Chapter 4

FINDINGS AND AGENCY RECOMMENDATIONS

Members of the U.S. Arctic Research Commission Permafrost Task Force met in Salt Lake City, Anchorage, San Francisco, and Seattle between November 2001 and December 2003. Discussions were also held with scientists, private industry, the U.S. Permafrost Association, senior managers of federal agencies, and State of Alaska departmental personnel. An integration of these meetings and discussions with the background provided by Chapters 1 through 3 of this report resulted in the following findings and recommendations. The entire report with recommendations has been reviewed by the Commissioners and five independent, outside reviewers.

4.1 U.S. Federal Permafrost Research Programs

4.1.1 Permafrost: Equal Attention

Despite publication of several reports specifying needs and strategies (Committee on Permafrost, 1974, 1975, 1976, 1983; Brown and Hemming, 1980), permafrost research, both basic and applied, has received less attention within U.S. government research programs than it warrants. This situation may in part result from a perception that permafrost is very slow to respond to climate change. On the contrary, permafrost has significant roles in climate change: as a record keeper of past temperatures, as a translator of climate change through the effects of its degradation on ecosystems and human infrastructure, and as a facilitator through its potential for release of sequestered carbon. The importance of permafrost in the global system, combined with our incomplete understanding of the role and behavior of frozen ground and associated processes, dictates that permafrost research should have equal weight with other components of the cryosphere in climate-change research. *The Task Force believes it is critical that programs such as SEARCH, ACIA, PACE, ACD, Arctic-CHAMP, Land–Shelf Interactions, the Fourth International Polar Year, and others have permafrost research as one of the critical elements of their science plans.* ***The Task Force recommends*** *that all responsible funding agencies review their interdisciplinary Arctic programs to ensure that permafrost research is appropriately integrated in program planning and execution.*

4.1.2 Lack of a Visible U.S. Federal Research Program

The Task Force found no focused federal research program dedicated to permafrost. The National Science Foundation funds investigators in a wide range of disciplines and, under the Office of Polar Programs (mostly through its Arctic System Science Program), makes awards in permafrost science. The two components of GTN-P are examples of highly successful research programs that have received recent support from NSF. Another good example is the development of a Permafrost Observatory at Barrow by the International Arctic Research Center, University of Alaska Fairbanks. In past decades, particularly during the Cold War and the construction of the DEW Line and the Trans-Alaska Pipeline, CRREL and USGS had viable and robust long-term research programs on permafrost science and engineering. These once highly visible federal programs no longer exist. ***The Task Force recommends*** *that the USGS, because of its key responsibilities in Alaska, should develop a long-term permafrost research program with emphasis on field programs. Recognizing DOD's responsibilities in the areas of contaminants on formerly used defense sites and future military construction in Alaska,* ***the Task Force recommends*** *enhanced funding for permafrost research and continued development of permafrost expertise at CRREL.*

4.2 Data Collection, Protocols, Monitoring, and Mapping

4.2.1 Standardized Collection of Basic Environmental Parameters

Standardized collection of basic environmental parameters is essential to all scientific and engineering endeavors in cold regions. Effectively designed and implemented monitoring programs and sampling strategies provide data that form the foundation upon which all efforts ultimately depend. Moreover, the data derived from such programs are invaluable for modeling efforts (e.g., general circulation models). ***The Task Force recommends*** *that the WMO GHOST (Global Hierarchical Observing Strategy) hierarchical monitoring scheme discussed in Chapter 2 be implemented in its current or a modified format in permafrost monitoring programs.* Effort should be made to support the instrumentation deemed necessary to collect basic data, in addition to the information collected for process-based field studies. At the lowest level of instrumentation, air, near-surface, and upper-permafrost temperature measurements should be collected at subdiurnal frequencies. Complete meteorological instrumentation at the higher end of the spectrum should include measurements of wind speed and direction, insolation, surface albedo, soil moisture, and snow cover thickness, and it should include a dense vertical array of thermistors extending from the soil surface, through the active layer, and deep into the underlying permafrost. The basic aspects of data collection at these sites should be standardized (e.g., all air temperature measurements should be made at the same height above the ground surface using a standard radiation shield). Such sites should be linked via satellite to provide real-time data to users. Further, a concerted effort should be made to assess the degree to which instrumented sites are representative of the landscape. At this scale, timely acquisition of current and historical remotely sensed imagery is essential. In this way, a standardized set of basic environmental measurements, representative of a larger region, can be collected and incorporated into a spatially extensive data set that can serve the needs of the national and international cold-regions science and engineering communities.

4.2.2 Measurement Protocols for Permafrost Monitoring

A specific set of measurement protocols should be developed for monitoring permafrost and closely related phenomena. The protocols should be established by the scientific and engineering communities for the purpose of obtaining appropriate measurements at appropriate spatial and temporal frequencies and resolution. These protocols should cover the scale of instrumentation, ranging from site to satellite. Inherent in these protocols are the requisite accuracy and precision of thermistors, optimal depth of soil measurements, and requisite ancillary data. This effort should be coordinated and integrated with the GTN-P to ensure collection of data useful for global climate observation (Burgess et al., 2000; GTN-P web site). Similarly, methods of monitoring active-layer thickness and thaw subsidence should be integrated with those of ongoing international projects (e.g., CALM, PACE) following discussion and any appropriate modification of those protocols currently in place. In all cases, effort should be made to assess the spatial variability of thaw depth and soil temperature and to collect ancillary data.

4.2.3 Permafrost Data Management

Data collected by federally funded permafrost projects should be archived in the Frozen Ground Data Center at NSIDC within appropriate time periods. Details about data-collection sites and meteorological and ground measurements should be available in metadata files with standardized formats. Some data would be processed in accordance with identified and established user needs (e.g., modelers and engineers may make better use of average daily temperatures or accumulated degree-days of freezing, thawing, heating, and cooling rather than hourly air temperatures). Spatially intensive measurements, such as satellite imagery or thaw depths collected on a regular grid, should be available in a format conducive to generation of descriptive statistics and rapid mapping. Ultimately, these data will become part of an international cold regions environmental data directory with links to other databases.

4.2.4 NSIDC Frozen Ground Data Center

A recent initiative at the National Snow and Ice Data Center (NSIDC) in Boulder has been to archive permafrost and seasonally frozen ground data (for example, borehole data, Arctic Coastal Dynamics program data, and maps and soils data from Russia and China). These activities are partially funded by the International Arctic Research Center at the University of Alaska Fairbanks. The data activities are an outgrowth of the International Permafrost Association's data rescue program, the Global Geocryological Database. Long-term funding for the Frozen Ground Data Center is required. *Recognizing that NSIDC is funded primarily by NOAA,* ***the Task Force strongly recommends*** *that additional funding be provided by both NOAA and USGS to fully develop and sustain the Frozen Ground Data Center (an estimated $300,000 annually is required for adequate support).*

4.2.5 Baseline Permafrost Mapping

The Task Force recommends *that U.S. and international funding be sought to update the International Permafrost Association's* Circum-Arctic Map of Permafrost and Ground Ice Conditions *(Brown et al., 1997), using the most recent international databases and maps. In addition,* ***the Task Force recommends*** *the funding and production of a high-resolution permafrost map for Alaska, a critical requirement for the state's future with regard to climate change. Federal and state agencies and, potentially, the private sector should jointly fund this effort (USGS; Army Corps of Engineers, Alaska District; Alaska State agencies; and industry)*. The evolving Arctic Coastal Dynamics (ACD) program, a joint effort of the IASC and IPA, could also be a vehicle for facilitating data collection and mapping of coastal erosion and flooding regimes. A continuing research theme should be the integration of existing permafrost maps with elements of Arctic infrastructure, using GCMs and GIS. These products should include new information on the distribution and properties of offshore and alpine permafrost.

4.2.6 Measurement Technologies and Remote Sensing

Typical measurements for the different hierarchies of permafrost sites are provided in Section 2.3. Measurements range from probing the active layer once annually to observing soil temperature approximately hourly; annual to semi-annual permafrost temperatures have also been taken at 100-m depths. A fully instrumented single site for examining temporal variability would include measurements of soil temperature, soil moisture, active-layer thickness, thaw settlement, and near-surface permafrost temperatures. Air temperature, wind speed, precipitation, and snow depth are also high-priority measurements. With the exception of soil moisture, off-the-shelf instrumentation can make these measurements automatically and relatively inexpensively. Presently, data are typically recorded on a datalogger downloaded during an annual visit to the site. Retrieval of data by satellite uplink would mitigate the need for large data storage capacity on-site and would allow sites to be monitored in near-real time. A critical instrumentation issue that needs to be addressed is the development of advanced technology for monitoring soil moisture. ***The Task Force recommends*** *support for the development of instrumentation for sensors in cold-regions terrain by NSF's Office of Polar Programs and Directorate of Engineering and by NASA.*

Satellite remote sensing offers the greatest opportunity for large-scale monitoring of the state of ground. The capability of current sensors for permafrost monitoring needs to be fully evaluated and exploited, as the study of permafrost by satellites has been a low-priority issue in the remote sensing community. ***The Task Force recommends*** *that NASA continue development of new satellite sensors optimized for monitoring state of the surface, temperature, moisture, and ground ice in cold regions.* A greater capability to detect ground ice would have additional planetary applications. All remote sensing techniques will require thorough field validation. Until reliable permafrost sensors become available, methods that combine remotely sensed data with ground-based measurements and soil thermal modeling should be developed and tested. Further, much can be inferred about permafrost from combining digital elevation measurements (DEMs) with other remotely sensed parameters such as those concerning snow cover and vegetation. However, the DEMs currently available for much of Alaska are extremely coarse and sometimes inaccurate, limiting their utility. ***The Task Force recommends*** *support for advanced studies involving synthesis of remotely sensed data with other data sets, including model output.*

4.2.7 Monitoring and Analysis Requirement

The Task Force recommends *a new approach (via federal legislation) for funding the monitoring of cold-regions environments in which federal projects are planned. Federal agencies that fund all or portions of major public works (in excess of $1M in cost) in Alaska should specify that 1% of the project planning, design, and construction costs for future Alaskan projects be invested in monitoring in the vicinity of the construction site*. In this way climate change can be more adequately monitored and observations analyzed and mapped into the future.

4.3 Basic Permafrost Research

4.3.1 Process Studies in Permafrost Research

Transfer functions: air–surface–permafrost, snow, vegetation. Quantitative estimation of the air–surface–permafrost transfer function remains a significant problem, because of non-linearity in the near-surface layer (air, snow, vegetation) and because of numerous feedback effects. Continued basic research on these processes is critical if a complete understanding of arctic energy flows is to be achieved.

Carbon cycle considerations. Greenhouse gases (carbon dioxide and methane) released from thawing permafrost into the atmosphere could create a strong positive feedback in the arctic system, and this topic is under investigation at several sites. Counterbalancing this prediction, there may be increased arctic ecosystem plant productivity, which could enhance the carbon sink (Kolchugina and Vinson, 1993). The carbon cycle in the nearshore zone of the Arctic Ocean has received less attention and requires significant investigation. Key questions remain: What is the major mechanism regulating the distribution and associated rates of carbon transfer, transformation, and burial in the arctic land–shelf system? How do biogeochemical processes on the Arctic Ocean margins influence the chemistry and biology of surface waters and associated fluxes of CO_2 between the air–water (or air–ice) interface? Answers to such questions require much more research on the state of offshore and onshore permafrost in the atmosphere–land–shelf system in the Arctic.

Hydrology and hydrogeology. Although Arctic hydrology has received serious attention in many science planning documents, little attention has been devoted to subsurface hydrologic and hydrogeologic processes. This is a critical omission because subsurface flow and subsurface storage are extremely important in the arctic hydrological system and in the arctic water cycle as a whole. Studies of permafrost hydrogeology are practically nonexistent in the U.S., a serious gap in research for the high Arctic and Subarctic. ***The Task Force recommends*** *that NSF's new arctic programs, Arctic-CHAMP and Land–Shelf Interactions, fully incorporate permafrost hydrology and hydrogeology in their science plans.*

Permafrost degradation. Stratigraphic and paleogeographic evidence indicates that permafrost will degrade if recent climate warming continues. Degradation of ice-rich permafrost has been documented under contemporary conditions in central Alaska and elsewhere (Osterkamp and Romanovsky, 1999; Osterkamp et al., 2000; Jorgenson et al., 2001). Little is known, however, about specific processes associated with the thawing of permafrost, either as a function of time or as a three-dimensional process affecting the geometry of permafrost distribution over a wide spectrum of geographic scale. There is urgent need to conduct theoretical and numerical studies and additional field investigations to address these critical issues; stratigraphic and paleoclimatic studies incorporating stable isotope dating should be included, as has been done in the field of glaciology.

Geomorphic investigations. The study of landforms and geomorphic processes is a critical component of permafrost science but has received little attention in Alaska in recent decades. Process-based and modeling investigations focused on the evolution of slopes and other geomorphic features are urgently needed. Particular attention should be given to how processes interact over a spectrum of geographic scale. Studies focused on landscape evolution over extended periods are also critical and can contribute to existing programs (e.g., SEARCH, Arctic-CHAMP) concerned with hydrological and sediment budgets over extensive areas. Geomorphological studies should, where possible, employ a systems approach that combines expertise from closely related disciplines.

4.3.2 Permafrost Modeling

Modeling is a powerful tool in permafrost research. Although significant progress has been achieved during the last three decades, the importance of permafrost in a global context has been underestimated. Until recently, GCMs did not incorporate permafrost and permafrost-related processes. The modeling community has begun to understand that unless permafrost and permafrost-related processes are incorporated, there is little reason to expect that GCMs will produce physically reasonable results for the Arctic (Slater et. al., 1998a, b). Inclusion of permafrost in GCMs is a major challenge to both modelers and permafrost researchers, and continued cooperative research between the two communities is a necessity. Funding of modeling efforts for arctic and subarctic regions must require that permafrost be incorporated in the research plans.

Another important issue related to GCMs is how well they can predict the extent, duration, and thickness of snow. Permafrost degradation under a changing climate scenario is strongly influenced by the regional snow cover. To date, GCMs do not provide an adequate predictive capability for snow.

Analytical models. Many methods have been proposed to calculate active-layer thickness and mean annual permafrost surface temperatures using simplified analytical solutions (Pavlov, 1980; Zarling, 1987; Romanovsky and Osterkamp, 1995; Smith and Riseborough, 1996). For work involving point locations where subsurface data are available, the importance and utility of analytical solutions is diminished. Numerical models are widely available for permafrost problems and can be used with some confidence when adequate information about climatic, boundary layer, and subsurface parameters is available. Serious problems arise, however, when complex models are employed in a spatial context, particularly when little is known about the spatial variability of parameters important to geocryological investigations. In such cases, stochastic modeling (Anisimov et al., 2002) or analytic procedures in a GIS environment (Nelson et al., 1997; Shiklomamov and Nelson, 1999; Klene et al., 2002) often yield results superior to complex, physically based models. Analytical equations can also be helpful in providing insights into the physics of the coupling between permafrost and the atmosphere. However, these simple equations are presently limited in their usefulness because they do not include the effects of inhomogeneous active layers with multiple layers, variable thermal properties, unfrozen water dynamics, and non-conductive heat flow. Deterministic models must be transformed to probabilistic models if the risk of permafrost degradation is to be assessed under a changing climate scenario (Bae and Vinson, 2001; Vinson and Bae, 2002). More research on refining analytical models (both deterministic and probabilistic) for use in permafrost environments is a necessity.

4.4 Applied Permafrost Research

4.4.1 Synthesis for Cold-Regions Engineering Applications

Scientific research programs are not necessarily tailored to the needs of engineering practice and design criteria development. Predictions of frost effects and the behavior of frozen ground are highly empirical and are based on limited numbers of field and laboratory investigations. Far-reaching assumptions are necessary to arrive at any decisions regarding changes to the natural pattern of warming or cooling of foundations for buildings, roads, railways, or airstrips in a permafrost environment. Engineers tend to rely a great deal on the proven performance of past construction as essential validations of analytical predictions.

In a period of accelerating global warming, the recent past provides only partial guidance for predicting future permafrost conditions. Extrapolation of the recent air temperatures can be misleading. ***The Task Force believes*** *decisions regarding new infrastructure on permafrost will be more credible if they consider climate change, as predicted by global circulation models, weighed by associated probabilities.*

A history of seasonal temperature is represented through freezing and thawing indices, the annual sums of daily average temperatures below or above freezing, respectively. Freezing and thawing indices are translated to corresponding ground surface freezing and thawing indices for general categories of ground surface types, e.g., snow, turf, sand, and gravel. The transfer of atmospheric heat energy into lower layers of the soil is proportional to the soil thermal conductivity, which varies with soil grain size, dry density, water content, and water state (frozen or unfrozen). More precise computations of heat transfer are possible but impractical in all but carefully controlled research settings. Alaskan records of air temperature are sparse, and maps of soil characteristics are poorly resolved. ***The Task Force recommends*** *that a denser network of environmental monitoring stations be funded by NOAA, USGS, USDA, and responsible state agencies for Alaska.* Such a network of monitoring stations, along with the application of GIS mapping methods, will allow improved procedures to be developed for predicting permafrost behavior that can better account for natural variability and probabilistic considerations.

4.4.2 Cold-Regions Design Criteria Development

There is a significant requirement for a cold-regions engineering database to enhance the design, construction, and maintenance of infrastructure. Existing environmental atlases of Alaska are nearly twenty years old. A new database should take advantage of GIS technology and include geotechnical information, such as permafrost distribution, soil type, and soil properties, as well as climatic information including air temperature and snow depth. The system should allow standard calculations for practical engineering applications, such as freezing and thawing indices, active-layer thickness, and soil bearing capacity. There is also a need to establish a database or information clearinghouse on existing cold-regions transportation infrastructure (design, construction, and operations). Methods for site-specific forecasts of climate change must be developed. A rational approach to developing design criteria using GCM results will perhaps be more affordable than applying an arbitrarily large factor of safety to conventional design criteria. We cannot continue to treat forecasts of future climate deterministically (i.e. linearly extrapolating a rate of temperature change over a future time interval at a given location) and must move to a more probabilistic approach. Adaptating conventional statistical analyses of trends and extremes to apply GCM-predicted accelerated change is a challenging topic for researchers.

4.4.2 Trans-Alaska Pipeline System (TAPS)

In its *2001 Comprehensive Monitoring Report* (a series of three reports dealing with

TAPS operations, construction, and operation), the Joint Pipeline Office (JPO) of the U.S. and the State of Alaska indicated a range of problems regarding changing permafrost. The following conclusions were reached:

- The warming trends could have some effect on the foundations of the elevated portions of the pipeline, some 423 miles with 78,000 vertical support members (VSMs).
- More than 25,000 VSMs are currently subject to movement. Of those VSMs having heat pipes (because they are located in areas of warm permafrost), 84% have some degree of blockage that could affect the structure's load-bearing capacity.
- A long-term maintenance and reconstruction program is necessary for the VSMs.

The pipeline owners and their operating consortium, Alyeska, have contracts underway to determine the scope of the operating and maintenance program that will be necessary over the next 30 years, the period requested for a right-of-way renewal. The current lease expires in 2004 for both the federal and state rights of way.

When the present lease was issued, scientific and engineering decisions were based on the permafrost and climate regimes of the previous three decades. Permafrost engineering applications were limited until World War II and reached their peak during the construction of the DEW Line from 1948 to 1962. The expertise of CRREL and the USGS was made available to the TAPS design team, which spent four years working out the present design of the VSMs. ***The Task Force recommends*** *that a similar effort be made today that closely coordinates the efforts of the TAPS and JPO with a significantly upgraded federal research effort on permafrost.* Linkages with the Arctic Climate Impact Assessment (with its secretariat at the University of Alaska Fairbanks) should be established early in this effort.

4.4.3 Contaminants in Permafrost Environments

Past practice favored burial of contaminants in permafrost because it was assumed to be impermeable and therefore a safe and effective method for isolating contaminated wastes. Contaminants are mobile in the active layer, however, and some can even be mobile within frozen ground. Moreover, when permafrost thaws, the ground becomes permeable, allowing contaminants to spread laterally and to reach deeper unfrozen and frozen layers. The Arctic contains a significant number of contaminated sites; in Alaska DOD has responsibility for formerly used defense sites, some of which are contaminated. To determine the extent of the problem, sites known to be contaminated must be assessed individually, identifying the contaminants as well as the physical characteristics of the site. The potential for diffusion of contaminants will require an estimate of the impact of regional climate warming on the specific sites. To develop models to predict the transport of contaminants, the hydrological connections between the near-surface and deeper layers or ground water systems must be established. Research is also required on the chemical interaction of contaminants with the thawed soils, as well as on such mitigation techniques as bioremediation. CRREL is the logical federal laboratory for this research, and the University of Alaska (Fairbanks and Anchorage campuses) has experienced research groups in this field. ***The Task Force recommends*** *substantially increased federal funding for contaminants research in cold regions by DOD, EPA, and NSF, as this research is deemed critical to the Nation's cleanup effort in Alaska.*

Federal Agency, State of Alaska, and National Research Council Recommendations

U.S. Geological Survey (Department of the Interior)

- Develop a long-term permafrost research program with emphasis on field work and monitoring of deep boreholes; formulate the program as a contribution to SEARCH.
- Adopt the WMO GHOST hierarchical monitoring program for environmental data collection for new boreholes and mapping.
- Jointly fund with NOAA the Frozen Ground Data Center at NSIDC.
- Participate in joint funding of a high-resolution permafrost map of Alaska.
- Fund (with NOAA, USDA, and state agencies) a denser network of environmental monitoring stations for Alaska.
- Provide technical expertise (on permafrost and other cold-regions issues) to the TAPS JPO during the right-of-way renewal process.
- Develop jointly with the Minerals Management Service a study of offshore undersea permafrost.
- Expand stratigraphic investigations and mapping of Quaternary permafrost in Alaska and the contiguous states.
- Expand investigations of periglacial landforms and processes (both contemporary and relict) in Alaska and the contiguous states.

U.S. Army Corps of Engineers (Department of Defense)

- Provide enhanced funding for permafrost research and support the continued development of permafrost expertise at CRREL.
- Participate in joint funding of a high-resolution permafrost map of Alaska.
- Increase funding for research on contaminants in cold regions at CRREL.
- Plan for climate change and permafrost degradation at existing and new military facilities to be built in Alaska.
- Rescue past agency data and contribute present and future data to national archives.
- Expand the role of the National Permafrost Test Site [a node in the National Geotechnical Experimentation Sites (NGES) network] on Farmer's Loop Road outside Fairbanks.

National Science Foundation

- Review all interdisciplinary arctic programs to ensure that permafrost research is appropriately integrated in program planning and execution.
- Within the Office of Polar Programs, restructure the Glaciology program under the heading Cryosphere, which would include snow, ice, and permafrost.
- Adopt hierarchical, spatially oriented monitoring strategies (preferably variants of the WMO/GHOST approach) as appropriate for all arctic research programs.
- Fund proposals for the development of instrumentation for sensors in cold regions (e.g., an autonomous soil moisture sensor) (Office of Polar Programs and Directorate of Engineering).
- Incorporate permafrost hydrology, hydrogeology, and geomorphology in arctic programs such as Arctic-CHAMP and SEARCH; incorporate permafrost research in global carbon programs.
- Increase support for research on permafrost-related geomorphic processes and terrain/landform analysis.
- Increase support for geocryological hazards research at local, regional, and circumpolar scales.
- Increase funding for proposals dealing with research on contaminants in cold regions.
- Support international permafrost activities, including conferences and workshops.
- Integrate the use of the Permafrost National Test Site at Fairbanks into U.S. Arctic research logistics planning.
- Include permafrost research at the Barrow Global Climate Change Research Facility.

National Aeronautics and Space Administration

- Continue the development of satellite sensors optimized for monitoring the state of the surface, temperature, moisture, and ground ice in cold regions.
- Explicitly include geocryological applications in competitive grants programs concerned with the use of satellite remote sensing data.
- Include the development of frozen ground sensors in NASA contributions to SEARCH.
- Support the Barrow Global Climate Change Research Facility as a satellite sensor validation site; use the facility to ground-truth satellite frozen ground sensors.

National Oceanic and Atmospheric Administration
(Department of Commerce)

- Jointly fund with USGS the Frozen Ground Data Center at NSIDC.
- Jointly fund with USGS, USDA, and the State of Alaska a denser network of environmental monitoring stations around Alaska.
- Adopt the WMO GHOST hierarchical monitoring program for environmental data collection.

Environmental Protection Agency

- Increase funding for research on contaminants in cold regions, and fully develop a program in Alaska.
- Make funding available for permafrost-related hazards research, particularly in urban areas.

U.S. Forest Service
(Department of Agriculture)

- Increase the number of soil moisture and temperature monitoring stations in Alaska.
- Formalize and extend existing programs in soil physics and carbon sequestration.

U.S. Natural Resources Conservation Service
(Department of Agriculture)

- Refine and extend activities devoted to characterizing, classifying, and mapping cryosols in Alaska and the contiguous states.
- Formalize and extend existing programs related to carbon sequestration in tundra regions of Alaska and the contiguous states.
- Formalize and extend existing programs investigating soil physics and ground temperature in Alaska, the western cordillera of the contiguous states, and the northern Appalachians.

State of Alaska

- Review the arctic engineering certification process for knowledge of permafrost under changing climate conditions.
- Seek federal support for test programs for non-standard pavements for roads and airport runways.
- Review building codes with a view to near-term changes in the permafrost regime.
- Intensify and extend geological and geophysical investigations of permafrost and its role in Quaternary history by the Division of Geological and Geophysical Surveys (DGGS).
- Survey community infrastructure located in permafrost environments, with specific emphasis on rural sewage and ground water systems.

National Research Council
(National Academies of Science and Engineering)

- Have the Transportation Research Board (TRB), in cooperation with the Polar Research Board (PRB), develop a proposal for a study on the impacts of changing permafrost on transportation systems in Alaska.
- Have the Polar Research Board (PRB) include global permafrost monitoring and research in the U.S.-supported programs for the International Polar Year, 2007–2008.

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Glossary

Most of the definitions given below were taken from the *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms* (van Everdingen, 1998). This source should be consulted for more extensive definitions. Updates, modifications, or new definitions are indicated by inclusion of additional references.

Active layer
The layer of ground subject to annual thawing and freezing in areas underlain by permafrost.

Active-layer detachment slide
Shallow landslides that develop in permafrost areas, involving reduction in effective stress and strength at the contact between a thawing overburden and underlying frozen material. Active-layer detachment slides can occur in response to high seasonal air temperature, summer rainfall events, rapid melting of snowcover, or surface disturbances. See Lewkowicz (1992).

Active-layer thickness
The thickness of the layer of ground subject to annual thawing and freezing in areas underlain by permafrost (Also see **thaw depth**). See Nelson and Hinkel (2003).

Alas
A large depression of the ground surface produced by thawing of a large area (e.g., > 1 ha) of very thick and exceedingly ice-rich permafrost.

Cryoturbation
(a)A collective term used to describe all soil movements due to frost action.
(b)Irregular structures formed in earth materials by frost penetration and frost action processes, and characterized by folded, broken, and dislocated beds and lenses of unconsolidated deposits, included organic horizons, or bedrock.

Degree-day
A derived unit of measurement used to express the departure of the mean temperature for a day from a given reference temperature. Also see **freezing index** and **thawing index**.

Depth of zero annual amplitude
The distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature.

Excess ice
The volume of ice in the ground that exceeds the total pore volume that the ground would have under natural unfrozen conditions.

Freeze–thaw cycle
Freezing of material, followed by thawing. The two fundamental frequencies involved are *diurnal* and *annual.*

Freezing index
The cumulative number of degree-days below 0^{o}C for a given time period (usually seasonal).

Frost action
The process of alternate freezing and thawing of moisture in soil, rock, and other materials, and the resulting effects on materials and on structures placed on or in the ground.

Frost creep
The net downslope displacement that occurs when a soil, during a freeze–thaw cycle, expands perpendicular to the ground surface and settles in a nearly vertical direction.

Frost heave
The upward or outward movement of the ground surface (or objects on or in the ground) caused by the formation of ice in the soil.

Frost mound
Any mound-shaped landform produced by ground freezing, combined with accumulation of ground ice due to groundwater movement or migration of soil moisture. Also see Nelson et al. (1992).

Frost penetration
The movement of a freezing front into the ground during freezing.

Frost-susceptible soil
Subsurface earth materials in which segregated ice will form (causing frost heave) under the required conditions of moisture supply and temperature.

Frozen ground
Soil or rock in which part or all of the pore water has turned into ice.

Gas hydrate
A special form of solid clathrate compound in which crystal lattice cages or chambers, consisting of host molecules, enclose guest molecules.

Gelifluction
The slow downslope flow of unfrozen earth materials over a frozen substrate. Also see **solifluction**.

Geocryology
The study of earth materials and processes involving temperatures of 0^{o}C or below.

Geothermal gradient
The rate of temperature increase with depth below the ground surface.

Ground ice
A general term referring to all types of ice contained in freezing and frozen ground.

High-center polygon
An ice-wedge polygon in which melting of the surrounding ice wedges has left the central area in a relatively elevated position.

Ice lens
A dominantly horizontal, lens-shaped body of ice of any dimension.

Ice segregation
The formation of discrete layers or lenses of segregated ice in freezing mineral or organic soils, as a result of the migration and subsequent freezing of pore water.

Ice wedge
A massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice.

Ice-wedge polygon
A network of ice wedges defining the boundaries of a geometric polygon in plan view.

Intrusive ice
Ice formed from water injected into soils or rocks.

Latent heat of fusion
The amount of heat required to melt all ice (or freeze all pore water) in a unit mass of soil or rock. For pure water this quantity is 334 J g^{-1}.

Low-center polygon
An ice-wedge polygon in which thawing of ice-rich permafrost has left the central area in a relatively depressed position.

Mass wasting (mass movement)
Downslope movement of soil or rock on or near the earth's surface under the influence of gravity.

Massive ice
A comprehensive term used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice, and large ice lenses.

Mean annual air temperature (MAAT)
Mean annual temperature of the air, measured at standard screen height above the ground surface.

Mean annual ground-surface temperature (MAGST)
Mean annual temperature at the surface of the ground.

Mean annual ground temperature (MAGT)
Mean annual temperature of the ground at a specified depth.

N-factor
The ratio of the freezing or thawing index at the ground surface to that derived from air temperature records.

Palsas
Permafrost mounds ranging from about 0.5 to about 10 m in height and exceeding about 2 m in average diameter, comprising (1) aggradation forms and (2) degradation forms. The term "palsa" is a descriptive term to which an adjectival modifier prefix can be attached to indicate formative processes. See Washburn (1983) and Nelson et al. (1992).

Patterned ground
A general term for any ground surface exhibiting a discernibly ordered, more or less symmetrical, morphological pattern of ground and, where present, vegetation.

Periglacial
The conditions, processes, and landforms associated with cold, nonglacial environments, regardless of proximity to past or present glaciers.

Permafrost
Earth materials that remains continuously at or below 0°C for at least two consecutive years.

Permafrost, continuous
Regions in which permafrost occurs nearly everywhere beneath the exposed land surface. At the circumpolar scale the term *continuous permafrost zone* refers to a broad area, crudely conformable with latitude, in which permafrost is laterally continuous. See Nelson and Outcalt (1987).

Permafrost, discontinuous
Regions in which permafrost is laterally discontinuous owing to heterogeneity of material properties, subsurface water, and surface cover.

Permafrost, dry
Permafrost containing neither free water nor ice.

Permafrost, ice-rich
Permafrost containing excess ice.

Pingo
A perennial frost mound consisting of a core of massive ice produced primarily by injection of water, and covered with soil and vegetation.

Retrogressive thaw slump
A slope failure resulting from thawing if ice-rich permafrost.

Seasonally frozen ground
Ground that freezes and thaws annually.

Solifluction
A general term referring to the slow downslope flow of saturated unfrozen earth materials over an impermeable substrate (also see **gelifluction**).

Thermokarst terrain
Irregular topography resulting from the melting of excess ground ice and subsequent thaw settlement.

Thaw depth
The instantaneous depth below the ground surface to which seasonal thaw has penetrated (also see **active-layer thickness**). See Nelson and Hinkel (2003).

Thaw lake
A lake whose basin was formed or enlarged by thawing of frozen ground. See Hopkins (1949) and Washburn (1980, p. 271).

Thaw settlement
Compression of the ground due to loss of excess ground ice and attendant thaw consolidation.

Thawing index (DDT)
The cumulative number of degree-days above 0^oC for a given time period (usually seasonal).

Thaw consolidation
Time-dependent compression resulting from thawing of ice-rich frozen ground and subsequent draining of excess water.

Thermal erosion
Erosion of ice-bearing permafrost by the combined thermal and mechanical action of moving water.

Thermal conductivity
The quantity of heat that will flow through a unit area of a substance in unit time under a unit temperature gradient. In permafrost investigations thermal conductivity is usually expressed in $W\ m^{-1}\ {}^oC^{-1}$.

Thermal offset
Temperature depression in the upper layer of permafrost, resulting from the combined effects of seasonal differences of thermal conductivity and the operation of nonconductive processes in the active layer. See Williams and Smith (1989) and Nelson et al. (1985).

Zero curtain effect
Persistence of a nearly constant temperature very close to the freezing point of water during annual freezing (and occasionally thawing) of the active layer. See Outcalt et al. (1990).

List of Acronyms

ACD
Arctic Coastal Dynamics (IASC)

ACIA
Arctic Climate Impact Assessment

ADOT&PF
Alaska Department of Transportation and Public Facilities

ALT
active-layer thickness

ARCSS
Arctic System Science program (NSF/OPP)

Arctic-CHAMP
Community-wide Hydrological Analysis and Monitoring Program (U.S. National Science Foundation initiative)

BEO
Barrow Environmental Observatory

CALM
Circumpolar Active Layer Monitoring program

CEON
Circumarctic Environmental Observatories Network

CRREL
Cold Regions Research and Engineering Laboratory (U.S. Army Corps of Engineers)

DGGS
Division of Geological and Geophysical Surveys (Alaska Department of Natural Resources)

DOD
U.S. Department of Defense

EPA
U.S. Environmental Protection Agency

FAO
Food and Agriculture Organisation (of the United Nations)

FGDC
Frozen Ground Data Center (NSIDC)

GCOS
Global Climate Observing System

GCM
general circulation model (or global climate model)

GHOST
Global Hierarchical Observational Strategy (WMO)

GIS
geographic information systems (or geographic information science)

GSC
Geological Survey of Canada

GTN-P
Global Terrestrial Network for Permafrost

GTOS
Global Terrestrial Observing System

IASC
International Arctic Science Committee

ICSU
International Council of Scientific Unions

IPA
International Permafrost Association

IPCC
Intergovernmental Panel on Climate Change

IPY
International Polar Year

JPO
Joint Pipeline Office (U.S. federal and State of Alaska)

LTER
U.S. Long Term Ecological Research Network

MAAT
mean annual air temperature

MAGST
mean annual ground surface temperature

MAGT
mean annual ground temperature

NASA
U.S. National Aeronautics and Space Administration

NOAA
U.S. National Oceanic and Atmospheric Administration

NRCS
U.S. Natural Resources Conservation Service (USDA)

NSF
U.S. National Science Foundation

NSIDC
U.S. National Snow and Ice Data Center (Boulder, Colorado)

OPP
Office of Polar Programs (U.S. National Science Foundation)

PACE
Permafrost and Climate in Europe program

SEARCH
Study of Environmental Arctic Change (U.S. federal government multiagency initiative)

TAPS
Trans-Alaska Pipeline System

TDR
time-domain reflectometry

TEMS
Terrestrial Ecosystem Monitoring Sites network

TOPC
Terrestrial Observational Panel for Climate

UAF
University of Alaska Fairbanks

UNEP
United Nations Environment Programme

UNESCO
United Nations Educational, Scientific and Cultural Organization

USACE
U.S. Army Corps of Engineers

USDA
U.S. Department of Agriculture

USPA
U.S. Permafrost Association

USARC
U.S. Arctic Research Commission

USGS
U.S. Geological Survey

VSM
vertical support member

WMO
World Meteorological Organization

UNITED STATES ARCTIC RESEARCH COMMISSION

The U.S. Arctic Research Commission (USARC) was created by the Arctic Research and Policy Act of 1984 (as amended in November 1990). The Commission, whose seven members are appointed by the President of the United States, assesses national needs for arctic research and recommends to the President and the U.S. Congress research policies and priorities that form the basis for a national arctic research plan. Other key USARC functions include facilitating cooperation in arctic research between federal, state, and local governments; recommending improvements in arctic research logistics; recommending areas for enhanced international scientific cooperation in the Arctic; cooperating with the Governor of Alaska in formulating arctic research policy; and conducting special studies such as *Climate Change, Permafrost, and Impacts on Civil Infrastructure*. USARC biennially submits a strategic document, *Goals and Objectives for Arctic Research*, to the Interagency Arctic Research Policy Committee for its use in revising a national five-year Arctic Research Plan. The Commission normally meets four times annually (at least once each year in Alaska) to hear invited and public testimony on all facets of Arctic research. The USARC staff has offices at 4350 North Fairfax Drive, Suite 510, Arlington, Virginia 22203, and 420 L Street, Suite 315, Anchorage, Alaska 99501.

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Back Cover: South-facing view of the Trans-Alaska pipeline near Sukakpak Mountain, southern Brooks Range foothills. This area is in the zone of discontinuous permafrost. Nearly 80% of the Trans-Alaska pipeline lies within the state's permafrost regions (see Figure 15). Photo by F.E. Nelson, October 1982.