and initiate a negative feedback that slows further sublimation of the underlying ice. This negative feedback involves the development of secondary-ice lenses at the base of polygon troughs. In-situ ashfall deposits in Beacon Valley provide evidence that polygons are stable landforms that persist for >1 million years and that underlying ice there is >8.1 million years old. The high-centered sublimation polygons of Beacon Valley may be analogous to the latitude-dependent polygons and basketball-textured terrain on Mars.

C12C-07 1730h INVITED

Geomorphic Indicators of Ground Ice on Mars and Evidence for Climate Change

John F Mustard (John_Mustard@brown.edu)

Department of Geological Sciences, Box 1846 Brown University, Providence, RI 02912, United States

Until recently, indications of the presence of ice in the near surface of Mars, outside the polar caps, has depended upon the interpretation of morphology from imaging data. Early work in this area was based primarily on Viking orbiter images where several large landforms (100s to 1000s of meters in scale) were interpreted to be related to the presence of ice in the regolith or upper crust. These include lineated valley fill, concentric crater fill, softened terrain, and polygons, and are typically found between the latitudes of 30°-60° N and S. Without direct measurements of the presence of water, the interpretations rely on analogies with Earth's periglacial and glacial morphologies as well as geophysical modeling of ice-rich soils and crustal material. New spacecraft data from the Mars Global Surveyor and Mars Odyssey missions have significantly added to the family of morphologies with ground-ice affinities. From the high spatial resolution images acquired by Mars Orbiter Camera (MOC) a new array of polygons have been detected which range in size from 25-200 m and show strong latitudinal gradients above 50°. A possibly related morphology exhibiting a regularly spaced surface texture resembling the texture of a basketball is also found in these high latitudes. A number of morphologies indicating viscous flow on steep slopes are found in the mid-latitudes and are consistent with an ice-rich soils deforming under martian surface conditions. A continuous deposit, meters-thick and interpreted to be ice rich is observed at latitudes above 60°, but that is in a degraded condition at lower latitudes (formerly ice-rich) and absent in the equatorial regions (within 30°). The neutron spectrometer on the Odyssey spacecraft made direct measurements of hydrogen which shows clearly the presence of high water-ice abundance (>70% by volume) in the surface soils in the northern and southern latitudes above 60°. This critical observation ties in well with theoretical modeling of ice stability under current martian surface conditions. The array of morphologies interpreted to be ice-rich are thus strongly supported by direct measurements of water ice for those observed at latitudes >60° and for those at lower latitudes for conditions in the past when ice was stable to lower latitudes. This array of landforms provides an excellent research environment to investigate periglacial features formed in a very cold environment with long term climate change.

C12C-08 1745h INVITED

Icy Satellites: Perpetual Permafrost

Robert T. Pappalardo[1] (303-492-6423; robert.pappalardo@colorado.edu)

Jeffrey M. Moore[2] (650-604-5529; jeff.moore@nasa.gov)

[1]LASP, University of Colorado, Box 392, Boulder, CO 80309

[2]Ames Research Center, MS 245-3, Moffett Field, CA 94035, United States

The ice-rich moons of the outer solar system are worlds of perpetual permafrost. By analogy to the terrestrial roles of silicates and water ice, surface materials of these worlds commonly consist of components that are respectively refractory and volatile at local environmental conditions. We consider the physical properties, volatile components, and geomorphological characteristics of outer planet satellite surfaces and shallow regoliths as analogs to permafrost environments. Near-surface temperatures of 40 to 165 K preclude melting of water-ice, except where endogenic activity has increased surface temperatures locally. However, water and/or more volatile ices can be transported in the vapor phase, and can liquefy in the deeper subsurface. In the water-ice-poor regolith of Io, SO2 and possibly H2S are volatile ices that can be transported in the vapor phase and can liquefy at depth, resulting in degradation and local collapse of the ground surface. Sublimation degradation is especially evident in images of Callisto, where slow diffusive loss of CO2 is the likely erosive agent. On Neptune's large moon Triton, nitrogen plays the role of a permafrost volatile, near its melting temperature in a regolith of more refractory ices. Most large icy satellites probably have water-rich subsurface oceans, and it has been proposed that Europa's subsurface ocean might sustain life. Frigid surface temperatures and severe charged particle radiation preclude near-surface metabolism, but organisms could potentially survive within deeper regions and local upwelling plumes that approach the ice melting temperature.

C21A MCC: 3010 Tuesday 0800h

Advances in Glacier Geophysics I

(joint with G, H, OS, PP)

Presiding: **B Kulessa,** Queen's University of Belfast**; T Murray,** University of Leeds

C21A-01 0800h INVITED

Ice stream D, West Antarctica, subglacial conditions from a combined seismic reflection, refraction, gravity and radar survey

Sridhar Anandakrishnan[1] (814-863-6742; sak@essc.psu.edu); David L Morse[2]; Andy M Smith[3]; Donald D Blankenship[2]; Richard B Alley[1]; J P Winberry[1]; Leo E Peters[1]; Donald E Voigt[1]; E C King[3]; A Miranov[2]

[1]EMS Environment Institute and Dept. of Geosciences, Pennsylvania State University, University Park, PA 16802, United States

[2]Institute of Geophysics, University of Texas at Austin, Austin, TX 78759, United States

[3]British Antarctic Survey, Madingley Rd, Cambridge CB3 0ET, United Kingdom

A high resolution reflection seismic profile on ice stream D, West Antarctica, has revealed the presence of dilatant till beneath the far upstream sections of the ice stream. The characteristics of the reflection from the base of the ice stream (such as phase, magnitude, angle-dependence of amplitude, etc.) are clear indicators of the acoustic impedance of the material beneath the ice. We detect an extremely low acoustic impedance (product of density and seismic velocity) over much of the region, which we interpret as dilatant, actively deforming till. This discovery is particularly surprising given the location of the experiment: in the "tributary" region of the ice stream, 10s of kilometers upstream of the location where the "onset of ice streaming" has been hypothesized to occur. Our experiment was conducted in the region of moderate flow speeds (< 100 m·a^{-1}), and suggests that the onset region of the ice stream could be substantially farther upstream than previously thought. We combine the reflection seismic work with phase-coherent radar data to differentiate between basal roughness and subglacial acoustic impedance. In addition, we use refraction and gravity data to constrain deeper structure. A joint reflection/refraction seismic and gravity experiment successfully imaged sedimentary basins beneath the ice stream that are clearly associated with locating the boundaries of the ice stream. Finally, we report on the expanded capabilities that are possible with a new shothole drill, ranging from high resolution internal layer imaging to Moho reflections.

C21A-02 0815h

Subglacial Sediments as a Control on the Location of Ice Streams C and D, West Antarctica, from Seismic Refraction and Reflection Imaging

Leo E Peters[1] (lpeters@geosc.psu.edu); Sridhar Anandakrishnan[1] (sak@essc.psu.edu); J Paul Winberry[1] (winberry@essc.psu.edu); Richard B Alley[1] (ralley@essc.psu.edu); Donald D Blankenship[2] (blank@ig.texas.edu); David L Morse[2] (morse@ig.texas.edu); Andrew M Smith[3] (amsm@bas.ac.uk); Edward C King[3] (ecki@bas.ac.uk)

[1]The Pennsylvania State University, Department of Geosciences, 503 Deike Building, University Park, PA 16802

[2]The University of Texas at Austin, Institute for Geophysics, 4412 Spicewood Springs Rd., Bldg. 600, Austin, TX 78759

[3]British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, United Kingdom

Ice streams discharge a majority of the inland ice from the Ross Embayment of West Antarctica. This increased ice flow is believed to be aided by a dilatant subglacial till, but the mechanisms controlling the initiation of streaming flow within the ice sheet are uncertain. The focus of our study is to image the presence of subglacial sediments and interpret their importance in ice stream velocity and location. We present the results of two refraction seismic experiments in the onset regions of ice streams C and D during the 2002 - 2003 Antarctic field season that were performed to image subglacial geology and develop a better understanding of its role in initiating ice streaming. The refraction experiments consisted of a 31.2km longitudinal profile of ice stream C (C1B) and a 34.5km transverse profile of ice stream D (DT1), giving the opportunity to image the shallow (upper 1-2km) subglacial geology in the onset regions of these two Ross ice streams. Coupled with reflection seismic data, gravity (for DT1), and GPS data, the inverse modeling of the refraction data imaged the presence of sedimentary basins in both locations. The C1B results reveal a thin (<50m) cover of sediments in the upstream (non-streaming ice) portion of the longitudinal profile that quickly thickens into a ∼600m sedimentary basin in the downstream (streaming ice) reaches. The DT1 results reveal a large sedimentary basin extending across the width of the ice stream, with a maximum thickness of ∼600m near the center of the ice stream. We determined these sediment thicknesses by creating a 2D model consisting of a sedimentary layer, whose velocity ranges from 2400m/sec to 2500m/sec, between the ice and the underlying bedrock. The thick sedimentary basins along both C1B and DT1 also correspond with increased ice velocities along the two profiles. Our results reveal that the presence of sediments is a necessary requirement for initiating ice streaming in the onset regions of the Ross ice streams. Thick sedimentary basins at the onset provide a source for the dilatant subglacial till that acts as a lubricant in aiding ice flow along the length of the ice streams. It appears that tributary C1B of ice stream C has reached the inland extent of subglacial sediments, which may mark the paleo-shoreline of the West Antarctica during complete deglaciation (presumed to have occurred within the last 600,000 years). This sediment boundary may also outline the maximum inland extent of the Ross ice streams.

C21A-03 0830h INVITED

Subglacial Conditions From the Seismic Reflection Technique

Andy M Smith (44-1223-221481; amsm@bas.ac.uk)

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, United Kingdom

For many decades the use of seismic methods in glaciology was overshadowed by radar. Radar acquisition is quicker, easier and can be done from an aircraft. However, recent years have seen a resurgence in seismic techniques, enabled largely by improved instrumentation. Seismic data have been particularly effective at determining basal conditions and here I discuss some of our seismic reflection results. Seismic acquisition parameters can be tailored to many different targets of interest. Here I concentrate on near-vertical incidence seismic reflection data, where source-receiver offsets are small relative to the ice thickness. Energy loss can then be attributed to geometrical spreading, attenuation and transmission/reflection coefficients without any influence from amplitude- (or phase-) vs-offset effects. This makes the analysis of field records particularly straight-forward. Quantitative interpretation of the data to determine basal conditions relies on the ability to calibrate the reflection coefficient at the ice-bed interface. Hence, the seismic data need to include multiple reflections from the bed, either all the way along a profile or at a number of specific locations. The reflection coefficient is controlled by the acoustic impedance contrast at the interface, ie the change in the product of seismic velocity and density in the two materials. In most situations, the impedance of the ice is known accurately enough for that of the sub-glacial material to then be calculated and the nature of the material determined, eg. deforming sediments, non-deforming sediments, permafrost or bedrock. I present results from Antarctic ice streams. Variations in the basal conditions can be identified, which in some cases can show major transitions over short distances. Data from a number of different sites can be used to quantify the way that basal conditions control the ice flow.

C21A-04 0845h INVITED

New Airborne Radar Sounding Approaches for Quantifying Basal Reflection and Scattering, With Application to Ice Stream C (and Whillans Ice Stream), West Antarctica

Donald D Blankenship[1] (blank@ig.utexas.edu)

Matthew E Peters[1] (mattp@ig.utexas.edu)

David L Morse[1] (morse@ig.utexas.edu)

[1] University of Texas, Institute for Geophysics, 4412 Spicewood Springs Rd, Bldg 600, Austin, TX 78759

The grounding zones of ice streams are a sensitive indicator of ice sheet variability and sea-level change. These dynamic systems involve the interaction of the moving ice mass with the underlying materials, including liquid water, saturated lubricating tills, and rough or frozen bedrock sticky spots. In addition, bottom crevasses result from tidal flexure. Imaging and characterizing the subglacial environment of grounding zones is fundamental to understanding these complex systems. Airborne radar sounding is an increasingly valuable tool for investigations of polar ice sheets and glaciers, especially when studying the basal interface. We present results from airborne radar data acquired over ice stream C, West Antarctica, in 2001 using a uniquely configured airborne radar system. Our focus was on characterizing the basal interface within the grounding zone of this ice stream through radar reflection and scattering analyses. These new results are also used to extend the interpretation of data from regional surveys flown in 1988 over the downstream portions of both ice streams C and Whillans ice stream. The newly integrated radar system uses a programmable signal source with a dual-channel coherent down-conversion receiver linked to a 10 kW transmitter. The radar operates in chirped pulse mode at 60 MHz and 15 MHz bandwidth. High and low-gain channels allow for recording both weak bed echoes and strong surface echoes simultaneously and without range-dependent gain control. Data acquisition includes integrations of 16 returned radar signals about every 15 cm along-track. Pulse compression and unfocussed synthetic aperture radar (SAR) processing using additional along-track integration were significant components of data analysis. The radar system used for the 1988 surveys operated in pulsed mode at 50 MHz and recorded both SAR (along-track integrated) and individual signal observations every second, or about every 60 m along-track. Echoes from the basal interface generally consist of both specularly reflected and diffusely scattered energy. Unfocussed SAR narrows the along-track radar beam, thus increasing resolution and the likelihood of specular reflection from the bed. Basal reflection coefficients are computed from these data and used for inferring subglacial materials, most notably regions where significant quantities of liquid water are present immediately beneath the ice. However, echo strength statistics based on reflection and scattering theory show that diffuse scattering can still dominate these echoes. Scattering analysis includes imaging of the basal interface at very short along-track integration distances coupled with echo strength statistics and the rates of change of echo amplitude (fading) and phase with distance. Using the new radar data, we quantify off-nadir scattering from the subglacial interface to infer both the small-scale roughness and the distribution of slopes and facets associated with bottom crevasses and bedrock sticky spots. Finally, we extend these results to the less well-sampled radar surveys over the grounding zones of ice stream C and Whillans ice stream where we complement our previously identified distribution of water and saturated sediments with a distribution of anomalously rough areas that are most likely to contain sticky spots.

C21A-05 0900h

Glaciogeophysics at Matanuska Glacier, Alaska

Gregory S Baker[1] (716-645-6800 ext 2252; gbaker@geology.buffalo.edu)

Daniel E Lawson[2] (Daniel.E.Lawson@erdc.usace.army.mil)

Edward B Evenson[3] (ebe0@lehigh.edu)

Grahame J Larson[4] (larsong@pilot.msu.edu)

Richard B Alley[5] (ralley@essc.psu.edu)

[1] University at Buffalo, Dept of Geology, Buffalo, NY 14260, United States

[2] U.S. Army Cold Regions Rsch and Engineering Lab, 72 Lyme Rd, Hanover, NH 03755, United States

[3] Lehigh University, Dept of Earth and Environmental Sciences, Bethlehem, PA 18015, United States

[4] Michigan State University, Dept of Geological Sciences, East Lansing, MI 48824, United States

[5] Pennsylvania State University, Dept of Geosciences, University Park, PA 16802, United States

Numerous near-surface geophysical studies on and near Matanuska Glacier, Alaska, have been used to test and develop hypotheses related to several important aspects of glacier margin dynamics. First, high-resolution seismic reflection data constrains the 3D distribution of debris-rich basal ice and have been used to confirm the predicted distribution determined by the basal freeze-on mechanism of sediment entrainment. Second, seismic reflection and refraction, GPR, and electrical resistivity data indicate the presence of extensive buried ice beneath the ice-proximal outwash plain. These data are used to hypothesize an alternative means for pitted-outwash plain formation that does not rely on the "buried block-of-ice" mechanism. Third, extensive GPR data collected on an ice-cored moraine complex–at the same site over a period of three years–indicate that the buried ice rigidly deformed in response to impact from re-advancing active ice. As a result (as imaged in 3D using the GPR and based on surface exposure) the overlying sediments in the ice-cored moraine deformed. This data is used to support the hypothesis that glaciotectonic deformation need not rely on stresses propagating through soft sediments; rather, buried ice can be a dominant mechanism in the deformation process. Finally, seismic reflection and refraction tomography are used to constrain depth-to-bedrock in the valley proximal to the glacier in order to constrain erosion and sedimentation rates.

URL: http://www.geophysics.buffalo.edu

C21A-06 0915h

Glacial earthquakes

Göran Ekström[1] (ekstrom@eps.harvard.edu)

Meredith Nettles[1] (nettles@eps.harvard.edu)

Geoffrey A. Abers[2] (abers@bu.edu)

[1] Dept of Earth and Planetary Sciences, Harvard University, 20 Oxford St, Cambridge, MA 02138

[2] Dept of Earth Sciences, Boston University, 685 Commonwealth Av, Boston, MA 02215

We have identified a new class of moderate earthquakes (seismic magnitude around 5) that occur beneath glaciers. The previously unknown glacial earthquakes generate long-period (20–60 sec) seismic surface waves that are well recorded on globally distributed seismic stations, but which have previously gone undetected because they do not generate the high-frequency seismic waves on which traditional earthquake detection and location methodologies are based. A glacial earthquake on September 4, 1999, beneath the Dall glacier (Denali range, Alaska) was well recorded by the BEAAR temporary broad-band seismic network. Inverse modeling of the regional long-period seismograms shows that the seismic waves are inconsistent with tectonic faulting beneath the glacier, but instead consistent with sudden and massive glacial sliding. Using the centroid-single-force formalism developed by Kawakatsu (1989) for analysis of landslide-generated seismic waves, we obtain an estimate of the product of sliding mass and sliding distance. The value of this parameter for the Dall glacier event is 1.3×10^{14} kg-m, consistent with the displacement of 10 km^3 of ice by 13 meters, though we cannot constrain the mass and distance independently. The duration of sliding was approximately 40 seconds. By analysis of data from the Global Seismographic Network for 1999–2001, we have detected and located forty-two glacial earthquakes of similar magnitude beneath the Greenland ice sheet. Preliminary analysis of the five best-recorded earthquakes indicates that these, too, are consistent with glacial sliding. We speculate that the dynamics of these earthquakes are controlled by stick-slip motion of the glacier along its basal surface, and that the phenomenon involves the displacement of a large mass over a relatively short distance. Microearthquakes occur in association with glaciers, and some have been linked to sliding motion at the base, and in particular to motion on so-called sticky spots. Alternatively, rapid variations in pore pressure at the glacier base or the non-linear weakening of a deforming till may generate conditions for rapid lowering of the effective friction, growth of a slipping patch, and sudden large-scale motion of the glacier.

C21A-07 0930h

Interactions Between Ice and Ocean Near an Ice Shelf Grounding Line

Adrian Jenkins[1] (+44-1223-221493; ajen@bas.ac.uk)

Hugh Corr[1] (hfjc@bas.ac.uk)

Keith Nicholls[1] (kwni@bas.ac.uk)

Criag Stewart[1] (cste@bas.ac.uk)

Chris Doake[1] (csmd@bas.ac.uk)

[1] British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, United Kingdom

We describe a series of high precision, high temporal resolution measurements of surface deformation and ice thickness change made near the grounding line of Rutford Ice Stream, West Antarctica. Our observations span two periods of two to three weeks each, separated by one year. We measured surface deformation by GPS survey of a triangular pattern of markers, and changes in ice thickness using a phase-sensitive radar sounding system. Near the point of maximum tidal flexure we observed a tidal component to the horizontal strain of up to $\sim 0.1 \times 10^{-3}$. Hence the magnitude of the cyclical (predominantly semi-diurnal) strain rate far exceeds that of the steady, long-term deformation rate, which we observe to be of $\sim 1 \times 10^{-3}$ yr^{-1}. We made direct measurements of the vertical strain rate in the upper 500-600 m of the ice column from the relative displacement of internal reflectors visible in the radar records. Once again we see a tidal component superimposed on a long-term trend, and both of these are reflected in our measurements of total ice thickness. Overall the ice column is subject to a net vertical strain of up to $\sim 0.01 \times 10^{-3}$ over half a tidal cycle. The long-term trend in thickness differs from that implied by the long-term vertical strain rate. We attribute the difference to basal melting of 1.18 ± 0.03 m yr^{-1}. There appears to be no seasonal variation in the melt rate, nor any change between times of spring and neap tides. The measured melt rate is consistent with an earlier estimate of that required to maintain the ice shelf locally in equilibrium (1.2 ± 0.5 m yr^{-1}).

C21A-08 0945h INVITED

C

Ground-Based Deep-Penetrating Radar Studies Along The US-ITASE Traverse

Robert W. Jacobel[1] (507-646-3124; jacobel@stolaf.edu)

Brian C. Welch[1] (507-646-3620; welchb@stolaf.edu)

Matthew T. Bills[1] (bills@stolaf.edu)

Thomas J. Engle[1] (tjengle@wisc.edu)

[1] Department of Physics, St. Olaf College, 1500 St. Olaf Ave., Northfield, MN 55057, United States

In recent years airborne geophysical surveys have provided high-quality data over selected portions of the West Antarctic Ice Sheet (WAIS). Coupled with new information at visible and radar wavelengths from satellite sensors, these surveys have greatly enhanced our understanding of the dynamics of the WAIS. Until recently, ground-based radar studies have generally been limited to more localized areas and small-scale ice dynamics problems where they provide greater spatial resolution than airborne surveys, often with higher definition (S/N) of imaged features. During the past four years, the US-ITASE platform has provided an opportunity for ground-based deep radar profiling over several thousand kilometers of the WAIS and portions of the East Antarctic Ice Sheet, including more detailed studies of selected sites where ice cores have been drilled. These traverses have enabled us to produced high definition images of bedrock and internal stratigraphy on a continental scale, combining attributes of both airborne and ground-based surveys. We have developed a ruggedized impulse-based radar system to withstand the physical demands of a heavy vehicle traverse at speeds up to 15 Km/hr and also obtain data with high spatial resolution along-track and high definition of internal reflectors. Operating at a center frequency of 3 MHz this system utilizes a 14 bit A/D board at digitizing rates of 100 MHz and records stacked waveforms depicting bedrock and ice internal reflections approximately every 15 meters of surface travel. Surface coordinates are obtained from precision GPS measurements which together with the high data density enable us to migrate profile sections to correctly image steeply-dipping reflectors. We present here a sample of results from over 2000 km of profiles completed during the 2001-2003 field seasons, including routes from Byrd Station toward Siple Station and Byrd to South Pole. In addition to the bedrock record that identifies a number of new regions of high topographic relief, we have obtained radar profiles across several of the major ice divides that will enable us to investigate divide stability from model studies of the internal layers. We have a grid of profiles showing details of the bedrock and internal layer stratigraphy beneath Hercules Dome, a site of possible interest for a deep climate core just upflow from "The Bottleneck" where ice is funneled from the East to West Antarctic Ice Sheets. Our profiles also depict several unusual areas with disturbed internal stratigraphy that may result from bedrock topographic features with large (>50% of ice thickness) and abrupt (> few km) relief. Our interpretation of sub-ice reflectors is aided by information on surface features and ice flow from MODIS and RADARSAT imagery.

URL: http://www.stolaf.edu/other/cegsic/itase/