does not change in the upper 60 cm layer), but warming is observed below 80 cm. The latter is also attributable to the increase of winter SAT and GT. There are small linear trends of GT in perennially frozen layers and these are insignificant at most of the stations where permafrost exists. Thus, there is no significant warming of perennially frozen ground over most of the permafrost zone of Russia. These results are in accordance with observed energy exchanges in permafrost regions and with the estimates of current permafrost status that have been made using other approaches. Nevertheless, this work shows that some methods used to assess tendencies in times series of meteorological data over large territories are not suitable for those of GT. First, spatial interpolation of GT linear trends to a regular grid was impossible because of the strong variability and irregularity in the distribution of these trends. Second, the use of linear trends is not justified in all cases. For a number of stations, linear trends, even if high and significant, may be false. This can arise due to a low value at the start of the time series and higher ones at the end. Hence, trend estimates made on the basis of such records are misleading. In addition, in some cases, the GT time series for the period 1960s - 1990 include both positive and negative temperature trends, that are lacking in the corresponding SAT time series. The use of linear trends is also inappropriate in these cases. This situation arises due to the effect of fluctuations in the timing, duration, and thickness of snow cover and ground water content on GT. Thus, in comparison with SAT, the analysis of GT data requires their more detailed information at each station. In turn, this will provide fuller understanding of processes occurring in the permafrost zone of Russia.

C21B-0821 0830h POSTER

Spatial and Temporal Variation of Soil Temperatures in the Kuparuk River Basin, Alaska

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A series of environmental studies have been carried out in the northern foothills of the Brooks Range and the Arctic Coastal Plain in the Kuparuk River Basin, Alaska to develop a better understanding of the physical and climatic dynamics of an arctic ecosystem. As part of these studies, soil temperature measurements were made continuously at eight locations along a transect from near the Beaufort Sea coast across the coastal plain to the Brooks Range foothills. Soil temperatures measurements were made in the active layer and permafrost to depths exceeding 10 meters. Data collection began at three of these sites in 1986 with other sites being added until 1994. These data sets are of sufficient length to begin showing long-term trends in arctic soil temperature. All locations show a trend to warming soils over the period, especially in the deeper permafrost soils. Soil temperatures at all sites indicate warming of the permafrost and an increase in the active layer thickness. Summertime soil temperatures within the active layer do not indicate warmer soils. This paper summarizes trends observed in soil temperature spanning the last 17 years in the Alaskan Arctic.

C21B-0822 0830h POSTER

Warming and Thawing of Permafrost in Alaska: Recent Results and Impacts

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There has been a widespread warming of air temperatures in Alaska since 1977 and some warming of permafrost. Constant or cooling permafrost temperatures followed this in the early 1980s, probably due to thin snow covers and a short cooling trend. Permafrost temperatures along a north south transect from Prudhoe Bay to Gulkana and at other sites have generally warmed since the late 1980s, initially in response to thicker snow covers. The warming north of the Brooks Range is comparable in magnitude to the century long warming there (2 to 4°C). The trend has not been followed at Eagle and the Yukon River bridge. Warming of the discontinuous permafrost is typically $\frac{1}{2}$ to $1\frac{1}{2}$°C. Thin discontinuous permafrost is thawing at the base at a rate of 0.04 m per year at one site. New thermokarst and thawing permafrost have been observed at several sites. Significant impacts of warming and thawing permafrost and thermokarst on the environment, ecosystems and on infrastructure will be presented.

C21B-0823 0830h POSTER

The Driving Force of Frost Boils and Hummocks Formation

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Formation of frost boils has several aspects to be explained, including the bowl shape of boils, the formation of an organic layer at the periphery of the frost boils, the elevated center of the boils, and resistance of the soil surface to vegetation colonization. Genesis of frost boils and hummocks have been widely attributed to cryoturbation-a complex of seasonally interchanging processes of frost heave and thaw settlement. Existing hypotheses, however, do not consider changes in the upper permafrost as factors of frost boil and hummock formation. Most of features listed above cannot be explained by reversible seasonal changes in the active layer. Frost boils and inter-boil areas form a well-organized and long-term functioning system closely linked to upper permafrost dynamics. Formation of this system starts with the occurrence of vegetation in inter-boil areas in shallow thermal cracks limited by the thickness of the active layer. Vegetation and its decomposition change the thermal properties of the active layer that steadily decreases with formation of aggradational ice and perennial frost heave beneath vegetated inter-boils. Due to the three-dimensional nature of the freezing front, frost heave in inter-boil areas is not perpendicular to the soil surface but is inclined in the direction of the boils, thus forming the bowl shape of boils. The organic matter formed in inter-boil areas intrudes under boils due to formation of frost cracks and thawing of ice lenses and layers at the bottom of the active layer. Penetration of organics along the active layer - permafrost boundary from an inter-boil area leads to formation of additional aggradational ice in the intermediate layer at the top of the permafrost accompanying the intruding organics. This aggradational process reinforces the bowl shape of frost-boils. Accumulation of organic matter at the lower part of the active layer leads to a decrease in active-layer thickness under the boils, which in turn leads to accumulation of aggradational ice and perennial irreversible frost heave. This increases the difference in elevation of the surface between frost boils and inter-boil areas. Vegetation colonization is then impeded by the elevation differences and formation of needle ice on the surface of the exposed mineral soil. With time, the organic layer often encircles completely the periphery of boils. The net result is carbon sequestration at the active layer-permafrost boundary. The organic matter at the bottom of the active layer is not accessible to cryoturbation. To be susceptible to seasonal frost heave, the organic matter accumulated at the bottom of the active layer has to be pushed upward in to cracks in the mineral soil, which occasionally form at the bottom of the active layer with the opening toward the bottom. Active cryoturbation of mineral and organic soil throughout the entire active layer by seasonal frost heave and thaw settlement, as is postulated in most existing explanations of frost-boil formation, have never been evident in our field observations. In the continuing evolution of frost boils, vegetation development on the boil surface and readjustment of the upper permafrost lead to the development of hummocks. The development of vegetation and accumulation of organics at the surface leads to decreasing active-layer thickness. This in turn causes increased accumulation of aggradational ice, incorporation of the previously intruded organics underneath the frost boil into the upper layer of permafrost, and increased perennial heave of the surface.

C21C MCC: Level 2 Tuesday 0830h

Planetary Permafrost II Posters *(joint with B, P)*

***Presiding:* J F Mustard,** Brown University**; M Mellon,** University of Colorado

C21C-0824 0830h POSTER

Fabric Measurements of Ice Crystallized Within the Pore Networks of Chalk and Diatomite

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The phenomenon of the crystallization of ice through porous bodies is a concern in many branches of science; e.g., porous materials; biological cells and related cell damage; and permafrost on earth and other planetary bodies. Whereas in unconsolidated sediments particle-pushing and ice lens formation occur, these are not significant processes within rock, and the ice must crystallize through a pre-existing pore network. At issue is whether the pore walls act as efficient nucleation sites or whether a coherent crystallization front of ice moves through the connected porosity. In the former case each pore can be considered independent and in the latter case the state (frozen/unfrozen) is dependent on the states of its neighbors, and the ice crystallization front advances through the porosity in a manner analogous to models of invasion percolation of fluids through pores. In the latter case, one would also predict the development of strong fabric (crystallographic texture) of ice as the ice front grows through the network. We present neutron diffraction measurements of deuterated ice Ih forming *within* the pores of bulk specimens of chalk and diatomite. Preliminary neutron "powder diffraction" measurements suggested a very highly textured nature to the ice. Subsequently, we built a Peltier cooler device to form ice within the pore networks of highly porous rocks. This device was placed in a Eulerian cradle and mounted on a neutron diffractometer. The pole figures we measured strongly suggest the advance of a coherent crystallization front throughout the connected porosity.

C21C-0825 0830h POSTER

Crater-Based Evidence of Periglacial Processes in Northwest Utopia Planitia

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Pingos are ice-cored, perennial frost mounds of which there are two main types: closed or open. Along with ice wedge polygons they are benchmarks of periglacial processes in cold-climate, non-glacial landscapes. The genesis and development of both pingo types is contingent upon three limiting factors: 1. the availability of water in liquid form; 2. an impermeable and constraining boundary layer in the ground; and, 3. surface deformation driven by hydrostatic pressure (closed pingo) or hydraulic pressure (open pingo). In the case of a closed pingo, ground temperatures also must be above the freezing point of water for pingo genesis to be initiated. Ice-wedge polygons are the product of a different set of periglacial processes: thermal contraction, the infiltration of liquid water into surficial cracks, ice wedge-development and surficial temperatures supportive of freeze-thaw cycles. The existence of a Martian periglacial landscape highlighted by pingos and ice-wedge polygons would point to: 1. liquid water having been available prior to landscape genesis; and, 2. surface temperatures having been high enough to sustain water-freezing processes and repeated freeze-thaw cycles. As of yet, active periglacial landscapes on Mars have not been identified. By contrast, the existence of artefactual periglacial landscapes comprising pingos and ice wedge polygons has been hypothesised in a number of instances. However, poorly resolved Viking imagery and hypothesised periglacial landscapes not consistent with terrestrial analogues have left some key questions unanswered. On the basis of MOC2-357 we have identified a possible periglacial landscape comprising 15 pingo-like mounds arrayed in a field of small-scale, ice-wedge like polygons. The mounds, bracketed by the polygons, sit on the floor of an isolated, medium-sized, impact crater in the northwest corner of Utopia Planitia (64.8°N / 292.7°W). If the formation of the northern plains dates back to the late Hesperian or early Amazonian period, then the age of the impact crater and of the landforms residing within it must be younger still. Using the data generated by the Mars Orbiter we conducted image enhancement and photoclinometric analyses of the crater basin. Morphometric measurements of the mounds and polygons are consistent with the dimensions of terrestrial pingos and ice-wedge polygons. Equally, the location of these mounds and of the surrounding polygons on the crater floor, possibly the floor of an ancient ice covered basin or paleo-lake, is consistent with the location of closed pingos and ice-wedge polygons on the floor of drained arctic lakes. Adjacency to a region of hydrogen abundance, possibly ice-rich sediments or ground ice, has been mapped. On Mars as on Earth these sediments

could be geocryological artefacts of surficial liquid water that percolated down through the regolith and froze in situ. The availability of liquid water is a requirement of pingo and ice-wedge genesis. Equally, the presence of ice-rich sediments would meet the ground impermeability requirement of pingo genesis. No less suggestive of periglacial processes are the hundreds of small pits and depressions that are ubiquitous in Utopia Planitia. The morphology of these pits and depressions is reminiscent of terrestrial thermokarst and differential frost heave. We argue that the disparate but interconnected strands of surficial and sub-surficial geomorphological data sustain the hypothesised presence of a crater-based and water-fed periglacial landscape in northwest Utopia Planitia.

C21C-0826 0830h POSTER

Potential Ground Ice and Small-Scale Polygons on Mars

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Martian geomorphology reveals many Martian landforms suggesting the presence of ground ice-rich sediment. Fractured polygonal networks, which are similar in size and shape to polygons commonly found in Earth's permafrost and desiccated lake and stream beds, are observed in numerous localities at middle and high latitudes on Mars, but are rare at low latitudes. If polygons on Mars form similarly to those on Earth, they would provide information about the distribution and history of the Martian hydrosphere and especially the cryosphere. Although these and other features have been compared morphologically to those on Earth, there has previously been no way to independently determine whether the process which formed the polygons on Mars also involves ground ice or water. The Mars Odyssey mission, specifically the Gamma Ray Spectrometer (GRS), has provided unprecedented maps of subsurface hydrogen on Mars. Presented is the global polygon distribution in context with recent measurements of near-surface hydrogen abundance. Of roughly 34,000 narrow angle MOC images investigated, 730 sites containing polygons were identified. A cluster in Utopia Planitia (centered at 45°N, 90°E) accounts for about 15% of total sites. Excluding the polygons in Utopia Planitia, 99% of sites correspond with hydrogen levels measured by epithermal neutron flux that are equivalent to or >35% water ice by weight. MOC images from Utopia Planitia show the presence of beaded-drainage within polygonal permafrost-like features, and gravity- driven slumps indicating flowing liquids in Amazonian time.

C21C-0827 0830h POSTER

The Association of Liquid Water Springs With Permafrost Regions on Earth and Mars

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Recent space missions have confirmed the presence of ice-rich ground in the middle and high latitudes of Mars. Geologically recent gully features on Mars show a geographic distribution that is correlated with theoretical models of ground ice stability which is suggestive of a genetic relationship between ground ice and gully activity. Possible mechanisms of gully formation are thus examined. A liquid water aquifer on Mars activated by freezing cycles is the favored model of gully formation based on an analysis of Mars Global Surveyor spacecraft data. Additionally, liquid water spring activity occurs in regions of continuous permafrost on Earth. Spring systems in the Canadian High Arctic (Axel Heiberg Island) as well as the Norwegian Arctic (Spitsbergen) demonstrate different morphologies and mechanisms of formation for spring systems in polar desert environments. On both Earth and Mars, liquid water springs in permafrost regions provide a unique setting for the possible preservation of biological signatures.

C21C-0828 0830h POSTER

Understanding the Vertical Distribution and Exchange of H_2O in the Subsurface of Mars.

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Prompted by the recent discoveries of Mars Odyssey, we aim to better understand the exchange of water vapor between the atmosphere and the subsurface and the vertical distribution of water ice and adsorbate. We model vapor transport, adsorption, and sublimation of water ice in the regolith over diurnal, seasonal, and millennial time scales. We find that in long-term equilibrium the transition to the subsurface ice table is sudden, and, as expected, the depth to the ice table can be determined from the frost point at the surface. Accumulating subsurface ice reduces the vapor transport deep into the regolith, but, eventually, ice can amass through sublimation to great depths. Physical adsorption of water onto the regolith may deplete the water vapor substantially and can lead to considerable diurnal breathing, but it has little influence on the frost point. These are examples of dynamical effects not described by standard equilibrium models.

C21C-0829 0830h POSTER

Pingos in Solar System

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Periglacial geomorphology is one of the best ways to map permafrost distribution and to understand the sub-surface hydrologic conditions there. Polygons and thermokarst landscapes are indicative of permafrost terrain, but they may persist as relict features in ground that is now permafrost-free. However, pingos only exist in ground that is currently permafrost, since they are ice-cored, and thus are the most important indicators of active permafrost environments. Pingos are widely distributed in the terrestrial northern hemisphere of Earth. Because most of the outer solar system is in a cryophilic condition, I examined potential pingo growth environments on Mars, Io, and Titan as terrestrial analogues. At least two types of pingos are potentially in existence on other planetary bodies in our solar system: hydraulic and hydrostatic systems. Hydrostatic system pingos are most likely to be developed during climatic change, such as a cooling period in the Martian surface. Hydraulic system pingos are most likely in Martin brinish groundwater systems or Titan's methane or ammonia groundwater systems. I have examined these environments for pingos and will present characteristics of terrestrial pingos and a model of how pingos may develop in the rest of our solar system.

C21C-0830 0830h POSTER

Modeling the Deformation of Lobate Debris Aprons on Mars by Creep of Ice-rich Permafrost

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Martian softened terrain and debris aprons have often been attributed to deformation of ground-ice within kilometer-thick layers of permafrost. We are using MGS MOC and MOLA data to document the structural and topographic characteristics of softened landforms and debris aprons in the Hellas and Noachis regions and comparing the observed landforms to the results of finite-element simulations of viscous creep to constrain the conditions necessary to allow such deformation on Mars. We have characterized debris aprons in a region east of the Hellas impact basin: 30° - 50° S, 240° - 280° W. No debris aprons are found around mountains at low elevation or west of 265° W, i.e., within Hellas. We are evaluating the characteristics of mountains with and without debris aprons outside of Hellas to look for other factors that may control ground ice distribution. The only attributes that show weak correlations to the existence of debris aprons were latitude (debris aprons are more abundant to the south of our study region) and slope. We have applied finite-element analysis to investigate the deformation of debris aprons by creep of an ice-rich surface layer. Our simulations demonstrate that the final morphology is very dependent on the initial distribution of the ice-rich material and on the conditions applied at the base of the ice-rich debris. Furthermore, even under present Martian conditions, viscous creep can occur quite rapidly; on timescales of 1-10 thousand years. We are investigating the extent to which blocks of intact rock distributed within the ice-rich regolith could serve to increase the deformation timescales.

C21C-0831 0830h POSTER

Searching for Ground Ice at the Martian Equator

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The Mars Global Surveyor and Mars Odyssey results suggest that the present distribution of High-Latitude ground ice on Mars is spatially continuous from the poles to 60N and 60S. However, Mars Odyssey results show large regions at mid and equatorial latitudes with 5 to 10% equivalent water content. We are exploring the hypothesis that the mid and low latitude water observed by Odyssey is due to the presence of discontinuous, thermally stable, near-surface ground ice in localized cold niches formed by topographic relief. We use the Mars Global Surveyor Thermal Emission Spectrometer and Mars Orbiter Laser Altimeter data to map the global distribution of cold niches at high spatial resolution and compare the results with low spatial resolution maps of the global distribution of near-surface water derived from the Mars Odyssey Neutron Spectrometers.

C21D MCC: 3010 Tuesday 1020h

Glaciers and Ice Sheets II *(joint with G, H, OS, PP)*

Presiding: **J Weertman,** Northwestern University**; W Pfeffer,** Institute of Arctic and Alpine Research, University of Colorado

C21D-01 1020h INVITED

US International Trans Antarctic Scientific Expedition Overview

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Antarctica plays a pivotal role in Earth's complex climate system. It is: encircled by the world's most biologically productive oceans, the largest reservoir of fresh water on the planet, a major site for the production of the cold deep water that drives global ocean circulation, a significant influence (through albedo effects) on Earth's energy budget, and a crucial driving component for Southern Hemisphere atmospheric circulation. Yet despite its importance, instrumented records of climate change over this vast continent are extremely sparse spatially and temporally. Fortunately, through the recovery of ice cores in combination with glacier geophysics, surface glaciology, and atmospheric chemistry programs, Antarctica has the potential to be the best understood region on Earth climatically. On 2 January 2003 the United States component of the International Trans Antarctic Scientific Expedition (US ITASE) arrived at South Pole having completed, over the period 1999-2003, >5000 km of over snow traverses that included much of West Antarctica and a portion of East Antarctica. During the traverses US ITASE focused on the collection of data that will allow the reconstruction of sub-annual scale climate variability and change in the chemistry of the atmosphere for the last 200+ years. In the process US ITASE collected an integrated, multi-disciplinary assemblage of data extending from the bed of the ice sheet (>3000 m) to >20 km in the atmosphere. Results from US ITASE offer new insights into the understanding of Southern Hemisphere climate variability (eg., temperature, accumulation rate, atmospheric circulation, atmospheric chemistry, climate forcing), with particular emphasis on the