by the recently developed affine self-consistent homogenization scheme, which allows the description of the overall mechanical behavior of the aggregate with respect to the local elastic and viscoplastic behavior of the grains. Comparison of model results to a large set of experimental data will be given.

C61A-10 1115h

The Excess Diffusion of Stable Isotopes in Polycrystalline Ice

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Post-depositional processes must be taken into account when ice cores are used to infer the history of past climates. For example, the effects of diffusion in the firn are modeled and inverted to recover the original stable isotope ratios δ^{18}O and δD, which yield records of past temperature. Fortunately, beneath the level of pore close-off, post-depositional alteration is slowed considerably. Nevertheless, diffusion continues to smooth the isotope records, leading to the loss of seasonal and other high-frequency information. In fact, Johnsen and others (1999) found that the rate of diffusive smoothing in the Holocene ice sampled by the GRIP core is much faster than would be predicted by diffusion through solid ice alone. Nye (1998) argued that the presence of liquid veins at the boundaries of ice grains might explain this apparent “excess” diffusion. However, the analysis of Johnsen and others (2000) suggests that the required vein dimensions are unrealistically large. Here, we model the diffusion of stable isotopes in polycrystalline ice and show that the predictions of Nye (1998) and those of Johnsen and others (2000) represent two end-members in a spectrum of potential behavior. Our analysis ties together the two approaches and provides a rostrum for data analysis. In the Nye-model regime, the degree of excess diffusion depends on the wavelength of the isotopic signal. In the Johnsen-model regime, the rate of diffusive smoothing varies with the square of the grain size. We identify the physical characteristics that determine which of these asymptotic regimes more closely resembles the prevailing conditions and quantify the role of premelted liquid in the smoothing of isotopic signals. A deeper understanding of the processes by which the isotope records evolve will help to increase the accuracy and resolution of paleotemperature reconstructions.

S.J. Johnsen and others 1997 J. Geophys. Res. **102**, 26397.
S.J. Johnsen and others 2000 in: Physics of Ice Core Records, (ed. T. Hondoh) Hokkaido Univ. Press, 121.
J.F. Nye 1998 J. Glaciol. **44**, 467.

C61A-11 1130h

A Two-dimensional Model of Post-depositional Changes in Stable-Isotope Ratios in Polar Firn

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Stable-isotope ratios in precipitation are used as a proxy for the temperature above the inversion layer at the time of snow formation. We explore the possibility that the initial stable-isotopic ratios in snow may be modified by water-vapor exchange between pore-space vapor and the ice matrix.

We present a model which estimates the isotopic change of a two-dimensional section of firn through time. We model water-vapor motion through the firn as a result of diffusion along vapor-pressure gradients and of ventilation associated with air flow over the snow surface microtopography. Water vapor in firn pore spaces is a mixture of advected vapor from neighboring pores and vapor derived from sublimation of ice grains. We assume that stable isotopes do not fractionate upon sublimation and that ventilation continually advects air and water vapor through the firn. We calculate the mass of water vapor that changes phase (by either sublimation or condensation) in the firn through time. We also allow for water vapor loss to the atmosphere through advection. Our model inputs are the surface temperature, the firn microstructure (assumed constant), the isotopic composition of atmospheric water vapor, the relative humidity of the atmosphere, the mean wind speed and the microtopography of the firn.

Our model suggests that δ^{18}O can change by a few tenths of a part per mil per year. In high accumulation rate environments, surface snow is advected down through the ventilated zone before stable isotope ratios are modified significantly. However, post-depositional changes could be significant in low-accumulation-rate environments where snow remains within the near-surface ventilated zone for several years prior to deep burial. We also use this model to predict how the deuterium excess could change with time.

C61A-12 1145h

Laborative studies of the diffusion rate of stable isotopes in firn

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The diffusion of stable isotopes of water (d18O and d2H) in ice and firn is a question of interest for ice core glaciology. The back-diffusion (or de-convolution) models used today can be improved by having better knowledge of the diffusivity within firn, and ice. This is a laboratory setup, where we study the diffusion rate of stable isotopes of water within a matrix of fabricated firn. The laboratory procedure is such that two bodies of isotopically different waters are frozen. Flakes are shaved of the ice, making firn grains. The density of this manually fabricated firn is approximately 500 kg / m3. The firn of the two isotopically different waters is then sandwiched in an isolated box held in a freezer. The thickness of the different layers are varied in the stack at the setup, the ice temperature and the ice density are held relatively constant. Samples of the stack are taken over consequent longer time periods. Both d18O and d2H of the water are analyzed, using isotope ratio mass spectrometry. Comparison the results of the diffusion experiment with diffusion models will tell if the measured diffusion rate is similar to theoretical diffusion rates, or not.

C62A MCC: Hall C Saturday 1330h

Glaciers and Ice Sheets III Posters
(joint with A, H, GC, PP)

Presiding: **T Murray,** University of Leeds**; W T Pfeffer,** University of Colorado

C62A-0902 1330h POSTER

Radar Studies of Englacial Water in Storglaciaren, Sweden

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We present results from a second season of ground-based ice-penetrating radar studies on Storglaciaren, a polythermal glacier in arctic Sweden. The purpose of this research is to investigate the morphology and hydraulics of englacial channels - a problem of central importance to understanding glacier movement. Previous work has for the most part been limited to theoretical studies with few observations. We used a multi-frequency ground-penetrating radar in conjunction with borehole video (see companion paper by Fountain, et al., this session) to image englacial water passages.

Coarse surveys were carried out in the ablation zone using an impulse radar at a frequency of 50 MHz to characterize the surface cold layer, and to search for promising sites where englacial water bodies might be imaged and located. Subsequent detailed grid surveys with a spacing of 2 meters were completed using both 50 and 100 MHz radars. Two sites were found where bright englacial echoes suggested a sloping water-filled feature with linear dimensions on the order of several meters. Boreholes were drilled at both sites and directly intersected each feature. The borehole video camera confirmed that both features were narrow (1-10 cm) channels carrying water at slow speeds. At a third site, radar surveys located a point-like reflector at a depth of 20 meters within the surface cold layer. The borehole camera revealed this to be an oblate water-filled cavity approximately half a meter in extent and not connected to the englacial hydraulic system.

Our radar surveys showed that success in imaging water bodies from multiple positions on the surface was dependent on the object size and orientation, as would be expected for an extended reflector with complex geometry. Like other surveys, we detected many reflectors in single profiles that could not be indentifed in multiple views, and thus the source could not be located precisely. Likewise, the borehole drill intersected a number of water-filled channels that were not resolved by the radar. This result confirms the difficulty of imaging and locating extended objects with a broad beam antenna. At the same time, the correspondence between borehole and radar results in those cases where channels were located, shows the utility of the technique. The radar surveys together with the borehole experiments suggest a new model for englacial drainage, wherein crevasse-like features are the main conveyors of water and form a fracture-like network consisting of numerous pathways rather than the traditional view of a few melt-enlarged conduits in ice.

C

C62A-0903 1330h POSTER

Visualizing glacial sediment inclusions using 3-D ground-penetrating radar

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Retreat since the 1940s surge of Kongsvegen, Svalbard has exposed sediment structures on the glacier surface and along a 1 km long, 5–20 m high, grounded cliff section near the terminus. Glacier ice provides an almost ideal target for ground-penetrating radar (GPR) because low attenuation means that penetration up to 100s metres can be achieved. Reflections result from changes in the dielectric properties of the ice, typically due to changes in sediment or water content of the ice. Coincident GPR and real-time kinematic GPS data were collected on Kongsvegen by towing the instruments behind a moving snowscooter. Grids ($\sim$ 100 m x 50 m) of closely spaced common offset GPR lines ($\sim$ 0.25 m in line and 1 m between line spacing) were imaged over prominent englacial sediment features. The data were tied through a time stamp at each radar trace. The data have been 2-D interpolated at each time interval onto a regular grid to allow visualization. Prior to interpolation each line was de-spiked, and filtered to remove low frequency noise and horizontal banding resulting from ringing in the antennae. After interpolation the data were topographically corrected and migrated before visualization. The grids imaged two sub-horizontal reflectors. The upper reflector is strong and continuous, dips gently upglacier, and is interpreted to be the base of the glacier or the top of a basal ice layer. The lower reflector is discontinuous and is interpreted either as a thermal boundary (between frozen and unfrozen sediments) or as a décollement layer within the sedimentary bed material. Above the basal reflector a series of strong up-glacier dipping faults were imaged, which do not cross the basal reflector. Weaker features occur between the basal reflector and the lower reflector. We interpret these structures in terms of the surge history of the Kongsvegen glacier complex.

C62A-0904 1330h POSTER

Ground Penetrating Radar Imaging of Glaciotectonic Sediment Deformation in an Ice-Cored Moraine Generated by Movement of the Buried Ice During a Re-advance of the Active Ice, Matanuska Glacier, Alaska

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Ground penetrating radar data are used to demonstrate that geophysical data collection at a glacier margin can improve our understanding of sediment deformation associated with glaciotectonic processes. The data show that sediment overlying stagnant, buried ice in an ice-cored moraine was passively deformed when the ice moved in response to direct interaction with active ice during a re-advance.

The study area is the western terminus of the Matanuska glacier, a 35-km-long temperate alpine glacier located in the Chugach Mountains of southeastern Alaska. Data were collected at concurrent locations in July 2001 and 2002 on a well-developed ice-cored moraine. In 2001, the moraine was roughly 20 m from the active ice, even with seasonal fluctuations. During the winter of 2001-2002, however, the ice margin advanced to its furthest position in about fifteen years. As a result, the normal re-sedimentation processes associated with ice-cored moraine evolution in the study area were interrupted. The GPR data indicate that the advancing ice collided with the edge of the ice buried in the moraine, and the buried ice subsequently shifted and developed thrust planes, verging in the down-ice direction. The overlying sediments were observed to passively deform in response to the movement of the underlying ice.

C62A-0905 1330h POSTER

An Innovative Technique for Using Ground Penetrating Radar to Track Ice-Flow Velocities at Depth, Matanuska Glacier, Alaska

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Ground penetrating radar (GPR) data will be presented to demonstrate an innovative technique for determining glacier flow velocities at depth. A metallic target fixed in a borehole within a glacier can be detected using GPR when either the borehole is water-filled or the borehole is allowed to close around the target. In addition, the vertical and horizontal position of the target within the ice can be determined by collecting a grid of GPR data surrounding the borehole. Furthermore, by re-collecting the grid of GPR data at known time intervals, the velocity of the target–and hence the glacier flow velocity at the point of the target–can be estimated. An example of this technique will be presented.

The study area is the western terminus of the Matanuska Glacier, a 35-km-long temperate alpine glacier located in the Chugach Mountains of southeastern Alaska. In July 2002, several targets were positioned at various depths in two boreholes (80-120-m deep) drilled near the terminus. The GPR data were collected several times during a month-long period in July and August 2002, and again during a week-long period in October 2002.

C62A-0906 1330h POSTER

Polythermal glacier firn and ice stratigraphy imaged with ground-penetrating radar

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Ground-penetrating radar (GPR) profiles have been recorded along the centerline of Kongsvegen, Svalbard for five years, in spring. The GPR operates at 500 MHz, and the profiles extend to a maximum depth of about 12 m in firn. The images show a series of layers originating upglacier of the location of the mean equilibrium line altitude, and increasing in thickness upglacier. The layers correspond to previous years summer surfaces, and can be correlated in the upper part of the firn area with the net balance measured at stakes as part of the mass balance monitoring program. The GPR-imaged layers terminate at the firn-ice transition, which lies upglacier of the point predicted using a simple stratigraphic model driven by the mass balance measurements. The discrepancy between the imaged and calculated stratigraphy can be explained by superimposed ice formation and water percolation in the firn at the firn-ice transition zone. The firn-ice transition as imaged by GPR coincides in location with the transition from weak to strong back-scatter observed in satellite SAR imagery, and does not change position significantly during the years for which there are measurements.

C62A-0907 1330h POSTER

Borehole Optical Stratigraphy: a new Tool for Ice-Sheet Paleoclimate Studies

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We have developed a system for studying optical stratigraphy in polar firn boreholes, based on a down-hole video camera and digital video processing software. A downward-looking wide-angle camera unit is lowered down the borehole, simultaneously recording a digital image of the borehole wall and the depth from a pulley-mounted optical encoder. Processing through commercial DV editing software and image-processing software can produce a variety of products. Our first simple product is a single sequence representing the average brightness at each depth. Optical stratigraphy data are routinely recorded when processing an ice core. Our method allows data to be collected from the hole itself. Registering the depth of a given feature is more reliable, and the position and character of the features can be observed as they evolve, allowing measurement of strain rates. The ability to view continuous sections of stratigraphic data much longer than a typical core section allows investigators to look for longer-term climate trends, which may occur over a depth scale of several meters or more.

In field tests at Siple Dome, West Antarctica, the optical-brightness signal has high repeatability and a high signal-to-noise ratio, and persists from year-to-year. We also see annual layers and longer-term trends in brightness.

C62A-0908 1330h POSTER

History of Debris-bearing Basal ice: Comparing Numerical Simulations of Basal Freeze-on to Borehole Video Images and Laboratory Experiments

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Debris-bearing basal ice are frequently observed in a variety of glaciers as well as in ice cores drilled to the base of modern ice sheets. A common feature of frozen-on basal ice is an layered structure of debris-rich, dirty ice and clean, transparent ice. The thermodynamic aspects governing the segregation mechanism that separates dirty ice and clean ice are poorly understood and quantitative assessments of basal freeze-on are rarely conducted.

We have investigated the response of subglacial sediments to basal freeze-on in a high-resolution numerical model (node spacing: 0.01 m). The model adapts thermodynamics of frost heave (which is a much-studied process in permafrost engineering) to subglacial conditions. In fine-grained sub-ice stream till, in-situ freezing of pore water is inhibited due to surface tension arising from a small characteristic particle size. The till becomes super-cooled by up to 0.35°C from the pressure-melting point and thermally driven pore water flow is induced. This water flow feeds accretion of clean ice onto the ice base while the till dewaters.

Our model predictions compare favorably with observations from the Ross sector of the West Antarctic ice sheet. When the ice base is in direct contact with the till, ice stream stoppage is predicted to occur ca. 70 years after basal freeze-on is triggered. Fast ice stream flow may be prolonged if a widespread basal water system is capable of separating the freezing ice base from the till. However, the small thickness of water filled gaps (ca. 1-2 mm) limits the time of enhanced flow prolongation. After the freezing ice base has consumed the water film, the ice stream will shut down due to dewatering of the till. However, the bed remains unfrozen and highly porous for long time periods subsequent to stoppage. We predict that complete freeze-up of a 5 m till layer takes several centuries. This result is supported by radar data showing that Ice Stream C, which stopped ca. 150 years ago, has a largely unfrozen bed, while Siple Ice Stream, which stopped about 300 years earlier, exhibits a partially frozen bed.

A self-adjusting upper boundary in our numerical simulation allows the freezing front to move downwards into the till domain. This occurs when the ice-till interface is no longer the thermodynamically most favorable location for freezing. We can thus simulate growth of ice lenses within the till. Our model reproduces basal ice with a layered structure consisting of uniform bands of debris-filled ice and clean segregation ice. Medium-grained till develops thin ice lenses that are closely spaced while fine-grained till develops thick ice lenses with a wider spacing. Comparison of our results to borehole video images of basal ice beneath Ice Stream C and images from laboratory studies of freezing porous media indicates that thermodynamics of basal freeze-on and frost heaving are fundamentally related.

C62A-0909 1330h POSTER

Ice Core Borehole Sonic Logging at GISP2 and GRIP, Greenland, and Siple Dome, Antarctica

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Studies of ice cores yield important information about the history of ice sheets and past climates. Interpretation of paleoclimate records from ice cores depends on understanding the ice sheet flow to determine depth-age relationships and whether the ice has been affected by folding. The alignment of crystals in ice, called fabric, is an important factor in understanding ice sheet flow since preferentially aligned crystals cause the ice to flow more easily in certain directions, and less easily in others. Fabric is commonly determined using thin sections cut at intervals from an ice core. Another method of determining fabric is sonic logging, where a probe is lowered into a borehole to measure the velocity of compressional waves through the ice. Sonic logging is a valuable tool for understanding ice fabric because it provides a continuous profile of the ice fabric and averages the alignment of ice crystals over a much larger volume than do thin sections.

The objective of this project is to measure sonic velocity profiles at a variety of ice core borehole sites and use these profiles to: 1) improve the understanding of the relationship between thin section and sonic velocity data; 2) determine if sonic velocity data can be used to identify the depth at which paleoclimate record continuity is lost and if so, formulate criteria to identify this depth; and 3) provide verification and input data for anisotropic flow law models. Fabric estimates from sonic velocity profiles recently measured at the GISP2 and GRIP boreholes in Greenland and from the borehole at Siple Dome, Antarctica are compared to fabrics estimated from thin section data. The GISP2 site located 28 km west of Summit experiences flank flow while the GRIP and Siple Dome sites are both dome divides. For the GISP2 borehole, the sonic velocity profile is also compared to sonic velocity measurements made on sections of the GISP2 ice core. The sonic velocity profiles are also used to determine if the depth at which the paleoclimate record continuity is lost can be identified from sonic logging.

C62A-0910 1330h POSTER

Application of novel fabric and texture analysis techniques to GISP2.

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Recent development of a fully automated digital instrument for fabric analysis has led to a dramatic increase in the quality and quantity of c-axis data from ice cores (Hansen and Wilen, 2002 J. Glaciol.). The new data allow straightforward application of statistical techniques to evaluate nearest-neighbor correlations between grains for probing active grain formation processes such as polygonization and/or recrystallization

(Alley and others, 1995 J. Glaciol.). After demonstrating some of the software tools we have developed to facilitate this type of analysis, we will present and discuss results for horizontal and vertical sections from a range of depths at GISP2. These results show unambiguous correlations in c-axis direction for nearest-neighbor grains, but there are fairly large variations in the strength of the correlation even among multiple sections from a single depth.

We will also present experimental results of correlations between grain shape and c-axis orientation. The results will be discussed in relation to expected correlations from simple models of fabric evolution. There are surprising discrepancies that might be attributed to polygonization. If this conjecture proves correct, this type of analysis may provide an alternative technique (to that described above) to probe active grain formation.

C62A-0911 1330h POSTER

Grain Growth in Polycrystalline Fine-grained Ice Ih

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Deformation and flow of polycrystalline ice crystals in ice sheets and glaciers depends strongly on crystal size and temperature. In order to help understand grain-size effects on flow, we performed laboratory experiments on fine-grained, polycrystalline ice Ih samples to investigate the effect of temperature on the rate of grain growth in statically annealed ice. Fine-grained (5-8 mm) ice disks (25mm in diameter x 5 mm thick) were encapsulated and then annealed in a low-temperature bath of oil at ambient pressure. Temperature was varied from 230-240K. Ice samples were placed inside the bath for 1-75 hours to examine the effect of time and temperature on grain growth, grain-size distribution, and grain orientation. Low-temperature scanning electron microscopy (SEM) was used to measure grain size and growth. Neutron scattering is proposed for quantitative textural analysis and examination of the qualitative preferred crystallographic orientations deformed samples. SEM examination revealed grain growth at 234K, while at 230K samples appeared the same as starting material after 18 hours in the bath, showing no growth. Two samples annealed for 1 hour and 18 hours at 234 K showed strong grain growth with equant grain shape and distribution. Samples annealed at 235K revealed significant grain growth after 1 hour, with grain size nearly doubling after 75 hours. The results are significant in establishing grain growth rates under ambient conditions and temperatures applicable to natural ice settings, such as in glaciers and ice sheets. If changes in grain size occur at depth in natural ice bodies, such changes can significantly alter the nature of ice sheet rheology and glacial flow.

C62A-0912 1330h POSTER

A Rock Glaciers Response to Climate and Influence on Water Quality in the Colorado Front Range

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Little research has been conducted on the chemical content of ice and runoff from rock glaciers. However, recent work has refocused efforts on the potential of rock glaciers to indicate past climate signals and reflect current changes in climate. Furthermore, rock glaciers have the potential to affect biogeochemical processes, water quality, and buffering capacity in alpine systems. In this study, we examine water quality from the Green Lake 5 Rock Glacier outlet stream in the Green Lakes Valley, Colorado Front Range. We compare the stream water quality with that of precipitation and outlet streams from the nearby Arikaree Glacier and Martinelli Snowpatch. Precipitation samples were collected year round, and stream water samples were collected roughly between May and October in the years 1998 to 2001. Water samples were analyzed for ANC, NH_4, Ca, Mg, Na, K, Cl, NO_3, SO_4, Si and δO^{18}. The water quality from all three land types was strongly controlled by chemical weathering and hydrologic flow paths, among other variables. In contrast with the other land types, solute concentrations in the rock glacier were lowest at snowmelt and then increased through summer and into early fall. Solute concentrations in snowpatch and glacial runoff were highest during snowmelt. On average, the solutes from chemical weathering products were often an order of magnitude higher in the rock glacier runoff. For example, mean Ca was 447 μeq/L at the rock glacier compared with 17 μeq/L at the Arikeree glacier and 66 μeq/L at the Martinelli snowpatch. Mean NO_3 concentrations were also higher at the rock glacier at 50 μeq/L compared with 8-12 μeq/L in the glacial and snowpatch runoff. The exception is that Na and Cl concentrations were not significantly different between the rock glacier and snowpatch (95 % confidence level). The high concentrations of solutes in the rock glacier, especially in late summer and early fall, suggest the melting of old ice and change of climatic conditions. The increased yield of chemical weathering products indicates that rock glaciers have the potential to alter water quality and buffering capacity locally, and this land type should be considered when modeling water quality at fine spatial scales.

C62A-0913 1330h POSTER

Growing and Advancing Calving Glaciers in Alaska

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In stark contrast with the majority of glaciers in Alaska that are losing volume and retreating in response to climate forcing, about 10 large glaciers are increasing in volume and advancing. All of these are calving glaciers that are advancing into seawater. Hubbard Glacier, at the head of Disenchantment Bay near Yakutat, Alaska, is one of the advancing glaciers and is the largest calving glacier on the North American Continent. Hubbard Glacier?s current advance began shortly before 1895 and has recently been newsworthy because its advance blocked the entrance to Russell Fiord between June and August 2002. Other prominent examples are Meares Glacier, at the head of Unakwik Inlet in Prince William Sound, which is advancing into old-growth forest, and Harvard Glacier, at the head of College Fiord, which has a well-documented history of advance beginning between 1905 and 1911.

Calving glaciers that are currently growing and advancing have at least four things in common. All of them (1) are at the heads of long fiords, (2) have undergone massive retreats during the last thousand or more years, (3) presently calve over relatively shallow moraine shoals, and (4) have strongly positive mass balances that are a consequence of a surface-area distributions that have unusually small ablation areas compared to the accumulation areas. For example, Hubbard Glacier retreated about 61 kilometers between 1000 A.D. and late in the 19th century. The depth of seawater at the calving terminus averages between 60 and 80 meters in a fiord that reaches 230 meters below sea level in front of the glacier and 400 meters below sea level under the ice. The accumulation area of Hubbard Glacier is 95 percent of the entire glacier area and, like the other advancing glaciers, is far from being in equilibrium with climate on the positive mass balance side.

Glaciologists often point out that glaciers are sensitive indicators of climate. This paradigm should not be applied to calving glaciers. During most of the calving glacier cycle, the slow advances and relatively rapid retreats are not very sensitive to climate. For example, the calving glaciers that are currently growing and advancing in the face of global warming, were retreating throughout the little ice age. Calving glaciers become sensitive to climate only late in the advancing phase, when the mass flux out of the accumulation area approaches the mass lost by melting in the ablation area and losses due to calving can no longer be replaced. No reasonable change in climate will change this imbalance and stop the advances of these few glaciers.

URL: http://ak.water.usgs.gov/glaciology/hubbard/

C62A-0914 1330h POSTER

Glacier Fluctuation and Climate Change: the NOAA/NSIDC Glacier Photo Digitization Project

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The study of historic glacier photographs is an excellent source of information about climate change. Glaciers are sensitive to temperature and precipitation patterns associated with climate change. Ice cores from glaciers can provide a long-term climate record and aid current scientific research in understanding changes that have occurred over tens of thousands of years. Within recent history, a warming climate has resulted in the unfortunate retreat and disappearance of glaciers around the world. Comparisons of glacial area and mass balance over time can help scientists understand a glacier's response to climate change.

The National Snow and Ice Data Center is the repository of several thousand glacier photographs taken and collected by the American Geographical Society. The dates of the photographs range from the 1880s to the 1970s and the collection consists of both aerial and terrestrial photos. The digitization of these photographs will help inform users of their existence and will provide easier access to the images. It will also be an important first step in a project to display matching images of the same glaciers over time, thus providing an instantaneous visual representation of climate change.

A searchable online database is being created for several thousand photographs and their accompanying metadata. Images will be retrievable by glacier name, photographer name, state, geographic coordinates, and subject keywords. This work is being done with funding by the National Oceanic and Atmospheric Administration's (NOAA) Climate Database Modernization Program (CDMP), whose goal is to make major climate databases available on the web.

URL: http://www.nsidc.org/glaciers/index.html

C62A-0915 1330h POSTER

Elevation Changes on Malaspina, Agassiz and Marvine Glaciers, Alaska, from the Shuttle Radar Topography Mission

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The Chugach−St. Elias Mountains bordering the Gulf of Alaska is the location of the largest connected glacier and icefield complex in continental North America: The Bering and Malaspina glacier systems (Molnia, 1993; Sharp, 1951). The Malaspina Glacier piedmont lobe has an area of about 2200 km^2. Agassiz and Marvine Glacier, on the west−east sides of the Malaspina piedmont, have areas of about 591 and 223 km^2 respectively. The combined Malaspina−Seward system, including tributaries, has an area of about 4,300 km^2. Malaspina has a quasi−periodic surge period of 20 to 30 years.

The Shuttle Radar Topography Mission/X−Synthetic Aperture Radar (SRTM/X−SAR), flown on STS-99 (February 2000)

was the first spaceborne single-pass interferometric SAR mission (Geudtner and others, 2002). The SRTM/X−SAR system was composed of C and X−band SAR. The single-pass SAR interferometer configuration with an inboard (transmit and receive) and outboard (receive only) antenna system enabled the removal of large error sources inherent with the repeat-pass technique. X−band digital elevation models (DEM) produced by the German Remote Sensing Center (DFD) have a nominal pixel size of 25 m−by−25 m in UTM projection. The vertical and horizontal reference datum is World Geodetic System 84 (WGS 84). Nominal vertical accuracy is 6 m (16 m absolute) and horizontal accuracy is 15 m (20 m absolute) at the 90% confidence level.

We present new surface elevation changes on the Malaspina piedmont lobe, Agassiz and Marvine Glaciers from 1972−73 to 2000 based on spatial analysis of co-located Shuttle Radar Topography Mission X-band DEM with United States Geological Survey DEMs. X-band DEM elevations were changed from the WGS 84 vertical datum (ellipsoid) to the GEOID 99−Alaska (NOAA National Geodetic Survey geoid) datum. USGS DEMs were transformed from North America Datum 1927 (NAD 27) to WGS 84 in UTM projection. A correction for X-band radar penetration depth of snow cover is in progress. Preliminary results indicate the Malaspina piedmont surface lowered on average by 43 $\pm$ 4 m from 1972 to 2000 (1.6 $\pm$ 0.1 m a^{-1}) for a volume loss of 59 $\pm$ 5 km^3 in water equivalent (we). The spatial distribution of surface lowering is non-uniform for all three glaciers. The Marvine Glacier shows an average of 50 $\pm$ 4 m we of surface lowering. The Agassiz Glacier shows an average of 24 $\pm$ 4 m we of surface lowering. However, Agassiz Glacier has a bulge of surface rising up to 52 $\pm$ 4 m, about 4 km in diameter, located across from Agassiz Lakes.

Geudtner and 3 others, Interferometric alignment of the X−SAR antenna system on the Space Shuttle Radar Topography Mission, IEEE Trans. on Geoscience RS, 40 (5), 995−1005, 2002.
Molnia, Major surge of the Bering Glacier, Eos, 74 (29), 321−322, 1993.
Sharp, Accumulation and ablation on the Seward−Malaspina glacier system, Canada−Alaska, Bull. Geo. Soc. Am., 62, 725−744, 1951.

C62A-0916 1330h POSTER

Rapid Downstream Discharge Attenuation During Recent Icelandic Jokulhlaups

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Little attention has been paid to downstream discharge attenuation during glacier outburst floods (jokulhlaups). In non-glacial environments, floods resulting from dam failure exhibit major downstream reduction of peak discharge. Transmission losses within ephemeral rivers are also well-known for generating large reductions in peak discharge. We report on three recent jokulhlaups associated with major downstream discharge attenuation: (1) Solheimajokull July 1999; (2) Kverkjokull January 2002; and (3) Tungnaarjokull July 2002.

Peak discharges calculated using slope area techniques showed that the 1999 Solheimahlaup decreased in discharge from 4400 m^3s^{-1} to 1700 m^3s^{-1} over a downstream distance of less than 7 km. The Kverkhlaup was gauged at 400 m^3s^{-1}, 40 km downstream of the glacier snout. By contrast, less than 1 km from the glacier snouta peak discharge of 2000 m^3s^{-1} was reconstructed using slope-area techniques. The July 2002 jokulhlaup from Tungnaarjokull had a gauged peak discharge of 600 m^3s^{-1} 23 km downstream of the glacier snout. Discharge reconstructed at the glacier snout was 2-3 times greater than the downstream gauged value.

The degree of downstream attenuation of these jokulhlaups reflects a number of factors. The rapidity of rising stage water release. The drainage of warm water during these three jokulhlaups is thought to have resulted in a characteristic sudden, short-lived, rise to peak discharge. In the case of the 1999 Solheimahlaup the hydrograph peak was enhanced by a wave-like burst from a flood-filled ice-dammed lake basin. Flow through high resistance complex bedrock (lava) and braided channels is effective in damping jkulhlaup peak discharge. Transmission loss into highly permeable substrate materials such as lava flows and alluvium visibly reduce peak discharge under normal flow conditions will also be significant during jokulhlaups which flow through wide reaches.

Our study of three recent Icelandic jokulhlaups illustrates the operation of major downstream peak of flood discharge attenuation within glaciated volcanic settings. Downstream reductions of peak jokulhlaup discharge have important implications for proglacial geomorphology and sedimentology, and for flood hazard management. In order to provide a true hydrograph record, reconstruction or gauging of jokulhlaup peak discharges needs to be carried out as close to glacier margins as possible. This will permit better understanding of jokulhlaup drainage mechanisms and provide a sound basis for prediction of the characteristics and impacts of future jokulhlaups.

C62A-0917 1330h POSTER

Detection and Monitoring of Jokulhlaup-Induced Topographic Changes Using NASA ATM Lidar Data: Skeidararsandur, Iceland

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Skeidararsandur, southern Iceland, sustained severe erosional and depositional damage from a catastrophic volcanically-triggered glacial outburst flood or jokulhlaup from November 5-7, 1996. Active parts of this site are continuing to experience daily centimeter- to meter-scale accretion and erosion. Jokulhlaups exert a significant influence on sandur evolution through erosion, transport and deposition of sub-glacial and pro-glacial sediments. Flood inundation extent can normally be monitored by conventional remote sensing. However, centimeter-scale elevation changes caused by fluvial erosion or deposition are costly and time-consuming to obtain in the field, especially over large areas such as occurred in the 1996 event. Here, we show that lidar (LIght Detection And Ranging) remote sensing technology has great potential for providing such information. NASAs Airborne Topographic Mapper (ATM) laser altimeter was deployed in 1996, 1997, 1998 and 2001, allowing direct measurement of centimeter-scale elevation changes caused by the 1996 jokulhlaup, as well as subsequent normal flows and smaller flood events. A careful assessment of ATMs performance was conducted by detailed ground surveys. The ATM sensor acquired swaths (normally about 250 m wide) of highly precise topographic measurements with typical posting of 2-5 m, and a vertical precision of 10-15 cm. An E-W transect close to the coastline crossing major rivers was measured by ATM before (June 1, 1996) and after (May 6-7, 1997) the event. A Comparison between the ATM profiles shows that this event substantially reshaped the terrain, with more deposition (a depth of 25 cm over a distance of 35 km) than erosion (23 cm over 4.6 km). The 2001 ATM profile (May 19 2001) suggests that the fluvial system is recovering to its pre-flood level, flushing away the flood deposit at a rate of 2.4 cm/year. Digital elevation models (DEMs) of 5 m resolution were produced for the years 1997 and 2001. Both DEMs are of high quality and detail, with both fluvial landforms and human structures clearly evident.

C62A-0918 1330h POSTER

The causes and characteristics of July 2002 Skaftarhlaup, Tungnaarjokull, Iceland

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Recent research has demonstrated that some jokulhlaups exhibit a linear rise to peak discharge, the processes responsible for which are improperly understood. In July 2002, a linearly rising jokulhlaup exited Tungnaarjokull, an outlet glacier of Vatnajokull, southern Iceland. The aims of this paper are to use rare observations of the glacier surface and ice margin to reconstruct the dynamics of a complex jokulhlaup, and to explain its causes and characteristics.

Aerial reconnaissance in July 2002 showed the growth of an ice-surface cauldron suggesting the rapid evacuation of subglacially stored meltwater at a site of known geothermal activity. Repeated overflights confirmed the rapid release of meltwater from the Western Skafta cauldron to the margin of Tungnaarjokull, 35km south-west, where a jokulhlaup drained into the river Skafta. Observations and photographic evidence were used to calculate ice cauldron dimensions in order to approximate the volumes of drained meltwater. Repeated observations of two main flood outlets at the margin of Tungnaarjokull, allowed flood discharges to be estimated at intervals. Peak discharge estimates from each outlet were calculated using fountain outlet and standing wave dimensions. These observations augment existing knowledge gained from downstream river gauging.

Evidence suggests that the jokulhlaup outlets at Tungnaarjokull developed sequentially. The western tunnel outlet was observed during its waning stage whilst the eastern fountain outlet was still rising, resulting in a double flood peak. Frazil ice development around the eastern fountain outlet at Tungnaarjokull implies that glaciohydraulic supercooling contributed to the development of flood outlets. Discharge reconstructed at the glacier snout was approximately 2-3 times greater than the downstream gauged value, pointing to a rapid rate of peak discharge attenuation during the jokulhlaup.

The July 2002 jokulhlaup from Tungnaarjokull was characterized by a double flood peak, sequential outlet development, downstream flood hydrograph attenuation and remarkable proglacial sediment reworking. This flood adds to our knowledge of linearly rising jkulhlaups and to our understanding of jokulhlaup mechanisms and routeways. The identification of the processes at work in this type of event are applicable in other regions prone to volcanically or geothermally-induced floods.

C62A-0919 1330h POSTER

Borehole Studies of Subglacial and Englacial Hydrology; Bench Glacier, Alaska

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Borehole studies provide an opportunity to examine both the englacial and subglacial hydrologic characteristics of a glacier. On the Bench Glacier, Alaska, a total of 24 boreholes were drilled to the bed of the glacier at regular intervals from the terminus to the headwall. Sensors measuring electrical conductivity, temperature, water velocity and pressure were placed at the base of the boreholes to collect data over the upcoming year.

In addition, a series of 16 slug tests were performed in 6 of the boreholes over a period of one week in early June. The slug tests were performed at various times of the day and in different weather conditions to help investigate the temporal changes in the system. Responses varied from an overdamped slow drain to an underdamped oscillatory response. Analysis of the slug tests in correlation with data retrieved from down-hole sensors provides valuable insight into the development of subglacial and englacial hydrologic systems as well as spatial and temporal changes that occur.

C62A-0920 1330h POSTER

Motion of a Temperate Glacier Over Hard and Soft Beds: Subglacial Experiments at Engabreen, Norway

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Recent work on basal motion of wet-based glaciers has focused on the role of debris, either entrained in ice sliding over bedrock or in a water-saturated layer dividing ice from rock. In the first case, debris in contact with bedrock is known to add resistance to basal motion but is thought to account for only a minor fraction of basal shear stress. Deformation of wet sediment separating ice from rock is thought to commonly reduce resistance to basal motion, although controversy persists regarding whether resistance to such deformation is viscous or predominately frictional and rate-independent.

During two spring field seasons, we have conducted experiments with instrumented hard and soft beds beneath Engabreen, a temperate glacier in Norway where the Svartisen Subglacial Laboratory provides human access to the bed beneath 220 m of ice sliding at 0.1-0.2 m/d. In one experiment, a smooth granite tablet (0.09 m^2) was installed flush with the bedrock surface so that debris-charged basal ice (2-11 % debris by volume) slid across it. The shear traction on the tablet, total normal stress, water pressure at the tablet surface, and upward heat flux were measured. In the other experiment, a trough (2 m x 1.5 m x 0.5 m deep) was blasted in the rock bed and filled with 2.5 tons of simulated till. Instruments recorded shear (tiltmeters), dilation and contraction, total normal stress, and pore-water pressure. Pore pressure was manipulated by feeding water to the base of the till with a high-pressure pump, operated in a tunnel in rock 4 m below the bed surface.

Inconsistent with the leading abrasion theory, shear traction on the rock tablet during two consecutive field seasons was about 100 kPa and depended sensitively on effective normal stress, which fluctuated in response to water-pressure variability. Deformation of till required low effective normal stresses associated with high pore-water pressures, highlighting the frictional nature of till. Shear strain decreased downward in the bed due to increasing friction with depth and the consequent suppression of force imbalances on individual grains (Iverson and Iverson, 2002, J. Glaciol, no. 158). Overall, results from both experiments indicate that rock friction associated with both abrasion and till deformation may play a major role in resisting basal motion of wet-based glaciers.

C62A-0921 1330h POSTER

Subglacial Environment Inferred from Bedrock-Coating Siltskins, Mendenhall Glacier, Alaska

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In the past two decades, retreat of the Mendenhall Glacier near Juneau, Alaska has exposed a bedrock ridge spotted with 'siltskins', patchy coatings of calcite-cemented clay to sand-sized lithic grains. Coatings range from 0.5 to 20 mm thick and occur in two distinct morphologies. Striated siltskins are thin, located mainly on stoss faces, and preserve local striation direction. Thicker, corrugated skins preserved on lee faces consist of parallel microridges elongated downslope.

Thin section analysis shows that siltskins consist of a basal, calcite-rich layer overlain by microlaminated layers of calcite-cemented lithic grains. Microstrata in layers of corrugated siltskins display complex internal structures including wavy microlaminae, truncated cross-bedding, convolute forms, and pockets of larger grains. SEM/EDS analysis of siltskin laminae and surfaces show laterally persistent Ca/Si differences. Isotopic values of ΔO^{18} and ΔC^{13} ranged from -19.52 to -12.74 and -6.18 to -3.44, respectively in five samples of cement, consistent with deposition from subglacial waters of varying isotopic concentrations and with derivation of carbon from inorganic sources.

Regelation processes probably caused precipitation of the basal calcite layer from ice enriched in Ca. After the basal layer reached a limiting thickness, deposition of microlaminae of the upper layer dominated. The relatively thick corrugated siltskins we studied are depositional features enhanced by erosional processes. Wavelengths of parallel microridges generally range from 1 to 10 mm and apparently formed as sediment-rich water dripped or oozed down lee slope rock faces. Ice-rock separation, flow energy, and the amount and grain size of transported sediment controlled the layering and depositional forms.

Deposition of siltskins depended on macro-scale processes in the glacier system, outcrop-scale features of the rock ridge, and micro-scale interactions of the ice, bedrock, and thin films of water in the regelation layer. Siltskins probably formed when a subglacial cavity system was active on the rock ridge, probably within the last 60 years. Siltskins provide clues about how micro-scale hydrologic processes interact with larger-scale subglacial systems.

C62A-0922 1330h POSTER

Are Dewatering Structures Necessary Criteria for Identifying Melt-out Till?

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One the most common characteristics used to identify melt-out till is the presence of dewatering structures, or sorted sediment zones formed during melt-out. However, calculation of the pore water discharge required to sort sediment (critical discharge) and 1-dimensional modeling of melt-out suggest that geothermally driven melt-out produces insufficient water to sort or transport sediment. Assuming pore water pressure within the till equals total pressure on the system, I use geotechnical data from the clayey Kewaunee Formation till of eastern Wisconsin to determine the critical discharge of the till. This till can transport up to 1.6 m^3 of water/year/m^2 without pore water pressure exceeding total pressure. Measured melt rates from valley glaciers and estimated melt rates for ice sheets produce 2 to 3 orders of magnitude lower discharge than the maximum discharge that can pass through the pore space of Kewaunee Formation till. Using basic laws of soil mechanics, I constructed a 1-dimensional model of a geothermally melted, stagnant ice block to analyze pressure distribution during melt-out and to determine the conditions under which dewatering structures can form. During every model run, the pore water pressure within the till never exceeded the total pressure in the till. This suggests that an additional source of water is necessary to form dewatering structures. The additional amount of water needed would require rapid melting of the ice block, which contradicts field observations of debris covered, stagnant ice existing for long periods of time (e.g. 10s to 1000s of years). Therefore, the majority of the water must come from an external source if dewatering structures are to form. Thus, calculation of critical discharge and modeling of stress distribution during melt-out argue that even low permeability, clayey till can dewater without forming sorted dewatering structures. This suggests that the use of dewatering structures as a criterion for recognition of melt-out till may be invalid, and that the lack of dewatering structures in till does not need to be explained by a lodgement or deforming bed genesis.

C63A MCC: 130 Saturday 1800h

Nye Lecture *(joint with H, GC)*

Presiding: **S Marshall,** University of Calgary

C63A-01 1800h

Consider an Ice Stream

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Forty years ago, John Nye was one of the leaders who introduced the rigors of classical physics to glaciology. His elegant treatments frequently took advantage of the then recent discovery that ice could be approximated as a plastic material. With this viewpoint, Nye was able to explain the shape of ice sheets and glaciers, to predict the expected pattern of stress and velocity within a glacier, and to derive the advance and retreat of a glacier from the record of accumulation and ablation. These advances have given generations of glaciologists tools to interpret the excellent observational record of glacier behavior and variation. In the 1980s, glaciologist, weaned on these works of Nye and of other similarly adept colleagues, carried their lessons to West Antarctica to study ice streams, the vast conveyor belts of ice that discharged nearly as much Antarctic ice as the much larger East Antarctic ice sheet. Ice streams were a glaciological conundrum. Despite the gently sloping surface, these broad features roared along, moving fastest when the gravitational impetus was least. After two decades of research, ice streams still have not given up all their secrets, yet much is now known. Internal deformation is negligible. Basal friction is frequently nil leaving the shattered margins as the primary means to avoid rapid wastage of the ice sheet. Within the margins, the resistive force results from a delicate balance of heat and evolving ice fabrics. Nevertheless, the bed beneath an ice stream cannot be ignored. It is ultimately the state of the underlying marine sediment that determines whether the ice stream can slide at all. There too, the heat balance is critical with an influx of water required to keep the bed wet enough to let the streams glide along. Ice stream research has been the portal through which glaciologists have seen and identified the complexities of West Antarctic ice sheet dynamics. Remarkably, nearly all time scales seem important. Ice stream positions in past millennia conform to radically different flow patterns while on the scale of hours an ice stream's motion is halted completely, then released to move at surge-like speeds, in tempo with the tides. Explaining these complexities constantly reminds us that the rigorous physics applied to ice so effectively by Nye still work.

C72A MCC: 120 Sunday 1330h

The Role of Microstructure and Layering in the Physical Properties, Metamorphism, and Deformation of Snow Covers I *(joint with A, H)*

Presiding: **M Schneebeli,** Swiss Federal Institute for Snow and Avalanche Research**; J Johnson,** U.S. Army Engineer Research and Development Center

C72A-01 1330h INVITED

Snow Layering and Spatial Heterogeneity

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Snow packs are made up of snow layers, each differing in physical and microstructural properties from those above and below. The sequence and characteristics of the layers affect the electromagnetic, thermal, physical and mechanical properties of the pack. Layer boundaries are also important in determining the strength of the pack and the transport of air, water and heat through it, though relatively little attention has been focused on the nature of the boundaries themselves. In general, layers are used (some times tacitly) as the basis for spatial extrapolation of properties, with the assumption that layers are laterally homogenous. On ice sheets and large glaciers, this assumption may be valid, but in seasonal snow covers the layers vary laterally at multiple scales (10^{-1} to

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