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The ice-surface elevation and flow directions within relatively small ice caps, such as those occurring in the Alps during the Last Glacial Maximum (LGM), are primarily affected by regional climate. Therefore, a reconstruction of the LGM Alpine accumulation zone should reflect the principal areas of precipitation and catchment, and thus yield information about paleocirculation. Detailed mapping of glacial trimlines and other erosional features allows an interpretation of the ice-surface elevation and flow directions within the LGM Alpine accumulation zone. Paleocirculation interpretations are derived based on the location of high-elevation "domes" of the ice-cap surface and the direction of ice flow over mountain passes.

A three-dimensional model of the LGM western Alpine ice cap, created using a Geographical Information System, is based on mapped erosional features. This digital reconstruction shows two principal ice domes from which ice flowed outward in all directions. The Matterhorn ice dome existed in the southern Valais and was the highest dome of the Alpine ice cap. The large mass of ice in this region, most of which flowed north into the Rhone Valley, explains the presence of far-traveled erratic boulders, which occur on the northern Alpine foreland. Another lower ice dome existed over Mont Blanc. Trimline elevations imply that the ice surface on the southern side of this dome was approx. 200-300 m higher than on the northern side. Ice flow over high passes to the east of Mont Blanc was from south to north.

Previous work indicates that southerly airflow was dominant during LGM ice accumulation in the central Alps (Florineth and Schluechter, QR, v. 54, 2000). Such paleocirculation, which is different from the present prevalent (north)westerly storm pattern, is interpreted to have resulted from an intensified jet stream which crossed the Atlantic south of the LGM Polar Front (44 N Latitude). The surface geometry of the Mont Blanc ice dome suggests that ice accumulation in the western Alps was due to a greater influence of precipitation from the south. The location of the Matterhorn ice dome is consistent with a pattern of dominant southerly circulation, however, ice flow in this southern Valais region was controlled to a large degree by the high land-surface topography. A projection of the LGM ice domes mapped in the central and western Alps shows that the ice domes decrease in thickness and areal extent from southeast to northwest, also indicating that the prevalent paleocirculation which led to the build-up of the LGM Alpine ice cap was southerly.

Important questions exist with respect to the ages of the glacial erosional features. Without absolute age dating, all features are assumed to have formed during the global LGM (21,000 yr B.P.). Preliminary results from cosmogenic exposure dating of surfaces in the western Alps show that the erosional features are LGM or younger in age. More samples from the southern Valais are currently in preparation. These new data may provide critical information about the LGM deglaciation of the Alps.

IP11A-0659 0830h POSTER

Overriding or Plug-Flow: the Advance of Rock Glaciers Over Different Grounds

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The flow field close to the glacier terminus is poorly described by commonly used theories of glacier flow, such as the shallow ice approximation. It is, for example, not fully understood to what extent glaciers advance by viscous overriding without any significant basal motion, or by plug flow. This question is particularly important with regard to the depth-to-age relationship in active rock glaciers. We present a numerical model describing the advance and retreat of a gravity driven creeping viscous medium. Previous modeling work has shown the front to be capable of advancing by overriding if no basal motion is allowed. In the present study we allow for basal motion by subglacial deformation. We estimate the relative contribution of basal motion to the rate-of-advance of the terminus position using different rheological models of the subglacial material.

IP11A-0660 0830h POSTER

Tritium - Helium-3 Dating of Basal ice of the Matanuska Glacier, Alaska

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Previous studies by Strasser et al (1996) revealed post-bomb tritium concentrations within the basal ice of the Matanuska Glacier consistent with accretion of the basal ice by freeze-on of very recent meteoric waters. The englacial ice at the glacial terminus is tritium free. These observations led us to investigate the use of the tritium - helium-3 isotope pair which has been successfully used in determining rates of transport in groundwater, in the oceans, and in lakes. A three-dimensional profile of tritium and helium-3 in the basal ice showed that this method has the potential to establish high resolution ages of ice and rates of basal ice accretion. Tritiogenic 3-He was measured in this profile with apparent ages up to 17 years. We found that some helium is lost from the system by diffusion, especially at the ice-air interface although loss was much smaller 50 cm away from the interface. Absolute dating of the basal ice requires an understanding of the redistribution of helium by diffusion. Diffusion experiments to address this problem are underway.

IP11A-0661 0830h POSTER

Descriptive Statistics for Analysis of Borehole Inclinometry Data

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Borehole inclinometry data were obtained for the Worthington Glacier in Alaska in order to construct a three-dimensional deformation field of the glacier. This spatial-temporal data set contains some missing information that needs to be predicted to allow for a full description of the deformation field. As a preliminary step to building models that incorporate both the spatial and temporal components for these data, descriptive statistics are computed to gain an understanding of the structure of the data. Given the complicated nature of the multi-dimensional data set, appropriate descriptive techniques include measures such as cross-correlations of the borehole trajectories across space and time. We discuss and illustrate the use of such statistics using available data.

IP11A-0662 0830h 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 four 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. However, 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 during the years for which there are measurements.

IP11A-0663 0830h POSTER

Osmium isotopes and the Upper Devonian "Kellwasser" event

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The Upper Devonian "Kellwasser" horizon at the Frasnian/Famennian boundary (367 Ma) records one of the most severe world-wide catastrophic bio-events in Earth's history. Current theories for the causes of mass extinction include (e.g. Schindler 1990) (i) meteoritic impact, (ii) sea-level changes, shifts of the sedimentary realm and generation of anoxic milieus, (iii) enhanced clastic input and modification of sea water chemistry, and, possibly, (iv) a combination of (ii) and (iii). The time-integrated Os isotopic composition of Kellwasser limestones appears to be a suitable tool to shed light on these options and possibly place constraints on the Os isotopic evolution of Upper Devonian sea water. We present complete Re-Os analyses of limestone and shale whole rock samples, and some biogenic/diagenetic constituents (conodonts, Fe oxides).

The results indicate extreme Re and Os compositional variations between different limestone and shale sublayers (Re = 0.1 - 40 ppb, Os 26 - 830 ppt, Re/Os = 4 - 240). The present Os isotopic ratios of the rocks were found to be very radiogenic (187Os/186Os = 9,865 - 388,35). For the first time, conodont samples extracted from the Kellwasser sequence were tested as potential tracers for the Os isotopic composition of Upper Devonian sea water. Their Os contents are in the range of 210 - 112 ppt, which required analysis of about 15.000 specimens per sample to obtain sufficient Os for mass spectrometry. The Os of the conodonts (187Os/186Os = 14,35 - 67,89) is significantly less radiogenic compared to their complementary host rocks. Their 187Re/186Os, however, exceed the 187Re/186Os ratios of the host limestones by at least 1-2 orders of magnitude. Recalculation of the 187Re/186Os ratios of all rock and conodont samples for an age of 367 Ma yielded in all cases unrealistic and very contrasting values with respect to any hypothetical Os isotopic composition of Upper Devonian sea water. Our Re-Os isotopic data do establish several points at least for the studied localities: (I) The Os isotopic composition of all limestone and shale samples as well as separated biogenic/diagenetic rock components is very radiogenic. Even the conodonts reveal no obvious contribution of primitive Os supplied by extraterrestrial material, as would be expected when considering the meteoric impact theory. Thus, such an event at the Frasne/Famenne boundary appears to be highly improbable.

(II) A drastic peak reflecting elevated Re, Os concentrations during the upper gigas subzone may point to an enhanced clastic input of upper crustal material to the Kellwasser sea.

Brauns, M. (2001): A rapid, low-blank technique for the extraction of Osmium from geological samples. Chem. Geol. In press.

Schindler, E. (1990): Die Kellwasser - Krise (hohe Frasne-Stufe, Ober-Devon). Diss. Gttingen. 116 S.

Tagami, K. & Uchida, S. (2000): Separation of rhenium by an extraction chromatograpic resin for determination by inductively coupled plasma-mass-spectrometry. Anal. Chim. Acta. 405, 227-229.

IP12A MC: 121 Monday 1330h

Snow, Ice, and Permafrost II *(joint with H)*

Presiding: **G Flowers,** University of Iceland**; S Marshall,** University of Calgary

IP12A-01 1330h

Seasonal Subglacial Hydrological Evolution and Impact on Ice Dynamics in a High Arctic Glacier

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An improved understanding of the response of Arctic glaciers to climate change is required in order to provide inputs for models of global sea-level change. Currently, our knowledge of subglacial hydrological processes in polar regions, and how they impact upon patterns of ice dynamics, remains poor. However, recent research has shown that subglacial hydrology is a crucial determinant of ice dynamics and ice profiles in temperate regions - could this also be the case for polythermal ice masses?

During summer 2000, intensive field investigations were undertaken at John Evans Glacier, a polythermal valley glacier situated on eastern Ellesmere Island in the Canadian High Arctic, in order to: i) determine the subglacial drainage system structure, and whether it evolves over the course of the melt season; and ii) investigate whether variations in subglacial hydrology affected rates of glacier motion. Known quantities of fluorescent dye were periodically injected into the englacial system via moulins, and dye emergence was detected in a single stream emerging from the base of the glacier at the snout 5 km downstream. In early June, dye return curves were highly dispersed and dye velocities were low (0.14 m/s), implying that inefficient distributed drainage was taking place. By late July, little dispersion of dye was observed, and dye velocities reached 0.69 m/s. These results suggest that the subglacial drainage system evolved over the course of the melt season. Frequent survey measurements made during the season reveal that much of the surface of the lower sector of the glacier was uplifted and experienced highest horizontal velocities during late June. This period of increased motion may be a direct result of large supraglacial inputs entering a still-inefficient distributed subglacial drainage system at this time. We emphasise the importance of understanding these processes further in order to provide realistic data for future models of Arctic glacier response to climate change.

IP12A-02 1345h

Simulating the Climatic Controls on Oxygen-18 in Tropical Andean ice Cores

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Current distribution patterns of oxygen-18 concentration in meteoric waters (rain and snow) reveal a close relationship among some climatic parameters such as air temperature or amount of precipitation and the isotopic composition of precipitation. These relationships have been used to extract paleoclimatic information from records of past precipitation preserved in tropical Andean ice cores, even though very little is known about the oxygen-18 - climate relationship at low latitudes and the framework for the correct interpretation of tropical ice cores is still incomplete.

We use two high-resolution atmospheric general circulation models with improved topographic control over the Andes (ECHAM-4 and GISS II), which both include stable isotopic tracers in order to simulate the climatic conditions and the oxygen-18 composition of precipitation in the tropical Andes over the last 2 decades (1979-98). The model results will be compared with the available observational data from ice cores retrieved from Huascaran (Peru), Quelccaya (Peru), and Sajama (Bolivia). Based on several modeling experiments, we will discuss the effects of local temperature and precipitation amount, the influence of seasonality, changing moisture sources and transport paths on the stable isotope composition of tropical Andean ice cores.

IP12A-03 1400h

Numerical modelling of the Antarctic Ice Sheet

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We present a newly developed model of the Antarctic Ice Sheet that couples an existing thermomechanical model of the grounded portion of the ice sheet with a model of ice-shelf flow. Provision is also made for the high-resolution modelling of ice-stream flow. The model code has been developed to run on parallel-processor computers using a spatial decomposition method and message-passage protocols.

An extensive sensitivity analysis is presented which aims to identify the likelihood of the ice sheet suffering rapid collapse. Two principal collapse mechanisms are investigated. The first is associated with grounding line retreat. Two rival theories of grounding-line stability exist. The first considers the grounding line of ice sheets resting on inwardly sloping terrain to be inherently unstable [e.g., Thomas and Bentley 1978]. While the more recent work of Hindmarsh [1993] finds them to be neutrally stable. We examine the stability of both the full model and a simplified (without ice streams and thermodynamics). The second mechanism is related to the thermodynamics of the ice sheet and could either generate large-scale surging behaviour [e.g., MacAyeal 1992; Payne 1995] or localized ice-stream switching. We investigate under what combinations of boundary conditions each type of behaviour is most likely.

IP12A-04 1415h

Premelting, Snowballs and Climate Change: the ice Physics in Geophysics

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A basic question in the theory of surface phase transitions is "How does a crystalline solid melt?" Although we can date the scientific study of phase transitions to at least calcolithic times, today we still rely almost exclusively on empirical descriptions of melting phenomena. For practical reasons much of what we know today has been driven by studying the properties of surfaces, but in the process much has been assumed about the behavior of bulk solids. When we pursue the answer to this fundamental question in the context of ice, we find that a microscopic understanding has a plethora of geophysical implications. Recent advances show that the microscopic interfacial structure of ice is central to pattern formation during ice crystal growth, the adhesion of ice, the evolution of the polycrystalline fabrics of the glaciers, and the underlying dynamics of frost heave. Current research focuses on, in part, consequences of microphysics in the scavenging of atmospheric pollutants by snow, the role of stratospheric ice in ozone destruction, the mechanism of charge transfer driving thunderstorm electrification, the effects of frost heave on engineered structures, and natural ice sheets. This talk describes our emerging understanding of the materials physics of ice, its implications for the basic principles of melting, and several of their geophysical consequences.

IP12A-05 1430h

The Physics of Frost Heave

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Frost heave — the deformation of the ground surface caused by the growth of ice lenses in frozen soil — plays a central role in sculpting the landscape of regions subject to prolonged freezing. The economic impact of frost damage to roads, pipelines and buildings and the environmental impact associated with the influence of ice lenses on groundwater and contaminant transport have prompted extensive investigations into the physical interactions that underlie this freezing behaviour. Despite these efforts, many misconceptions regarding the causes of frost heave remain and even the most successful models rely on ad hoc parameterizations for key processes that have eluded more physically-based treatment. We examine the conservation conditions at an ice lens boundary and show how the net effect of the intermolecular forces that promote lens formation and growth can be calculated explicitly. The rate of heave is determined by the water supply through premelted liquid that separates the ice and mineral surfaces — both as a result of these same intermolecular interactions, and due to the more passive role played by the surface energy of curved interfaces. The effect of the intermolecular forces is explained in terms of the concept of "thermodynamic buoyancy". By properly accounting for the physical interactions that take place on these microscopic length scales we are able to construct predictive models for the initiation and growth of macroscopic ice lenses in consolidated porous media.

IP12A-06 1445h

Characterization of Particles Recovered From a 4 Km Ice Core Above Lake Vostok, Antarctica

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Nine samples of glacial ice from distinct glacial maxima and interglacial periods have been recovered from depths ranging from 179 to 3351 meters above Lake Vostok, Antarctica, representing a record of ~420,000 years, and three samples of ice from depths of 3540-3590 meters interpreted as having accreted from Lake Vostok, have been analyzed to determine the mineralogic and biologic constituents of these ice cores. Known quantities of ice were melted and particulate matter was collected on 0.2 micron filters for imaging and analysis using cryo-SEMBSE and EDS techniques. The mineralogy of the glacial ice generally follows continental crustal abundances, with modal quartz (19-65%)> alkali feldspar (16-42%)>plagioclase (5-25%). Combined micas (bio-musc-chlor) range from 1-43%, with the higher values recorded in interglacial intervals. Volcanic glass constitutes up to 34% of some samples. Most of the analyzed grains are sub-angular to subrounded and occur in the size range of 1-5 microns; 5-10 micron particles of angular volcanic glass and ternary feldspars occur in both glacial and interglacial intervals. In addition, one grain with a Fe-Ni composition is interpreted as a micrometeorite, and fibrous grains of a Mg-Fe silicate are interpreted as enstatite whiskers. Organic matter occurs irregularly throughout the ice column and includes fragments of diatom frustules, mats of organic debris, and rare rods and coccoids that are most likely microbial. In contrast, sediments in the accreted ice typically have grain sizes <1 micron, with modal biotite (73%)> quartz (13%)> Kspar (9%)>plagioclase (2%). Rod-shaped bacterial cells are readily observed on the filter substrate and attached to mats of organic debris (Priscu et al., 1999). There is a clear distinction in particle composition and morphology and the type of organic material found in the glacial ice compared with accreted ice. Sediments in the glacial ice contain minerals representative of typical continental crust, with little evidence of sorting by grain size or composition. Airborne modifications of the modal mineralogy of the glacial ice may occur through episodic infusions of volcanic ash or crystallites, enrichment of micas through aeolian sorting, and rare capture of meteoric particles. Enrichment of biotite in the accreted ice is interpreted as the result of differential settling in the lake waters prior to accretion. The relatively large abundances of bacteria in the accreted ice implies that Lake Vostok may support microbial life, whereas rare microbes and fragments of diatom frustules in the glacial ice may have been transported and deposited by aeolian processes.