C11D MCC: Level 2 Monday 0830h

Fracture Processes in Glacier Ice I Posters *(joint with OS)*

Presiding: **H A Fricker,** Scripps Institution of Oceanography**; C Hulbe,** Portland State University

C11D-0853 0830h POSTER

Deformation of the Hidden Creek Lake ice dam: evidence for faulting through the entire thickness of a glacier

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As a glacier-dammed lake fills, a large volume of water may be stored beneath the ice dam (the part of the glacier adjacent to the lake) and then released during a subsequent jökulhlaup. The surface of the ice dam rises and falls accordingly. At Kennicott Glacier, Alaska, the kinematics of such motion during the annual jökulhlaup cycle of Hidden Creek Lake provide strong evidence that the ice dam is pervasively faulted through its entire thickness, and that "mega-crevasses" extending across the entire width of the ice dam are in fact the surficial expression of these faults. The surface of the ice dam rises by a distance $h \geq 20$ m every year as the lake fills to a volume of about 25 million m^3, then drops by about the same amount as the lake drains over a period of 2 to 3 days. The change in h with distance x from the lake is abrupt: h decreases from ca. 20 m to less than 1 m as x increases by only a few hundred m. Such a large gradient in vertical movement cannot be explained using any plausible model of flexural deformation. Horizontal movement of targets on the ice dam is steady and oblique to the face of the ice dam as the lake fills, but during drainage, movement speeds up greatly and target trajectories become nearly perpendicular to the face of the ice dam. Outside the zone in which $|dh/dx|$ is large, the strain rate $\dot{e}_{xx}$ is always positive (extensional), but within the zone of large $|dh/dx|$, $\dot{e}_{xx} < 0$ as the lake fills, then reverses sign as the lake drains. Survey targets separated from one another (in x) by large crevasses move relative to one another in a nearly reversible fashion as the lake fills and drains, with trajectories of relative displacement plunging at an angle of about 75 to 80 degrees towards the lake. These relative-movement trajectories evidently reflect movement along high-angle faults that extend from the surface to the base of the ice dam through as much as 250 m if ice. Fault movement is in the reverse sense ($\dot{e}_{xx} < 0$) as the lake fills and the normal sense ($\dot{e}_{xx} > 0$) as the lake drains. The extensional strain rate during lake drainage is as much as 1 a^{-1}. The onset of both vertical downdrop and accelerated horizontal motion lags the onset of lake drawdown, with the lag time increasing with distance from the ice-dam face. The existence of such a lag may reflect the residual strength and complex geometry of the fault surfaces. Although some sections of the ice dam break apart as they collapse into the lake basin during lake drainage, and thereby serve as the source of icebergs during the subsequent lake-filling episode, the *overall pattern* of crevasses is regenerated from year to year, presumably reflecting bedrock control on the stress field within the ice.

C11D-0854 0830h POSTER

Crevasse Patterns and Grounding Line Change Along the Siple and Gould Coasts, West Antarctica

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Crevasses and strealklines observed in composite MODIS imagery of the Ross Ice Shelf have been used to infer changes in flow across the transition from ice sheet to ice shelf. We focus on changes in crevasse type and orientation as a guide to recent (100s of years) changes grounding line dynamics and location at the now-quiescent Kamb, and fast flowing Whillans and Mercer Ice Stream outlets. Across the grounding line of a rapidly flowing ice stream, the transition in the basal stress condition is slight so few (if any) crevasses are formed. In contrast, along-flow tension is relatively large across downstream no-slip/slip transitions (i.e. the downstream ends of ice rises and interstream ridges, and the current Kamb grounding line) and will produce crevasses transverse to flow. This is distinctly different from the upstream pointing orientation of crevasses that form due to shear at lateral boundaries. At a no-slip/slip grounding line that is transverse to flow, only tensional crevasses may form so the presence of other crevasse types in the ice stream effluent, or the transition from one type to another, indicates a change in flow style. The Kamb Ice Stream grounding line is now generating transverse crevasses while most of the Mercer/Whillans ice plain grounding line is not. The southern end of the current Kamb grounding line was established as a no-slip/slip boundary sometime after Steershead became an ice rise, as evidenced by the change from shear crevasses to tension crevasses about 20 km downstream from its present location. At the northern end of the grounding line, the first tensional crevasses are only a few km downstream from its present location. If, as seems likely, ice stream deceleration coincided with the transition from a Mercer/Whillans type grounding zone to a no-slip/slip grounding line, then the oldest tensional crevasses should have advected about 1.5 km downstream (the present speed is 10 m/a and the stream shut down 150 years ago). The observed and computed advection distances are similar at the northern end of the Kamb grounding line, but crevasses are an order of magnitude too far downstream at its southern end. Previously measured grounding line retreat of 30 m/a (Thomas and others,1988) in combination with downstream advection of crevasses still cannot account for the change in crevasse style at the southern edge of the ice stream. The implication is that the grounding line was substantially seaward of its present location several hundred years ago and that it has retreated rapidly since that time.

C11D-0855 0830h POSTER

Hydroacoustic signals from large icebergs drifting in the Southern Pacific, 2001-2003

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Following our detection of hydroacoustic activity in the Ross Sea in Late 2000, we report on a series of new signals generated at more Northern latitudes (55 to 63 deg. S), and detected both in Polynesia and by IMS stations in the Indian Ocean, during the period 07 Mar 2002 to 15 Jan 2003. Apart from a strong swarm in Nov.-Dec. 2002, they occur as isolated events, lasting between 200 and 1800 s. They consist of numerous repetitive signals (with broad spectrum) superimposed on a background featuring preferential eigenfrequencies. With a few exceptions, the epicenters correlate spectacularly well with the position of Mega-Iceberg B-19 (and its fragments), as it drifted from West of Balleny Islands in Feb. 2002 to (53deg.S; 167deg.W) in Feb. 2003. In particular, the acoustic swarm of Nov.-Dec. 2002 correlates in space and time with a series of erratic motions of B-19 over an area 300 km by 100 km centered at (57 deg.S; 170 deg.W). Since the spectrograms of these more Northerly sources are significantly different from those recorded from the Ross Sea, their sources must involve different physical processes. The latter, which may include the discharge of large boulders, remain mysterious.

C11D-0856 0830h POSTER

A Model of Ice-Shelf Thermodynamics and Surface Hydrology Under Melting Conditions With an Application to the Recent Disintegration of the Larsen A and B Ice Shelves

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Break-up of Larsen A and B ice shelves in 1995 and 2002, respectively, is thought to be a consequence of extensive warming within the Antarctic Peninsula region observed in recent decades. The most notable glaciological effect of this warming has been the emergence of pervasive surface melting on the two ice shelves in the summers prior to their disintegration.Indeed, the mechanical effects of surface meltwater in the propagation and deepening of surface and basal crevasses has been proposed as the mechanism by which the ice shelves were fractured to the point of disintegration. To develop an understanding of how surface conditions on the Larsen Ice Shelves converted from essentially dry, polar conditions to wet, temperate conditions, we have developed a simple model that describes the hydrological and thermodynamic evolution of surface firn and melt under warming environments. Energy conservation aspects of the model are designed to simulate the formation of subsurface melt due to the absorbtion of solar radiation and the formation of in situ ice layers in response to latent heat release. Hydrological aspects of the model are concerned with how meltwater percolates down and re-freezes at colder horizons. Storage aspects of the surface hydrology are parameterized in a simple manner so that the evolution of metwater ponds and water-filled surface crevasses can be simulated as a consequence of progressively saturating the firn with meltwater and impermeable re-frozen ice lenses. The model is tested by comparing its evolution with observations of the Larsen Ice shelf under model forcing conditions (atmospheric pressure, temperature, precipitation, specific humidity and wind speed) representative of conditions on Larsen B ice shelf in the years prior to it's disintegration.

C11D-0857 0830h POSTER

Evolution of a Rift System on the Amery Ice Shelf, East Antarctica

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We use satellite imagery to monitor the growth of an active rift system on the Amery Ice Shelf, East Antarctica. The rift system, which has been developing at the ice front over the last 15 years, consists of two longitudinal-to-flow rifts and one transverse-to-flow rift. The longitudinal rifts are located within the boundaries between adjacent flow bands. These flow bands originated from ice streams that merged several hundred kilometers upstream to form the Amery Ice Shelf. The high transverse (lateral) strain rates acting at the front of the ice shelf force these merging bands of ice apart, forming a rift. The transverse rift extends from the tip of the westernmost longitudinal rift and is one branch of a three-way fissure which formed around 1995. The transverse rift has elongated by approximately 15 km over the last 7 years, and once it has reached the eastern longitudinal rift an iceberg will be released. The rate and direction of propagation of the rift have not been constant. We use moderate resolution MISR, and high resolution Landsat, and ERS and RADARSAT SAR imagery to show how it has evolved over the last few years. This work is the first stage of a broader investigation of processes contributing to rift development and calving of icebergs, involving fieldwork, satellite remote sensing, and modelling.

C11D-0858 0830h POSTER

Log-periodic oscillations in the acceleration phase prior to break-off of a large ice mass.

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Large ice masses do not break off hanging glaciers without prior characteristic changes in appearance and movement. Formation of deep crevasses, and cracked ice near the glacier base are indications of a pending breakoff event. An empirical power-law fit is routinely used to predict the time of failure. The recognition and assessment of ice avalanche hazards from hanging glaciers largely relies on these facts. Several remarkable properties of the acceleration phase prior to failure can be described with a model system based on damage mechanics. The empirical formula used to predict failure time is obtained, which allows a physical interpretation of the empirical parameters. The solution reveals that two parameters of the empirical formula are related. This considerably reduces the complexity of predicting the time of failure. Characteristic length and time scales seem to be universal quantities of the failure process in hanging glaciers. The numerical values $t_f = 550$ days and $s_f=55$ m are obtained by analyzing survey data from 15 break-off events. Measured ice velocities prior to break-off exhibit oscillations which can be described as log-periodic corrections to the leading velocity singularity. The exact cause for these oscillations is still unclear, but dynamical crack interactions or damage reduction due to healing are likely explanation.

URL: http://gi.alaska.edu/˜luthi/

C11D-0859 0830h POSTER

Modelling of the ice-shelf rifting around Hemmen Ice Rise, prior to the calving of iceberg A38.

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The calving of icebergs from the Ronne Ice Shelf is controlled mainly by the propagation of rifts originating from Hemmen Ice Rise (HIR) and d'Orville Coast. Using interferometric radar images collected by ERS-1, ERS-2 and Radarsat-1, we observe the evolution of rifts near Hemmen Ice Rise, prior to the large calving event of October 13th 1998, which resulted in the formation of iceberg A38. Using LEFM models combined with INSAR, Larour (in press 2003) showed that the propagation of those rifts is linked to their opening rate. The opening rate is inferred from the velocity field on each flank of a rift. Therefore, an accurate modelling of the ice-shelf flow is required to predict the evolution of the rifts prior to calving. Forward modelling of the ice-shelf flow by MacAyeal and others (1998) showed that softening along the ice-shelf margins and the presence of melange in between the rifts are key factors influencing the ice flow around Hemmen Ice Rise. Here we use a control method based on MacAyeal (1992) and Rommelaere and others (1997) to infer the distribution of the flow parameter and ice thickness on Ronne Ice Shelf to best match a velocity map from INSAR. The residual misfit between model and INSAR is reduced +-30m/a on the ice shelf. We then apply this parameter selection to run an ice-shelf flow model, coupled with LEFM, to predict the evolution of rifts. The results compare well with satellite observation. We thank the California Institute of Technology for making this study possible.

C11E MCC: 3004 Monday 1020h

The Roles of Permafrost in Climate Change: Archive, Translator, and Facilitator II *(joint with A, B, H, PP, GC)*

Presiding: **N I Shiklomanov,** University of Delaware**; W R Eisner,** University of Cincinnati

C11E-01 1020h INVITED

The Role of Permafrost-Affected Soils in Climate Change

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Whereas permafrost-affected soils comprise 20% of the global land area, they contain an estimated 42% of the global soil carbon pool. In the Northern Hemisphere, dramatic increases in winter and spring air temperature since 1970 have been accompanied by increases in the seasonal thaw layer, warming of permafrost, and a possible shift in Arctic Tundra from being a net sink to a net source for atmospheric CO2. There are several challenges in determining C pools in permafrost-affected soils, including large small-scale variability due to patterned ground, mixing of organic C into the subsoil by cryoturbation, the presence of large amounts of C in the permafrost at depths > 1 m, and the difficulties in scaling up from the pedon to the landscape or regional level. Cryopedologists are addressing these challenges through specially adapted field techniques including the use of ground-penetrating radar and satellite imagery. Some issues, however, will require development of international methodological protocol to ensure that results can be compared between regions, within the circumarctic, and between hemispheres.

C11E-02 1035h

ISOTOPIC VARIATIONS IN PERMAFROST ON THE NORTH SLOPE OF ALASKA

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Anadarko Petroleum Corporation, Maurer Technology, and the U.S. Department of Energy drilled the Hot Ice #1 borehole on the North Slope of Alaska during March/April of 2003. Its purpose was to explore for the possible occurrence of methane hydrates in the base of the thick permafrost zone present on the North Slope. The borehole reached a depth of 425 m, passing through the bottom of the permafrost at about 380 m. The entire hole was cored, with core recovery exceeding 90%. The bedrock geology consists of interbedded sequences of siltstone, conglomerate, sandstone, coal and shale with some bitumens and/or ice lenses. The borehole represents an ideal opportunity to study geochemical signals present in the North Slope permafrost. Thirty samples, obtained over the entire length of the core, were collected for isotopic analyses and are currently being analyzed at the Center for Isotope Geochemistry at the Lawrence Berkeley National Laboratory. The samples were chosen to best determine whether any broad isotopic trends exist within the permafrost. Measurements are being made of the hydrogen and oxygen isotope ratios of the ice and the carbon isotope ratios of carbon dioxide trapped in the permafrost. In addition, the carbon isotope ratios of any methane contained in the samples will also be determined. Preliminary results for the oxygen isotope compositions of the permafrost yield δ^{18}O values ranging from -18$^{o}/_{oo}$ to -22$^{o}/_{oo}$ with a general trend towards lower values in the deeper part of the core. The concentrations of the CO_2 in the samples (possibly representing dissolved inorganic carbon in the pore water?) range from 0.6 to 2.5 millimoles/liter with concentrations increasing with depth. The δ^{13}C values of the CO_2 range from -7$^{o}/_{oo}$ to -27$^{o}/_{oo}$ with the lowest values in the higher concentration, deeper samples. This trend is consistent with increasing inputs of CO_2 derived from hydrocarbons/hydrates with depth and may yield insight into the affecting methane hydrate formation within the permafrost.

C11E-03 1050h

Discontinuous Permafrost Thaw Accelerates in Boreal Peatlands During Late-20th Century Climate Warming

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Permafrost covers 25% of the land surface in the northern hemisphere, where mean annual ground temperature (MAGT) is less than 0^{o}C. A 1.4-5.8^{o}C warming in mean annual air temperature (MAAT) by 2100 will likely change the sign of MAAT and MAGT over most of the zone of discontinuous permafrost in the northern hemisphere, causing widespread permafrost thaw. However, there is little direct evidence documenting the magnitude of high-latitude warming and its impact on permafrost thaw. In this study, I examine rates of discontinuous permafrost thaw in the boreal peatlands of northern Manitoba, Canada, using a combination of tree-ring analyses to document thaw rates from 1941-1991 and direct measurements of permanent benchmarks established in 1995 and resurveyed in 2002. I use instrumented records of MAAT, mean winter snow depth, and duration of continuous snow pack from climate stations across northern Manitoba to analyze temporal and spatial trends in these variables and their potential impacts on thaw. I show that permafrost thaw in central Canadian peatlands has accelerated significantly since 1950, concurrent with a significant, late-20th-century average climate warming of +1.39^{o}C in this region. Projecting current warming trends to year 2100, I show that trends for north-central Canada are in good agreement with general circulation models, which suggest a 4-8^{o}C warming at high-latitudes. This magnitude of warming will likely eliminate most of the present range of discontinuous permafrost in central Canada by 2100.

C

C11E-04 1105h

Feedbacks in Climate - Permafrost - Vegetation System: Predictive Modeling Approach.

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Permafrost models driven by scenarios of climate change predict that reduction of the total (continuous) permafrost area in the northern hemisphere by 2030, 2050, and 2080 is likely to be 10%-18% (15%-25%); 15%-30% (20%-40%), and 20%-35% (25%-50%), respectively. Predicted changes of the seasonal thaw depth in the following three decades are relatively small, typically within 10%-15%. By the middle of the century thaw depth may increase on average by 15%-25%, and by 50% and more in the northernmost locations. By 2080 layer of seasonal thawing will become markedly thicker (by 30%-50% and more) all over the permafrost area. Vegetation above permafrost plays important role in regulating ground temperature and depth of seasonal thawing. In the warm period organic layer of peat, mosses, and lichens has low thermal conductivity and protects permafrost from thawing. Results from coupled climate - permafrost - vegetation model suggest that 5cm, 10cm, 15cm, and 20cm thick organic layer reduces seasonal thaw depth by 10%, 25%, 40%, and 60%, respectively, compared to bare ground. Enhanced growth of non-vascular plants under warmer climatic conditions may thus mitigate the effects of climatic warming on permafrost. Controlled experiments involving continuous localized warming at selected sites in the northern Europe and in Alaska indicate a multiyear tendency towards the replacement of mosses and lichens by vascular plants. In the long term climate-induced changes of vegetation may thus cause enhances warming and deeper seasonal thawing of the frozen ground ultimately leading to degradation of permafrost. Acknowledgement. This work is supported by the National Science Foundation of the Netherlands, grant # 047.011.2001.003.

C11E-05 1120h

The Circumpolar Arctic Vegetation Map: A tool for analysis of change in permafrost regions

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Arctic vegetation occurs beyond the northern limit of trees, in areas that have an Arctic climate and Arctic flora. Here we present an overview of the recently published Circumpolar Arctic Vegetation Map (CAVM), an area analysis of the vegetation map, and a discussion of its potential for analysis of change in the Arctic. Six countries have Arctic tundra vegetation, Canada, Greenland, Iceland, Russia, Norway (Svalbard), and the US (Total Arctic area = 7.1 million km2). Some treeless areas, such as most of Iceland and the Aluetian Islands are excluded from the map because they lack an Arctic climate. The