Alley
10:30	BREAK (30 min.)	
11:00	In Cold Pursuit: the Devious Designs of NSF Grantee W-218-M [Abstract] [PPT]	Andrews

11:15	Poster Introductions (1-2 min. each)	
12:00	Poster Viewing (30 min.)	
12:30	LUNCH (1 hr. 30 min.)	
	***Session #2.* More History**	
2:00	Glacial Geology of the Ohio Range, Antarctica: Constraints on Ice Elevation during the Last Glaciation [Abstract] [PDF]	Ackert
2:15	Post-LGM evolution of Reedy Glacier, Antarctica, as an indicator of current ice sheet stability [Abstract] [PPT]	Bromley
2:30	Evolution of Reedy Glacier from the last glacial maximum to present [Abstract] [PPT]	Todd
2:45	Glacial history of the ridge between Mercer and van der Veen Ice Streams [Abstract] [PPT]	Conway
3:00	Grounding-line incursion into the southernmost Ross Sea - a comparison of lower Scott and Reedy Glaciers [Abstract] [PDF]	Stone
3:15	Can sulfate signatures in ice cores verify the source volcano? [Abstract] [PDF]	Kurbatov
3:30	ASEP-Terrestrial Geology [PDF]	Stone/Hall
4:00	BREAK (45 min.)	
	***Session #3*. Accumulation**	
4:45	Impacts of Accumulation Rate on Firn Properties [Abstract]	Courville
5:00	Mapping accumulation rate by observing the characteristic time scale of microwave emission [Abstract] [PPT]	Steig
5:15	Inferred accumulation and thickness histories near the Ross/Amundsen divide, West Antarctica [Abstract] [PPT]	Neumann
5:30	Influence of ice dynamics on firn layers in the WAIS [Abstract] [PPT]	Gray
5:45	Snow Surface Height Change Induced by 2 Decades Surface Air Temperature Variations Over Antarctic Ice Sheet [Abstract][PPT-contact author]	Li

6:00	Poster Viewing	
6:30	DINNER	
Friday, September 30, 2005		
8:00	CONTINENTAL BREAKFAST	
	Session #4. **Ice Dynamics**	
8:30	WAIS Elevation changes estimated by the ICESat mission so far [Abstract] [PPT]	Smith
8:45	Modeling of Negative Magnetic Anomalies Over the WAIS Partially Constrains Age of Sub-glacial Volcanic Activity [Abstract] [PPT]	Behrendt
9:00	Discontinuous Sediment Cover and "Fast" Ice Flow: Observations from the Upper Reaches of Tributary C1B [Abstract] [PPT]	Peters
9:15	Sediment transport and erosion, and water redistribution, on decadal timescales beneath Rutford Ice Stream [Abstract] [PPT]	Smith
9:30	Control of ice stream stick-slip dynamics by frictional healing [Abstract] [PPT]	Winberry
9:45	Radar Studies of the Trunk and 'Sticky Spot' of Kamb Ice Stream [Abstract] [PPT]	Jacobel
10:00	Subglacial conditions of inland West Antarctica from US-ITASE deep radar reflection analysis [Abstract] [PPT]	Welch
10:15	BREAK (30 min.)	
10:45	ScITESEN - a scientific drilling traverse in West Antarctica investigating the influence of ice-ocean-lithosphere interaction on ice sheet stability, by direct means [Abstract] [PPT]	Vogel
11:00	Integrating satellite observations with modeling: basal shear stress of the Filcher-Ronne Ice Streams, Antarctica [Abstract] [PPT]	Joughin
11:15	Glacier changes in Pine Island Bay and the Antarctica Peninsula from Radarsat-1 2000-2005 [Abstract]	Rignot
11:30	Pine Island Glacier Basin - we have the data, now what does it all mean? [Abstract] [PPT-contact author]	Vaughan
11:45	The rough and the smooth: what the radar saw in PIG [Abstract] [PPT]	Corr
12:00	Summary of the 2004-05 Airborne Geophysical Survey of the Amundsen Sea Embayment, Antarctica (AGASEA) with preliminary	Holt

	results for the Thwaites Glacier catchment [Abstract]	
12:15	Boundary conditions on the Thwaites Glacier Catchment and Walgreen Coast of the West Antarctic Ice Sheet from the AGASEA survey [Abstract]	Young
12:30	ASEP-Ice Dynamics [PPT]	Anandakrishnan/Joughin
1:00	LUNCH (1 hr. 30 min.)	
	Session #5. **Ocean-Ice Interactions**	
2:30	Interaction of the Great Sumatra Earthquake with an Antarctic ice shelf rift: Preliminary results from GPS and seismic observations of a rift on the Amery Ice Shelf 2004-2005 [Abstract] [PPT]	Bassis
2:45	Subsurface melting on iceberg C16 (Ross Sea) [Abstract] [PPT 1 of 2] [PPT 2 of 2] [MOVIE]	Sergienko
3:00	Icebergs Behaving Shelf-ishly: why wait for the Larsen C? [Abstract] [PPT]	Scambos
3:15	Getting into the Zone: Ice Shelf Margins from ICESat [Abstract] [PPT]	Padman
3:30	BREAK (45 min.)	
4:15	Grounding Line Zone Studies Using a Tethered and Well Instrumented ROV/AUV & The world beneath the ice shelves: Let's have a look! [Abstract][PPT]	Scherer
4:30	IPY in the Antarctic Peninsula-Ice Shelves, Oceans, and Climate [Abstract] [PPT]	Domack
4:45	ASEP-Ocean/Ice Interactions [Abstract]	Holland/Jacobs
5:15	Poster Viewing	
6:00	DINNER	
Saturday, October 1, 2005		
8:00	CONTINENTAL BREAKFAST	
	Session #6. **Modeling**	
8:30	Investigating feedbacks between basal sliding, frictional melting, and longitudinal-stress transmission [Abstract] [PPT]	Price

8:45	Effects of anisotropy on ice flow at Siple Dome, West Antarctica [Abstract] [PPT]	Pettit
9:00	Wind-Blown Snow Infilling of a Rift in the Ross Ice Shelf [Abstract] [PPT] [MOVIE]	Leonard
9:15	Recent Antarctic accumulation variability and trends from Polar MM5 [Abstract] [PPT]	Monaghan
9:30	Numerical modelling of ocean-ice interactions under Pine Island Bay's ice shelf [Abstract] [PPT]	Payne
9:45	BREAK (30 min.)	
10:00	Embedded Models: Application to the Ross Sea and Amundsen Sea Sectors, Retreat from LGM [Abstract] [PPT]	Fastook
10:30	Better Physics in Embedded Models: Iceberg arcing and Lake-surface profiles [Abstract] [PPT]	Sargent
10:45	ice streams stop and start: numerical model interpretation of Ross Ice Shelf surface [Abstract] [PDF][MOVIE-contact author]	Hulbe
11:00	Elevation Change Anomalies in West Antarctica - New Windows Into Dynamics of Subglacial Water Flow [Abstract] [PPT]	Tulaczyk
11:15	ASEP-Modeling [Abstract] [PPT]	Johnson/Hulbe/Payne
11:45	Comments by Invited Guests	
12:00	WAIS Program: Activities, Actions and Needs	Bindschadler
12:30	Adjorn	
	Posters	
	New High-resolution VIS/NIR Satellite Image Mosaics of Greenland and Antarctica: MOG and MOA [Abstract]	Bohlander
	Evidence for rapid ice stream margin migration and sudden narrowing of Kamb Ice Stream, Antarctica [Abstract] [TIF]	Catania
	IC, ICPMS and Water Isotope Measurements From the 2002 and 2003 US ITASE [Abstract] [PPT]	Dixon
	Progress on Radiocarbon Dating of Antarctic Marine Sediments [Abstract]	Domack
	The Importance of Small Ice Shelves to Inland Ice [Abstract]	Dupont

	New aeromagnetic and aerogravity survey over the drainage basin of Pine Island Glacier [Abstract] [PPT]	Ferraccioli
	An ultra wideband plane wave radar for mapping near-surface isochronous layers [Abstract]	Gogineni
	Tectonics and glacial-marine sedimentation in Pine Island Bay: Survey plan of an upcoming RV Polarstern cruise [Abstract]	Gohl
	The Holocene Radiocarbon Reservoir Effect in the Western Ross Sea [Abstract]	Hall
	Relict Algal Mats at Reedy Glacier: Radiocarbon Dating at 86S; [Abstract]	Hall
	Headwall Initiation of Ice Stream and Outlet Glacier Onsets: Evidence from Satellite Imagery [Abstract] [PDF]	Hamilton
	Comparing velocity profiles of Byrd Glacier with a simple 2D flow model [Abstract][PPT]	Hofstede
	Dynamics of the Grounding Line of Whillans Ice Stream [Abstract]	Horgan
	Relating Longitudinal Tension, Basal Shear, and Side Shear To Ice-Bed Coupling Beneath Ice Streams[Abstract]	Hughes
	Global Ice Sheet Mapping Orbiter [Abstract] [PDF]	Jezek
	NRC Decadal Survey [DOC]	Jezek
	Seismic Studies of the Amery Ice Shelf, East Antarctica [Abstract] [PPT]	McMahon
	Wideband Radars for Imaging the Bed and Mapping Internal Layers [Abstract]	Paden
	Radar Wave Speed and Attenuation Studies Using Constant Midpoint Profiles on Kamb Ice Stream [Abstract]	Pettersson
	Ice-flow sensitivity to sticky spots, side shear, and buttressing [Abstract]	Parizek
	Proposal for a Collaborative REU Site Program: REAL ICE - Research Experience in Antarctica Linking Ice and Climate Education [Abstract] [PPT]	Pettit
	Flow and thickness history of Siple Dome, West Antarctica [Abstract] [PDF]	Price
	Laboratory Study of Till Rheology [Abstract]	Rathbun
	Self-organizing maps in review: recent applications in polar (paleo)climatology [Abstract]	Reusch
	What ever happened to the Byrd "Snow Cruiser"? [Abstract]	Scambos
	Forget WAIS, Totten is submarine too [Abstract]	Shepherd

	ICESat Altimetry - Lots of Data, Lots of Details [Abstract]	Shuman
	ASTER Imagery of Antarctica: Geographic Coverage, Data Availability and Glaciological Applications [Abstract] [PPT]	Stearns
	Deglaciation of the southern Ellsworth Mountains, Weddell Sea Sector of the West Antarctic Ice Sheet	Todd
	Will Kamb Ice Stream Restart or Get Captured by Whillans Ice Stream? Preliminary Insights From Changes in Ice Surface Velocities in the UpC Area Between 1996 and 2004 [Abstract]	Tulaczyk
	A most beautiful view of Antarctica for the IPY: the Landsat-7 mosaic [Abstract] [PDF]	Vornberger
	Transition Flow of Ice Surrounding Subglacial Lake Vostok [Abstract]	Wang

2013 Agenda

2012 WAIS Workshop

2012 Agenda

Previous Meetings

Glacial Geology of the Ohio Range, Antarctica: Constraints on Ice Elevation during the Last Glaciation

Robert P. Ackert Jr.
Sujoy Mukhopadhyay

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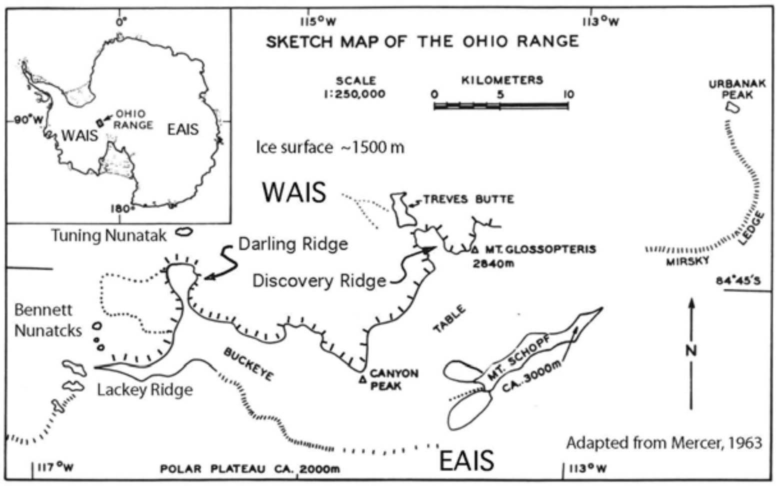
Knowledge of past ice elevations in the Antarctic interior is critical to constrain reconstructions of the West Antarctic Ice Sheet (WAIS) during the last glacial maximum (LGM) and to initialize dynamic ice sheet models of deglaciation following the LGM. Mountains that project through the ice sheet serve as dipsticks that gauge past ice elevations that are recorded by glacial deposits and erosional features preserved on their slopes. The Ohio Range lies at the southern end of the Transantarctic Mountains (85¡S, 114¡W) at the boundary between the East Antarctic Ice Sheet (EAIS) and the WAIS. Near the onset area of the Mercer Ice Stream, the Ohio Range is ideally situated to record past ice elevations in this important sector of the WAIS (Figure 1).

The Ohio Range forms an east-west trending escarpment rising 500 m above the adjacent surface (~1500m) of the WAIS. The escarpment consists of a series of embayments separated by ridges that project into the WAIS and that often are exposed as nunataks beyond the escarpment. Because little ice spills over the escarpment from the Buckeye Table, ice elevations at the base of the escarpment are determined by the adjacent WAIS. Blue ice areas and morainal deposits occur in the lee of the prevailing easterly winds on the west sides of Discovery and Darling Ridge (Figure 1). Mercer (1963) reported the presence of granite erratics 60 m above the adjacent ice surface at Discovery Ridge. During the 2004-2005 field season we visited Discovery Ridge, Darling Ridge. Tuning Nunatak, and the Bennett Nunataks in order to provide constraints on past WAIS elevation at the Ohio Range (Figure 1). The granite cliffs forming the escarpment and nunataks typically exhibit deep cavernous weathering with areas between pits reduced to delicate structures only several centimeters thick (tafoni). The sinuous caverns and pits commonly exceed 50 cm depth and occasionally reach over one meter in size. The granite basement is overlain by sandstone, tillites, coals and shale. At Tuning and Bennett Nunataks (Figure 1), this deeply weathered surface extends to (and presumably beneath) the present ice surface. In many locations, the weathered surface has clearly been overridden by ice. Granite, tillite (particularly molded and striated clasts derived from it) and sandstone clasts occur on and within the cavernously weathered granite on nunataks and in recesses on granite cliff faces where the erratic clasts cannot have fallen from outcrops above. In such locations, the most delicate weathering features have been broken off, resulting in a vandalized appearance. The transition (typically several meters) from such surfaces to those lacking erratics and on which delicate weathering features are preserved is interpreted as a trim line that marks the upper limit of ice during the last high stand of the WAIS while the erratics on the peaks of the nunataks provide minimum constraints.

At Discovery Ridge, granite erratics occur on a terrace at an elevation of 1720 m. The lack of erratics on the sedimentary rocks comprising the slopes above the terrace suggests that the ice level was not significantly higher. A trim line, determined from the lowest elevation of preserved delicate tafoni on the southern end of Treves Butte, immediately adjacent to Discovery Ridge, occurs at ~1750 m, and provides a maximum ice elevation at this location. This result is consistent with the preservation of delicate tafoni in a medium to coarse-grained sandstone layer within the tillite on Discovery Ridge at 1765 m. However, it is not certain this trim line corresponds to the ice that deposited the granite erratics on Discovery ridge or an earlier event. Fresh erratics on rounded and knobby granite bedrock occur to the top of a transect up a flatiron rock formation on the east side of Darling Ridge to 1700 m. Cavernous weathering with delicate tafoni occurs on the cliff about 20m above. A transition from smoothed to deeply weathered rock occurs at a similar elevation on the adjacent ridge line near the northern end of Darling ridge. These features are interpreted as trim lines indicating the WAIS elevation was ~1700 m at Darling Ridge. Based on these observations we conclude that the elevation of the WAIS was approximately 200 m higher during the most recent highstand. These results are the first constraints on maximum ice elevation in this key sector of the ice sheet.

Measurement of cosmogenic nuclides in the erratics and underlying bedrock is underway in order to constrain the timing of ice surface recession in the Ohio Range. Because the summit elevations of the nunataks vary from 1585 m at Tuning Nunatak to 1475 m at the lowest Bennett Nunatak, which is only 13 m above the ice surface, exposure ages of the erratics should document emergence of the nunataks and the rate of down draw of the WAIS in the interior part of the continent. The ubiquitous presence of weathered bedrock surfaces and minimal evidence of glacial erosion, means prior exposure of many erratics is likely. We collected only unweathered angular granite erratics for exposure dating in order to minimize this problem. Although helium is known to diffuse out of quartz, for young samples at Antarctic temperatures, helium appears to be quantitatively retained (Brook et al., 1993). We are in the process of measuring 3He in quartz separates in order to screen the samples for prior exposure before undertaking 10Be and 36Cl analyses. Initial results show that 3He in the quartz is cosmogenic and the 3He concentrations in replicate samples are reproducible. Model exposure ages of three erratics assuming no diffusive loss of 3He range from 4600 yr at Discovery Ridge to 44000 yr at Tuning Nunatak (Figure 1). The younger age provides a minimum estimate for the start of ice recession in the Ohio Range consistent with evidence for propagation of a wave of thinning during deglaciation (Ackert et al., 1999; Conway et al., 1999; Steig et al., 2001; Stone et al., 2003). The older sample may have been deposited during an earlier advance or have prior exposure. Minimum bedrock exposure ages are 130,000 yr at Tuning Nunatak and 1.5 Ma at Bennett Nunataks consistent with the evidence for greater erosion at Tuning Nunatak.


SKETCH MAP OF THE OHIO RANGE
115°W
113°W
SCALE 1:250,000
KILOMETERS
0 5 10
Ice surface ~1500 m
WAIS
TREVES BUTTE
MT. GLOSSOPTERIS 2840m
URBANAK PEAK
LEDGE
MIRSKY
84°45'S
N
Tuning Nunatak
Darling Ridge
Discovery Ridge
Bennett Nunatcks
Lackey Ridge
BUCKEYE
TABLE
CANYON PEAK
MT. SCHOPF
CA. 3000m
Adapted from Mercer, 1963
117°W
POLAR PLATEAU CA. 2000m
EAIS
113°W
0°
90°W
OHIO RANGE
WAIS
EAIS
180°

Good things happening and great things coming: An update on the WAIS Divide Core

R.B. Alley, E. Brook, J. Severinghaus, K. Taylor (Chair) and J. White
(the WAIS Divide Steering Committee, in alphabetical order)

Site selection is accomplished, great effort is advancing drill development, early research is moving to the field, hard work by NSF is putting funding and logistics into place, and the WAIS Divide core really is coming. With the promise of providing the first truly long, high-resolution southern record of climate, ice flow, biology, and related topics, the WAIS Divide core provides a wonderful opportunity for science. Schedule, progress, and options will be discussed.

In Cold Pursuit: the Devious Design of NSF Grantee W-218-M

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Communicating science to the public is tricky business. In an era of information overload and specialization of knowledge, we have by necessity become bridge builders, bringing our understanding to those who benefit from our discoveries and findings. Professional jargon, PowerPoint, and the constraints of technical writing can narrow our audience to a handful of colleagues, isolating our message. Instead of building public trust, this communication bias can create misunderstandings and separation. The success of our projects, the progress of knowledge, and, increasingly, the continuation of funding are at stake.

In Cold Pursuit, a science-based novel (number eleven in the "Em Hansen forensic geology" series) will frankly soft-sell science by conveying Antarctic pursuits in fictionalized form. Lay readers lack the specialized knowledge necessary to read scientific texts and journals, but most love to learn recreationally by reading a well-researched story. As an added bonus, the power of the narrative voice will make the reader a participant in our work, counteracting negative stereotypes of creepy, untrustworthy scientists that are so common in popular literature. Instead, our passion to understand Antarctica will be revealed within the correct story form: the hero's journey. By thus restating the quest for scientific understanding as an archetypal story form, I use the same engine that drives us to the coldest place on Earth in pursuit of knowledge to convey the reader to a place of understanding.

Interaction of the Great Sumatra Earthquake with an Antarctic ice shelf rift: Preliminary results from GPS and seismic observations of a rift on the Amery Ice Shelf 2004-2005

J.N. Bassis, H.A. Fricker, J.B. Minster

Scripps Institutions of Oceanography

Rifts in the Antarctic ice shelves are large through-cutting fractures that penetrate the entire thickness of the shelf. The largest glaciological fractures on Earth, rifts eventually form the boundaries from which large tabular icebergs calve. Despite the important role that iceberg calving plays in the mass balance of the Antarctic ice sheet -accounting for more than two thirds of the total mass lost to the ocean - very little is known about the processes that cause rifts to initiate and, subsequently to propagate. The relative contributions of glaciological and environmental forces to rift propagation are still unknown -- e.g. how do factors such as storms and ocean swell affect rift propagation? To learn more about rift propagation we have been monitoring a rift on the Amery Ice Shelf using seismometers and GPS. Observations from previous field seasons have shown that the rift propagates episodically in bursts that are neither correlated with winds nor tides. Serendipitously, during the latest field season (2004-5) our instruments were deployed one week before the magnitude 9.3 Sumatra earthquake. Not only is the earthquake clearly visible in our seismic records, but we also see the arrival of T-waves (acoustic waves which propagate through the ocean) as well as the tsunami triggered by the earthquake. This presents us with a novel opportunity to not only study the effects of winds and tides, but also whether the earthquake and tsunami influenced rift propagation. We present preliminary results comparing patterns of seismicity before and after the earthquake which we then use to determine if either the earthquake or tsunami were able to trigger a burst in rift propagation. Based on these results, we discuss the implications for how other other external environmental processes which we haven't been able to directly measure (e.g. ocean swell from large storms) might affect propagation.

Model Fit to Negative Magnetic Anomaly over Mt. Resnik, a Subaerially Erupted Volcanic Peak Beneath the West Antarctic Ice Sheet, Partially Constrains the Ages of Subglacial Volcanism.

John C. Behrendt,1,2 Carol A. Finn,2 David Morse,3 Donald D. Blankenship3
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3Institute for Geophysics, University of Texas, Austin

Mt. Resnik, a conical peak (likely a subaerially erupted volcano) 300 m below the surface of the West Antarctic Ice Sheet (WAIS), has ~2 km topographic relief defined by radar ice-sounding of bed topography; it is associated with a complex negative magnetic anomaly revealed by the Central West Antarctica (CWA) aerogeophysical survey. We interpret a magnetic model fit to this anomaly as a volcanic source comprising reversely magnetized (in the present field direction), 0.5-2.5-km thick volcanic flows at the summit overlying normally magnetized flows and a subvolcanic intrusion. The Mt. Resnik 305-nT negative anomaly is part of an approximately 45- by 35-km 600-nT positive anomaly complex extending ~30 km to the west of the Mt. Resnik peak, associated with an underlying source complex of about the same area, whose upper surface is at the bed of the WAIS. However the bed relief of this shallow source complex has a maximum of only ~400 m, whereas the underlying modeled source is >3 km thick. From the spatial relationship, we interpret that this source and Mt Resnik are approximately contemporaneous, but that any subglacially (older?) erupted edifices comprising hyaloclastite or other volcanic debris, which formerly overlaid the source to the west, were removed by the moving WAIS into which they were injected.

The Mt. Resnik volcano was erupted subaerially, during a time of magnetic field reversal from normal to reversed polarity at least as old as 780 Ka (the Brunes-Matuyama reversal). Mt. Resnik is one of five peaks to have an associated negative magnetic anomaly of the previously reported 18 inferred subaerially erupted volcanoes, which have high bed topography beneath the WAIS. There are ~100 short-wavelength, steep-gradient, negative magnetic anomalies observed in the CWA survey, or ~10% of the approximately 1000 short-wavelength, shallow-source, high-amplitude (50->1000 nT) "volcanic" magnetic anomalies observed in this survey. These negative anomalies indicate volcanic activity during a period of magnetic reversal and therefore must also be at least 780 Ka.

The earlier reported (1994) minimum volume of 10 million cubic km of volcanic centers (primarily subvolcanic intrusions) associated with the ice-covered West Antarctic rift system (WR) interpreted from the CASERTZ aeromagnetic survey appears to still be valid now that 10 times more data are available, and implies a large igneous provence of interpreted late Cenozoic age. While the age of the known volcanism in the WAIS area of the WR extends from the present to ~30 Ma and the WAIS has been active since >10 Ma, the age of the ice in the WAIS is 100-200 Ka at most.

A new Deep Ice Sheet Coring (DISC) drill for coring to the bed at the WAIS Divide site

C. R. Bentley
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As a contribution to IPY 2007-2008, the U.S. ice core research community, supported by the National Science Foundation, plans to core through the West Antarctic ice sheet (WAIS) at the ice-flow divide between the Ross Sea and Amundsen Sea drainage systems ("WAIS Divide"). To accomplish the coring a Deep Ice Sheet Coring (DISC) drill is being built at the University of Wisconsin. The modular design of the bore-hole assembly (sonde) provides a high level of flexibility to produce a 122 mm diameter ice core to depths of 4,000 m with maximum core lengths of 4 m. The DISC drill has a rotating outer barrel that can be used without or without an inner non-rotating barrel designed to improve core recovery in brittle ice. The drill utilizes separate and independent motors for the pump and drill allowing cutter speeds from 0 to 150 rpm and pump rates from 0 to 140 gpm. A high speed data acquisition system allows the "real time" monitoring of 30 parameters for operational and scientific use. Data are transmitted from the sonde to the surface through optical fibers contained in the drill cable, which also provides power to the sonde. The drill incorporates a user-friendly "expert" control system. The Quick connectors allow for fast core removal and sonde servicing. The drill tower is a tilting tower utilizing modular truss construction for flexibility and portability. The drill is scheduled for testing in Greenland in the summer of 2006 and for first drilling at the WAIS Divide site late in the 2006-07 austral field season. Our hope is to reach the bed in the 2009-2010 season. Beyond that we plan to develop means for drilling into the bed and for retrieving replicate cores in depth sections of particular interest.

A most beautiful view of Antarctica for the IPY: the Landsat-7 mosaic

Robert Bindschadler, NASA
Jerry Mullins and the EROS Data Center, U.S. Geological Survey
Ted Scambos, National Snow and Ice Data Center
Patricia Vornberger and Hyeungu Choi, Science Applications International Corp.

Landsat imagery has long been sought-after for preparation of maps of fieldwork areas, particularly at proposed aircraft landing sites and surface traverse routes, to assess the safety of travel in these areas. Other sources of image data such as the RAMP, AVHRR, and MOA mosaics, while effective for some applications, are not well-suited for this purpose due to their much coarser resolution or microwave wavelengths. Landsat data are applicable to many of the diverse aspects of Antarctic research due to the unique and valuable combination of fine spatial resolution (as small as 15 meters), relatively large scene coverage (approximately 180km x 180km), and radiometric resolution (5 bands in the visible/near infrared, 2 thermal, 1 panchromatic). Applications include feature mapping, feature tracking, change detection, surface grain size studies, geologic mapping, and use in elevation mapping (shape from shading).

The launch of Landsat-7 in April 1999 was the most recent in a series of these spacecraft that began in 1972, and the ETM+ instrument on board includes improvements to its predecessor, the Thematic Mapper. So a campaign to collect new cloud-free images of the entire Antarctic continent was conducted beginning in September 1999, and nearly 20,000 scenes have been collected since then. Additional annual coverage of coastal and dynamically active regions continues.

With the IPY and its associated major field programs to begin in 2007, the utility of a high-quality, accurately geolocated, high resolution, multi-channel Landsat mosaic available for all researchers to obtain prior to starting fieldwork and other research is obvious. This has been proposed and accepted, and work has begun.

The mosaic comprises about 2000 scenes, chosen from the master collection of almost 20,000. Scene selection is taking place at NASA Goddard Space Flight Center. The digital mosaicking will be conducted at the EROS Data Center, and finally, distribution will occur via the National Snow and Ice Data Center. The poster presented here provides a progress report and we discuss the pertinent issues, problems encountered (both expected and unexpected), and their solutions.

Post-LGM evolution of Reedy Glacier, Antarctica, as an indicator of current ice sheet stability

Gordon Bromley, Brenda Hall, John Stone, Claire Todd, Howard Conway, Maurice Conway

Reedy Glacier (86˚S) is a major outlet glacier of the East Antarctic Ice Sheet which, like many other outlet glaciers flowing into the Ross Sea Embayment, has been shown to respond to volume changes in the West Antarctic Ice Sheet. The advance of grounded ice through the Ross Sea at the Last Glacial Maximum blocked the mouths of the outlet glaciers causing a significant change in surface profile and elevation. Subsequent recession of the Ross Sea grounding line and removal of this damming effect during the Holocene caused lowering and steepening of glacier profiles and the isolation of drift sheets, moraines, and erratics on adjacent mountainsides. In contrast to the older glacial deposits at Reedy Glacier, these LGM-age landforms typically consist of unweathered grey drift and moraines, with widespread buried ice where sediment thickness is sufficient. Because Reedy Glacier currently emerges from the Transantarctic Mountains ~100 km behind the grounding line its surface profile and thickness are still partially controlled by the size and thickness of the West Antarctic Ice Sheet. Mapping of landforms deposited alongside Reedy Glacier at the LGM has revealed changes in surface elevation and profile that are contemporaneous with the Holocene retreat of the Ross Sea grounding line. For example, postglacial thinning has been asynchronous – 40 m at Hatcher Bluffs (head of Reedy Glacier), 140 m at Polygon Spur, 250 m in the Quartz Hills, and at least 110 m at Cohen Nunatak (glacier mouth) – and reflects Holocene thinning of the WAIS. Additionally, simple extrapolation of the LGM surface profile suggests that the nearby West Antarctic Ice Sheet may have been as much as 750 m thicker at the LGM than at present. Ultimately, a fully constrained record of the deglaciation of Reedy Glacier is crucial to ascertaining the current stability of the WAIS and will indicate whether deglaciation of the Ross Sea has ended or is ongoing. The exposure-age chronology of this record will be discussed by Todd *et al*. in the following presentation.

Recent variability and trends in Antarctic snow accumulation from Polar MM5 simulations

David H. Bromwich, Andrew J. Monaghan, and Sheng-Hung Wang

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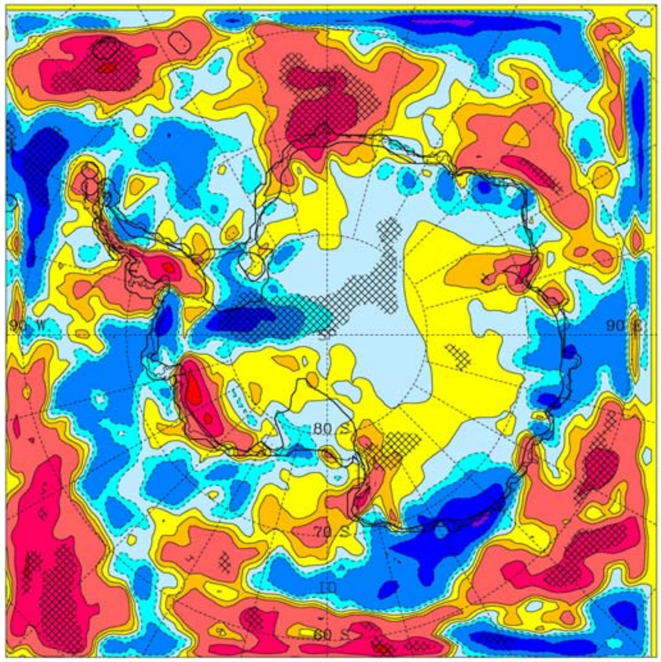
Polar MM5, a mesoscale atmospheric model optimized for use over polar ice sheets, is employed to simulate Antarctic accumulation in recent decades. Two sets of simulations, each with different initial and boundary conditions, have been run for the ~24-y period from January 1979-August 2002. The initial and boundary conditions for the two sets of runs are provided respectively by the (1) European Centre for Medium-Range Weather Forecasts 40-year Reanalysis (ERA-40), and (2) National Centers for Environmental Prediction – Department of Energy Reanalysis II (NCEP-II). This approach has been used so that uncertainty can be assessed by comparing the two resulting data sets.

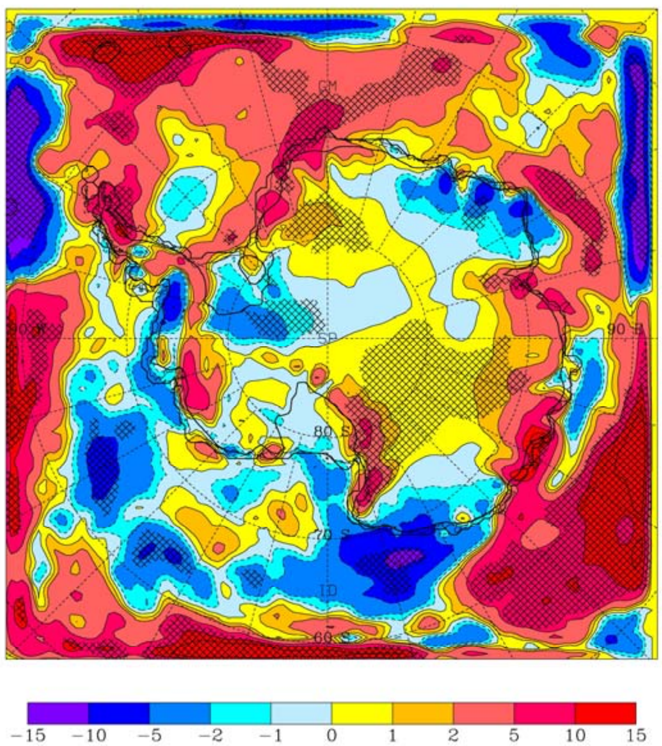
There is broad agreement between the two data sets for the annual precipitation trends for the 17-y period spanning 1985-2001 (Fig. 1). This period is chosen, rather than the entire 1979-2001 period, because agreement between the simulations for the longer period is not as good. The reason for this may be related to adjustments in the ERA-40 assimilation system after the onset of the modern satellite era and prior to the mid-1980s. The trends shown in Fig. 1 generally agree with ice core and snow stake accumulation records at various locations around the continent (not shown). The similarity between the trends for the two runs, as well as their agreement with observations, lends confidence that the trends are robust.

Areas of strong upward and downward trends are apparent in Fig. 1. Statistically significant (at the 90% confidence interval) upward trends are occurring near the Antarctic Peninsula, in the ocean regions north of the coastline at ~0^{o} E and between 105^{o}-150^{o} E, and in the Transantarctic Mountains in Victoria Land. Statistically significant downward trends are occurring just inland of the Ronne-Filchner Ice Shelf. Strong downward trends are also indicated in coastal regions of East Antarctica in both simulations, although these are, for the most part, not statistically significant. Averaged over the continent, the trends in Fig. 1 are small in both simulations, and not statistically significant, suggesting that the role of Antarctica in mitigating sea-level rise in recent years may not be as large as reported by other authors.

Our results indicate that there is an enormous amount of spatial and temporal variability in the Antarctic surface mass balance. The annual variability and trends over Antarctica tend to be the small residual of larger seasonal variability and trends (not shown) that are related to recent climate change.



a) PMM5 E40 Annual Trends



b) PMM5 NN2 Annual Trends

Fig. 1. Annual trends (mm y^{-2}) for 1985-2001 derived from a linear fit through each grid point for the (a) PMM5 E40 and (b) PMM5 NN2 runs. Hatching indicates the trend is significant from zero at the 90% confidence interval.

Evidence for rapid ice stream margin migration and sudden narrowing of Kamb Ice Stream, Antarctica

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High and low-frequency ice-penetrating radar data confirm the presence of two relict ice stream margins representing two different positions for the northern margin of Kamb Ice Stream in West Antarctica. Ice stream margins are identified by surface topographic troughs in satellite images and disrupted internal layers coincident with near-surface buried crevasses. Our data indicate that the shift in margin position occurred roughly 340 years ago (±20 years) and was sudden; burial depth of near-surface crevasses remains constant from one margin to the next but rises steeply one kilometer from the innermost margin. Sudden changes in margin position are likely accomplished through rapid changes in basal conditions beneath the margin and adjacent portions of the ice stream. In this case, the timing of inward migration may be coincident with a reduction in basal lubrication as ice in this area became grounded subsequent to grounding line re-advance. In the context of Kamb ice flow history, this inward margin migration represents a narrowing of the ice stream by 25% 200 years prior to its shutdown. Model studies of ice stream cyclicity by Bougamont et. al (2003) suggest that ice stream width is a key factor in sustaining fast flow with increases in width leading to ice stream stoppage through basal freezing. Our evidence suggests that the opposite may also be true; fast ice stream flow may be prolonged despite decreased basal lubrication by sufficient narrowing.

The rough and the smooth: what the radar saw in Pine Island

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Over the 2004/05 austral summer the University of Texas (UT) and British Antarctic Survey (BAS) executed an airborne geophysical survey of the Amundsen Sea Embayment, Antarctica (the AGASEA project). The BAS component was to map the Pine Island Glacier drainage basin for which a total of 32,000 line kilometres were flown from a USAP supported field-depot. The BAS survey aircraft fit comprised gravity, magnetics and ice-radar instruments. The principle purpose of the ice sounding radar was to measure ice thickness and compute the basal topography. However, here we present an overview of the radar system and discuss specific features identified within the 5 Terabytes of radar data. Of note are:

- 'Lake like' reflectors that occur in the valleys of the sub-glacial topography near the Ellsworth Mountains.
- The remarkable smooth bed, akin to the echoes observed from an ice-shelf base, which marks the onset of the fast flowing tributaries of Pine Island Glacier.
- An extremely bright internal reflector in the vicinity of the Hudson Mountains.
- A Raymond bump observed beneath the Rutford/Pine Island ice divide.
- Internal layer fold anatomy.

Furthermore, although the BAS and UT radars have similar spatial and temporal resolutions they operate at different centre frequencies (150 MHz and 60 MHz respectably). From an overlapping transect we present a comparison of the data collected by the two radars.

The BAS survey aircraft at PNE camp. Note the mag pods on the wingtips and the antennae array beneath the wings.

BAS radar parameters: Single or full quad polarisation capability. Centre Frequency 150 MHz, transmit Power 4 kW, transmit and receive aerial gain 11 dBi. Transmit pulses: 4 μS 10 MHz chirp interleaved with a 0.1 μS conventional pulse. PRF 15,625 Hz. Effective PRF (after hardware stacking) for each pulse 312.5 Hz. Dual gain receiver channels. Baseband sampling frequency 22 MHz.

Impacts of Accumulation Rate on Firn Properties

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A key factor in the mass balance of the world's ice sheets is the determination of accumulation rate. Remote sensing techniques show great promise, but there is a lack of data for understanding relationships between accumulation rate and snow and firn properties. Results from a recent field campaign in a megadunes region of East Antarctica, an excellent natural laboratory for snow physics, show the impacts of accumulation rate on the physical properties of the firn in areas subject to the same ambient temperatures. Megadunes are surface features caused by varying accumulation patterns. They are not readily apparent when viewed from the ground, with amplitudes of 2-5m and wavelengths of 2-5km. The variation in accumulation rate does appear in photographs and microwave images of the region, with the low accumulation areas appearing dark and the high accumulation areas appearing light. AWS stations installed within 2 kilometers of one another show that while the temperature and wind patterns of the sites are nearly the same, the variation in accumulation rate from site to site causes significant changes in the physical properties. Grain size, pore size and permeability are most affected by accumulation, while the density shows little influence. The variation in firn physical properties caused by accumulation rate differences is expected to be evident in a variety of signals, including microwave signals, which are sensitive to grain size, and in permeability profiles, which are sensitive to a combination of both grain size and pore size. The near-surface firn properties hold clues to present climate as well as influencing the ability of the firn to store climate information over time in ice core records.

IC, ICPMS and Water Isotope Measurements From the 2002 and 2003 US ITASE Traverses

Daniel Dixon

A collection of 100 surface snow samples collected approximately every 30 km along the ITASE-02 Byrd to Pole and ITASE-03 LGT traverses. Each sample is analyzed for 35 different trace elements, 8 major ions and water isotopic content. IC and water isotope measurements taken from ice core tops along the same route are used to verify the seasonality of the surface snow samples and thus reveal the spatial distribution of typical seasonal snow chemical concentrations over a large area of inland Antarctica.

IPY in the Antarctic Peninsula-Ice Shelves, Oceans, and Climate

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An integrated multi-disciplinary field program is outlined that addresses the rapid and fundamental changes now taking place across the Antarctic Peninsula region. By making use of a marine research platform we can bring glaciologists, oceanographers, marine geologists and biologists together on the same team, working collaboratively to answer vital questions with regard to:

1) the stability of the Larsen Ice Shelf and Antarctic Peninsula ice sheet
2) the integration of paleoclimate records from marine and lacustrine sediment cores
3) the response of, or contribution of, oceanographic systems to ice shelf disintegration
4) the climate history of the Peninsula as recorded in ice cores, and
5) biotic changes in the ocean, including wide ranging shifts in benthic ecosystem dynamics.

Although the logistics of such a program are multilayered, the field work makes use of existing technologies aboard the *N. B. Palmer* and will allow access (via helicopter support) to a wide range of glacial systems adjacent to the Larsen Ice Shelf system. At these locations we will conduct both dynamic monitoring of glacial flow and recover high resolution ice core histories using light-weight drilling equipment, successfully tested at other sites around the world. We will also maximize the use of seafloor imaging systems of the *Palmer* by extending existing swath mapping coverage, into previously unexplored regions. Recovery of long sediment cores (up to 26 m) will be facilitated by use of a proven jumbo piston core system and will target newly discovered sedimentary sections of expanded resolution now lying exposed in the Larsen B embayment. Long-term monitoring of deep water outflow will, for the first time, be integrated into changes in ice shelf extent (bottom water source) by linking near source observations (five instrumented moorings are now in place in front of the Larsen A, B and C) to distal sites of concentrated outflow (the South Orkney Plateau channel now has 10 + years of bottom water flow data). Sediment traps are now connected to both proximal and distal moorings and the records of sediment flux can be linked directly with existing ice dynamics (post break-up surging of tidewater glaciers) and future changes in the ice shelf extent. Finally, the robust space and dynamic positioning of the *Palmer* will allow an international team to deploy a remotely operated vehicle (ROV) to examine, map, and sample a newly discovered chemotrophic ecosystem that was uncovered by the loss of the Larsen B ice shelf in 2002. Such access is vital to assessing life in extreme environments and understanding the role of rapid (climate) change on the ice shelf and benthic ecology.

The results of this international, multi-disciplinary effort will significantly advance our understanding of linkages amongst the earth's systems in the polar regions and are proposed in the true spirit of IPY.

Progress on Radiocarbon Dating of Antarctic Marine Sediments

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Over the last five years we have been working on a number of innovative methods to improve the reliability of radiocarbon dating within Antarctic marine deposystems. Problems in application of the method are particularly troublesome in Antarctic marine settings where a large reservoir age, deep sediment mixing, reworking of organic particulates, and lack of inorganic carbon (calcite) carriers of ^{14}C result in uncertain age corrections. We outline progress on four specific experimental methods that include: compound class and compound specific (sterol) separation, stepped combustion at high and low temperatures, and fine-scale sampling of ^{14}C activity profiles within the sediment column. We also provide examples of how the methods are applied to specific dating questions within the Late Quaternary record from the Antarctic margin including: sub ice shelf systems, sediment drift systems, and glacial deposits. The specific challenges to radiocarbon dating include: the transition from glacial to glacial marine sediments (which typically involve large shifts in particulate carbon source), assignment of correction factors based upon ^{14}C activity within surface sediments at a core site (this correction may not always be appropriate), and assessments of the reservoir correction for ^{14}C activity which is complicated by vital effects between calcite secreting organisms. We provide a standard methodology by which to evaluate radiocarbon ages from marine sediments in Antarctica that emphasizes: selectivity in core site collection, multiple/replicate analyses, and independent age assessment using techniques independent from radiocarbon, including high-resolution ^{210}Pb profiles.

The Importance of Small Ice Shelves to Inland Ice

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We find that the weakening of small ice shelves can have as much, if not more, of an impact on inland ice as an equal weakening of big ice shelves. Recent observations show marked acceleration and thinning of several outlet glaciers and ice streams in Antarctica and Greenland (e.g., Rignot et al., 2004; Scambos et al., 2004; Thomas et al., 2004; Joughin et al., 2004, Shepherd et al., 2004). These observations are consistent with changes in small ice shelves. Here we use a simple diagnostic stress-equilibrium model to examine some of the controls on the ability of ice streams to produce buttressing.

Embedded Models: Application to the Ross Sea and Amundsen Sea Sectors, Retreat from LGM

James L. Fastook

Embedded modeling has been described before at these meetings. Embedded modeling allows the use of higher resolution without the computational penalty of simulating the whole ice sheet. With embedded modeling, the whole ice sheet can be run with lower resolution, and the area of interest run as an embedded grid within the coarser solution. This allows us to focus on small-scale features such as ice streams that would not be well resolved in the coarser grid.

We apply the embedded technique to the Ross and Amundsen Sea sectors, focusing on the period from LGM to the present. A sequence of nested grids allows us to go from a continental view at low resolution, to a regional view at intermediate resolution, and finally to an ice-stream-specific view at the full resolution of the BEDMAP data set. Fast flow regions of wet bed, as predicted by the UMISM basal water component, are compared with known ice streams.

New aeromagnetic and aerogravity survey over the drainage basin of Pine Island Glacier

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The Pine Island Glacier (PIG) and the Thwaites glacier are major drainage systems of the Amundsen Sea Embayment. This is a key area of the WAIS where there is mounting evidence for possible melting, thinning and retreating (e.g. Shepherd et al., 2001; Thomas et al., 2004). However current knowledge of regional ice thickness and subglacial boundary conditions are insufficient to improve models of its evolution and sensitivity to climate change.

During the 2004-05 campaign a US-UK team accomplished the first comprehensive airborne geophysical survey over the Amundsen Sea Embayment. Overall 100,000 km of new airborne geophysical data, including airborne radar, aeromagnetic and airborne gravity were acquired. Here we focus on aeromagnetic and airborne gravity data collected by the British Antarctic Survey over PIG basin. A total of 32,000 line km were acquired during 32 survey flights. Three constant elevation blocks were flown at 8100, 6300 and 4600 ft to obtain high quality airborne gravity data over PIG, while also ensuring ice radar returns from bedrock.

High-sensitivity caesium magnetometers (Scintrex Cs-3), placed in fixed wing configuration, provided the total field aeromagnetic measurements. A three component fluxgate magnetometer was used for magnetic compensation. A Geometrics caesium magnetometer was installed at the base camp to monitor external magnetic field variations, while Leica and Ashtech receivers were installed on the aircraft and at the base camp to supply the GPS data. The gravity signal was measured using a LaCoste and Romberg air/sea gravimeter, recently modified and upgraded by ZLS.

Aeromagnetic processing included: magnetic compensation, base station and IGRF corrections, levelling and microlevelling (Ferraccioli et al., 1998). Aerogravity processing (Jones et al., 2002) involved calculating vertical and horizontal platform accelerations, latitude, Eotvos and Free-air corrections. This was followed by low-pass filtering, levelling and Bouguer corrections.

This new potential field dataset will provide a unique tool to analyse geological controls on the dynamics of the WAIS in the PIG drainage basin area. This region is thought to conceal the tectonic boundary between the Thurston Island and Marie Byrd crustal blocks (Dalziel and Elliot, 1982), a segment of the West Antarctic Rift system (Behrendt et al., 2004 and ref.), and the boundary between the rift and the adjacent Ellsworth-Whitmore Mountains block. To the north of the PIG, the Hudson Mountains contain several parasitic cones protruding above the WAIS, and possibly resting on eroded stratovolcanoes. Satellite data indicate that an eruption may have taken place during 1985, although this has not been confirmed (LeMasurier and Thomson 1990). Active, or recently active, volcanism has previously been proposed as a critical boundary condition for WAIS stability (Blankenship et al., 1993; Behrendt et al., 2004 and ref). Hence our aeromagnetic imaging will specifically target the subglacial extent of volcanism beneath the PIG basin. Additionally, subglacial sediments, in the form of narrow rift basin infill, or regional marine sediment drape have been previously proposed as geological templates for enhanced ice flow (Bell et al., 1998; Studinger et al., 2001). Analysis of new potential field data will therefore address the possible presence of subglacial sediments beneath the PIG basin.

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Tectonics and glacial-marine sedimentation in Pine Island Bay: Survey plan of an upcoming RV Polarstern cruise

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Pine Island Bay forms the third-largest outflow area for the West Antarctic ice-shield. The main ice streams from the WAIS into Pine Island Bay flow through the Pine Island and Thwaites Glacier systems, through which most of the glacial-marine sediments onto the shelf of Pine Island Bay and across the continental slope into the deep sea have been transported. This drainage pattern probably owes its existence to the an assumed crustal boundary between the Thurston Island/Ellsworth Land blocks and the Marie Byrd Land block. The Pine Island Bay represents an ideal working area in which the hypotheses of a total melt-down of the WAIS during the Quaternary can be tested. With the exception of a few single-channel seismic profiles and bathymetric tracks, a dense and systematically sampled grid of geophysical and geological data does not exist in Pine Island Bay at this stage. Dense and detailed surveys of the glacial-marine sedimentary sequences over large areas from the shelf and slope of Pine Island Bay and its adjacent continental rise would allow reconstructions of the onset of large-scale glaciation in West Antarctica, the long-term dynamics of the WAIS and the reaction of WAIS dynamics to the global glacial-interglacial cycles of the Late Quaternary.

A geoscientific cruise with RV Polarstern to the Amundsen Sea embayment is scheduled for February to April 2006 in cooperation between AWI, the British Antarctic Survey (BAS) and the New Zealand Institute of Geological & Nuclear Sciences (GNS). The main objectives are:

" Recording of the youngest sedimentary sequences since the Oligocene across the shelf, slope and the continental rise, using high-resolution reflection seismics, sub-bottom profiler and swath-bathymetry in order to derive a sedimentation model

" Sampling of sediment cores to determine sedimentological and physical parameters of the youngest deposits and to reconstruct depositional and erosional events in space and time.

" Mapping of the acoustic basement and its structure with seismic reflection methods to obtain tectonic geometries to understand sediment transport and depositional processes.

" Identification of the tectonic boundaries between suspected crustal blocks, in particular of those between the Thurston Island and Marie Byrd Land blocks. It is suspected that the glacier troughs and Pine Island Bay developed along such a tectonic boundary.

Helicopter-magnetic, gravimetric and deep crustal seismic surveys will provide the necessary data base for a tectonic model.

" During and after separation from the Chatham Rise and Campbell Plateau (New Zealand), the continental margin of Marie Byrd Land developed as a passive margin, probably accompanied by intensive volcanism. The question is whether this volcanism occurred mainly during the rifting process or during post-rift phases, or whether it developed in relation to the West Antarctic rift system. Heli-magnetic mapping and deep crustal seismic profiling of the continental margin of Marie Byrd Land as well as petrological sampling and geochemical analyses of volcanic rocks from seamounts (e.g. Marie Byrd Seamounts) and parts of exposed mainland will provide data to develop models of the magmatic evolution.

Influence of ice dynamics in WAIS tributaries on firn layer stratigraphy

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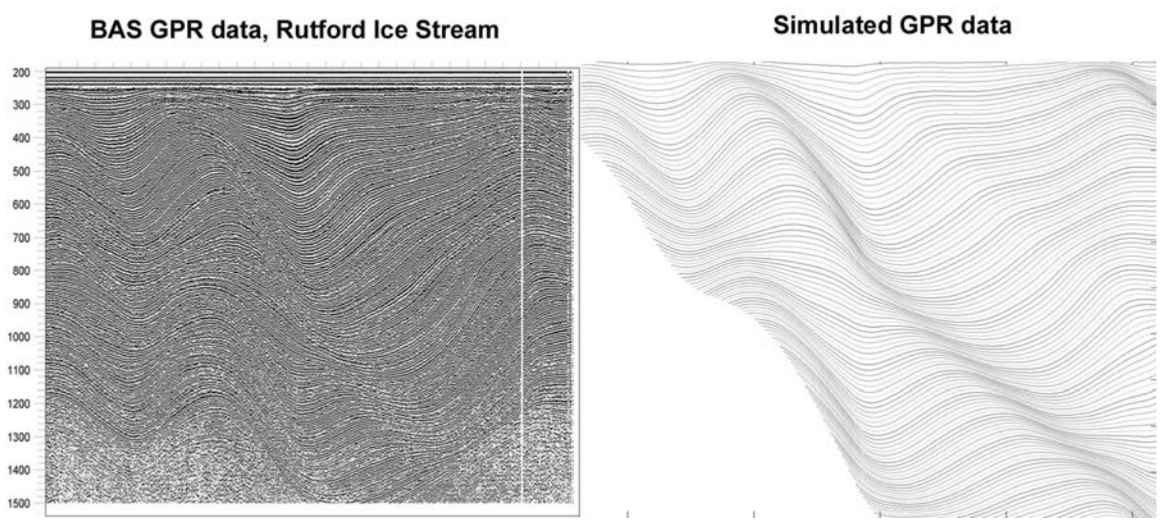
Last year we[1] showed a strong correlation between C-band RADARSAT image radiometry and 'folding' in the near surface firn stratigraphy measured by high frequency ground penetrating radar (GPR). The data demonstrate that the linear features in the C-band imagery, which are often referred to as 'flow stripes', are accompanied by cross-flow layer folding such that bright 'stripes' suggest low snow accumulation and dark 'stripes' suggest high accumulation. This is consistent with the darker radiometry often associated with dips in the surface elevation where one expects, and observes, higher accumulation. However, for these flow stripes neither the height nor slope variation across the flow stripes appears to explain the apparent accumulation variation, suggesting that the accumulation pattern may be modulated by stresses associated with flow.

In an attempt to learn more about how ice dynamics in tributries and ice streams affect near surface GPR stratigraphy, a simple model was developed to simulate isochronal firn layers. The model is 2-dimensional, along-flow and vertical, and uses surface velocity and relative accumulation as input. A comparison between actual and simulated GPR data from the Rutford Ice Stream[2] has shown that layer patterns can indeed be simulated in this straightforward manner. We explore other data from WAIS ice streams in the hope that it may be possible to observe past velocity changes.



[1] *Fast-flow signatures on Kamb Ice Stream,* H. Conway, L. Gray, E. King, F. Ng and B. Smith, WAIS 2004
[2] GPR data collected for BAS by Dr. J. Woodward now at Div. Of Geography, Northumbria University UK

Relict Algal Mats at Reedy Glacier: Radiocarbon Dating at 86°S

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We report here the discovery of relict algal mats at Polygon Spur (86S, 126W, 1600 m elevation) adjacent to Reedy Glacier. These well-preserved mats are found beneath large boulders, similar to the situation in the Dry Valleys (i.e., Hall and Denton, 2000) and at Hatherton Glacier (Bockheim et al., 1989).

The algae once grew in proglacial lakes dammed by an expanded McCarthy/Reedy Glacier system and are found at elevations as much as 100 m above present-day ponds and ~90 m above ice level. In order for these lakes to have formed, Reedy Glacier must have been thicker than at present. Based on our mapping and dating of drift sheets (see Bromley et al., and Todd et al., this meeting), we speculate that the higher lake levels date to the last glacial maximum. Radiocarbon dating of algal remains (in progress) at different elevations should help to define the McCarthy/Reedy Glacier ice-thinning history and will afford useful comparisons to cosmogenic exposure ages, also in progress. To our knowledge, these samples will yield the southernmost radiocarbon dates yet produced.

The Holocene Radiocarbon Reservoir Effect in the Western Ross Sea

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The chronology of Holocene deglaciation of the Ross Sea Embayment (Conway et al., 1999) relies, in part, on radiocarbon dates of marine materials. These dates must be corrected for a marine reservoir effect caused by upwelling of water that has been out of contact with the atmosphere. Dating of historical samples (i.e., collected before the formation of ^{14}C by nuclear weapons testing) reveals that the modern reservoir effect is approximately 1300 years (Berkman and Forman, 1996 and others). However, temporal variations are possible, particularly if changes in ocean circulation have occurred. Application of today's correction of 1300 years to ancient samples potentially could introduce error of several hundred years.

To document any Holocene variations in the marine reservoir effect we analysed solitary corals from the western Ross Sea by both the radiocarbon and uranium-thorium disequilibrium methods. U/Th dates should be the true ages of the samples. The offset, therefore, between the radiocarbon date (converted to calendar years) and the U/Th age for the same sample, gives the radiocarbon reservoir effect at that time. We have performed paired analyses on more than 40 solitary corals that span the past 6500 years. Our preliminary data indicate that the radiocarbon reservoir effect has remained virtually unchanged throughout this time (~1250 +/- 150 years). This stability validates previous application of the modern correction (1300 years) to ancient samples. It also suggests that the Ross Sea region has not experienced any changes in ocean circulation detectable by radiocarbon variations in the last 6500 years.

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HEADWALL INITIATION OF ICE STREAM AND OUTLET GLACIER ONSETS: EVIDENCE FROM SATELLITE IMAGERY

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Ice streams and outlet glaciers are the most efficient means of draining mass from ice sheet interiors to the ocean. Any change in the extent and configuration of these features will have significant impacts on ice sheet mass balance and sea level. An analysis of high-resolution satellite imagery shows that the onset regions of enhanced flow appear to be geologically controlled. A characteristic feature is the presence of a "headwall", immediately downstream of which flow stripes and crevasses are observed. Examples will be presented from Antarctica and Greenland. If this geological control is correct, it implies that inward migration of enhanced flow will be difficult to achieve. In that case, lateral migration of unconstrained flow margins is likely to be the dominant cause of changes in ice stream and outlet glacier configuration.

Comparing velocity profiles of Byrd glacier with a simple 2D flow model

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Velocity profiles of Byrd glacier show a transition from parabolic transverse profile upstream to a plug flow transverse velocity profile. A big change in this velocity profile is observed at the grounding line of Byrd glacier. An explanation for this transition is that the uncoupling of ice from bed and sidewalls is causing the plug flow like behavior. A simple 2D flow model is used to simulate the surface velocity field. The model geometry consists of two parallel plates, representing a simplified top view of Byrd glacier, through which a Non Newtonian fluid flows. The transverse velocity profiles show a similar trend as the field data; a transition from parabolic transverse profile upstream to a plug flow transverse velocity profile. Interestingly enough the transition is taking place as a result of the parallel plates ending, immediately affecting the transverse velocity profiles between the parallel plates. This provides a new insight in the transverse velocity profiles of Byrd glacier; their plug flow like transition is, at least partly, caused by the ending fjord walls or the entering of the ice stream in the Ross Ice Shelf. The ending fjord walls of Byrd glacier affect the transverse velocity profiles between the walls in the same way as the ending plates in the simple model affect the transverse velocity profiles. Uncoupling of the ice itself may be a result from the ending fjord walls.

Summary of the 2004-05 Airborne Geophysical Survey of the Amundsen Sea Embayment, Antarctica (AGASEA) with preliminary results for the Thwaites Glacier catchment

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The glaciers of the Amundsen Sea Embayment (ASE) have become a focus for integrated studies by both the U.S. and European scientific communities due to satellite observations of non-steady behavior and the ASE's dominant role in WAIS mass balance. The community-driven Amundsen Sea Embayment Science and Implementation Plan (ASEP) has the overarching objectives of assessing the present and predicting the future behavior of the ice sheet in the ASE. In order to accomplish some of the primary ASEP objectives and to guide future surface-based research, the University of Texas (UT) and the British Antarctic Survey (BAS) have recently undertaken a comprehensive aerogeophysical survey encompassing the two major drainage basins within the Amundsen Sea Embayment - Pine Island and Thwaites glaciers. We conducted this survey during the 2004/05 austral summer, operating from two remote field camps and using two survey aircraft. The survey design that was originally proposed required modification due to logistical support limitations which restricted fieldwork to one season. We developed a strategy that balanced coarse coverage of the glacier catchments, higher-resolution coverage of the fast-flow regimes, and along-flow profiles. In spite of the distance from logistical centers and significant weather hindrances, the survey was a clear success. Over 65,000 line-km of multi-instrumented aerogeophysical data covering both the Thwaites and Pine Island Glacier catchments were collected in 73 flights of the UT aircraft and 31 flights of the BAS aircraft. Due to the limited extent of previous geophysical data in that region, this survey represents an enormous step forward in our ability to understand the dynamics of Thwaites and Pine Island glaciers.

The multidisciplinary nature of coupled lithosphere and ice sheet studies requires a broad approach for which multi-instrumented airborne surveys are well suited. Radar sounding data were acquired to determine bed morphology and to provide measurements of ice thickness necessary to calculate ice sheet driving stress and hydrologic potential. Gravity and magnetics data were collected to help identify crustal blocks, sedimentary basins, volcanic activity, and to characterize geothermal flux, all of which are critical to models of ice sheet dynamics. Laser surface elevations were acquired to enable detailed mass balance calculations and satellite altimeter calibrations. We have produced grids of surface elevation, ice thickness and bed elevation for use by the community for planning new field studies. Gridded potential fields data will be available in the near future.

The radar sounding data have been analyzed to determine surface and bed elevations. This yields a new picture of bed topography that is a major extension of what was previously known. Most of the region lies below sea level, with a broad coastal sill bounding an extensive Thwaites Glacier interior basin fed by broad, deep drainage channels. The relatively high ground of the Marie Byrd Land volcanic province to the west of Thwaites Glacier is deeply incised. In this area, several volcanic edifices are visible above the ice surface. The radar data reveal many additional edifices below the ice surface. Surface elevation and preliminary potential fields data will also be presented.

Dynamics of the Grounding Line of Whillans Ice Stream

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The dynamics of a portion of the grounding line of Whillans Ice Stream is reported using a combination of satellite data and GPS observations. The grounding line is considered at two time scales. Firstly, Radarsat interferometry grounding line picks from late 1997 are compared to late 2003 GLAS ICESat picks, and a kinematic GPS survey from late 2004. Secondly, a strain grid occupation, which straddled the grounding line in late 2004, is reported and interpreted.

The grounding line picks between 1997 and 2004 show a small apparent retreat, of the order of a kilometer, over the seven year period. This may, however, be due to uncertainties in the Radarsat grounding line positions and how they relate to the grounding zone (i.e. which point in the grounding zone the Radarsat picks correspond to).

The strain grid data allows a detailed examination of the grounding zone over a tidal cycle, during which strain is correlated with tidal motion. Even at timescales as short as one day, a period at which others have assumed elastic behavior, we observe inelastic deformation. We address this inelastic deformation by comparing Young's modulus at different phases of the tidal cycle, and observing the magnitude of strain evident across the network.

Relating Longitudinal Tension, Basal Shear, and Side Shear To Ice-Bed Coupling Beneath Ice Streams

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Ice-bed coupling can be quantified as the ratio of basal water pressure P(w) to ice overburden pressure P(i). Maximum coupling occurs when P(w)/P(i) = 0 and maximum uncoupling occurs when P(w)/P(i) = 1. In previous work, the longitudinal deviator tensile stress in an ice stream and its longitudinal force gradient have been related to P(w)/P(i) quantitatively using a geometrical force balance. That work is now extended to relate both the basal shear stress and the side shear stress to P(w)/P(i) such that resistance to stream flow is transferred from the bed to the sides of an ice stream as P(w)/P(i) increases from zero to unity. This allows transitions from sheet flow to stream flow to shelf flow to be expressed in terms of basal shear, side shear, longitudinal tension, and the longitudinal force gradient using two physical parameters. First, ratio P(w)/P(i) is a direct measure of ice-bed coupling. Second, since P(w) is directly related to the height h(w) of water above the bed that would be supported by the basal water pressure, h(w) is a direct measure of the hydraulic head that drives basal water from sources to sinks beneath an ice stream. The greater the variation in absolute values of h(w) and the steeper its longitudinal gradient, the more forcefully basal water will be transported from sources to sinks. Sources can include surface meltwater that reaches the bed through crevasses, and sinks can include discharge of basal water across an ice-shelf grounding line. The cause of P(w)/P(i) and of h(w) at any point along an ice stream, and their gradients from point to point, is the downstream resistance to stream flow that can be represented by a compressive back-stress at every point. This resistance can be reduced rapidly where surface meltwater reaches the bed and when all or part of a buttressing ice shelf disintegrates, as has happened for Jakobshavn Isbrae in Greenland and perhaps for some West Antarctic ice streams. The geometrical force balance therefore allows the significant stresses in an ice stream to be linked to ice-bed coupling and subglacial hydrology, and to processes at the surface and beyond the grounding line. Perturbations in these processes cause ice velocities and thinning or thickening rates to change rapidly along the whole length of an ice stream upstream from where the perturbations occurred.

Ice streams stop and start: evidence from the Ross Ice Shelf, interpreted using numerical models of ice shelf flow

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Flow features on the surface of the Ross Ice Shelf record two episodes of ice stream stopping and re-starting within the last 1000 years. We document those events using maps of streaklines emerging from individual ice streams and of ice provenance, together with numerical models of ice shelf flow. Forward model experiments lead us to conclude that only a limited set of discharge scenarios could have produced the current streakline configuration. In particular, Whillans Ice Stream (formerly B) must have stopped its rapid flow about 850 calendar years ago and restarted about 400 years later and MacAyeal Ice Stream (formerly E) either stopped or slowed significantly between 800 and 700 years ago, restarting about 100 years later. Previously, ice-stream scenarios emphasized runaway retreat or stagnation on millennial time scales. Here, we identify a new scenario: century-scale off/on cycles. This introduces uncertainty into predictions for future sea-level withdrawls by the West Antarctic Ice Sheet, which are based in part on recent slowing of Whillans Ice Stream and the "stopped" condition of Kamb Ice Stream.

Radar Studies of the Trunk and 'Sticky Spot' of Kamb Ice Stream

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This past field season we acquired approximately 275 km of ground-based ice penetrating radar data on the trunk of Kamb Ice Stream (KIS) as a part of a two-year program of radar and GPS studies examining the possibility of ice stream reactivation. Many of the profiles explore the region of the 'sticky spot' and adjacent portions of the ice stream in the vicinity of a series of camps occupied throughout the 1980's and 1990's, collectively referred to as "Upstream C." We also investigated a separate area approximately 80 km upstream where a sequential pair of laser altimeter profiles indicated a localized anomalous region of surface uplift of 2 m/a over a two year period,1998-2000 (Spikes, et al., 2003).

The radar data provide detailed depictions of bedrock and internal layer stratigraphy; in many cases the layers are present nearly to the bottom. We have identified a bright layer at about two-thirds to three-fourths of the ice thickness in all profiles that likely is the same bright layer dating to 17.5 KY that we have detected throughout West Antarctica in ITASE traverses (Jacobel and Welch, 2004). We have also produced maps of variations in bed reflectivity from the radar returns that correspond closely (but not identically) with the surface expression of the sticky spot in satellite imagery (Figure). Bright areas of the bed are found in the trunk of the ice stream both north and south of the sticky spot and along the south margin where a layer of liquid water was identified in Cal Tech bore hole 00-01.

However, the brightest bed reflections are found in the trunk region 80 km upstream where anomalous surface uplift has been noted. Also, echoes from near the bed at this location indicate the possible presence of a highly reflective surface off to the north side of our profiles. Our bed amplitude studies are augmented by two densely-spaced constant midpoint profiles that enable us to characterize attenuation and e/m wave speed within the ice (Pettersson, et al., abstract this meeting).

In addition, we have re-imaged fold features in the internal layering of the ice that correspond to structures seen in our 1988 ground-based radar studies in the UpC vicinity when the sticky spot was first identified as overlying an area of raised bedrock (Jacobel et al., 1993, Retzlaff et al., 1993). These two surveys enable us to measure components of the accumulated strain over the intervening 16 years.

Weak Underbelly Work: At Sea with IPY in the Amundsen

SS Jacobs, DM Holland et al.

Research during the past decade has shown that portions of the WAIS draining into the Amundsen Sea and off the Antarctic Peninsula are moving, melting, thinning and retreating much more rapidly than elsewhere around the continent, and may be contributing to sea level rise. The Amundsen Sea Embayment Project (ASEP; Anandakrishnan et al. 2001) outlined the field work that may be needed to better understand ongoing change in that area. Developments since that time have only increased the general sense that the Amundsen sector of WAIS is more vulnerable to a warming climate than previously assumed. IPY presents a potential opportunity to update and implement ASEP, while taking advantage of international interest in this region.
We will report the status of interest in shipboard studies and ocean modeling of the Amundsen Sea's role in the evolution of WAIS ice shelves. In particular, we will seek input and discussion on efficient ways to address a variety of related issues. These could include the following questions: What ocean and sub-ice measurements and models are needed to monitor the temporal and spatial variability in ocean circulation and properties, to refine and validate models of that circulation and its ice/ocean interactions, and to ground-truth remote observations? What meteorological measurements are needed, and where, to monitor regional atmospheric forcing and improve the NCEP/ECMWF Reanalysis products in the sparsely observed SE Pacific sector? What observations and modeling efforts are needed to evaluate the roles of sea ice and icebergs in the regional ocean circulation and ice shelf decay? What bathymetric measurements are needed, and where, to assess the role of bottom topography in channeling seawater from the continental shelf break to glacier grounding zones? What seawater, sediment or other sampling is needed to determine freshwater sources, the timing of ice shelf retreat, possible past ice sheet collapse through the Amundsen, and the relevance to WAIS of life in this cold, dark environment? How broadly/narrowly in geographic extent should shipboard work be focused, over what time frame, and with what types of logistic support?

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Earth Science and Applications from Space: A Community Assessment and Strategy for the Future Thoughts on the Climate Panel � K. Jezek VISION for Climate Change and Variability Research for 2015-2020 If current climate projections are correct, then climate changes of the next ten to twenty years will significantly and noticeably impact human activities. This impact will shift research from climate change detection to research on the predictive capability necessary to protect life and property, promote economic vitality, enable environmental stewardship, and support a broad range of decision-makers. Realization of future climate change forces our current decadal vision to extend outside of the current state of the science in several ways: Climate change research will be increasingly tied to improving predictive capabilities The drive to create more comprehensive models will grow significantly The �family� of forecasting products will grow substantially. The tie between climate research and societal benefit will emphasize regional or higher spatial resolution climate prediction. The connection between climate and specific impacts on natural and human systems will require a more comprehensive approach to environmental research. Decadal Survey Goal Develop a consensus of top level science questions for the period 2005-2015 Recommend a prioritized list of measurements and identify potential new space based capabilities Identify important directions that will influence planning for beyond 2015 Panel Objectives Identify general needs and opportunities for space borne observations to advance our science in next 10 years Propose program or missions to meet those needs Rank proposed programs or missions in priority order Describe each mission in terms of science payoff, cost, benefits to society Identify observations that cannot be made from space but needed to complement spaced based data Identify other essential components (telemetry, data management). Science Challenges Driving Cryospheric Research: 2005-2010 Understand glaciers and ice sheets sufficiently to determine their contribution to present sea level rise. Understand sea ice sufficiently to explain present observations of thinning and reduced sea ice extent Measure how much water is stored as seasonal snow and its variability Measure how much carbon is exchanged between the permafrost and the atmosphere Understand which aspects of the changing polar atmosphere most influence changes in sea ice, snow extent, surface melting. Understand how changes in the cryosphere affect human activity Challenges for 2010-2020 Determine the long-term impacts of a changing cryosphere on other components of the earth system Predict the response of glaciers, ice sheets and sea ice to changing climate Quantify internal and external feedbacks between terrestrial, oceanic ice and snow cover and global climate and climate variability Instruments Requirements Repeat altimetry for elevation (radar/laser; spaceborne and airborne) Repeat Spaceborne InSAR Airborne VHF/UHF sounding radar Repeat multifrequency passive microwave radiometers Repeat multifrequency, high resolution Visible/IR Grace-type gravimetry C-band scatterometer Innovative orbit geometries (e.g. Molniya, Pole-sitter) RFI�s Submitted and which could be applicable to CyroResearch Cold Land Processes Water and Oceans Wind Sensor Global Environmental Microsensors Grace Follow-on Global Water Resources Satellite Operational Ocean and Land Mission Suborbital Earth System Surveillance Insar Applications for Exploration of the Earth Polar Environmental Monitoring Molniya Orbit Imager Advanced Ice Sat WaTER GISMO Outstanding Issues Constellations vs individual projects Role of International Partners DATA MANAGEMENT IS GENERALLY NEGLECTED IN ALL PROPOSALS CONSIDERED SO FAR

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A DESIGN CONCEPT FOR SPACEBORNE IMAGING OF THE BASE OF TERRESTRIAL ICE SHEETS AND ICY BODIES IN THE OUTER SOLAR

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Glaciers and ice sheets modulate global sea level by storing water deposited as snow on the surface and discharging water back into the ocean through melting and via icebergs. Only recently have we recognized, primarily from satellite observations, that the size of this frozen reservoir can change as demonstrated by the rapid thinning of Jacobshavn Glacier in Greenland [1], the Pine Island and Thwaites Glaciers in Antarctica [2] and the demise of the Larsen Ice Shelf followed by thinning of interior Antarctic Peninsula Glaciers. Yet none of these events are captured by current glaciological models suggesting that there are critical gaps in observations and theory about the dynamics of large ice sheets.

Missing from the constellation of satellites currently observing the polar regions, is a sensor capable of probing the volume of the ice sheet and measuring the topography and properties of the glacier bed. While much work has been done to measure ice thickness from aircraft, gaps in coverage remain especially over part of Antarctica [3]. Very little information is available about variations in properties of the subglacial bed where we believe critical changes in the control on ice sheet flow takes place. Here, we present a concept for a new sensor to probe, systematically and comprehensively, the base of the polar ice sheets. We ultimately seek to perform pole-to-pole measurements of glacier and ice sheet thickness, basal topography, and physical properties of the glacier bed that will help to answer two fundamental questions: What is the impact of changing ice sheets on global sea level rise?; Can we predict changes in ice sheet volume and hence changes in global sea level as global climate changes?

Our technology concept addresses an approach for obtaining spaceborne estimates of the mass of the polar ice sheets with an ultimate goal of providing essential information to modelers estimating the mass balance of the polar ice sheets and estimating the response of ice sheets to changing climate. The science goals driving our concept are: 1) determine total global ice sheet volume by mapping surface and basal topography; 2) determine basal boundary conditions from radar reflectivity; and 3) understand the phenomenology of radar sounding of ice for applications to planetary studies.

Our concept is built around a VHF and P-band, multi-phase-center radar for measuring the surface and bottom topographies of polar ice sheets. Our approach, which relies on a combination of radar interferometry and multi-phase center tomography, serves to eliminate signal contamination from surface clutter, measure the topography of the glacier bed, and paint a picture of variations in bed characteristics. We have recently shown that is possible to image a small portion of the base of the polar ice sheets using an in situ SAR approach. We envision this technology transitioning to a spaceborne platform configured to make measurements over both of the great ice sheets. The technology will also have applications for planetary exploration including studies of the Martian ice caps and the icy moons of the outer solar system.

Our proposed system consists of a synthetic aperture radar interferometer (IFSAR) operating at P-band and using a 45 m interferometric baseline. We restrict data collection to near nadir incidence angles leading to a 50-km swath that starts at a cross-track distance of 10 km from the nadir track. Simulations show that we can obtain satisfactory signal–to-noise ratios for ice depths up to 4 km. Clutter contributions are the primary noise sources to the signal over the swath.

As soon as an off-nadir swath is required, brightness returns from a surface are insufficient to estimate height and an interferometric radar is required. The height accuracy which can be achieved with an interferometer depends on the signal-to-noise (SNR) and signal-to-clutter (SCR) ratios, the number of radar looks, and the interferometric baseline [4, 5]. Modifying the equations in those references to include ray bending and the presence of a second surface which generates clutter contamination, we can derive the expected retrieved height accuracy as a function of SNR and SCR. Due to the large number of looks and the 1 km spatial resolution of the planned system, we find that an SNR between –5dB and 0 dB is sufficient for achieving the desired height accuracy out to 60 km cross track distance. We also find that the clutter reduction need not be perfect: achieving rejection ratios so that the final SCR is in the range between –10 dB and 0 dB is sufficient to meet the science requirements.

We have selected the system to operate at 430 MHz for several reasons: 1) antenna size reduction; 2) baseline reduction so that it is achievable in a single spacecraft; and, 3) field experiments have shown that the attenuation due to ice propagation is relatively constant over the frequency range from 100 to 500 MHz. The main disadvantage of P-band is higher surface clutter and so we retain an option for a lower frequency system.

We have selected a polarimetric system to allow for corrections due to ionospheric distortions and Faraday rotation. Freeman [6] and Freeman and Saatchi [7] have shown that using polarimetric returns, one can achieve an azimuth resolution commensurate with our 1 km spatial resolution requirement and not lose significant signal power due to Faraday rotation [8].

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ASEP - Coordinated Modeling

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The Amundsen Sea basin is a compelling region for glaciological modelling. Ice dynamics here embraces a variety of ice flow styles and interactions with other components of ice sheet and climate systems. While the relevant issues are known, they have yet to be addressed in a thorough manner for predictive purposes. The IPY offers an ideal framework for such an effort. Issues that must be addressed by the ASEP modelling effort are summarized here.

Multi-physics coupling. Dynamical components of the Amundsen Sea region important to ice sheet mass balance include; grounded ice, ice streams, ice shelves, ocean circulation, tides, climate, sea ice, and grounding line treatments of ice. Each dynamical component is represented by a separate physical model. Coupling models, while upholding fundamental conservation laws such as conservation of energy, momentum, and mass will be constitute a major undertaking of this research.

Model Nesting. Each ice-dynamical component is characterized by distinct temporal and spatial scales. A second focus of model development will be the ability to nest model results in such a way that coarse scale runs provide essential inputs for finer scale runs, which have both improved resolution and more detailed physics.

Advanced treatment of basal conditions. This is a key focus of modern ice sheet model development and includes such topics as till fabric evolution and basal water flow. As there is a paucity of data relating to basal processes, generic formulations will be implemented, allowing a number of scenarios to be investigated quickly, and setting the stage for future efforts.

ASEP models will incorporate new data gathered by remote and ground-based operations conducted as part of the overall IPY effort. These data will be used to evaluate model performance and to drive models toward a present-day condition that will in turn form the basis for future-change simulations, including ice-sheet effects on sea level and ocean circulation.

The framework model presented in a separate EoI by Dr. Antony Payne is a logical platform for this effort although other options are possible. The framework would be extended in a manner that is consistent with the communal and collaborative nature of that work as part of the broader IGY internationalization and outreach efforts.

Integrating satellite observations with modeling: basal shear stress of the Filcher-Ronne Ice Streams, Antarctica

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Doug MacAyeal
Ted Scambos
Mark Fahnestock

We used control-methods inversions to determine the basal shear stress beneath the Filchner-Ronne Ice Streams where new high-resolution velocity data sets have recently become available. We used an existing inversion algorithm that has been applied successfully to the Ross Ice Streams. The data reveal areas of low basal shear stress that suggest the presence of weak dilatant till beneath the eight Filchner-Ronne Ice Streams we examined. The distribution of this till is patchier than that beneath the Ross Ice Streams, with several "sticky spots" supporting much of the driving stress. This is consistent with earlier studies that indicated a high degree of variation in till porosity beneath Rutford Ice Stream from seismic data. The higher mean basal shear stresses imply significantly higher basal shear heating, which may explain the more steady flow relative to the Ross Ice Streams.

An ultra wideband plane wave radar for mapping near-surface isochronous layers

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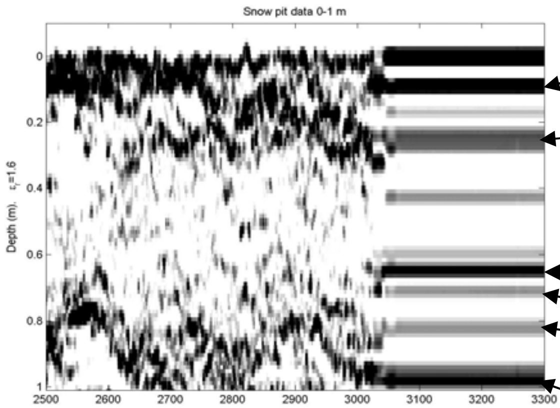
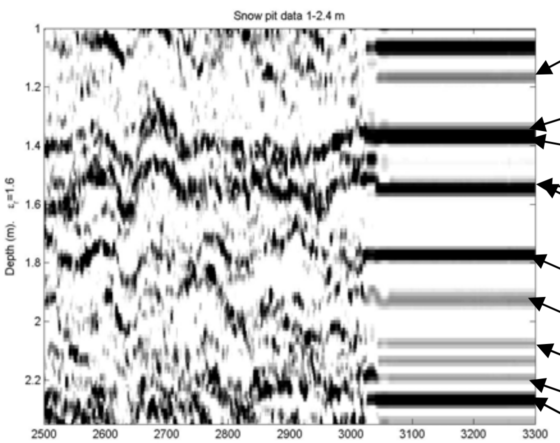
Information on spatial and temporal variation of snow accumulation is required to interpret satellite-based radar and laser surface elevation measurements. To map near-surface internal layers with fine spatial resolution, we developed a 12-18 GHz FM-CW radar to map the near-surface isochronous layers at a resolution of 3 cm and up to a depth of 10 m. We developed the radar to provide plane-wave illumination to a depth of about 10 m using a parabolic dish operated in the near field. The advantage of plane-wave illumination is that weak returns from internal layers are not masked by off-vertical surface scatter, which can occur for radars with traditional antennas. We also developed a sled with a gimbaled antenna mount with a tiltmeter and actuators to ensure that the antenna points at nadir.

The heart of the radar is a fast synthesizer developed using a voltage controlled oscillator (VCO) and phase lock loop with a linear reference chirp for the phase detector. The synthesizer can be swept from 12 to 18 GHz in 500 μs. The phase detector error signal to the VCO was generated by comparing the VCO signal to a highly linear chirp signal from an arbitrary waveform generator (AWG).

We tested our system at the Summit camp, Greenland, in July 2005. We collected a large volume of data along bamboo stakes that were used to monitor snow accumulation. We also dug 3 pits to obtain data on stratigraphy and density. Initial results confirm a high correlation between our data set and the pit stratigraphy. Figure 1 shows a comparison between the two. We used an average density to determine the dielectric constant and thus the velocity of propagation in firn. The solid line at the right side is from stationary measurements at the pit location. We collected more than 200 samples to compare with pit observations. Each sample consists of ten sweeps integrated coherently to improve signal-to-noise ratio. With our system, we can also monitor the spatial variability of the accumulation in a given area. Figure 2 shows layers being tracked over a distance of 150 m.

In this paper we will discuss the design and construction of the radar, as well as provide sample results from field experiments at the Summit camp. We will also show a comparison of experimental data with simulations obtained using density and stratigraphy data. We are also planning to perform measurements with this system at the WAIS divide deep core site during the 2005-2006 field season.





Depth (cm)	Layer type
10.4 – 14	Depth hoar
26 – 29	Wind crust
34 - 35.5	Wind crust
65	Layer (?)
72.5	Wind crust
81.5-83.5	Layer
86-89	Layer (x)
96.5-99	Ice layer
115.5-117.5	Layer
138-139	Layer
140-141	Layer
153-154	Layer
155-156	Layer
180	Ice crust
193	Ice crust
208	Wind crust
217	Wind crust
227-230	Depth hoar

Figure 1. Comparison between radar measurement and pit stratigraphy.

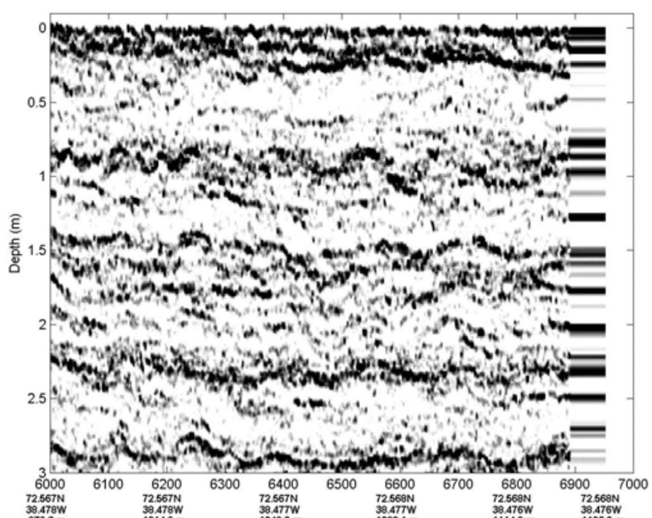


Figure 2. Layers tracked over a distance of 150 m.

Can sulfate signatures in ice cores verify the source volcano?

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Detailed volcanic records developed from continuous glaciochemical series in a number of West Antarctic ice cores reveal and improve the overall chronological record of Antarctic, South American, and equatorial volcanism. Ages of several large equatorial or southern hemisphere volcanic eruptions coincide with detected sulfate peaks in the developed volcanic ice chemistry records. However, geochemical 'fingerprinting' using electron microprobe analysis of glass shards filtered from meltwater samples adjacent to several sulfate peaks points to Antarctic volcanic centers as sources. These centers include Balenny Is., The Pleiades, Mt. Berlin, Mt. Takahe, Mt. Melbourne, as well as Mt. Hudson and possibly Mt. Burney volcanoes of South America.

Deposition of volcanic sulfate in West Antarctic snow from global- scale eruptions is thought to mainly occur by transport through the mid-upper troposphere and stratosphere (Legrand and Delmas, 1987; Dibb and Whitlow, 1996; Legrand and Wagenbach, 1999), but appears to be dependent on several additional factors. The stratospheric contribution of sulfate to Antarctic snow is generally assumed to be minimal (Legrand, 1997; Bergin and others, 1998) except after global scale volcanic eruptions (Legrand and Delmas, 1987; Dai et al., 1991; Dibb and Whitlow, 1996).

Volcanic sulfate from small local eruptions may be delivered through the troposphere or lower stratosphere, and appears to have the most significant impact on the area near the source eruption. Circulation patterns of lower tropospheric air masses influence magnitude of background sulfate concentration as controlled by elevation and distance from the coast, but the contribution from local volcanic eruptions is much greater than that of background sulfate. Glass shards associated with local, Antarctic volcanic eruptions overall show associations with the large sulfate signals. We observed a complex, non-linear relationship between the magnitude of the eruption and the sulfate signal. Three sulfate signals at 1259, 1809 and 304 C.E. possibly associated with tephra from Antarctic volcanoes show that local volcanic eruptions produce one of the largest sulfate spikes in the record. This findings suggest the need for reevaluation of proposed earlier tropical eruption sources for 1259 and 1809 volcanic signals.

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Wind-Blown Snow Infilling of a Rift in the Ross Ice Shelf

Katherine Leonard, Bruno Tremblay, Douglas MacAyeal

Iceberg-calving rifts in Antarctic ice shelves are often filled with a mixture of snow, marine ice, and ice talus referred to as ice melange. Ice melange may play various roles in the rates of propagation of rifts in the Ross and Amery Ice Shelves. This study examines the role of windblown snow in the formation and maintenance of ice melange within the idealized geometry of the "nascent rift" in the Ross Ice Shelf (78 08'S, 178 29'W). The rift axis is perpendicular to the regional wind direction, allowing us to employ a two-dimensional blowing snow model. The Piektuk-Tuvaq blowing snow model (Dery and Tremblay, 2004) adapted the Piektuk blowing snow model for use in sea ice environments by including parameterization for open-water leads within the sea ice. This is useful for modeling the initial conditions of a freshly-opened rift, as the input of blowing snow into the seawater within the rift promotes marine ice formation by cooling and freshening the surface water. Once the water surface is sealed with a layer of marine ice, snow and talus derived from the ice shelf can pile up on this surface, leading to the typically lumpy morphology of ice melange. While the rift initially acts as a trap for blowing snow, the topography within the rift eventually reaches steady-state. The presence or absence of such a topographic profile within a rift can potentially be used to determine whether or not the rift is actively propagating or deforming.

Snow Surface Height Change Induced by 2 Decades Surface Air Temperature Variations over Antarctic Ice Sheet

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In most regions of polar ice sheets, fluctuations of surface air temperature drive the firn temperature change hence the densification rate causing the snow surface elevation change. These changes are mainly in seasonal to decadal time scale and superimposed on the long-term changes due to the past and present mass imbalance of the ice sheets. Study of the firn compaction and the resulted elevation change is of great importance in the interpretation of satellite altimetry data and improves our knowledge not only in understanding the temporal variations but also in detecting long term changes in snow surface height. In this study, two decades (1982-2000) monthly mean surface air temperatures inferred from satellite infrared data (AVHRR) over the Antarctic ice sheet are applied to the time-dependent densification model to derive the corresponding surface height changes. The model is driven by surface climate forces (accumulation rate, temperature and temperature gradient) and characterized by the higher temperature sensitivity. Results show that the seasonality of surface air temperature causes clear seasonal variations in surface height with maximum and minimum occurring in late austral spring and fall respectively. The seasonal amplitudes of the surface height increase from millimeters to centimeters with increasing accumulation rate and surface temperature over the ice sheet. Interannual variations show that the surface height significantly decreases with mean rate of –1.9 cm yr^{-1} (92-2000) over the West Antarctica. Surface snow melting around ice shelf region enhances this decrease in surface height. Over East Antarctica, the surface increases with typical rate of several mm yr^{-1}.

The results will be applied to satellite observed surface elevation change (dH/dt) as a correction part to allow more accurate estimations of the ice sheet mass balance and the contributions to the sea level change.

Seismic Studies of the Amery Ice Shelf, East Antarctica

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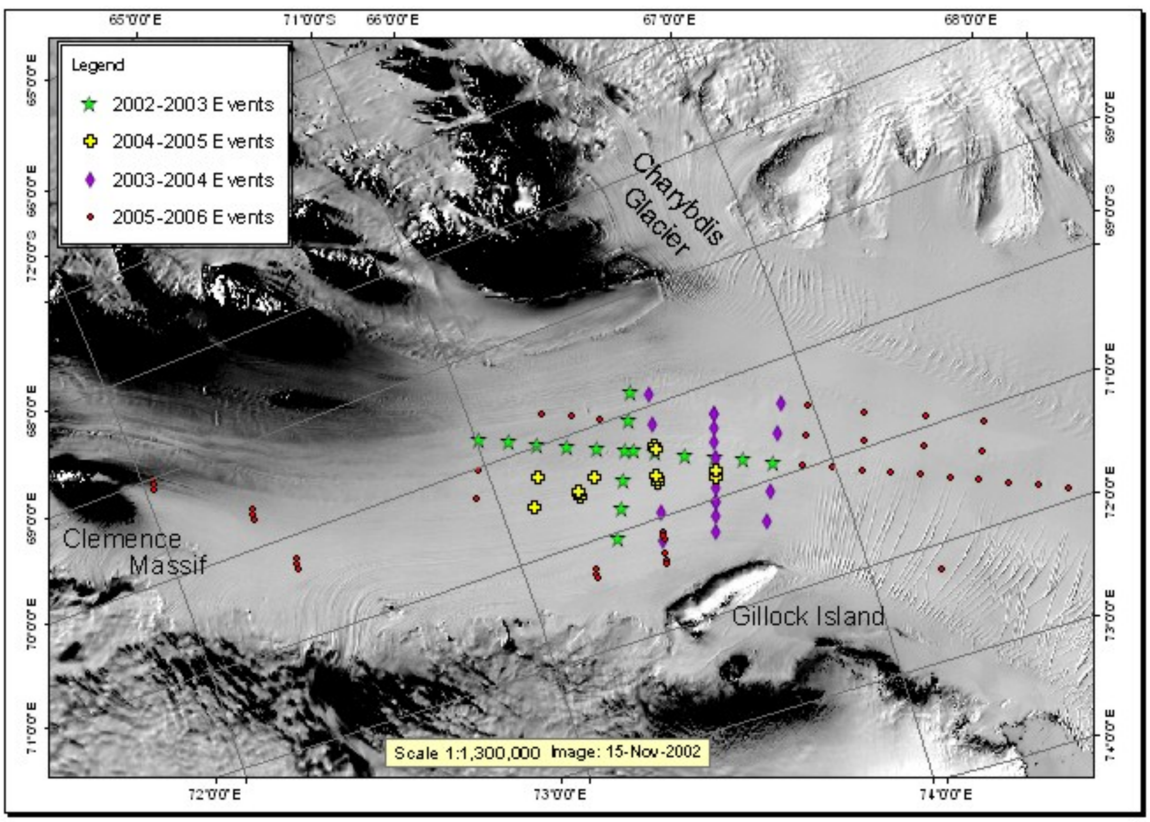
In the 2002/2003 and 2004/2005 Antarctic summer seasons, seismic research was carried out on the Amery Ice Shelf (AIS), East Antarctica. The AIS is located between Davis and Mawson Stations, on the coast of East Antarctica, at around 70°S, 70°E. It is the third largest embayed shelf in Antarctica, and the largest entirely in East Antarctica, and as such is one of the largest glacier drainage basins in the world. Due to this, and its thermal isolation, the AIS plays an important role in the global climate system (Allison, 2003). As such, the AIS is a very interesting site for study. The AIS has been the site for numerous glaciological surveys in the past, however seismic surveying had not been undertaken in a serious manner since the Soviet Antarctic Expedition (SAE) seismic surveys in the 1970s. These entailed about eighty seismic observations, none of these being taken south of 71°35´S (Hunter et al., 2004; Allison, 2003).

The initial aim of the research, beginning in the 2002/2003 season, was to undertake some regional mapping of the ice shelf, and to determine if marine ice could be differentiated from meteoric ice employing the seismic technique. Similar work was carried on in the 2003/2004 season by Hugh Tassell (UTas, GA). In 2002/2003, regional surveys were completed every 10 km along the north-south line running down the centre of the AIS (see Fig 1 for survey locations). A 50 km perpendicular line was carried out across the centre of the north-south line, and a 1 km detailed seismic reflection line was carried out just north of this intersection. This was done using overlapping spreads to maintain fold coverage. The resulting seismic stack showed two distinct reflections around the ice-water boundary, which results in a ~20 m thick marine ice layer here.

In the 2004/2005 season, the scope of the project was extended to include research into deformation and fracturing of the AIS. The major aim of the research was to ascertain whether the ice showed anisotropic properties, i.e. whether strain along stream margins had led to a realignment of ice particles, causing a difference in seismic ice velocity between the direction of flow propagation compared to the normal to the flow direction. For this season, this type of survey was initially proposed to be undertaken in regions close to Gillock Island on the eastern side of the AIS, along lines of high strain, seeing as these would be the areas most likely to show anisotropy. Sites to survey were picked from strain images of the ice shelf, produced from ice velocity images. Due to an inability to access these sites in 2004/2005, the anisotropy surveys were instead undertaken over flowline margins, as picked from Landsat images. It was hoped that the flowlines represented a margin which could possibly have undergone enough strain in the past to preserve a relict shear margin, to reveal anisotropic differences in the ice. Surveys were undertaken in sets of three, one survey spot in the middle of the "strained" area (i.e. on the flowline) and two spots either side of the flowline, approximately 1-2 km from the centre spot. This distance was used so as to be outside any influence of where strain had occurred, resulting in what we hoped to be measurable difference in seismic velocity, with central anisotropic ice, and isotropic ice to either side. Processing is still being done on data obtained last season, and results so far are inconclusive as to whether the seismic velocity variations are great enough to be outside the error margin.

Next season, the 2005/2006 Antarctic summer, more anisotropy surveys will be carried out closer to Gillock Island, and regional surveys will be continued to improve the detail and extend the boundaries on the current subsurface map of the AIS. The plans for this season are to access the anisotropy survey locations within the strained area close to Gillock Island, as well as in an area in the south of the AIS. By undertaking surveys on the same ice stream in both regions, it can be discovered if there's a difference in anisotropy properties related to the age of the ice since deformation, comparing data from younger ice in the south with data from older ice near Gillock Island.



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Hunter, J., Hemer, M., & Craven, M., 2004. Modeling the circulation under the Amery Ice Shelf. Forum for Research into Ice Shelf Processes, Report (15). Web address: http://www.gfi.uib.no/frisp/Rep15/hunter.pdf (accessed 15/06/05) Caption: Fig 1. Survey locations of recent seismic work on a satellite image of the Amery Ice Shelf.

Inferred accumulation and thickness histories near the Ross/Amundsen divide, West Antarctica

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The United States ice coring community has identified the ice divide between the Ross and Amundsen Seas as the next site for a deep U.S. coring effort (Inland WAIS). As part of this program, we have used ground based radar-detected internal layers (assumed to be isochrones) to derive depth-age relationships for a prospective ice core site in the Inland WAIS area approximately 25 km from the current divide on the Ross Sea side.

The depth-age relationship is based on radar layers tracked from the dated ice core at Byrd to the prospective site. The depth of the oldest distinct radar layer (observed at 1.5 MHz) corresponds closely to an acidity event in the Byrd core, which has been attributed to "excessive volcanism" 17.5 ka BP. Due to the lack of any layers between 8.4 ka and 17.3 ka BP, we are unable to resolve any details of accumulation rate in that time period. Consequently, we restrict our analysis to the most recent 8.4 ka. The traced-radar-derived time scale for Inland WAIS is compared with results from a one-dimensional flow model to infer possible combinations of past thinning, accumulation, and ice sheet geometry at the site in the Holocene. Our model is based on the formulation of Dansgaard and Johnsen (1969) and includes the effects of strain-thinning, variations in accumulation rate and ice thickness in the past and basal melting.

Our results suggest that the thick ice in the region (3,300m) makes the depth-age relationship relatively insensitive to small changes in ice thickness. Variations in layer thickness on short time scales (relative to the characteristic response time of ice thickness divided by accumulation rate) arise primarily from variations in accumulation rate. Model results suggest that the Holocene accumulation rate between 8.4ka and the present averaged ~125% of the modern value, and that accumulation rate reached a maximum value between 6 and 4 ka BP.

Title: Wideband Radars for Imaging the Bed and Mapping Internal Layers

Paden, J., T. Akins, D. Dunson, G. Jayaraman, C. Allen, V. Ramasami, P. Kanagaratnam, K. Jezek, P. Gogineni

We designed and developed a wideband coherent radar (120-300 MHz) for imaging the ice-bed interface, measuring ice thickness, and mapping layers at depth with fine resolution. The radar utilizes a phased-array with 10 elements for digitally forming multiple beams. Two off-nadir beams are generated for imaging about 700 m on either side of the track. One beam, pointed at nadir, is used to measure ice thickness and map layers at depth. We successfully operated this radar along with an ultra-wideband radar (500-2000 MHz) at Summit, Greenland (72.5789N, 38.4597W) in July 2005. The ultra-wideband radar is used to map near-surface internal layers to a depth of about 150 m with 10 cm range resolution. We mounted the two radars on a Tucker Sno-Cat vehicle and collected data along a 6.5-km swath over a distance of 25 km between the GISP2 and GRIP boreholes.

The results from these experiments show that we can map internal layers to a depth of 2800 m and these layers can be tracked between the GISP2 and GRIP boreholes. The observed resolution of the system is about 1 m and a strong bedrock return was seen at all locations in the grid. We will present the depth sounder results from the grid and the corresponding ice thickness map. Figure 1 shows preliminary results from the radar depth sounder. The data are taken as we drove away from the GRIP borehole towards the GISP2 borehole. The image on the left shows the data from the surface to the bedrock and the image on the right shows a magnified view from a depth of about 2550 m to 2850 m.

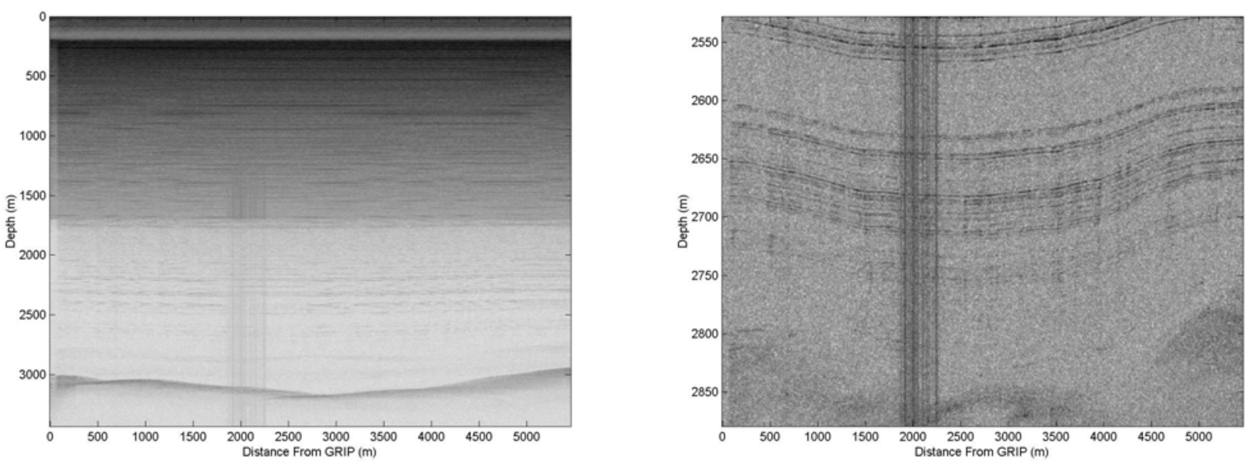

Figure 1. Radar depth sounder results near the GRIP borehole from data collected in July 2005.

During the 2004 field season, we collected data with a prototype radar to test the concept of synthetic aperture radar (SAR) imaging of the ice-bed interface [1]. We collected these data with a radar that operated at 80, 150, and 350 MHz with HH polarization. Figure 2 and 3 show sample SAR images obtained with the prototype radar. This system has a much lower bandwidth, signal-to-noise ratio, and fixed antenna beams, but follows the same fundamental operations as the newer radar. Sample images from data collected this year will be presented at this WAIS summit.

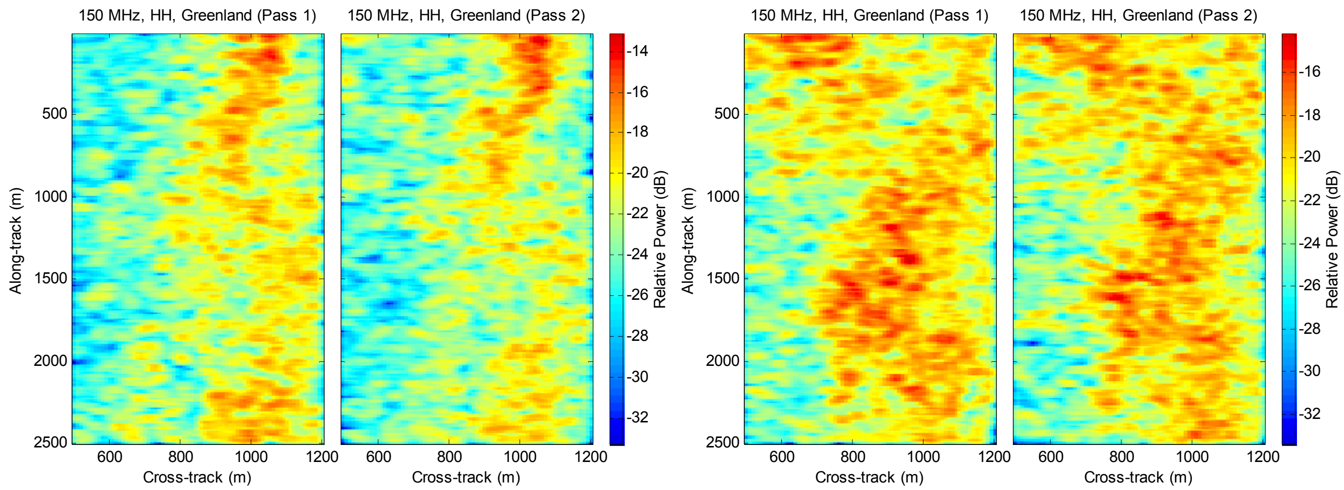

Figure 2. Shows two pairs of 150-MHz, HH-polarized, monostatic SAR backscatter maps from the base of the ice sheet near Summit, Greenland from data collected in 2004. Passes 1 and 2 refer to separate data collection passes over the same terrain.

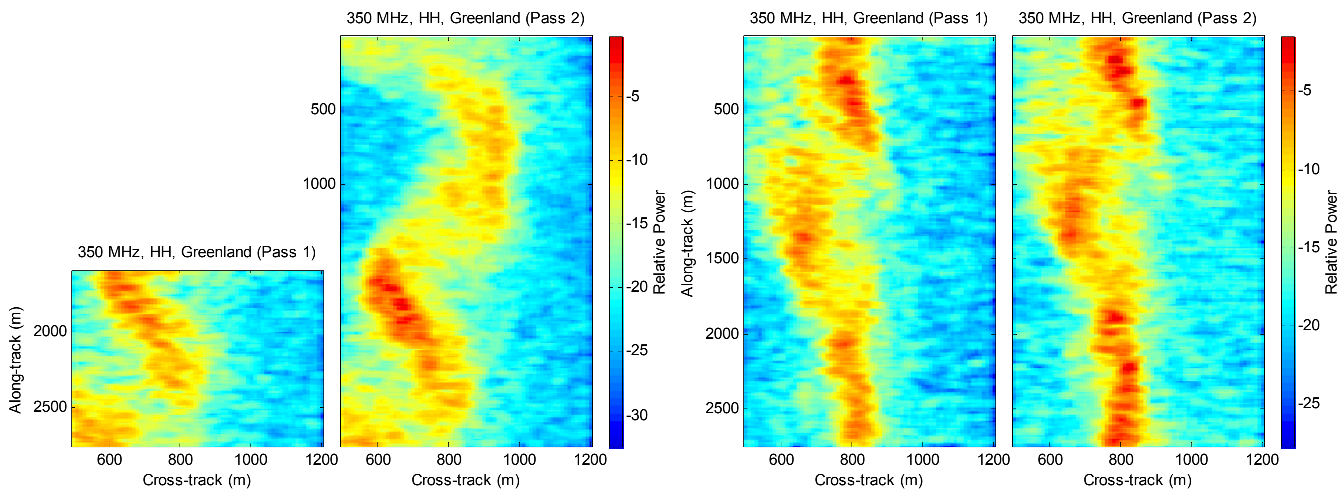

Figure 3. Shows two pairs of 350-MHz, HH-polarized, monostatic SAR backscatter maps from the base of the ice sheet near Summit, Greenland from data collected in 2004. Passes 1 and 2 refer to separate data collection passes over the same terrain.

Additionally, we will show results from the ultra wideband radar along with a comparison to layers found in nearby snow pits excavated during this field season. We plan to collect data with both these radar systems at the new WAIS ice core site during the 2005 to 2006 field season.

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Getting into the Zone: Ice Shelf Margins from ICESat

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Since its launch in January 2003, the ICESat mission has mapped the Antarctic ice sheet to 86 degrees south, well south of the ESA ERS and Envisat satellites, which have maximum latitudes of ~81.5 degrees. ICESat thus extends altimetry coverage to the entire floating portion of the ice sheet, including the southern parts of the Ross and Filchner Ronne ice shelves (RIS and FRIS), for the first time.

We have previously demonstrated that the accuracy and spatial coverage of ICESat over the free-floating interior of ice shelves is sufficient to allow us to identify the optimum ocean tide model for the Ross Ice Shelf (Padman and Fricker, 2005), with crossover data from just one laser operations period of ~40 days duration. Here, we consider another application of ICESat data over ice shelves: the use of repeat-track data across the grounding zones (GZ) to determine the location and characteristics of the GZ. ICESat samples every 172 m along-track with a footprint of ~65 m diameter, thus easily resolving the GZ which is typically several km wide. These characteristics can be used to precisely identify the grounding line (GL) and the seaward limit of the GZ, based on the limits of observed tidal flexure (Figure 1). Here, ICESat repeat-track analyses indicate that the GL is ~3 km further north than indicated in recent coastline databases. By repeating these studies around the perimeter of the RIS and FRIS, we can significantly improve the GL definition, with implications for the quality of models of ocean/ice and ice stream-ice shelf interaction and for mass balance estimates. By defining the characteristics of the GZ, including width and curvature, it will be possible for the first time to apply tidal corrections within the GZ, which is frequently a region of intense basal melt and thus a significant focus of shelf-ice mass balance studies.

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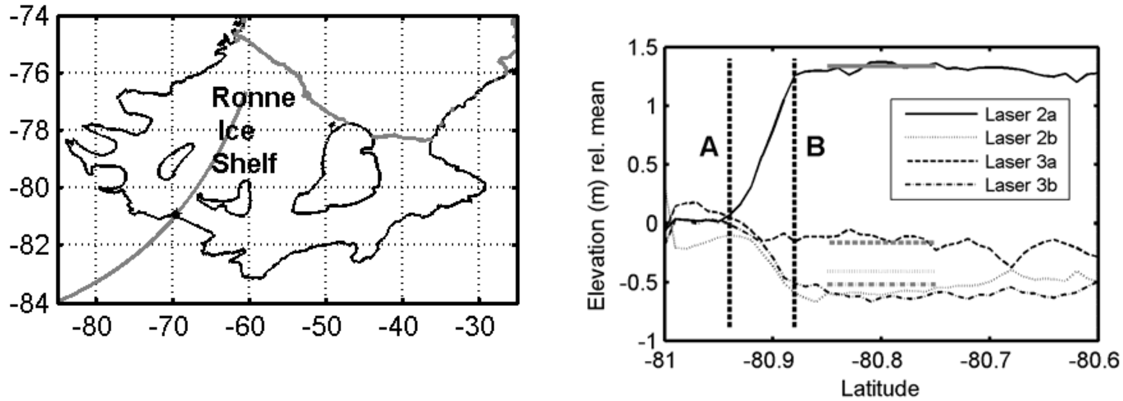

Figure 1: (left) Location of ICESat 91-day Track 1304 (gray arc), which crosses the southern Ronne Ice Shelf grounding line near 81°S, 69.6°W. Coastline (black) and ice front (gray) are from the SCAR database on the GEBCO 2003 CD. (right) Plots of ICESat-derived relative elevations, h'_i, smoothed at about 1 km along-track, for the four available repeat orbits of Track 1304. ICESat data have been "retided", adding back in the ocean tide and ocean tide loading corrections, which are applied during standard processing using the GOT99.2 tide model. Point **A** is the "limit of tidal flexure", slightly inshore of the grounding line. Point **B** is the seaward limit of tidal flexure. The width of the GZ, from A to B, is about 8 km. Horizontal dashed lines indicate tides predicted from CATS02.01 [*Padman et al.*, 2002] for a location just inshore of the GZ at the times of respective ICESat passes. A constant offset has been applied to each tide prediction in order to match the model to the offshore height deviation of Laser 2a. This offset accounts for tidal constituents which are aliased by ICESat's orbit to very long or infinite period. CATS02.01 underestimates the offshore tidal range by ~20 cm. The ICESat-derived GL is ~3 km north of the SCAR coastline.

Ice-flow sensitivity to sticky spots, side shear, and buttressing

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Longitudinal stresses, side shear, and oceanic backpressure have been combined with pre-existing vertical shear in the momentum balance within the PSU/UofC flowline model. This enables us to investigate the regional response of grounded-ice flow to variable resistance from the bed, lateral boundaries, and/or ice shelf, leading to an improved understanding of the thermodynamic impact of local and regional resistance to inland flow. We plan to direct our modeling efforts toward the interplay between basal lubrication, ice-shelf buttressing, and embayment geometry, and their evolving effects on the ice streams, outlet glaciers, and inland ice of Antarctica and Greenland.

Numerical modelling of ocean-ice interactions under the Pine Island Glacier ice shelf

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A two-dimensional numerical model is used to simulate the dynamics of the buoyant water plume believed to underlie the ice shelf occupying much of Pine Island Bay, West Antarctica. Recent studies have shown that this ice shelf, along with all others fringing the Amundsen Sea, is thinning at an anomalously high rate [Shepherd et al., 2004]. Forcing the numerical model with observed temperature and salinity profiles [Jacobs et al., 1996] yields an average melt rate of 20.2 m/yr, which is in good agreement with several data-based estimates. The model suggests that the observed thinning rates are consistent with a 0.3 to 0.5 deg. C warming of the Amundsen Sea; a value that has been observed for Circumpolar Deep Water in the nearby Ross Sea [Jacobs et al., 2002]. Results suggest that both the Coriolis effect and sub-shelf topography are important in controlling plume dynamics and the spatial distribution of ice melt.

Discontinuous Sediment Cover and "Fast" Ice Flow: Observations from the Upper Reaches of Tributary C1B

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Discontinuous sediment cover upstream of the onset of the West Antarctic ice streams may be a crucial component in developing streaming ice flow, as observed from a seismic reflection experiment along the upper reaches of tributary C1B. These pockets of soft sediment beneath the slow-moving ice stream tributaries produce localized basal lubrication that helps channel the inland ice reservoir to the fast-flowing and well-developed ice streams of West Antarctica. Our seismic experiment has imaged a discontinuous package of soft sediments beneath tributary C1B, just kilometers upstream of continuous sediment cover and full development of the ice stream tributary. This pocket of sediments is coincident with a localized decrease in basal shear stress and enhanced flow of the overlying ice, but the discontinuity of these sediments does not produce the streaming ice flow observed farther downglacier. Though streaming ice flow may not be able to extend beyond the reaches of continuous subglacial sediment cover, pockets of soft sediment well upflow of the ice streams may strongly influence the flow character of the West Antarctic Ice Sheet.

Radar Wave Speed and Attenuation Studies Using Constant Midpoint Profiles on Kamb Ice Stream

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Studies of radar wave speed and attenuation as a function of depth were carried out on Kamb Ice Stream this past field season as part of a two-year program of radar and GPS studies examining the possibility of ice stream reactivation. Two constant midpoint profiles were completed in which the radar transmitter and receiver were separated in 20 meter increments starting from 100 meters and extending to 1200 meters. The locations of these two profiles were in areas characteristic of both high and low bed reflectivity, one of them over rough bed topography on the "sticky spot" and the other at the south margin of the sticky spot where Cal Tech bore hole 00-01 located a layer of liquid water at the bed in 2000.

The semblance analysis from both profiles shows coherent returns from a number of prominent internal reflectors (figure). By differencing average two-way travel times from these reflectors we have produced a radar wave velocity versus depth curve that can be used to test theoretical models based on ice density and temperature. As expected it shows higher velocity from near-surface layers and decreasing toward the bed.

We have also carried out an analysis of the reflected power as a function of antenna separation giving us information about radar wave attenuation with propagation distance in the ice. These data complement results from our profile measurements where attenuation varies with ice thickness.

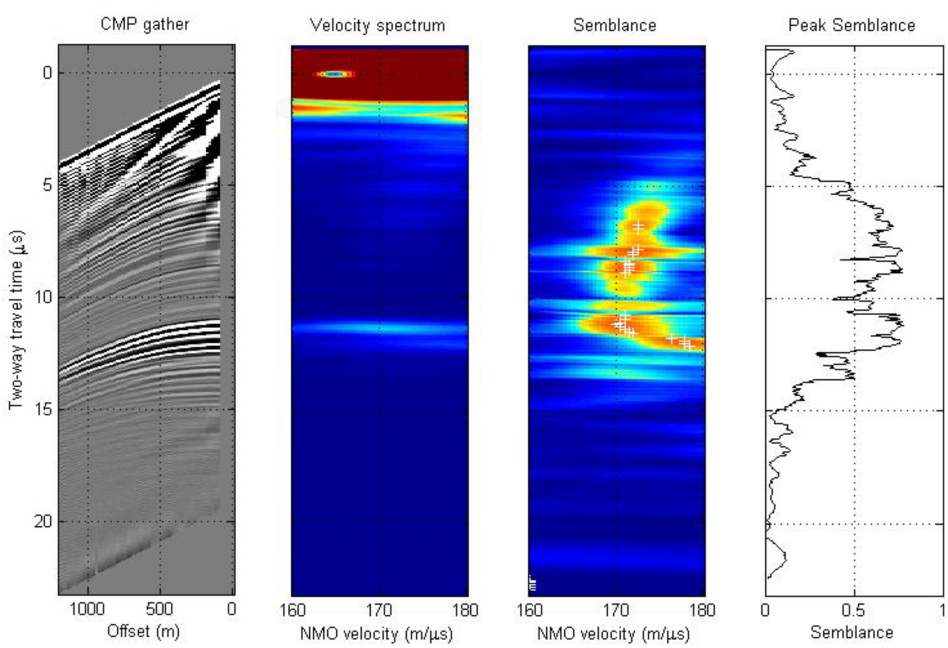

Figure Caption:
Semblence analysis for constant midpoint profile on Kamb Ice Stream centered on the “sticky spot.” Panel at the left shows hyperbolic returns from individual internal layers imaged at increasing transmitter – receiver separation. Second panel gives information about the return amplitude as a function of depth. Third panel shows decreasing average two-way velocity with depth. The first phase of the bed echo at approximately 11 microseconds has an average value just above 170 m/usec. Panel at the right indicates the relative strength of the semblance for each reflector. Note that the higher apparent velocities below the first bed echo are from returns off to the side of the profile in this area of bumpy bed topography and are not treated correctly by this analysis.

The effect of anisotropoy on flow of Siple Dome, West Antarctica

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Polycrystalline ice near an ice divide shows a crystal fabric (preferred crystal orientation) that typically has c-axes clustered vertically. We explore the effect of this fabric on the flow pattern near an ice divide. Our finite-element ice-sheet flow model uses a nonlinear flow law that accounts for deformation due to crystal fabric. We found that the resulting deformation depends on the vertical profile of crystal fabric, and that fabric significantly alters the flow pattern only when the fabric tightens to a cone angle of less than about 30 degrees. (The cone angle is the half angle of the cone within which the c-axes align.) A vertically-oriented fabric tends to decrease the steady state thickness of a divide and to amplify the special divide flow pattern that is produced by the stress-dependent viscosity of a nonlinear fluid.

The borehole sonic velocity log for Siple Dome shows a large increase in velocity (and therefore stronger crystal fabric) for ice that was deposited as snow during the Wisconsin when compared to that deposited during the Holocene. Using a comprehensive flow model for Siple Dome, we show that this change in fabric significantly changes the pattern of flow for Siple Dome. In particular, it introduces a bed-parallel shear band several hundred meters above the bed that behaves like a "false bed" for ice sheet flow. Also, the shear band enhances the difference between the flank and divide vertical strain-rate profiles. The flank/divide difference is a key characteristic of the special divide flow pattern resulting from the nonlinearity of ice that produces the isochrone pattern known as the "Raymond Bump". An important effect of this false-bed effect, and its association with the Wisconsin/Holocene climate transition, is that the shear band has strengthened and moved deeper in the ice sheet since the climate transition, affecting the dynamic history of the ice sheet. Finally, we compare the sonic velocity log for Siple Dome, with that recently available for three boreholes in Greenland.

Proposal for a Collaborative REU Site Program REAL ICE - Research Experience in Antarctica Linking Ice and Climate Education

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The ice-core deep-drilling program at the divide between the Ross and Amundsen Sea drainage basins of the West Antarctic Ice Sheet (WAIS) is a large collaboration among scientists and the National Science Foundation to augment our understanding of the history of global climate. To complement the substantial collaborative effort by the scientific community, we have proposed to NSF a program that will combine high profile public outreach with research experience for undergraduates. Although this program is still pending funding, we would like to encourage WAIS scientists to think about ways in which a program of this type might connect with their WAIS activities.

Each year that the deep drilling activities occur, ten undergraduate students in science, writing, education, and public policy from all parts of the country will be invited to join the "REAL ICE Outreach Team". They will spend the fall quarter of the academic year studying and doing research on climate change and the role of ice in the climate system. Each cohort of students will spend the first six weeks of the quarter on the campus of the University of Washington (UW) studying with UW and Portland State University faculty to deepen their knowledge of Earth's climate and learn how ice cores teach us about climate history. Also, during this time science writers and science educators will work with the students to teach them ideas and techniques in teaching and communicating scientific discoveries. They will then travel to McMurdo Station and on to the WAIS deep drilling site to continue their learning through research experience for another five to six weeks.

The overall goal of the program is to provide the public with a personal connection to the research that is happening in Antarctica. It is much easier for the general public to become interested in a project such as the WAIS Divide program if they can relate through people (the students) with whom they feel a connection.

This REU Site education and outreach program has two audiences, the ten undergraduate students we choose each year to be directly involved and the general public associated with educational institutions. For the the undergraduate students, we will 1) challenge them to think critically through making observations, framing questions, and designing scientific experiments, 2) teach the process of scientific discovery through their own experiments and working with scientists, 3) challenge the students to communicate their understanding through teaching each other, and 4) inspire the students not only to learn for themselves, but also to share that knowledge with others. The impact on the secondary audience occurs through high-profile outreach and recruitment activities which will not only interest students in participating, but also educate the public about the WAIS Divide drilling program. During and after the program, students will develop their own outreach activities, which they will then take with them and share with their local communities.

If you have ideas and suggestions for the implementation of this program please email Erin Pettit (epettit@ess.washington.edu).

Investigating feedbacks between basal sliding, frictional melting, and longitudinal-stress transmission

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Feedbacks between basal sliding, frictional melting, and longitudinal-stress transmission may allow for upstream migration of a slow-to-fast sliding transition, such as that occurring near and upstream from the ice stream onsets (i.e. along tributaries). We use an appropriate 2-dimensional, thermomechanical flowband model to explore the potential for such feedbacks along an idealized ice stream tributary and onset region. Sliding takes place through deformation of a basal layer with linear or power-law viscous (approximating plastic) rheology, the shear strength of which is a function of the basal melting rate. We explore the sensitivity of positive feedbacks to a number of parameters including lateral drag and drainage of basal meltwater.

Flow and Thickness History of Siple Dome, West Antarctica

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We use a high-order, transient, thermo-mechanical flowband model to explore possible flow and thickness histories for Siple Dome, West Antarctica. Changes to the model velocity and temperature fields are forced using specified accumulation-rate and surface-temperature histories. Changes are also forced by varying several unknown parameters, including the timing and magnitude of dome thinning, the timing of divide-flow onset, flow enhancement, and accumulation-rate scouring at the divide. Model output is constrained by the depth-age and depth-temperature profiles from the summit core site, the dome surface shape, and internal layer shapes derived from RES. Based on the model fit to these observations, we present a sensitivity analysis of the unknown parameters and a set of favored parameter values. Favored values indicate overall dome thinning of ~350m from 16-2 ka b.p., divide flow initiated at 3 ka b.p. followed by immediate northward migration, flow enhancement, consistent with current observations of crystal fabric, starting at ~7 ka b.p., and minor accumulation-rate scouring at the divide since 3 ka b.p.

Laboratory Study of Till Rheology

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Recent studies show that small-amplitude stress changes can trigger ice sheet motion and subglacial seismicity. Deformation in the subglacial region plays a key role in determining slip behavior, including creep, transient slip, stick-slip motion, and seismicity. However, progress in understanding these phenomena is limited by uncertainty in the rheology and frictional properties of glacial till. We report on detailed laboratory experiments to measure the creep of till sampled from the Matanuska Glacier, Alaska and Caesar Till from the Scioto Lobe of the Laurentide Ice Sheet, sampled in central Ohio.

Experiments were conducted in a servo-controlled, double direct shear apparatus with air dried samples at a normal stress of 1 MPa. Till was sheared in a three-block arrangement in which two layers are sandwiched between a central forcing block and two stationary blocks. We studied the effect of saturation, initial deformation fabric, stress history, and the boundary conditions of loading. The nominal frictional contact area is 100 cm^2 and remains constant during shear. The layer thickness is 1 cm prior to shear. All blocks are grooved perpendicular to the shear direction to ensure that deformation occurs within the layer. The Matanuska till has grains ranging from 6.3 mm to finer than .063 mm with a mean of 2.67 mm whereas the Caesar till has a smaller mean grain size of 0.60 mm, but lacks silt and clay sized particles.

We conducted both constant strain rate and constant stress tests. Constant strain rate tests were used to study rate/state frictional rheology using perturbations in slip rate, which were imposed during steady sliding. Constant shear stress experiments were employed to study frictional creep. In these tests, stress steps were conducted at 2 % and 5 % steps of the shear strength with strain rate calculated at 20 and 40 minute intervals after the stress steps. Strain rate was calculated by taking a linear fit of strain versus time over two minutes. The stress exponent, n was then calculated from the equation $d\varepsilon/dt = b\tau^n$. Where ε is strain, τ shear stress, and b is a constant. Under these conditions till was found to deform plasticly with a stress exponent that ranged from n=5 to n=13. Experiments taken directly to constant load conditions without an initial displacement exhibited a lower strain rate and smaller stress exponent than experiments, which first deformed the sample to failure with an initial 10 micron displacement.

Self-organizing maps in review: recent applications in polar (paleo)climatology

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The global climate system and natural archives of its history are linear only by approximation. Available observational and instrumental records are inadequate for full characterization of natural variability; proxy histories from, e.g., ice cores and tree rings are thus necessary to more fully understand climate change, past and future. Linear tools have proven highly valuable in understanding paleoclimatic records such as these, and others, but are inherently limited to linear relationships. Motivated by these and other reasons, we have assembled a suite of nonlinear, highly adaptive tools based on artificial neural networks and applied these tools to several problems in (paleo)climatology.

Self-organizing maps enable unsupervised classification of large, multivariate data sets, e.g., time series of the atmospheric circulation or sea-ice extent, into a fixed number of distinct generalized states or modes, organized spatially as a two-dimensional grid, that are representative of the input data. When applied to atmospheric data, the analysis yields a nonlinear classification of the continuum of atmospheric conditions. In contrast to principal component analysis, SOMs do not force orthogonality or require subjective rotations to produce interpretable patterns.

Results to date have been encouraging and include: improved reconstructions of past climates from ice-core and automatic weather station measurements; new perspectives on sea-ice variability; and a new look at Holocene variability in ice core chemistry datasets. Further data are needed, but we are optimistic that these neural-net techniques will prove a useful complement to the traditional linear approaches, capturing more of the rich nonlinearity of the earth system.

Glacier changes in Pine Island Bay and the Antarctic Peninsula from Radarsat-1 2000-2005

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Rapid changes are taking place in Pine Island Bay, West Antarctica and the Antarctic Peninsula, with important consequences for sea level change. Here we present the latest Radarsat-1 acquisitions in these regions. The results in Pine Island Bay are as follows: 1) Summer radar imagery reveals the presence of water-saturated snow at the surface of ice shelves in Pine Island Bay, which we never observed in prior data. This suggests that the regional warming experienced in the Antarctic Peninsula is reaching as far south and west as Pine Island Bay, which is corroborated by model predictions from M. Broeke and satellite surface temperature from J. Comiso; 2) Pine Island Glacier is still accelerating; we summarize its acceleration from 1975, 1980, 1992, 1996 with Landsat/ERS and 2000 through 2005 with Radarsat-1, with a high density of data starting in 2003 till present; overall the glacier increased its speed by more than 30 percent. An animation of the imagery will be presented to illustrate the dynamic character of the glacier; 3) A new set of cracks appeared 150 km from the ice front of Pine Island Glacier in Aug-Oct 2004, which continued to extend until late Dec 2004, over a region about 30 km wide and 10 km in length. These new crevasses suggest an increase in longitudinal stretching of the glacier far inland from the grounding line, consistent with prior observations that the speed up affects a vast area quickly; 3) new cracks are also visible near the grounding line of the eastern ice shelf of Thwaites Glacier. If the ice shelf severes from the glacier, it could double the width of Thwaites Glacier. An earlier study indeed suggested that Thwaites Glacier is widening. These changes are significant and indicate no slow down of glacial retreat in this sector of Antarctica. In the Antarctic Peninsula, Crane Glacier is still experiencing a spectacular retreat in the wake of the collapse of Larsen B ice shelf, while Evans/Hektoria/Green are now slowing down from their 8-fold speed up but still strongly retreating. We will discuss flow changes in other parts of the Peninsula at the meeting from the mapping of velocities along the entire coast of Graham Land.

Better Physics in Embedded Models: Iceberg arcing and Lake-surface profiles

Aitbala Sargent, Ted Scambos, James Fastook

The commonly used shallow ice approximation neglects all stresses except the basal drag, an assumption that is very good for inland ice but may be very poor for fast-flowing, low-surface slope ice streams, where longitudinal stresses may not only be important, but may in fact be the dominant stress.

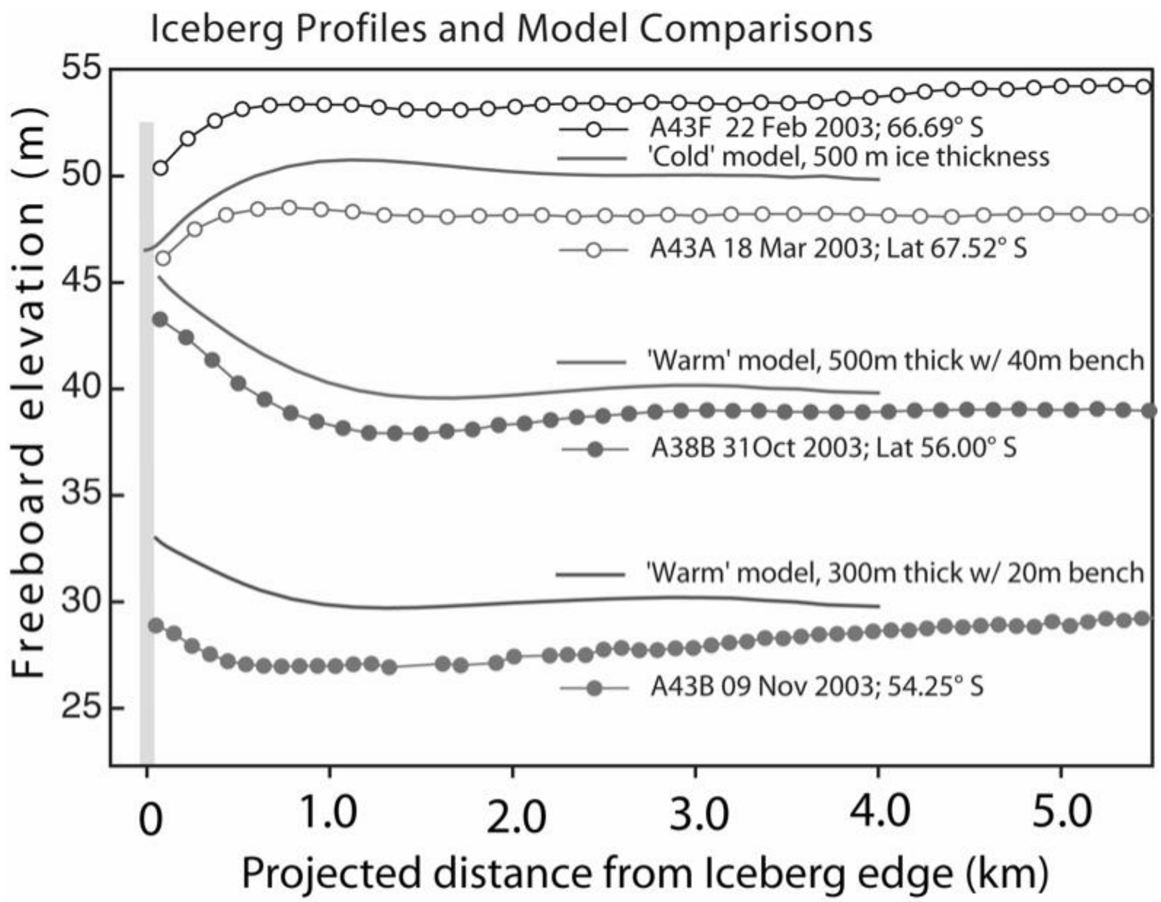
Treating the ice streams as barely-grounded ice shelves is another approach, which may be seen as the opposite end member in a spectrum of approximations. In this approximation the only stresses are the longitudinal stresses, the basal drag is not included in the fundamental formulation, but instead is added on as a small correction after integrating the vertical dimension with the assumption of no basal drag.

The only way to truly quantify the importance of longitudinal stresses is to solve the full momentum equation with none of the limiting assumptions that go into either the shallow-ice or the barely-grounded ice shelf approximations.

An implementation of a 2D solution of the full momentum equation is presented. Two examples dealing with 1) iceberg arcing and 2) lakes beneath ice sheets are also presented.

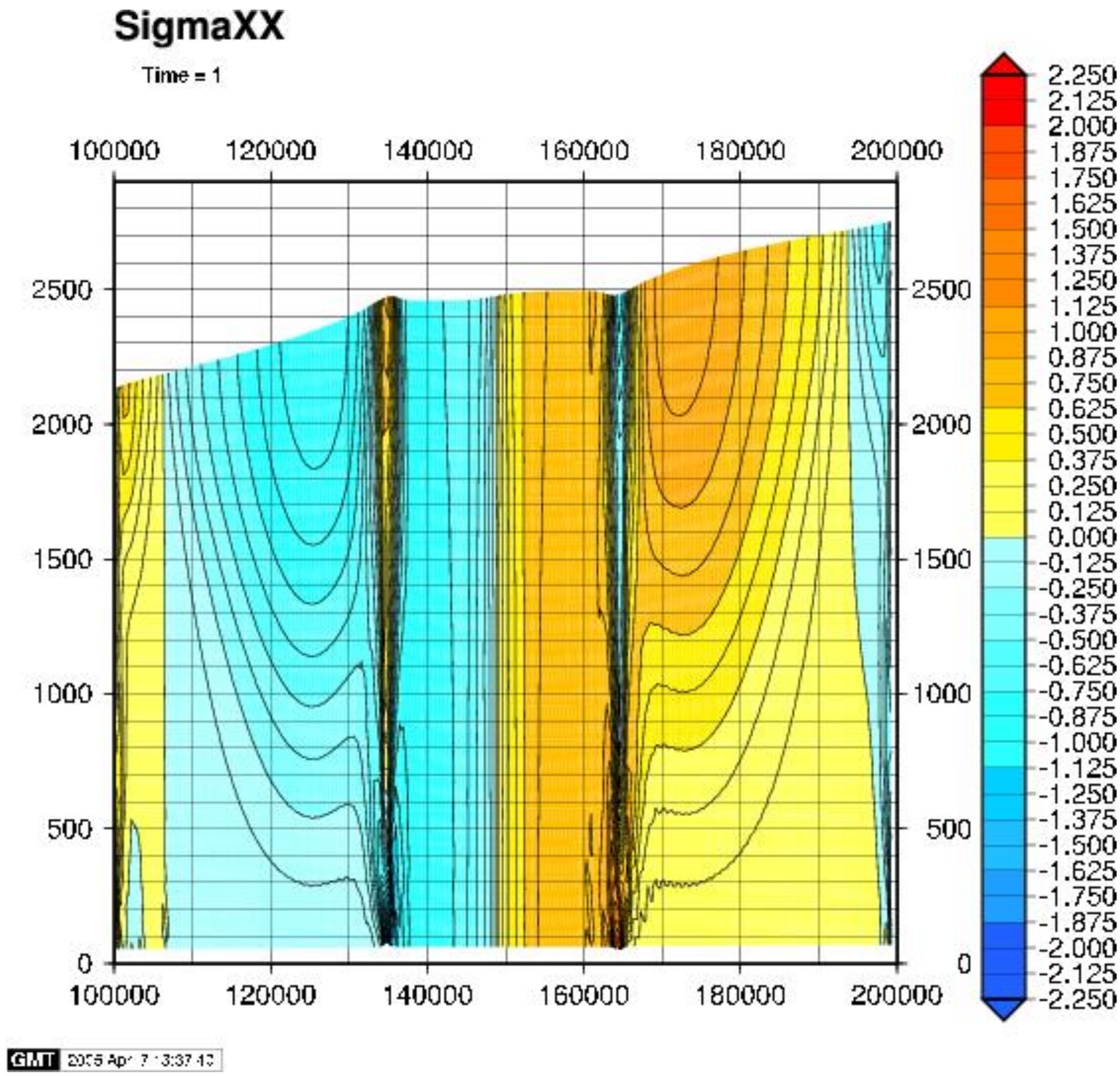
Icebergs observed by Ted Scambos are found to fit into two categories, toe-down and toe-up, and the categories appear to be associated with different temperature regimes. Toe-down icebergs are well-explained by beam theory, but the toe-up configuration is not. A proposed configuration with a submerged bulb was tested with the 2D solver and found to yield good agreement as shown in Figure 1.

Lake Vostok presents an inland situation where longitudinal stresses become dominant as the bed coupling disappears completely over the floating portion. A berm-and-trough feature observed in transects across the lake is modeled successfully using the 2D solver. Time-stepping from an initial parabolic profile shows the evolution of a flat lake surface with berm-and-trough features similar to those observed. Figure 2 shows the longitudinal stress component responsible for this feature.



Iceberg Profiles and Model Comparisons
A43F 22 Feb 2003; 66.69° S
'Cold' model, 500 m ice thickness
A43A 18 Mar 2003; Lat 67.52° S
'Warm' model, 500m thick w/ 40m bench
A38B 31Oct 2003; Lat 56.00° S
'Warm' model, 300m thick w/ 20m bench
A43B 09 Nov 2003; 54.25° S
Freeboard elevation (m)
55
50
45
40
35
30
25
0
1.0
2.0
3.0
4.0
5.0
Projected distance from Iceberg edge (km)

Figure 1


SigmaXX
Time = 1
100000
120000
140000
160000
180000
200000
0
500
1000
1500
2000
2500
2.250
2.125
2.000
1.875
1.750
1.625
1.500
1.375
1.250
1.125
1.000
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0.750
0.625
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-0.125
-0.250
-0.375
-0.500
-0.625
-0.750
-0.875
-1.000
-1.125
-1.250
-1.375
-1.500
-1.625
-1.750
-1.875
-2.000
-2.125
-2.250
GMT

Figure 2

What ever Happened to the Byrd "Snow Cruiser"? -- Analysis of the Evolution of the Bay of Whales, 1911-1963

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Analysis of a series of maps, sightings, satellite images, and aerial photos indicates that a ~5 km2 section of the eastern side of the Bay of Whales containing the buried remains of several bases from the 'heroic era' of Antarctic exploration calved in early 1962. A small iceberg from this event (or closely-spaced events), with the remains of Little America III exposed in the ice face, was sighted in Febuary 1963 near the western end of the Ross Ice Shelf front. More recent calving events, monitored by satellite images, confirm that most small icebergs generated in the eastern Ross drift westward and repeatedly impact the ice front, fragmenting as they move. This implies that a number of artifacts from the bases, such at the 1939-1940 Byrd Snow Cruiser, are likely strewn along the seabed near the 1962 ice front position. Major Ross Ice Shelf calving events of 2000 and 2002 have made much of the 1962 front area accessible to ships. Thus a search for the artifacts is technically more feasible for the next few years until shelf ice flow re-covers the area.

New MODIS-based Mosaics of Greenland and Antarctica: MOG and MOA

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Two digital image composites have been assembled from MODIS images of the two major ice sheets on Earth: Greenland and Antarctica. These composite images are manually cloud-cleared, and use image 'stacking' techniques (also called 'image super-resolution' or 'data cumulation') to improve spatial and radiometric detail beyond the 250-meter and 12-bit characteristics of single Band 1 and Band 2 MODIS images. The images are processed ('destriped') to remove artifacts incurred by the 40-detector whiskbroom scanner and two mirror sides of the MODIS sensor. Images are compiled over a relatively narrow range of time (~8hours UT MOA; ~5 hours UT MOG) so that the illumination direction is relatively constant across the two mosaics. The images are high-pass filtered, at a spatial scale equivalent of 60 km. This step enhances smaller-scale features and balances the histograms, thereby minimizing grey-scale variations from scene to scene. Image edges (from the cloud clearing masks or edge of the swaths) are further filtered to 'feather' them. This leads to seamless, high-contrast, high-detail products in the image stacking step.

The result is a very uniform, seamless, nearly perfectly cloud-free image of the surface of the ice sheets, ice shelves, mountains and mountain glaciers, with a contrast content (radiometric detail) capable of portraying both the gross geographic features near the coast and very subtle undulation and flow line structures in the ice sheet interiors. Spatial resolution is roughly 150 meters. The image is complementary to SAR-based mosaics because the MODIS mosaics are images of the true surface rather than composites of surface reflec-tion and volume scattering of the upper few meters. MOA is comprised of 260 250m images acquired between November 20 2003 and February 29, 2004; MOG is accumulated from ~135 scenes acquired between March 12 and April 30, 2005. The MOG grid includes islands of the eastern Canadian Archipelago, and the several small ice caps they contain. Grid spacing of MOA is 125m; for MOG it is 100m. Up to 40 images may contribute to the MOA mosaic at any one point; the mean is ~15 images.

Additionally, two simple grain-size composite images were generated by applying a normalized difference algorithm to Band 1 (red light) and Band 2 (near-infrared) of the composite scenes. To maintain a quantitative ratio, these images were not processed beyond geolocation and calibration, and so we expect to be able to provide a look-up table for mean grain size for the two ice sheets.

The mosaics are being distributed via a web-based map-server that permits on-the-fly zoom, a series of contrast stretches, and geolocated image delivery. The data are available from both UNH and NSIDC websites.

"Icebergs Behaving Shelf-ishly: Why wait for the Larsen C?"

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Over the past five years, a series of large icebergs have calved from the Ronne Ice Shelf front and drifted northward, first along the Antarctic Peninsula east coast, and later across the Scotia Sea towards South Georgia Island. The bergs broke up or disintegrated within a year of reaching the island. Observations of the icebergs using MODIS, ICESat, and QuikScat have revealed details of the evolution and break-up patterns. In cold (sea-ice covered) water, icebergs evolve slowly, with infrequent calving of large blocks, usually along pre-existing fractures. Margin profiles from ICESat show a 'berm' pattern, with a forward-leaning ice face. In warmer water north of the ice edge, bergs show more frequent edge-parallel calvings ('edge-wasting') in which berg shape is little changed, but berg area gradually decreases. ICESat profiles of these bergs show a 'rampart and moat' pattern. Scatterometry observations of the icebergs indicate the berg firn undergoes significant evolution during northward drift, due to melt and melt percolation. The pattern of winter backscatter change for icebergs (over time) is similar to the variations of ice shelf backscatter with melt frequency (over space, i.e. latitude). This supports the hypothesis that winter backscatter versus melt seaons length (or degree days) may be used as an indicator of ice shelf 'health'. A field expedition to establish automated sensors for weather, ice thickness, melt, firn temperature, and a digital camera with uplink, is planned for the February 2006.

Subsurface melting on iceberg C16 (Ross Sea)

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A field study of surface melting on iceberg C16 (77oS, 168oE) was undertaken during the Austral summer 2004-2005. The goals of field observations were to measure in situ firn density of the subsurface layer, and to set up an instrumentation system for continuous measurements of the subsurface-layer temperature and incoming solar flux. The purpose of this long term experiment is to observe how cold, polar firn evolves to surface melt ponds as the iceberg drifts North through the latitudinal environmental gradient.

Two sets of the density measurements were done on iceberg C16: density measurements of 2.5 m firn layer accessed via a snow pit, and density measurements of a 4.5 m firn core. Three well-distinguished ice layers were observed in the upper part of the snow pit: at 21 cm, 38 cm and 59 cm depth. In comparison with density measured at the Newall Glacier (location 77$o35'S, 162o30'E) by Mayewski and Whitlow (2000) subsurface density on iceberg C16 is relatively high. Considering the relative proximity of both sites, the denser firn on C16 might be due to increase of subsurface melting since 1987-88, when the Newall Glacier firn core was collected.
A core 4.5 m depth was obtained using a Kovacs drill. The core quality was fair, the core was broken into approximately 25 pieces, and some pieces had disintegrated into powdered snow. We can speculate, that large variations between maximum (0.63 g/cm3) and minimum (0.34 g/cm3) density are due to subsurface melting during the two previous summer seasons. The presence of melting is evident from the thin ice layers in the core.
Melting is more efficient in snow densification than compaction by the overburden. In addition, at shallow depths (depth of the core), the overburden load of snow is not big enough to compact the firn. Thus, melting is the only available explanation for the higher densities.
The instrumentation for long-term measurements consisted of a solar-flux pyranometer and twelve high-precision thermistors placed in the snow pit. Every 10 seconds, data from the thermistors and pyranometer is collected by means of a multiplexer data logger . This data, along with data obtained by AWS located in 5 m from the snow pit, is transmitted via the ARGOS satellite data system. Figure 1 shows the time series for all twelve thermistors. Analysis of the temperature data shows that during 23 days out of the 138 day observation period, the temperature in the snow pit was positive, while the daily averaged atmospheric temperature measured by the AWS exceeded the melting point only during one day. The positive subsurface temperature implies melting in the subsurface layer.

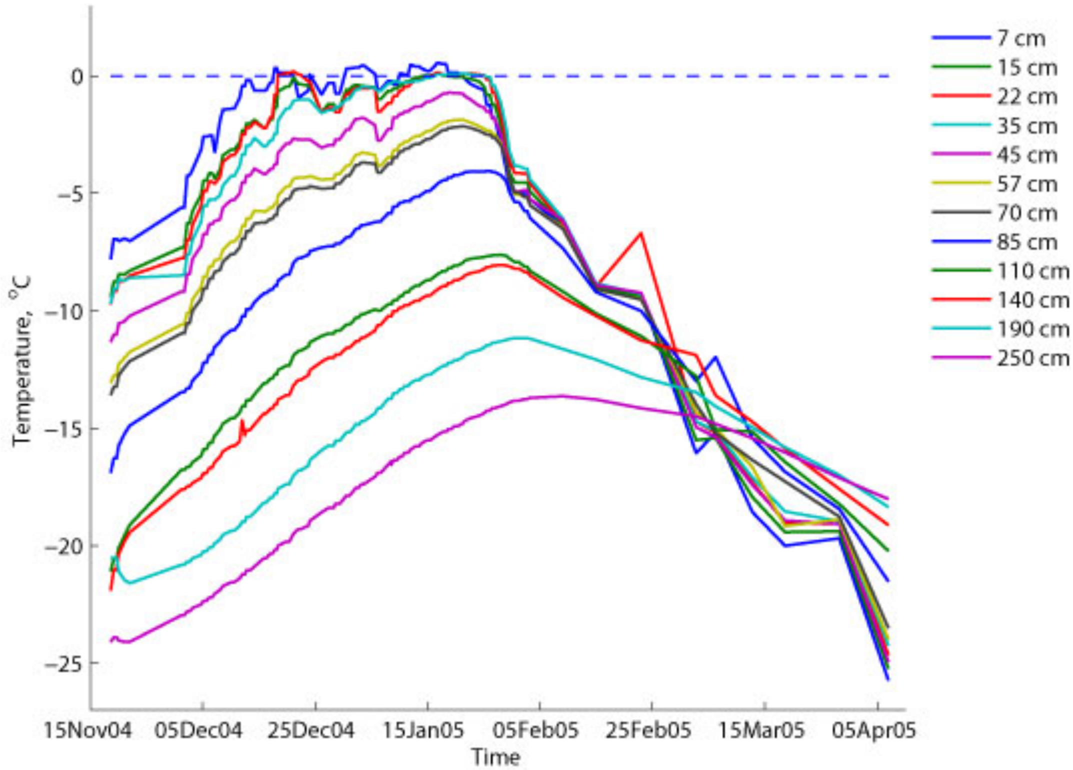

Figure. 1. Temperature of the 2.5 m subsurface layer, November 2004 - April 2005.
Each curve corresponds to one of the twelve thermistors.
Legend shows the location of the thermistors.

[Fig1.jpg](Fig1.jpg)

Reference

Mayewski P. and S. Whitlow, 2000. Newall Glacier snow pit and ice core, 1987 to 1989, Boulder, Co: National Snow and Ice Data Center, Boulder, Co, digital media.

Forget WAIS, Totten is submarine too

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The Totten Glacier (TG) in East Antarctica drains an ice volume greater than the entire West Antarctic Ice Sheet and is grounded, on average, 325 m below sea level. Despite recent increases in snow accumulation, the TG is losing mass due to an ice dynamic perturbation affecting its ~ 70,000 km^2 central trunk. Since 1992, the TG has lost 10 +/- 2 Gigatons of ice each year. The trigger for ice drawdown occurred ~ 200 years ago and predates the onset of global climate warming, suggesting that the retreat of other Antarctic glaciers may share similarly distant origins.

ICESat Altimetry - Lots of Data, Lots of Details

Christopher Shuman

Since ‘first light’ in early 2003, NASA’s Ice, Cloud, and land Elevation Satellite (ICESat) has enabled determination of surface elevations from ~86°N to 86°S latitude. Altimetry data have been acquired in seven discrete observation periods in repeated track patterns using all three Geoscience Laser Altimeter System (GLAS) lasers. This paper will focus on ice sheet and ice shelf elevation data that were obtained from 2003 into 2005; data acquisition continues in October/November 2005.

This poster illustrates the elevations across both polar regions, illustrates the technique's resolution for specific ice features, quantifies the relative accuracy and precision of the resulting ice sheet elevations using data from Antarctica, and discusses some factors impacting change detection and ice sheet mass balance assessments from this data. Currently, the relative accuracy of ICESat elevations is about 16 cm based on the standard deviation of low-slope crossover differences and its precision is nearly 2 cm using Laser 2a, Release 21, GLA12 data.

Rapid erosion and deposition of sediment, and water redistribution, beneath Rutford Ice Stream

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The movement of sediment and water beneath glaciers and ice streams affects the way they flow and the landforms they leave behind when they retreat. We present data from three seismic reflection surveys on Rutford Ice Stream in 1991, 1997 and 2004. All three surveys were conducted at the same geographic location and cover the same section of the ice stream bed, orientated perpendicular to the ice flow direction. The seismic data were used to determine the ice thickness and the acoustic impedance of the bed (the product of its density and seismic velocity), which is a useful indicator of the material beneath the ice. The whole of the bed in this area is made up of water-saturated sediments. In some places the sediments have high porosity (~0.4) and water pressure, and are probably deforming with the ice flow. Elsewhere, although still water-saturated, the sediments are lodged, porosity is lower (~0.3) and the ice is probably sliding over the bed.

Although there are few significant differences between the three surveys along most of the line, three sections of the bed show major changes in basal conditions over the intervening periods.

1. One 500 m wide section of bed in a basal sliding area, experienced 6m of erosion between 1991 and 1997. After 1997, erosion stopped and was followed by the transport of a large mound of deforming sediment, 50 m wide and 10 m high, which moved downstream on top of the underlying, less porous bed.

2. One boundary between deforming bed and basal sliding moved laterally into the basal sliding area between 1997 and 2004. In the process, a 100 m wide strip of lodged sediment increased in porosity, mobilised and became an area of deforming bed.

3. Between 1997 and 2004, the acoustic impedance of one lodged till area, 500 m wide, increased significantly, becoming (acoustically) harder.

These changes show rates of sediment erosion and deposition, as well as their initiation or cessation, which are much more rapid than we expected. They also show on-going, rapid variability in the subglacial water system.

WAIS Elevation changes estimated by the ICESat mission so far

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We analyze differences in ICESat crossovers within the Ross Embayment of the West Antarctic Ice sheet to estimate the short-term mean in elevation change rates. A linear regression of crossover elevation difference against time difference gives an estimate of the mean elevation-change rate during the first 24 months of the ICESat mission . We observe prevalent elevation change in the south, with uplift in the upstream end of Kamb Ice Stream at 0.25-0.28 m/a, and thinning in the parts of Whillans Ice Stream, Mercer Ice Stream, and the adjacent Conway and Engelhardt ice ridges at 0.06-0.18 m/a. We consider possible causes for these apparent changes apart from true elevation change: These rates are too large to be explained by the 0.02 -0.03 m/a formal regression error, by seasonal height variations, by time-varying biases in ICESat measurements or by accumulation- or densification-rate variability, suggesting that they reflect real variations stemming from the ice dynamics of the region.

ASTER IMAGERY OF ANTARCTICA: GEOGRAPHIC COVERAGE, DATA AVAILABILITY AND GLACIOLOGICAL APPLICATIONS

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The ASTER sensor onboard NASA's Terra satellite has been collecting high-resolution satellite imagery since March 2000. An aggressive imaging schedule and the use of appropriate gain settings for snow and ice ensure extensive coverage of much of the Antarctic ice sheet. Key characteristics of the imaging system include: good radiometric resolution provided by 14 spectral bands ranging from VNIR through TIR; 15 m resolution in the three VNIR bands; stereo imaging capabilities with nadir and backward looking telescopes; and off-nadir scene acquisition capabilities. The orbital characteristics and off-nadir pointing mean that imagery can be acquired as far south as ~84 S. Each scene covers a nominal ground swath of 60 x 60 km. Data are available via the Land Processes DAAC (http://edcimswww.cr.usgs.gov/pub/imswelcome/) at a nominal cost of $55/scene or free to approved investigators; higher level products such as DEMs are available at no-cost. Numerous Antarctic scenes are archived at UMaine. ASTER imagery is well-suited to polar glaciology. We shall present examples of DEM generation, velocity mapping using automatic feature tracking, and changes in frontal extent of small ice shelves.

Mapping accumulation rate by observing the characteristic time scale of microwave emission

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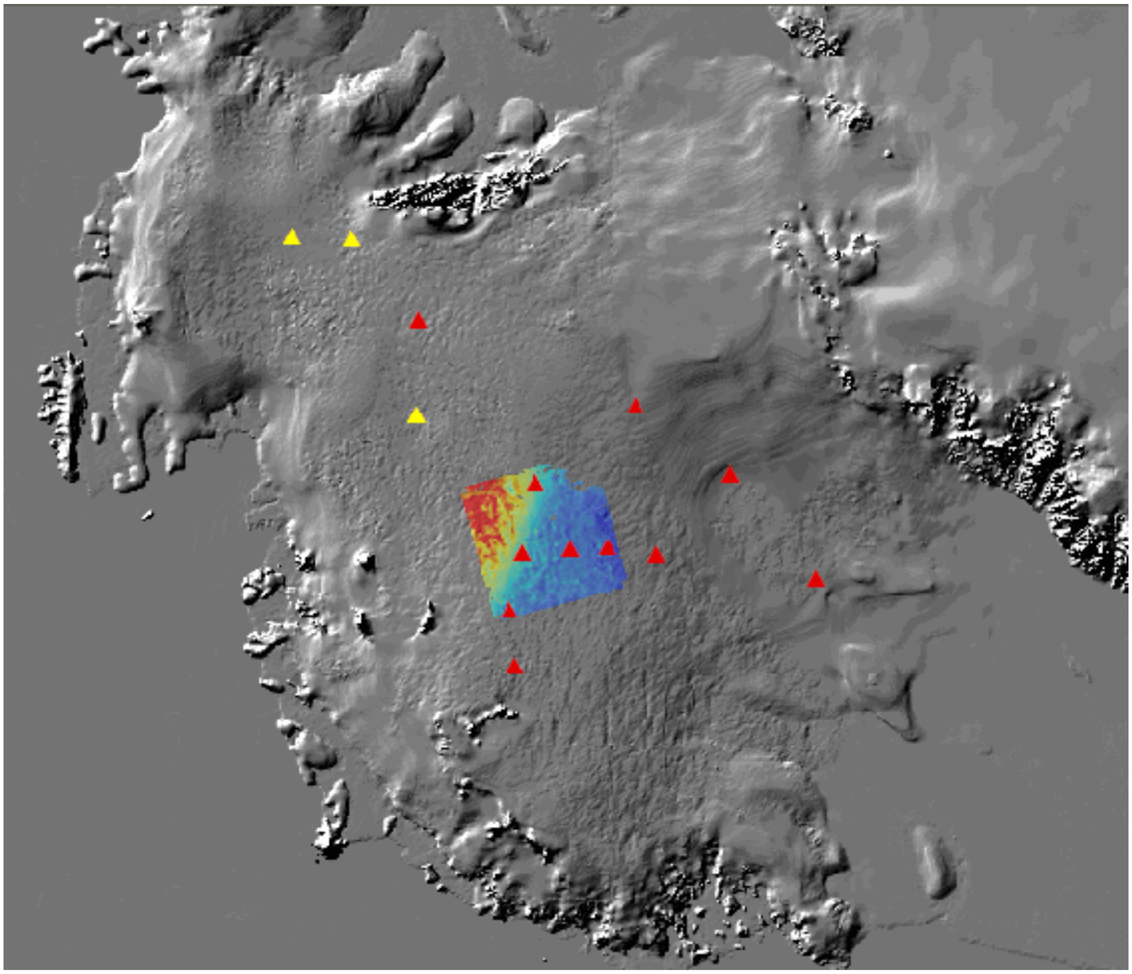
T. A. Neumann, Department of Geology, University of Vermont

Now that InSAR provides excellent velocity data, uncertainty in accumulation rates is one of the primary uncertainties in mass balance and ice dynamics calculations. West Antarctica is "small" enough for tracking of englacial layers using airborne sounding radar to provide accumulation rate fields for most areas of interest. East Antarctica is so big that the corresponding statement may never be true there. Moreover, accumulation rate variability in space and in time, on decadal scales or shorter, is of fundamental interest for altimetry, ice core interpretation, and meteorological studies. While it would be prohibitively expensive to do repeated radar measurements over all of Antarctica every few years, satellite measurements are taken continuously and provide nearly complete coverage over both West and East Antarctica. It is therefore of continued interest to pursue the use of satellite data to obtain accumulation rate fields.

We have found that the relationship between time series of surface temperature (which can be taken from thermal infrared data) and microwave brightness temperature provides a useful probe of snow properties that is governed by two parameters: the first is the emissivity, which relates long-term mean surface and brightness temperatures (and does not vary in time); the second is a characteristic time scale that describes, roughly speaking, how long into the past brightness temperature "remembers" past surface temperature variations.

For emission at 37 GHz (vertical polarization), the characteristic time scale varies from about 7 days to a couple of months. In much of West Antarctica, this characteristic time scale covaries linearly with accumulation rate (see the figures). The covariance is so strong that, for accumulation rates less than 40 cm of ice per year, we can infer accumulation rates near Byrd to an accuracy of approximately 10%. When we use 37 GHz (vertically polarized) emission data, the signal originates from roughly the upper meter of firn. This suggests that we may be able to track accumulation rate variations over times as short as the time necessary to accumulate about a meter of firn i.e., a few years in most locations. Moreover, we observe variations in the characteristic time scale over periods of a few years that are mostly likely due to accumulation rate variability.

These results suggest that mapping the characteristic time scale of emission over East Antarctica could refine accumulation rate estimates there and provide the first spatially extensive look at patterns of variability in accumulation in space and time. A priority will be to better understand the observed relationship between the accumulation rate and the characteristic timescale. The latter is a function of both emission length (relating to absorption and scattering properties in the snow) and of thermal diffusivity. Both of these can and should be measured in situ in as many locations as possible, for comparison with the satellite based measurements.



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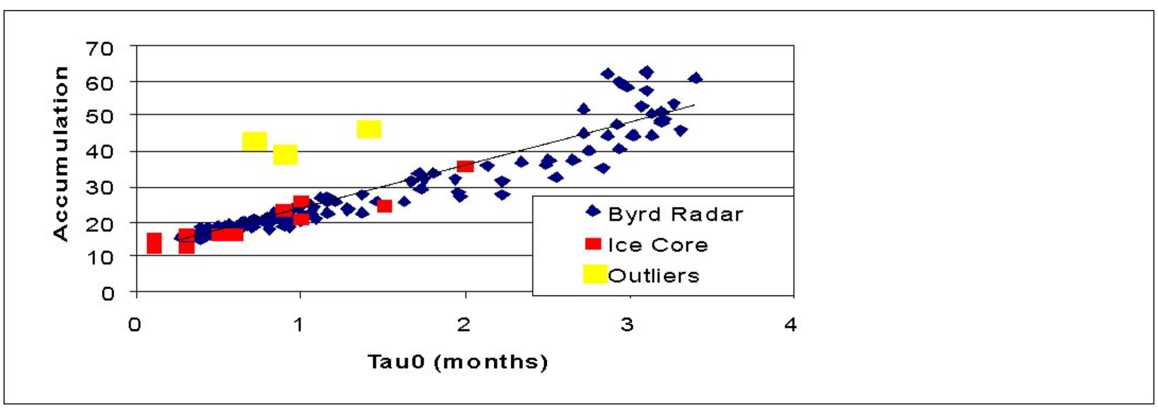

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Figure 1. a) Map of West Antarctica showing the radar-based accumulation rates from Morse et al. (2002), and the locations of ITASE and other ice cores with measured accumulation rates. b) Accumulation rates and calculated characteristic timescales for the locations in (a). Clear outliers to the general relationship are shown in yellow, and are all from very high accumulation sites.

Grounding-line incursion into the southernmost Ross Sea - a comparison of lower Scott and Reedy Glaciers

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During the last glacial maximum (LGM), thickening of the grounded West Antarctic Ice Sheet in the Ross Sea dammed outlet glaciers crossing the Transantarctic Mountains and raised their surface elevations by hundreds of meters at the mountain front [1-4]. Subsequent retreat of the ice sheet re-opened glacier outlets, lowering surface elevations to the level of the Ross Ice Shelf [3-5]. Radiocarbon dating of ice-marginal deposits laid down during retreat show that the grounding line passed to the south of McMurdo Sound around 7,600 cal. yr BP [5], and reached the foot of Hatherton Glacier a few hundred years prior to 6,800 cal. yr BP [3-6]. In the same way, exposure dating of deposits stranded above the level of Scott and Reedy Glaciers in the southernmost Transantarctic Mountains can be used to constrain the final stages of grounding-line retreat into the inner Ross Sea Embayment [1]. Scott Glacier drains to the ice shelf a few kilometers northwest of the grounding zone at the foot of Mercer Ice Stream. Reedy Glacier, which cuts the range further to the south and east remains dammed by Mercer Ice Stream, and emerges from the mountain front at an elevation of 600 m, approximately 170 km upstream of the grounding zone.

During the 2004-05 field season we mapped and sampled glacial deposits on a group of small nunataks along the lower reaches of Reedy Glacier. These consist of small bedrock knolls rising 15-30 m above the shear margin of the glacier, and peaks set back 1-2 km from the glacier with up to 180 m of exposed relief. The presence of fresh erratics on the summits of these peaks indicates that all were overrun by substantially thicker ice during the last glacial maximum. Exposure ages measured so far show that Cohen Nunatak (745 m) emerged 6,800 +/- 500 years ago. Outcrops at only slightly lower elevation, but located at the modern glacier margin, emerged between 3,800 and 700 years ago. The youngest samples dated so far give a maximum age of 520 +/- 70 years for emergence of the lowest and smallest outcrop sampled. Collectively, these results suggest narrowing of the glacier's flow, and less than 100 m of thinning on Mercer Ice Stream at the Reedy Glacier confluence, during the past 7,000 years. Most post-LGM thinning on lower Reedy Glacier took place before 3,800 years ago, but slow-moving ice, separated from the glacier trunk, continued to recede from Cohen Nunatak up to 1,700 years ago. The level of the glacier margin has dropped by less than 30 m since 3,800 B.P. Exposure of the youngest erratics 500-900 years ago, at sites only a few meters above the glacier margin, may be related to the variations in discharge from Mercer Ice Stream that created distorted streakline patterns on the Ross Ice Shelf, such as the "Cassassa Bulge".

We also made a brief reconnaissance trip to Karo Hills, which overlook the Ross Ice Shelf at the mouth of Scott Glacier. Here, bedrock forms are streamlined and highly polished, indicating the the Hills were covered by thick, warm-based, erosive ice during the last (and former) glaciations.

The area is mantled by a continuous drift sheet extending from the bedrock summit (290 m) onto the adjacent glacier surface (ca. 120 m). Exposure ages of two erratics show that the summit of Karo Hills emerged 4,800-4,300 years ago. Samples from lower altitude define a trend of steadily decreasing age with decreasing elevation, to 3,000 yr B.P. at 180 m. Extrapolation of this trend suggests that Scott Glacier reached the level of the ice shelf roughly 2,000 years ago.

Based on the combined data from Scott and lower Reedy Glaciers, we conclude that: (i) The Ross Sea grounding line reached its present position at the foot of Mercer Ice Stream approximately 2,000 years ago, and has remained close to that position since. (ii) Changes in the width and discharge of Mercer Ice Stream, and the configuration of grounded ice at its mouth, during the past 2,000 years have had little effect on the surface elevation of Reedy Glacier upstream, lowering it by less than a few tens of meters. (iii) These observations are consistent with evidence from Conway Ridge that the present-day flow regime on Mercer and van der Veen Ice Streams was established roughly 2,000 years ago [7]. (iv) Although weakly grounded ice at the foot of Mercer Ice Stream may have lifted off and re-grounded intermittently during the past millennium, as suggested by distorted streakline patterns down-flow in the ice shelf [8], such behavior has not been accompanied by significant net retreat of the grounding zone.

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Evolution of Reedy Glacier from the last glacial maximum to present

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The possibility that grounded ice may continue to retreat in the Ross Sea sector of the West Antarctic Ice Sheet (WAIS) is one aspect of uncertainty in predicting future sea-level change. Glaciers flowing from East Antarctica through the Transantarctic Mountains respond to changing ice elevations in the Ross Sea Embayment and can be used as indicators of grounding line migration. At the Last Glacial Maximum (LGM), thick ice in the Ross Sea dammed glacial flow [1,2]; during retreat of the ice sheet, thinning of this ice propagated up-glacier, stranding glacially transported material on emerging nunataks. Previous studies in the Transantarctic Mountains have tracked the retreat of the ice sheet as far south as Hatherton Glacier around 7000 cal. yr B.P. We are working to reconstruct the thinning history of Reedy Glacier, which flows through the Transantarctic Mountains south of the grounding line and thus remains sensitive to the level of ice in Mercer Ice Stream [3], in order to extend the chronology of WAIS retreat up to the present day.

During the LGM, Reedy Glacier thickened by more than 250 m at its outlet; 200-250 m in the Quartz Hills 90 km upstream, and 60 m at Hatcher Bluffs, close to where it enters the mountains from the polar plateau [4]. In the Quartz Hills, extensive ice-cored deposits cover a bench up to 200-250 m above glacier level and extend downslope 120-150 m from this limit. We interpret these deposits as material which emerged at an LGM ablation zone similar to the modern ablation area at the junction of Colorado and Reedy Glaciers. Ten samples from the upper edge of this deposit include five with apparent exposure ages greater than 30,000 years, which we interpret as recycled, and five with ages between 17,200 and 14,300 yr BP. The latter results suggest that Reedy Glacier stood 250 m higher than present 17,200 years ago, and remained at that elevation until at least 14,300 yr B.P., consistent with damming by the advanced WAIS occupying the inner Ross Sea. Samples collected downslope from the LGM limit include fewer pre-exposed rocks (3/13), but have a broad range of exposure ages from 15,000-8,000 years, which are largely independent of elevation or relative position. We interpret the range of ages as evidence that some of these rocks reached the ablating ice surface several thousand years before deposition. If so, the youngest sample at each site gives a maximum age for retreat of the glacier margin from that elevation. This suggests that Reedy Glacier had receded 60-90 m from its LGM position by 10,000 yr B.P., and 100-140 m by 8,000 yr B.P.

Down-glacier, close to the range front, peaks were completely overrun during the last glaciation. Thus, we can only infer a minimum LGM ice thickness. The highest peak sampled is Langford Peak, ca. 25 km upstream from the junction with Mercer Ice Stream. An erratic from its summit indicates ice was 250 m thicker 8,000 yr B.P. At this time Reedy Glacier had receded by more than 100 m from the LGM limit upstream, suggesting substantially thicker LGM ice cover at Langford Peak also. Younger exposure ages from sites at the lower end of the glacier extend from 6,100-500 yr B.P. Their distribution with elevation and distance from the glacier margin indicates that most thinning was complete by 3,800 years ago, when the glacier surface elevation was no more than 30 m above the present level. Subsequent changes have included the emergence of several small nunataks close to the glacier margin within the last 900-500 years.

In summary: Exposure ages from the Quartz Hills suggest a prolonged stillstand at close to maximum thickness, covering at least the period 17-14 kyr B.P. Deglaciation of the southern Ross Sea was underway during the early Holocene, while the ice-sheet remained grounded in McMurdo Sound and at Hatherton Glacier [1,2,5]. Data from the mouth of the glacier indicate that thinning continued into the late Holocene, and that changes within the last few millennia account for only a small fraction of the original thickness of LGM ice. We are working on a flowline model like that of Anderson et al. [6] to link changes in the surface profile of Reedy Glacier to the position of the grounding line at the foot of Mercer Ice Stream.

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[3] Mercer, J.H. (1968) GSA Bull. 79, 471-486.
[4] Bromley, G. (2005) Abstract; this meeting.
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[6] Anderson, B.M. et al., Global Planet. Ch. 42, 143-153.

Elevation Change Anomalies in West Antarctica - New Windows Into Dynamics of Subglacial Water Flow

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Water flow beneath ice sheets is notoriously difficult to quantify because it is hard to perform direct measurements of subglacial water volume and pressure changes. Monitoring of ice surface elevation changes may provide an important constraint on the relationship between water flux and water pressure wherever subglacial water thickness changes are large enough to be expressed at ice surface.

Elevation Change Anomalies (ECAs) have been recently recognized within the Ross Sea sector of WAIS through remote sensing analysis of ice surface elevation changes (Gray et al., 2005). The ECAs appear as ~5-km-diameter oval areas of anomalously high, up to ±0.5 m, surface elevation rise or drop in RADARSAT interferometric synthetic aperture radar (InSAR) images separated by 24 days in September and October 1997. In addition, two ~10-km diameter ECAs with elevation changes of 3.5-to-6 meters were revealed by repeat laser altimeter (LIDAR) lines from the austral summers 1997/98 and 1999/00.

Here we present the results of a quantitative model, which simulates deformation of an elastic ice layer over a subglacial cavity. The model demonstrates that ECAs may be an expression of cyclic filling and draining of subglacial water from such subglacial cavities. By combining measurements of ice-surface elevation changes over ECAs with our model it is possible to derive constraints on: (1) volume of subglacial water involved in cavity filling/draining, (2) associated water pressure changes, and (3) effective elastic properties of ice overlying the subglacial cavity.

Will Kamb Ice Stream Restart or Get Captured by Whillans Ice Stream? Preliminary Insights From Changes in Ice Surface Velocities in the UpC Area Between 1996 and 2004

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Understanding of temporal variability in ice stream flow is important in assessing the future contribution of West Antarctica to global sea-level changes. The stoppage of Kamb Ice Stream (KIS), ~150 years ago represents the most significant recent example of ice stream variability. It switched the Ross Sea sector of the West Antarctic ice sheet from negative to positive mass balance. However, it is unclear whether the stoppage is going to persist over longer term (1000s to 10,000s of years) or reverse over relatively short term (10s to 100s of years).

In an effort to evaluate the rate of ice surface velocity changes on KIS, we have performed GPS measurements in the UpC area during November and December 2004. This crucial area represents a transition zone between the stopped trunk of KIS and its two tributaries, which are still moving at dozens of meters per year. In addition, a number of previous investigators have measured ice velocity there in the past, providing a useful basis for velocity comparisons.

In the field, we were able to locate dozens of pole markers used by others in years 1996 and 2000 (H. Engelhardt and T. Scambos, personal communication). By re-measuring their position we can compare average ice surface velocities over the periods 1996-2004 and 2000-2004 to the original velocities (1996, 2000). The comparison reveals increases and decreases of up to a few percent. The preliminary spatial pattern of these changes indicates that ice is accelerating more clearly toward the direction of KIS trunk rather than pushing across the interstream ridge toward the Whillans Ice Stream. Our ice velocity database will increase by nearly a factor of ten after the next season, which will take place 12/2005.

Pine Island Glacier and basin - initial interpretation of AGASEA/BBAS radar data

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We present topographic grids of bed elevation for the Pine lsland Glacier basin produced from the data collected as part of the 2004/05, AGASEA/BBAS survey. Alongside the gridded data, we present a heuristic classification of bed-reflection and location of lake-like reflectors. We will discuss some preliminary interpretations of these data. When compared to the bed elevation it is clear that the inland tributaries of Pine Island Glacier lie in topographic troughs and have some of the smoothest and continuous ("ice-shelf-like") basal echoes we have seen. These types of echo are continuous for considerable distances and extend into some of the deepest parts of the Byrd Subglacial Basin. We assume that they represent areas underlain by smooth sedimentary material. However, it is not clear that the distribution of this material is constrained by simple factor (e.g., a palaeo-sea level), and many rough areas lie at similar elevations. We discuss the possibility other interpretations are possible. The apparent surfaces of the many new lake-like reflectors in the interior of the basin will be compared to test for hydraulic connection. Finally, the distribution of a single bright reflector, which appears, at mid-depth in the ice sheet, over a wide area in the region of the Hudson Mountains, is investigated, and hypotheses concerning its origin will be discussed.

Higher-resolution grids of the lower part of Pine Island Glacier will also be presented, and discussed with reference to the recent thinning of the grounded glacier, and of its ice shelf, acceleration of the glacier. In particular, the potential for the glacier to undergo a rapid and catastrophic retreat, will depend on the basal topography and conditions near the grounding line. And while the inland, a smooth and flat bed underlies slow-flowing tributaries of Pine Island Glacier, the lower reaches of the glacier (within 70 km of the grounding line) are underlain by a comparatively rough bed. We will provide some assessment of the length and height-scales of this roughness, as well as evidence for potential pinning points that might impede a rapid retreat of the grounding line of this glacier, and a prediction for the most likely route that grounding line retreat would follow, based on a detailed map of the existing hydrostatic overburden.

ScITESEN – a scientific drilling traverse in West Antarctica investigating the influence of ice-ocean-lithosphere interaction on ice sheet stability, by direct means.

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The West Antarctic Ice Sheet (WAIS) contains enough ice to raise global sea level by 5m. Even a sea level rise of only a few ten's of centimeter over the course of a century poses a significant threat to coastal areas in the US and around the world. Therefore the question about the stability of the WAIS is a question of global importance. In general subglacial conditions play a key role for the dynamic and stability of all ice sheets. The conditions at the base of an ice sheet (the subglacial environment) are governed by a variety of processes and are determined by the complex interaction between the ice sheet and its underlying lithosphere/geology. Where an ice sheet drains into the ocean this interaction is complicated by the ice-ocean interaction, which not only influences the stability of the floating ice shelves but in a feedback loop also influences the outflow of ice far upstream of its grounding zone.

Here we present an initiative for the International Polar Year in 2007/08 to investigate this complex interaction and the influence of the subglacial environment (including sub-ice shelf) on the dynamic of West Antarctic ice streams and the stability of the WAIS by direct means. The Scientific International Traverse Exploring Subglacial ENvironments (ScITESEN) will utilize a new highly mobile fast-access drilling system; a soft coiled tubing hot water drilling system. The drilling system will allow rapid access to the subglacial environment, while being able to traverse several hundred kilometers in a single field season. The multi-year project proposes to drill access holes along a transect from the edge of the Ross Ice Shelf to the WAIS interior following the flow of ice of Kamb Ice Stream. While the fast motion of ice in this WAIS ice stream had stopped about 140 years ago, this ice stream has the potential to resume fast ice streaming within a few decades to century. Along this transect research conducted within ScITESEN will focus on:

- ice-ocean interaction and dynamics of ice shelves;
- ice sheet stability and evolution;
- ice stream mechanism;
- subglacial hydrology;
- subglacial geology and subglacial volcanism;
- life in extreme environments.

The interdisciplinary ScITESEN will not only conduct research at one of the last frontiers in Polar Sciences. Combining oceanographic, glaciological, hydrological and geological investigations ScITESEN will provide data desperately needed for a better assessment of the stability of the West-Antarctic Ice Sheet and will provide a first glimpse into life in these extreme environments.

Transition Flow of Ice Surrounding Subglacial Lake Vostok

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The Ice, Cloud, and land Elevation Satellite (ICESat) provides precise, high-resolution surface elevation data that is improving glaciological studies in many aspects. One example, the research presented here, is the study of ice flow oversubglacial Lake Vostok in East Antarctica. Lake Vostok, about 240 km long and 50 km wide, is the largest subglacial lake in the Antarctic ice sheet. Using ICESat-derived surface elevation data we mapped the surface topography over the subglacial Lake Vostok region, and identified the transition zones between the lake and the surrounding ice sheet. The transition zones are characterized by a trough in the western shoreline and a ridge in the eastern shoreline of the lake. We measured the transition zone along the ~180 km long western shoreline to be 15-25 km wide and 4-20 m deep, while the transition zone along the ~180 km long eastern shoreline is approximately 15 km wide and 4-12 m deep. Numerical analysis of the ice flow status within the transition zone suggests that the trough is formed due to the dynamic change in the flow of ice which deforms from vertical compression to vertical extension. The ice flow from the upstream (ice-sheet interior) side is dominated by vertical shearing, while downstream of the lake's grounding line the flow is dominated by basal sliding into the lake.

Subglacial conditions of inland West Antarctica from US-ITASE deep radar reflection analysis

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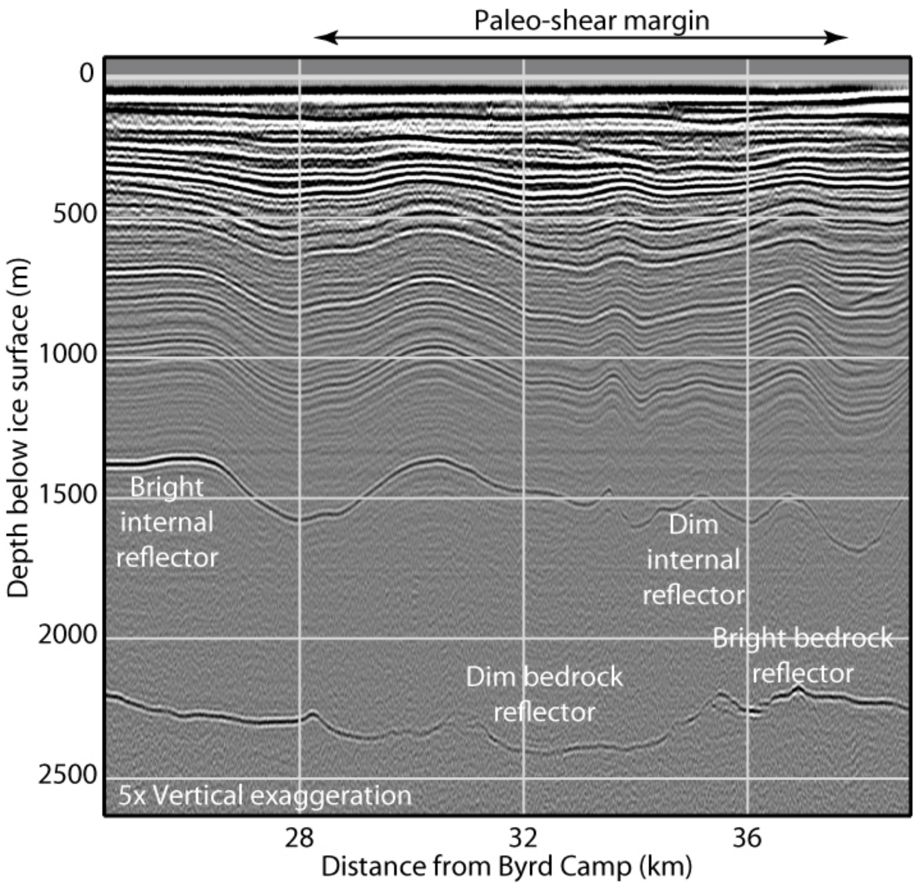
Conditions beneath ice sheets, particularly the presence of water, have significant impact on ice flow behavior. Numerous studies have discussed in the dramatic influence of water on the shear strength of the till beneath the WAIS ice streams compared to the nearly stagnant inter-ice stream ridges. Ice-penetrating radar observations provide a method for observing changes in basal conditions over large areas based on the strength of the subglacial reflection.

We present here the results of applying a method similar to that used by Gades et al. (2000) with data from Siple Dome to calculate a depth-attenuation function for the 2002 US-ITASE deep radar profiles in the central WAIS. Challenges arise because of the variability of ice-bed interface as well as within the ice itself. The traverse covers 1,400 km in length including: ice stream tributaries, mountain ranges, nearly stagnant ice, isolated subglacial melt events, and ice thickness up to 3.5 km. We examine the strength of the bedrock reflector as well as a particularly bright internal layer to determine the variation in reflector strength as a function of depth. Using the attenuation curves, we calculate the relative strength of the basal and internal reflections along the traverse. We find a different behavior in the bed reflectivity of the interior regions of WAIS than is seen in regions of the Ross Sea ice streams.


Paleo-shear margin
0
500
1000
1500
2000
2500
Depth below ice surface (m)
Bright internal reflector
Dim internal reflector
Bright bedrock reflector
Dim bedrock reflector
5x Vertical exaggeration
28
32
36
Distance from Byrd Camp (km)

Control of ice stream stick-slip dynamics by frictional healing

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Understanding the dynamics of Whillans ice stream is essential for predicting the future stability of the West Antarctic ice sheet, particularly in light of its recent slow-down. However, the observation that motion in the downstream portion is dominated by two stick-slip events per day has revealed a new complexity in the flow of this ice stream. A comprehensive model of stick-slip motion that can successfully explain the significant variability in slip-event recurrence interval and magnitude is needed for a complete understanding of ice stream dynamics, a critical element in assessing the future behavior of the West Antarctic ice sheet. Our analysis demonstrates that stick-slip variability is not well explained by a plastic model that assumes a constant yield stress. Instead, a time dependent-yield strength due to frictional healing after a slip-event, similar to that observed in laboratory studies of stick-slip phenomena, better explains the data. After a slip-event, stress at the glacier bed slowly increases due to the continued flow upstream. However, the rate at which stress accumulates at the bed is modulated by tidal fluctuations at the grounding line; during a falling tide, stress on the ice stream bed increases more rapidly than on the rising tide. In addition, the rate of stress accumulation varies throughout the spring-neap tidal cycle. Because our model has a time-dependent failure threshold, stress at the time of the slip-event varies, unlike a plastic model. This variation in stress explains the dependence of slip-magnitude on recurrence interval. Additionally, the time-dependent threshold model reproduces the observed recurrence times better than a plastic bed model. The observed behavior of Whillans ice stream indicates that basal shear strength can be dynamic at shot time scales, capable of changing by approximately ten percent over the course of a day.

Geometric constraints on the Thwaites Glacier Catchment and Walgreen Coast of the West Antarctic Ice Sheet from AGASEA radar sounding and laser altimetry

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The Thwaites Glacier catchment and grounding line have been noted has as zones of potential ice sheet instability, in part due to the deep Byrd Subglacial Basin (BSB) that underlies the catchment and exposure of coastal ice to a warming ocean. We present initial interpretations of new data constraining the geometry of the Thwaites Glacier catchment and the adjacent Walgreen Coast.

Prior to the 2004-05 AGASEA field season, profiles of bedrock topography in the Thwaites catchment region were restricted to three NSF/SPRI/TUD ice penetrating radar flights, two IGY era seismic traverses, and more recently, several NASA/CECS flights and ITASE traverses. We have added over 40,000 km of new flight line with the University of Texas HiCARS 60 MHz coherent radar, and ~3000 km from a new British Antarctic Survey 150 MHz coherent radar. The data was processed using a short unfocused SAR aperture to limit scattering; a focused SAR solution is in progress. Our use of a high-power chirped radar improves both resolution and penetration of the ice volume, allowing more than 90% bed recovery as well as the illumination of deep layer structure within the ice sheet.

A laser altimeter was also flown, which when combined with dual- carrier differential phase GPS positioning, provided sub-meter ice surface elevation resolution. We will also present results of calculations of hydraulic head at the ice/rock interface and ice sheet driving stresses based on our airborne laser/radar observations.

Our radar data confirms the existence of and greatly extends the ~2 km deep trough underlying the Smith-Kohler glacier [Thomas et al 2004], but appears to rule out a direct connection to the Byrd Subglacial Basin. Thwaites Glacier itself appears not to be confined by a distinct bedrock channel, consistent with interpretations of recent lateral expansion [Bamber and Rignot, 2002].

Further inland, the Crary Mountains volcanoes are flanked by two overdeepened, east-trending large valleys, which open into the BSB. The northern valley contains a significant 'dead zone' where ice losses were great enough to obscure the bed.

Longitudinal laser/radar profiles allow us to analyze buoyancy across the Smith Glacier and Thwaites Glacier grounding lines. We use laser altimetry across sea ice to establish local sealevel to within a meter, and using this reference, predict from glacier surface elevations and ice thickness the position of the floating bed. Where the observed bed matches this prediction, we can infer the position of the grounding line. The main trunk of Thwaites Glacier floats at a relatively shallow depth, and a broad lateral sill appears to localize the grounding line. Smith Glacier's grounding line is much deeper, and lacks a sill. Despite the apparent instability implied at Smith Glacier, Thwaites Glacier has higher observed flux variations [e.g, Thomas et al 2004]. Differential access of the subglacial cavity to warm circumpolar deep water [e. g., Shepherd et al. 2004] may in part explain this relationship.