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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10^{-3} m) in ways strongly dependent upon deposition conditions and substrate micro- and meso-topography. Some "slow" processes, like snow settlement and kinetic growth due to temperature gradients, produce spatial variations that are predictable where the layer geometry is gently varying. Other "faster" processes, like the development of dunes during wind transport or melt water percolation, produce high lateral gradients in properties over short (10^{-1} m) distances that are currently beyond our ability to either measure (except with intense effort) or predict. A number of important snow processes (i.e., wind pumping, avalanche release, melt water routing) seem to be focused in or dominated by these sharp gradient zones and narrow facies boundaries. Future progress in modeling snow covers is going to require a better understanding of spatial variability of snow layers, as well as an improved identification of those problems requiring prediction of average vs. outlier properties. New approaches in modeling will also be needed. Fortunately, there are currently a number of new tools (micro-penetrometers, snow radars, minidata loggers, digital imaging systems) that if we can figure out how to use in concert, should be able to generate the extensive data sets we will need in order to advance.

C72A-02 1350h INVITED

Sintering Concepts - Atomistic Mass Flow, Microstructure Evolution, and Macroscopic Property Changes

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Sintering is the process for bonding contacting particles by the application of thermal energy. At the atomistic level, mass flow is random, yet biased by subtle surface curvature gradients. During sintering microstructure changes become noticable and eventually bulk macroscopic property changes, such as strength increases and pore elimination, can be observed. Computer modeling of sintering has evolved to help understand and link the atomistic and macroscopic aspects. The recent emphasis in sintering models has forced theory to face up to some basic problems. From a perdictive view, the computer models are still behind observations, largely because of errors in our understanding of material property changes and the interactions between the evolving microstructure and kinetics of mass flow. New trends in sintering models will be introduced to show how accurate models require a firm grasp of these issues to predict bulk property changes. The identification of such problems sets in place an agenda for the sintering research community.

URL: http://www.cisp.psu.edu

C72A-03 1415h INVITED

Optical Properties of Snow for Solar and Infrared Radiation: Dependence on Grain Size, Grain Shape, Layering, and Microtopography

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The radiative properties of snow depend strongly on wavelength because the absorption coefficient of ice varies by eight orders of magnitude from the ultraviolet to the infrared. The reflectance, transmittance, absorptance, and emissivity of snow are determined by the distances that photons travel through ice between air-ice interfaces (i.e., between opportunities for scattering). Thus the grain size is the most important variable. To characterize the size of a nonspherical snow grain by a single number, the most relevant dimension is not the long dimension but rather the short dimension, which is proportional to the volume-to-area ratio. This effective optical grain size normally increases during destructive metamorphism, leading to increased path-lengths of photons through snow grains, more absorption and lower albedo. Alternatively, sorting of drift snow by wind can result in a concentration of the smallest grains at the top surface, raising the albedo.

The flux-penetration depth of radiation into snow can be several centimeters for visible light but less than a millimeter in the near-infrared, so the near-infrared reflectance is sensitive only to the surface grain size. A spectral signature thus results from layered snowpacks, which has been observed in measurements of spectral albedo on the Antarctic Plateau, where grain size increases with depth.

Snow cover on sea ice is often thin and vertically inhomogeneous, but very little snow is needed to effectively hide the underlying ice. Just 7 mm of snow can raise the albedo of thick ice from 0.5 to 0.8.

The angular distribution of the reflected radiation, knowledge of which is needed for remote sensing of snow in the solar spectrum, is affected not only by grain size but also by surface roughness, particularly sastrugi. However, the effects of sastrugi are mostly restricted to viewing-zenith angles greater than 50 degrees, so near-nadir viewing is recommended.

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C72A-04 1440h INVITED

Snow Microstructure and Hydrology

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The structure of naturally deposited snow on length scales from the grain scale to pit scale and above plays a very important role in the development of hydrological characteristics, both in seasonal snow packs where timing of water discharge and water chemistry may be of concern, and in the percolation zone of glaciers and ice sheets where routing of infiltrated water bears on the determination of glacier mass balance and the paleoclimatic interpretation of ice layers. The development of a predictive understanding of snow hydrology is complicated by the wide disparity between the length scales of the controlling processes and the much larger length scales at which the aggregate hydrological behavior is desired.

In this presentation examples are given of how water and heat flow alter microstructure, both in subfreezing and isothermal conditions, and how in turn microstructure influences large-scale hydrological processes. Details of some of the transient processes which create the heterogeneous character of snow structure at the pit scale are presented, and the significant differences between snow hydrology and conventional porous media hydrology are outlined. The difficulties of applying microstructural characteristics to large-scale aggregate behavior are considered, and some analytical methods, including geostatistical analysis, are outlined. Finally, direct methods for observing microstructure are described, including existing methods (snow pit stratigraphy, lysimeter arrays, and temperature arrays) as well as promising new methods (FMCW, GPR, and GPR cross-hole tomography).

C72B MCC: 120 Sunday 1515h

Snow and Ice in the Earth System I

(joint with A, H, OS)

Presiding: **P Brooks,** University of Arizona**; Z Yang,** University of Texas

C72B-01 1520h

Spatial Relationships Between Snow Contaminant Content, Grain Size, and Surface Temperature in Multi-spectral Remote Sensing Data of Mt. Rainier, WA

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Relating cryosphere change to climate change requires estimation of radiative fluxes on snow-covered surfaces. The distribution of, and relationship between, snow-pack properties that affect radiative balance can be estimated with high-resolution remote-sensing data. MODIS/ASTER airborne simulator (MASTER) data were collected at Mt. Rainier to reveal spatial patterns of, and correlations between, snow contaminant content, grain size, and temperature. The visible and near-infrared (VNIR: 11 bands, 0.4-1.0 μm) and the short-wave infrared (SWIR: 14 bands, 1.6-2.4 μm) data are processed to bi-directional reflectance (BDR) and albedo, by removing atmospheric effects and by normalizing to Solar irradiance and incidence angle. VNIR BDR and albedo are used as a proxy for snow contaminant content. Physical and optical grain size are estimated by comparing SWIR BDR and albedo to modeled and measured spectra, and ground-truth measurements. The thermal infrared data (TIR: 10 bands, 8-13 μm) are processed to temperature by removing emissivity and atmospheric effects. In combination, the VNIR, SWIR, and TIR data reveal a distinct pattern of contaminants, grain size, and temperature related to a recent snowfall and the end-of-the-summer melting season. At lower elevations, the surface accumulation of dirty lag deposits resulted in snow with very low visible albedo (20-30 %), large physical and optical grain radii (500-1500 μm, 200 μm), and temperatures near the melting point. At higher elevations, the recent snowfall left snow with low contaminant content, and a higher visible albedo (60-90 %). However, a region near the summit with smaller physical and optical grain radii (400 μm, 100 μm), and temperatures below the melting point, is distinguished from a middle elevation region with grain sizes and temperatures similar to the lower region. Contaminants reduce VNIR albedo and significantly enhance absorption of incoming solar radiation. The spatial correlation between temperature and grain size supports the idea that rapid, destructive metamorphism occurs when snow temperatures are at the melting point.

C72B-02 1535h

Snow and Ice in the Earth System Viewed by Space Scatterometer Observatory

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Snow and ice have an important role in the Earth climate system due to their interactions with land, ocean, and atmosphere in complex feedback processes. This paper presents recent results from satellite scatterometer which serves as a space observatory to study the role of snow and ice from aggregation to hemispheric and global scales. Hemispheric snow cover is mapped on the daily basis by the QuikSCAT/SeaWinds scatterometer. The timing and duration of snowmelt process can be determined accurately to address snow impacts in both radiative and hydrologic balances. Extreme events such rapid snowmelt causing spring floods in cold land regions can be monitored leading to possible early detection or prediction of flooding conditions. Anomalous melt zones over the Greenland ice sheet and extreme warming events at McMurdo, Antarctica, have been detected and monitored with the space scatterometer observatory. Sea ice mapping by the scatterometer uncovers the mystery of the Svalbard sea-ice barrier, a rapid growth (1 day) of an elongated sea ice feature (100's km) that blocks off the sea route and traps fishing ship. Sea ice together with ocean wind mapping results show strong interactions among ice cover, atmosphere, and ocean currents which are related to ocean bottom bathymetry. In cold winter conditions, areas of seasonal and perennial sea ice are obtained to study the distribution and balance of new sea ice production and old sea ice export in different regions of the Arctic ocean. During seasonal transitions, the timing of sea ice surface albedo changes is determined. The albedo transition timing is important to accurately estimate solar radiation input into sea ice. In warm summer conditions, areas of positive and negative integrated energy absorption can be identified and mapped. Results present a clear impact of clouds as evident from cyclonic patterns of sea ice surface melt around an Arctic low pressure center. The space scatterometer observatory results affirm that snow and ice should be observed and studied together within the integral of the Earth system, and not as separated parts.

C72B-03 1550h

Parameterization of the Sublimation of Blowing Snow in a Macroscale Hydrology Model

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