

Review of Existing Permafrost Monitoring Projects, With Application and Recommendations for the Central Alaska Network Ecological Monitoring Program

Prepared For:

National Park Service
PO Box 9
Denali National Park and Preserve, AK 99755

Prepared By:

Kenneth F. Karle
Hydraulic Mapping and Modeling
PO Box 181
Denali Park, AK 99755

and

Torre Jorgenson
ABR, Inc., Environmental Research and Services
PO Box 80410
Fairbanks, AK 99708

April 2004

Table of Contents

Table of Figures.....	iv
Table of Figures.....	iv
Acknowledgements.....	v
Abstract	vi
Introduction	1
Objective.....	1
Permafrost Mapping.....	2
Remote Sensing	3
USGS Black and White Aerial Photography	4
Color Aerial Photography	4
Color Infrared Photography	4
AHAP photography	4
LANDSAT.....	5
SPOT	5
RADARSAT	6
Interferometric Synthetic Aperture Radar	7
Lidar.....	7
Monitoring Networks.....	8
GTN-P and CALM.....	8
Canada	9
Europe.....	10
Alaska.....	10
Russia	11
Antarctica	12
Previous Studies Using Remote Sensing	12
Permafrost Degradation.....	14
Study Areas	17
Methods	18
Co-Registration of Images.....	18
Photo-Interpretation	18
Spectral Classification	20
Results and Discussion	20

Photointerpretation of Aerial Color Photography.....	20
Photointerpretation of Aerial Black and White Photography	22
Point Sampling of Aerial Color Photography.....	23
Point Sampling of Black and White photograph	23
Spectral Classification of Aerial Color Photography.....	23
Visual Interpretation of Landsat	24
Spectral Classification of Landsat	24
Spectral Classification of SPOT.....	24
Photointerpretation of Radarsat.....	25
Other Satellite Imagery Not Evaluated.....	25
Recommendations for CAKN Network.....	26
Assessment of Potential for Permafrost Degradation	26
Field monitoring.....	26
Remote sensing	27
References.....	28
Appendix A- Imagery overlays from the pilot-scale test evaluations.....	32

Table of Figures

Figure 1. Permafrost types in the three CAKN parks (after USGS, 1996).	3
Figure 2. Typical modes of thermokarst and permafrost degradation for central Alaska.	15
Figure 3. 1997 photo delineation over 1997 CIR airphoto.	33
Figure 4. 1987 photo-delineation over 1987 color airphotos.	34
Figure 5. 1984 photo-delineation over 1984 CIR airphoto.	35
Figure 6. 1957 photo-delineation over 1957 black and white photo.	36
Figure 7. 1957 photo-delineation over 1997 CIR air photo.	37
Figure 8. 1987 photo-delineatin over 1955 black and white photo.	38
Figure 9. 1984 photo-delineation over 1954 black and white air photo.	39
Figure 10. 1997 permafrost point samples on 1997 CIR air photo.	40
Figure 11. 1997 spectral analysis and 1997 photo-delineation over 1997 CIR air photo.	41
Figure 12. 1987 spectral analysis and photo-delineation over 1987 color air photo.	42
Figure 13. 1987 photo-delineation over 2000 Landsat image.	43
Figure 14. 1984 photo-delineation over 1999 Landsat image.	44
Figure 15. 2002 spectral analysis and 1997 photo-delineation over 2002 Landsat image.	45
Figure 16. 1987 photo-delineation over 1996 SPOT image.	46
Figure 17. 1996 spectral analysis and 1987 photo-delineation over 1996 SPOT image.	47
Figure 18. 1987 photo-delineation over 2003 radar image.	48

Acknowledgements

The research reported herein was performed under the National Park Service Purchase Order P9836030062 by Hydraulic Mapping and Modeling and ABR, Inc. Hydraulic Mapping and Modeling was the contractor for this study. The work undertaken by ABR, Inc. was under a subcontract with Hydraulic Mapping and Modeling. That work included the pilot-scale evaluations and thermokarst delineations using remote sensing imagery.

Kenneth F. Karle, P.E. Hydraulic Mapping and Modeling, was the principal author of this report. The other author is Torre Jorgenson, ABR, Inc.

We would like to thank Dr. Yuri Shur, Professor, University of Alaska Fairbanks, who provided technical guidance and advice for this report.

Abstract

One of the vital signs of interest for the National Park Service is the extent and state of permafrost within the three park units of the Central Alaska Network. Various remote sensing techniques were assessed to determine whether they are suitable for long-term permafrost monitoring, by evaluating the appropriate scale for use of such techniques, and determining the types of biophysical changes that can be documented. Pilot-scale evaluations of permafrost changes were conducted for several types of remote sensing, including aerial photography, satellite imagery, and satellite-based radar imagery. Evaluation methods included boundary delineation of collapse scar features, point sampling, and spectral analysis. Results from the pilot scale analyses indicate that long-term monitoring of landscape changes due to changes in the permafrost regime is viable with high-quality low-level aerial photography. Permafrost degradation should be delineated through photointerpretation of imagery because accurate mapping of thermokarst features is dependent on pattern recognition, micro-topographic differences evident in stereoscopic analysis, and vegetation patterns. The low resolution provided by the satellite imagery prevents any significant delineation of these features. Though not included in this study, LIDAR imagery should be evaluated for its suitability as a remote sensing technique for the CAKN program, due to the capability of providing data for analyzing vertical and volumetric changes in a permafrost landscape.

Introduction

In order to establish baseline resource information and to provide information on the long-term trends in the condition of the National Park System resources, the Central Alaska Network (CAKN) was established as part of the National Park Service (NPS) Inventory and Monitoring Program. It is composed of three national park units: Wrangell-St. Elias National Park and Preserve (WRST), Denali National Park and Preserve (DENA), and Yukon-Charley Rivers National Preserve (YUCH). The network is currently conducting baseline inventories of selected resources, and is developing and prioritizing a list of “vital signs” for long-term monitoring (MacCluskie and Oakley, 2002).

One of the vital signs of interest for the National Park Service is the extent and state of permafrost within the three park units. The literature is replete with papers describing the potential seriousness of environmental impacts as a result of global climate warming, especially in the Arctic and subarctic regions. Of particular concern are the potential effects of climate warming on ‘warm’ permafrost and the active layer. For example, increased seasonal thawing and deepening of the active layer could result in additional greenhouse gas release, further increasing global climate change. Additionally, active layer changes as a result of increased seasonal thawing could produce substantial effects on vegetation, soils, hydrology, and other natural processes. As such, permafrost has been listed as one of the proposed vital signs to be monitored as part of the CAKN Inventory and Monitoring program.

A scoping meeting was organized by the NPS in April 2002 to solicit ideas and suggestions for developing a permafrost monitoring program (MacCluskie and Oakley, 2002). Permafrost experts from the Natural Resources Conservation Service (NRCS), University of Alaska Fairbanks, and Long Term Ecological Research Network were invited to attend and provide information on existing monitoring networks and guidance for future work. It was determined that changes in the thaw-unstable (warm) permafrost regimes in the three CAKN parks would have a dramatic influence on the landscape. Two potential paths were identified; the first was a site-specific research effort with very high costs and limited landscape-level information, using boreholes to provide thermal data, and the second was to monitor permafrost landscape change through image analysis. Based on overall program goals and funding limitations, CAKN managers decided to direct future efforts to determining the feasibility of monitoring landscape change through remote imagery analysis (Guy Adema, NPS, oral commun., 2004).

Objective

Recognizing the specialized field of the subject matter, the NPS contracted a project in September 2003 to provide advice for CAKN managers. The goal of the project was to:

- assess the use of remote sensing techniques for long-term permafrost monitoring,
- evaluate the appropriate scale for use of such techniques,
- determine the types of biophysical changes that can be documented.

A short timeline in the contract restricted the project to literature review and imagery analysis, without field verification activities. To meet the project goals, the following project objectives were developed:

- Review literature on existing permafrost monitoring projects in the Arctic/Subarctic.
- Evaluate air photo and remote sensing interpretation techniques for monitoring permafrost changes.
- Conduct pilot-scale evaluations of permafrost changes for several types of remote sensing.
- Develop recommendations for development of a permafrost monitoring program for CAKN.

Permafrost Mapping

The mapping and long-term monitoring of permafrost presents several challenges to scientists and program managers. The first problem is related to the definition of permafrost. The general definition of permafrost is ground that remains at or below 0° C for at least two years, for natural climatic reasons (van Everdingen, 1998). As such, this requires the mapping or monitoring of a condition, rather than a physical object. Additional complications arise when the condition is transitory, on both geological and human timescales (Heginbottom, 2002).

The second problem related to permafrost mapping and monitoring is the sheer immensity of the condition to be studied. Permafrost is found extensively throughout the physical land mass encompassed by the three parks in the CAKN network (Figure 1). Effective long-term monitoring of such a large area requires that accurate and efficient methods be developed.

Data are acquired for permafrost mapping and modeling based on the desired goals of the individual mapping program or monitoring program. Typical attributes for general inventory maps include geographical extent of the permafrost region, ground temperature, and permafrost thickness. Additional attributes, such as thaw settlement sensitivity and others, are collected when compiling maps for engineering purposes (Heginbottom, 2002). See Table 1 for various methods of permafrost data acquisition.

Table 1. Methods of data acquisition for permafrost mapping and monitoring (after Heginbottom, 2002).

	Direct Observations	Indirect or Remote Observations
Geological Methods	Borings and Excavations, Laboratory Testing of Samples	Air Climate Data, Terrain Typing, Landscape Analysis, Vegetation Mapping, etc.
Geophysical Methods	Ground Temperature Measurements, Thermal Properties Measurements	Seismic, EM or Ground Radar Profiling and Sounding, Geothermal Modeling

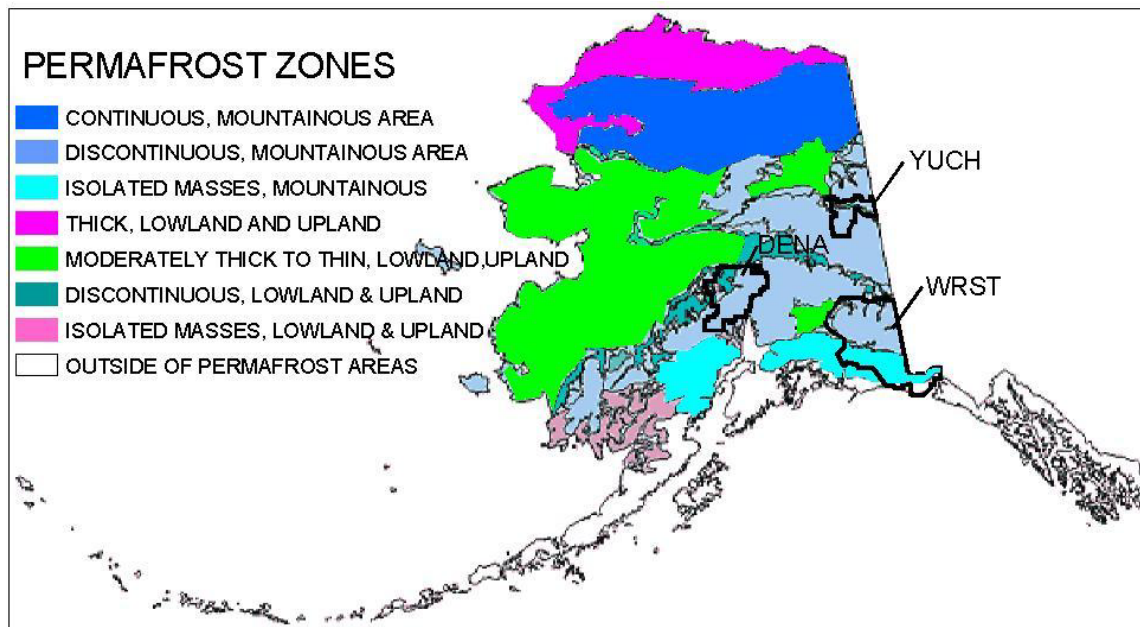


Figure 1. Permafrost types in the three CAKN parks (after USGS, 1996).

The use of boreholes is undoubtedly the most common method of acquiring thermal data by permafrost scientists. Boreholes are classified based on their drilled depths. The classifications are: surface (0-10m); shallow (10-25m); intermediate (25-125m) and deep (>125m) (GTN-P, n.d.). Boreholes are instrumented with thermistors, thermocouples, or other devices to record and log ground temperatures at predetermined depths from the surface. Additional descriptions for the various methods of permafrost data acquisition are beyond the scope of this paper, though information is widely available.

Remote Sensing

Remote sensing is commonly defined as the collection of information about an object without making physical contact with it. For the purposes of this study, the techniques used by remote sensing methods require the presence and use of electromagnetic radiation, with a range from ultraviolet to radio frequencies. These remote sensing techniques, which are used to observe properties or physical objects on Earth, are acquired from some elevation above the earth, through the use of an airplane (aerial) or earth-orbiting satellite.

Aerial-based imagery typically involves the acquisition of photographs. Color and black and white photography allow the detection and viewing of energy in a small wavelength band of 0.3 to 0.9 μm , which is the visible and near infrared spectrum. Multi-spectral scanners operate in a much larger spectrum, and can sense emitted energy from 0.3 to approximately 14 μm . Additionally, such scanners can be tuned to sense those energies in extremely narrow bands, which allows for greater correlation of the detected energy with the emitting object. These scanners are used on earth orbiting satellites for acquisition of remote sensing data.

There are many different types of remote sensing techniques, and a complete description of this field is beyond the scope of this report. The techniques included in this study were selected by NPS, based on existing remote sensing images that were readily available at the time of this study. A brief description of those techniques follows. Also included in this discussion are descriptions of two techniques that were not tested, but are of particular interest due to their ability to accurately map topography with high resolution.

USGS Black and White Aerial Photography

These black and white aerial vertical photographs were taken in the 1950s, during the creation of the USGS topographic map series, and range in scale from 1:40,000 to 1:46,000. These prints, in a 9 inch by 9 inch positive format, are still available from the USGS EROS Data Center in Sioux Falls, South Dakota by using photo indexes and map line plots. An individual photographic index is compiled by mosaicking a series of consecutive and adjacent overlapping photographs over a specified geographic map area. These indices of mosaicked photographs provide information (i.e., project, roll, and frame numbers) required for the ordering process (USGS, n.d.).

Color Aerial Photography

True color aerial photography offers an advantage over black and white photography due to the ability of the human eye to distinguish many more shades of color than shades of gray. Color aerial photographs were obtained from various Alaska National Park Service photography programs. The photography was flown from 1976 through 1996; photo flight scales vary from 1:3,000 to 1:44,000.

Color Infrared Photography

Color Infrared (CIR) photographs were obtained from various National Park Service programs, and from the AHAP program described below. The utility of color infrared film is derived from its increased sensitivity to vegetation. CIR film is produced to record only green, red, and the photographic portion of the near-IR scene energy. As a result of the special film emulsion layers used with CIR film, objects which reflect green energy appear blue, objects which reflect red energy appear green, and objects which reflect near-IR energy appear green. Additionally, a yellow filter is commonly used on the camera to prevent blue and ultraviolet energy from reaching the film. As healthy vegetation generally reflects near-IR energy much more strongly than it does green energy, vegetation can be readily identified on color-IR photographs.

AHAP Photography

These photographs are from the Alaska High Altitude Aerial Photography Program, which operated from 1978 through 1986; the color-infrared scale is at 1:60,000 and the black and white scale is 1:120,000. The CIR data are in 10" positive transparency format and the B&W data are in negative film.

LANDSAT

The Landsat Program is the longest running enterprise for acquisition of imagery of the earth from space (NASA, n.d.). The first Landsat satellite was launched in 1972; Landsat-7 was the most recent to be launched, in 1999. The Landsat-4 and -5 satellites, using sun-synchronous near-polar orbits, carry both MSS (Multispectral Scanner) sensors and TM (Thematic Mapper) sensors. The TM sensors offer multiple advances over the MSS sensors in terms of spectral, radiometric, and geometric design improvements. While the MSS has sensors for four spectral bands with an 80 meter ground resolution, the TM sensors can image seven spectral bands for data acquisition, with a 30 m ground resolution. Table 2 presents a brief summary of the seven spectral bands, and possible applications for each.

Table 2. Landsat spectral bands and applications (after Lillesand and Kiefer, 2000).

Band	Wavelength (μm)	Spectral location	Principal Applications
1	0.45-0.52	Blue	Water body penetration (water mapping), soil/veg discrimination, forest type mapping
2	0.52-0.60	Green	Vegetation discrimination, vigor assessment, green reflectance peak
3	0.63-0.69	Red	Vegetation species differentiation
4	0.76-0.90	Near IR	Vegetation types, vigor, biomass, soil moisture, water body delineation
5	1.55-1.75	Mid IR	Vegetation moisture content, soil moisture, snow/cloud differentiation
6	10.4-12.5	Thermal IR	Vegetation stress analysis, soil moisture, thermal mapping
7	2.08-2.35	Mid IR	Vegetation moisture, mineral and rock discrimination

The Landsat-7 satellite uses an Enhanced Thematic Mapper Plus (ETM+) system, which was designed to provide for the collection of unenhanced Landsat data sufficiently consistent with previous Landsat data to allow comparisons for global and regional change detection. Panchromatic data is collected at a 15 meter resolution, the thermal band data are collected at a 60 meter resolution, and all other band data are collected at a 30 meter resolution. The six banks of data in the visible, near-IR, and mid-IR spectral regions are the same as Landsat-4 and -5, with the exception of Band 7, which has a spectral range of 2.35-3.09 μm (near IR).

When working with large land units such as Alaskan national parks, one of the distinct advantages of using satellite imagery from Landsat or other sources is the image scale. With a scale of 1:1000000, a single Landsat image (185 mm x 185 mm) covers the same area as 400 aerial photographs at a scale of 1:40000 or 1600 aerial photographs at a scale of 1:20000.

SPOT

SPOT (Système Pour l’Observation de la Terre) is an international program for acquiring and distributing high resolution satellite imagery. SPOT images come in a full

range of scales, from 1:100000 to 1:10000, and covers an area of 117 km by 60 km. SPOT was the first system to have pointable optics, and can produce full-scene stereoscopic imaging of an area from two different satellite tracks. The SPOT-1, -2, and -3 satellites are in circular, near-polar, sun-synchronous orbits. These satellites contain two high resolution visible (HRV) imaging systems, which can operate either in a panchromatic (black and white) mode over the range 0.51 to 0.73 μm , or in a multispectral (color IR) mode over the ranges 0.50 to 0.59 μm , 0.61 to 0.68 μm , and 0.79 to 0.89 μm .

The SPOT-4 satellite, launched in 1998, was updated to carry a HRVIR (high resolution visible and infrared) sensor and a Vegetation Instrument. The Vegetation Instrument includes a blue band (0.43 to 0.47 μm), along with an extremely wide imaging swath of 2250 km (Lillesand and Kiefer, 2000). The SPOT-4 resolution is 20 m in all 3 spectral bands in the visible and near infrared ranges, and 10 m in the panchromatic mode. The SPOT-5 satellite was expected to have improved resolutions: 2.5, 5, and 10 m in all 3 spectral bands and 2.5 and 5 m in the panchromatic mode (SPOT, n.d.).

RADARSAT

Radarsat-1 is a Canadian satellite, launched in 1995. Radar systems use radio waves to detect the presence, position, and shape of objects. The brightness or amplitude of a reflected radio signal that has been transmitted from an antenna mounted on a satellite or aircraft, backscattered from the surface of the Earth, and received a fraction of a second later at the same antenna, is measured and recorded to construct an image.

These systems operate in the microwave portion of the electromagnetic spectrum, which includes wavelengths from 1 mm to 1 m. Because microwaves can penetrate the atmosphere under virtually all conditions, including light rain, snow and clouds, a microwave system offers an immediate advantage over other types of remote sensing systems which senses light or heat.

Radar images are processed and interpreted based on two main characteristics of the terrain they are sampling, geometric and electrical. These characteristics affect the amount and strength of the radar signal return. Geometric characteristics refer to the roughness of the terrain and the orientation of the objects. Electrical characteristics, measured as the complex dielectric constant, are determined by the reflectivity and conductivity of the material being illuminated. For example, water has an extremely high dielectric constant, and has a high radar reflectivity. As plants can have large surface areas and high moisture contents, they can provide high reflectivity also. Various radar wavelengths can be used for distinguishing leaf canopies and trunks.

Radarsat-1 operates a synthetic aperture radar (SAR) in the C-band (5.6 cm wavelength), which can be operated in several different beam selection modes. This provides for varying swath widths, with a maximum resolution of 8 m.

Interferometric Synthetic Aperture Radar (not tested)

The term *synthetic aperture radar* (SAR) refers to data recording and processing techniques which result in the synthesis of a very long antenna, even though a short physical antenna is actually mounted on the platform. A physically large antenna is needed to focus the transmitted and received energy of the radar into a sharp beam. The sharpness of the beam defines the azimuth resolution. The improved azimuth resolution results in much higher resolution imagery. As a satellite- or airborne synthetic aperture radar moves along a path, it collects and then processes the data as if it came from a physically long antenna. The distance the platform moves in synthesizing the antenna is known as the synthetic aperture. A narrow synthetic beamwidth results from the relatively long synthetic aperture, which yields finer resolution than is possible from a smaller physical antenna (Lillesand and Kiefer, 2000).

Interferometry is the use of interference phenomena for measurement purposes, either for very small angles or for tiny distance increments (the displacement of two objects relative to one another). SAR interferometry is possible because of the ‘coherence’ of the imaging system, which collects and retains both amplitude and phase information in the signal echo. By using the phase measurements to infer differential range and range change in two or more SAR images of the same surface, signal output can be processed to estimate topographic height from the differential range measured by two radar antennas looking at the same surface, or to estimate changes in topography based on range change in two or more successive SAR images (Chapman, 1995).

Lidar (not tested)

Lidar systems operate by emitting pulses of laser light toward the ground. The time required for pulse return is measured, and processing techniques use the return time to calculate the variable distances between the sensor and the various ground surfaces (Lillesand and Kiefer, 2000). Lidar systems are generally mounted in aircraft platforms, and use GPS to determine and maintain a georeferenced position.

Lidar data are processed into a file of x, y, z points, and are commonly used to construct digital elevation models (DEM) of the earth’s surface. These elevation data points are generated at the rate of thousands of points per second, with absolute vertical accuracies of up to 15 cm. For example, a typical lidar acquisition of open-spaced tall trees can produce a return with up to 135,000 points per square kilometer (Aeromap US, n.d.).

Lidar data is commonly integrated with other data sets, including orthophotos, multispectral, hyperspectral and panchromatic imagery. Lidar products include contour maps, slope/aspect, three-dimensional topographic images, and automatic feature extraction.

Monitoring Networks

A global permafrost network was established by the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS) and the International Permafrost Association (IPA) for the purpose of detecting, monitoring and predicting climate change (GTN-P, n.d.). The emphasis of the network is to collect temperature profile data and information on the active layer. In addition to temperature data, the network includes efforts to assess changes in permafrost-affected terrain by remote sensing techniques. A five-tier hierarchical system for surface observations was designed by the network to assist with site selection and implementation.

Components of the international network, as well as descriptions of national or agency networks, are described below. The overwhelming amount of permafrost monitoring network information available in the literature or on the World Wide Web is directed at thermal regime (temperature) and active layer data (thickness, depth, etc). Data collection efforts similar to the type described in this report (delineation of thermokarst waterbodies and collapse/scar features) are recommended in the five-tier GTOS/GCOS surface observation system; however, though many individual research studies have included such techniques, we found little information on the existence of operational, long-term repetitive monitoring efforts which employ such methods and contribute to the international network.

GTN-P and CALM

The Global Terrestrial Network for Permafrost (GTN-P) was established in 1999 by the International Permafrost Association (IPA) to provide long-term field observations of active layer and permafrost thermal state that are required to determine the present permafrost conditions and to detect changes in permafrost stability. The network to date consists of about 100 active layer monitoring sites that contribute to the Circumpolar Active Layer Monitoring Program (CALM) and over 300 candidate boreholes for permafrost thermal monitoring.

The CALM program was established in 1991 to monitor and model interannual, decadal, and secular variations in the active layer on a hemispheric scale so as to understand the roles of cold soils in global change. CALM is currently operated by researchers from Canada, China, Denmark/ Greenland, Kazakhstan, Mongolia, Norway, Poland/Svalbard, Russia, Sweden/Svalbard, Switzerland, and United States (Brown, 1998). The CALM network currently includes 130 active sites in both hemispheres, with 15 participating countries. At least twenty secondary sites are co-located with these primary sites, resulting in a total over 150 sites that report active-layer thickness on an annual basis. Approximately 100 sites collect soil and permafrost temperature data, most of which is derived from boreholes. Maximum active layer thickness is interpolated from these temperature profiles.

Most sites in the CALM network are located in Arctic and Subarctic lowlands, although 20 boreholes are in mountainous regions of the Northern Hemisphere above 1300 m

elevation. A new Antarctic component is being organized and currently includes 13 sites. Investigators at these sites measure the seasonal thaw depth across plots using a standard protocol. Soil and air temperature, and soil moisture content, are also measured at many sites.

The University of Cincinnati administers the CALM grant. Participants collect the necessary temperature and thaw depth measurements and provide them to the CALM program at the University of Cincinnati, where they are incorporated into several databases including the IPA Global Geocryological Database (GGD).

Canada

Over half the Canadian land mass is underlain by warm permafrost (Burgess et al., 2000). As such, Canada requires an effective and comprehensive monitoring strategy, as thawing of perennially frozen ground has important implications for landscape processes (terrain, slope and coastal stability), hydrology (surface and ground water regimes), surface characteristics (vegetation, albedo), greenhouse gas sources and sinks (peatlands, soils, gas hydrates), as well as for ecosystems, engineering and infrastructure. Over 17 researchers or agencies are involved in permafrost monitoring activities in Canada. The two largest monitoring networks are maintained by the Geological Survey of Canada (GSC) and the Centres d'études Nordiques at the Université Laval.

The National Permafrost Database, maintained by the GSC, contains data on permafrost thermal regime and permafrost thickness, and active layer characteristics in Canada. The data are compiled from observations of over 500 government, university and industry boreholes (Burgess et al., 2000). The data have been measured and/or compiled by the GSC over the last 30 years, as both published and unpublished databases. Site attributes include: type of observation (shallow or deep), status of measurement program (active monitoring or inactive), active layer depth, permafrost temperature data, permafrost thickness, other site or material characteristics, responsible agency, and published references.

The database includes a number of active monitoring sites which contribute to the GTN-P, through the international CALM program, and a new global borehole temperature monitoring program. The GSC maintains national databases on both permafrost temperatures (Smith and Burgess, 2000) and permafrost thickness (Smith and Burgess, 2002). These data sets have been compiled largely from borehole observations, ground temperature measurements and geophysics soundings obtained at GSC study sites and from other published sources. Information from over 500 sites has been entered into the temperature database and from over 1000 sites in the thickness database. Information on site characteristics such as air temperature, snow cover and vegetation which influence the ground thermal regime and the permafrost distribution has also been compiled.

The Centres d'études Nordiques (CEN) at the Université Laval in Quebec focuses on research studies of permafrost, as do several other universities in Canada. The main area of interest for CEN research focuses on the influence of climatic variations on permafrost properties. Some work is being conducted currently which involves the use of remote

sensing to detect and model permafrost. For example, researchers are using NOAA AVHRR (Advanced Very High Resolution Radiometer) remote sensing imagery to compare surface temperature changes during a twenty year time period in a large scale setting, using imagery from forested tundra in northern Quebec (Sonia Hachem, Universit  Laval, personal commun., 2004).

Europe

Several permafrost mapping programs have operated in Europe in the past 10 years. For example, the PACE project (Permafrost and Climate in Europe) was a 3-year research project which was funded by the European Union Environment and Climate Research Programme and the Swiss Government. Initiated in 1997, this program focused on detailed studies of permafrost-climate relationships (Odegard et al., 1999). The program has since been extended and transformed to the PACE21 Network, funded by the European Science Foundation.

One of the objectives of the PACE project was to develop methods of mapping and modeling the distribution of thermally sensitive mountain permafrost, and predicting climatically induced changes in this distribution (Vonder Muhll et al., 2002). A critical component of the PACE program was the establishment of a longitudinal transect of instrumented permafrost boreholes across the higher mountains of Europe, from Svalbard in the north to the Sierra Nevada in the south. In addition to borehole temperatures, research includes geophysical surveys, microclimatic investigations, numerical modeling of permafrost distribution, and physical modeling of permafrost-related slope instability. Mapping methods using remote sensing were generally not tested.

Detailed permafrost research has also been conducted in the Eastern Swiss Alps over the past 30 years. Methods have generally included borehole monitoring, geophysical soundings, and energy flux measurements above and within permafrost. Remote sensing techniques, specifically photogrammetric surveys, were used in this area to make surface velocity measurements of longitudinal creep over a period of years (Hoelzle et al., 2002). Permafrost distribution modeling for this area was conducted by using a regionally calibrated empirical-statistical model. Such methods related documented permafrost occurrences to topographic and climatic factors, such as altitude, slope, aspect, air temperature, and solar radiation (Keller et al., 1998).

Alaska

Permafrost research and monitoring has been conducted by a number of different groups in Alaska, including the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), scientists at Alaska Biological Research Inc., the U.S. Department of Agriculture, and others.

The major body of permafrost research and monitoring in Alaska is being conducted by the University of Alaska Fairbanks (UAF). These UAF researchers contribute data to the

National Snow and Ice Data Center, and contribute to the Global Terrestrial Network for Permafrost (GTNet-P).

The Geophysical Institute at UAF maintains a Snow, Ice, and Permafrost Group; that permafrost research has been directed toward problems in heat and mass transport, including those involving salt, the response of permafrost to climate change, the inverse problem of extracting information about past climate from present permafrost conditions, and the application of geophysical methods for detecting permafrost and related materials (UAF, n.d.).

Staff at the UAF Water and Environmental Research Center also conduct basic and applied research studies in water resources for arctic and subarctic environments, including permafrost studies. In conjunction with the Bonanza Creek Long Term Ecological Research (LTER) Program, UAF investigators have established long-term monitoring transects for measuring landform changes at several thermokarst depressions and pingo sites (UAF, n.d.). Transects are surveyed at 3 m intervals to assess ground lifting and subsidence. Transects with control points at additional thermokarst sites will be installed during the summer of 2004.

A long-term permafrost monitoring network, using multiple sites, was established in Alaska in the late 1970s. The purpose of the network was to help researchers establish how a warming climate will affect permafrost and the active layer (Osterkamp, 2003). A total of 22 permafrost observatories were established, using boreholes drilled from 15 to 80 m in depth. Temperatures are measured at each site, generally using calibrated thermistors and data loggers. In addition to temperatures, other measurements at the observatories often include snow cover, soil moisture, thermal properties, heave and settlement measurements, and others (Osterkamp, 2003).

The Barrow Permafrost Observatory was established in 2000; the project goal is to establish a long-term permafrost observatory, and to compare present permafrost temperatures with measurements of a 12-year record from the 1950s to early-1960s. The Barrow Permafrost Observatory is supported by the International Arctic Research Center (IARC) and the National Science Foundation.

Russia

Permafrost studies have been conducted in Russia for more than 100 years. Permafrost areas and areas of deep seasonal freezing are found in 80% of the Russian land mass (Pavlov, 1997). Long-term borehole monitoring data from over 120 boreholes are provided by Russian investigators to the CALM program, as well as layer thickness data, visual observations on core ice-content in the core, and depth of water table (Melnikov, 1998).

A bibliography of permafrost maps published in the USSR and Russia was compiled by the IPA for its Global Geocryological Data (GGD) system, and is available through the IPA's Circumpolar Active-Layer Permafrost System (CAPS) Version 2 (Streletskaia et

al., 1998). The maps are classified into four categories: (1) geocryological conditions, (2) regionalization, (3) predictive, and (4) special. The geocryological conditions maps display various permafrost characteristics, such as: composition and origin of frozen materials, ice content and cryogenic structure, permafrost distribution and thickness, ground temperature, active layer depth, cryogenic (periglacial) processes, and talik location. These maps are usually compiled by extrapolating permafrost information from existing landscape maps.

Regionalization maps identify geographical regions based on permafrost features, as well as geomorphologic, geological or landscape units or subdivisions. Predictive maps were developed from modeling efforts, and describe possible changes to permafrost areas from various impacts, both natural (i.e. climatic changes) and anthropogenic (surface disturbance). Special maps usually show several interrelated characteristics of permafrost, such as ground temperature and permafrost thickness.

Recent developments in Russia have focused on the creation and organization of a GIS/database system to archive and present geocryological data (Melnikov and Minkin, 1998). A GIS system has been developed which relies on a multilevel structure based on a hierarchy of geological and geographical subdivisions, using modern software such as ArcInfo/Arcview, MapInfo, dBASE, Oracle, and others.

Antarctica

Antarctica contains 37% of the world's permafrost (Gillespie et al., 1997.) The international research community has investigated many aspects of permafrost on the continent. The most extensive database for Antarctica permafrost is from the Dry Valley Drilling Project, in which 15 boreholes were drilled to depths ranging from 4 to 381 m (McGinnis, 1981). Additionally, electrical resistivity was used to estimate permafrost thickness. Recommendations for future work include monitoring long-term permafrost temperatures with drilled boreholes, establishing an observational network of active-layer monitoring sites, and interfacing with the CALM program (Bockheim and Hall, 2002).

Previous Studies Using Remote Sensing

Numerous investigators have conducted research involving the assessment of various remote sensing techniques for permafrost detection, mapping, and monitoring. A few of the studies which involve the specific methods or remote sensing products included in this study are briefly reported here.

A university study in Norway used results from snow temperature measurements at the bottom of the winter snow cover (BTS) to compare with Landsat TM data in order to determine the potential of using Landsat data in permafrost mapping (Odegard et al., 1999). Apparent satellite temperatures (AST) from the thermal band of the Landsat data were used to identify areas of high amplitude ground surface temperatures, while the normalized difference vegetation index (NDVI) was applied to detect vegetation density. The analysis ultimately showed that though AST may be used to explain some variance

of BTS in areas of similar altitude, there was no strong covariance between the two. The much larger scale of Landsat, compared to BTS, makes a direct relationship difficult to establish. Additionally, because of the high correlation between altitude and NDVI, the relevance of using NDVI in permafrost mapping is difficult to evaluate.

The potential use of SPOT 10-m panchromatic imagery to detect and identify features indicative of permafrost was investigated for 16 sites on Ellesmere Island (Lewkowicz and Duguay, 1999). A SPOT satellite image from summer 1990 was digitally enhanced by histogram stretching and compared to field observations and aerial photographs for localities in the northern and central regions of the Fosheim Peninsula. The investigation showed that in this area SPOT imagery can be used to detect: (1) large, well-developed, high-centered ice-wedge polygons (diameters of 30-60 m) and large, low-centered polygons containing shallow ponds; (2) anthropogenically-induced thermokarst 40 years after the original terrain disturbance; (3) recent active-layer detachment slides >500 m long; and (4) active retrogressive thaw slumps where they were previously known to be present. Edge filter algorithms applied to the SPOT image assisted in the delineation of polygonized terrain at some sites. However, image analysis was constrained by the size of the pixel relative to the feature, and in a blind test on polygons typically 10-15 m diameter, there was significant underestimation of polygonized terrain.

A method to predict the occurrence of permafrost in the discontinuous zone using Landsat data was developed for Interior Alaska (Morrissey, 1988). In that study, the author used environmental variables derived from the Thematic Mapper (TM) satellite data to develop a statistical routine for predicting the distribution of near-surface permafrost in a boreal forest watershed. Vegetation cover at the study site was classified from the TM data, using training sites and aerial photography. Thermal band data from the TM was used as a correlation to equivalent latitude, which is an index of long-term potential solar radiation incidence and has been found to correspond to the presence or absence of permafrost. Using these data, a probability analysis was developed to predict the probability of frozen ground, and further classify the frozen ground at the study site into three classes: frozen (95 to 100 percent frozen), unfrozen (0 to 5 percent frozen), and discontinuous (6 to 98 percent frozen). When ground-truthed with known permafrost extent from instrumented boreholes, the satellite-derived analysis provided a 75 percent accuracy rate for predicting the presence and class of permafrost. Errors in the permafrost prediction method occurred in two main areas: thick loess covered slopes, and areas disturbed by wildfire.

Several investigators have assessed the use of interferometric synthetic aperture radar for mapping landscape change in permafrost. Nolan and Prokein (2003) analyzed the ability of a radar-derived DEM to identify and quantify hydrologic features such as thaw lakes and pingos. They reported that a Star3i DEM of the Putuligayuk watershed in northern Alaska offered significant resolution improvements over the USGS-produced DEMs; they surmise that by using computerized algorithms, radar-derived DEMs can attain a resolution of centimeters, and should be used to monitor surface elevations in the Arctic to detect climate change.

Other investigators have noted the complications involved when using repeat-pass interferometric SAR to assess temporal change of the landscape surface. Sjogren et al. (2003) discuss the problems associated with temporal decorrelation, which occurs when the radar-scattering characteristics within each pixel of an interferometric SAR image change in the time between the two image acquisitions. Temporal decorrelation precludes or makes difficult the phase comparison of the two SAR images, and can occur as a result of small topography changes, such as in a permafrost environment during summer melt. Decreasing the repeat pass period of the sampling platform will improve the coherence between the images, but results in a period of time which is too short to detect changes in a permafrost environment. The authors note that including ancillary data into the imagery analysis will improve the capabilities of interferometric SAR for detecting permafrost changes and ground ice melt.

Obtaining information on Russian studies and programs is extremely difficult, due to complicated translation requirements and a publications structure which limits the reporting of significant research to small circulation Russian-language journals and monographs, virtually unobtainable outside of Russia (SPRI, n.d.). However, some information is available. For example, Russian investigators report that research directed to improve permafrost studies through the use of remote sensing techniques has been conducted since the early 1970s (Evgeny Melnikov, Earth Cryosphere Institute-Russian Academy of Sciences, personal commun., 2004).

These studies have focused on the development of techniques and methods to map the cryolithozone based on landscape indication. Terrain units are derived from remote sensing data and field verification, and are based on such factors as relief, soil, vegetation, and snow. A summary of the efforts in Russia to map the cryolithozone with remote sensing methods is described in a Russian dissertation abstract (Drozov, 2004), which has not yet been translated into English.

Permafrost Degradation

As reported earlier, NPS program managers have decided to assess changes to the permafrost regime by monitoring landscape change, rather than by site-specific methods such as permafrost observatories and borehole temperature measurements. Landscape change because of permafrost melting is manifested as surface subsidence, referred to as thermokarst. The extent of the subsidence and subsequent damage to the ecosystem is directly related to the amount of ice present in the permafrost. For example, thaw settlement in an ice-rich birch forest in the Tanana Flats area of central Alaska resulted in typical surface settlements of 1-2.5 m, with some settlements of 6 m (Osterkamp et al., 2000). Permafrost thaw may also lead to impacts at ice-poor upland sites as well (Osterkamp et al., 1998).

Such subsidence can lead to extensive ecosystem change, and can result in the conversion of a terrestrial system to an aquatic or wetland system. Much of the area of the Tanana Flats described above has shifted from a birch forest to one with fens and bogs; collapsed areas are being colonized by aquatic herbaceous plants, leading to the development of

floating organic mats (Jorgenson et al., 2001). Other typical modes of permafrost degradation common for central Alaska are described in Table 3, along with their associated terrain characteristics. A pictorial diagram of the typical modes of permafrost is found in Figure 2.

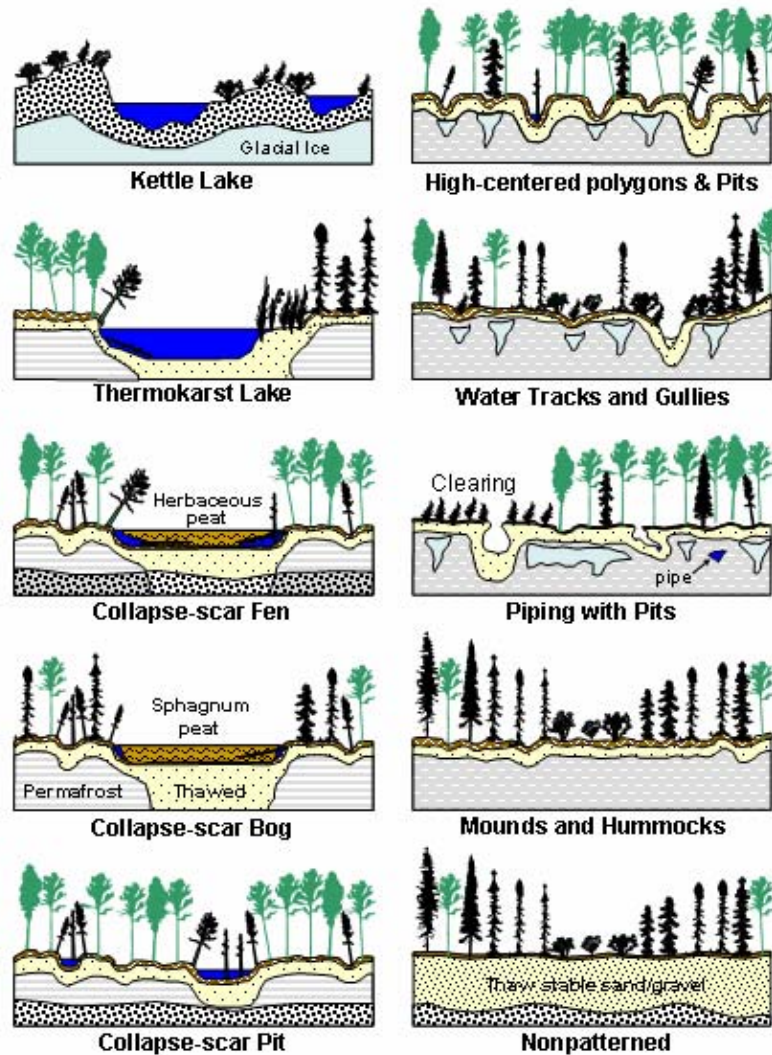


Figure 2. Typical modes of thermokarst and permafrost degradation for central Alaska.

Table 3. Modes of permafrost degradation and their associated terrain characteristics in central Alaska.

Degradation Mode	Landscape Position	Hydrologic Regime	Soil Texture	Excess Ice Content (%)	Dominant Ice Morphology	Maximum Feature Size	Thaw Settlement (m)	Lateral Degradation Rates
Kettle Lake	Kame and kettle	Flooded by precipitation	Dia-micton	>90%	Massive glacial ice	10s of ha	5–20	Highly variable
Thermokarst Lake	Flat to gentle Slopes	Flooded by precipitation, groundwater, surface flow	Silt to fine sand	60–90%	Thick layered ice, massive ice	100s ha	2–10	
Collapse-scar fens	Flat to gentle Slopes	Groundwater	Silt	40–60%	Thick layered ice	10s of ha	1–3	0.5–1
Collapse-scar bogs	Flat to gentle slope	Water below surface, precipitation	Silt	40–60%	Thick layered ice	1s of ha	1–3	0.1–0.5
Collapse-scar pits	Flat to gentle Slopes	Flooded, precipitation	Silt	40–60%	Thick layered ice	10s of m ²	1–2	0.1–0.5
Mixed Pits and Polygons	Flat to gentle Slopes	Partially flooded, precipitation	Silt to med. Sand	30–50%	Ice wedges	10s of m ²	0.5–2	0.1–0.3
High-centered polygons	Flat to gentle Slopes	Partially flooded, precipitation	Silt to med. sand	30–50%	Ice wedges	10s of m ²	0.5–2	0.1–0.3
Water tracks and Gullies	Gentle to mod. slopes	Surface flow	Silt	Uncertain	Uncertain	100s of m ²	0.2–1	0.1–1
Piping with Pits	Toe slopes	Groundwater	Silt	Uncertain	Ice wedges, tunnel (cave) ice	10s of m ² at surface	Pits 2–5	Little after collapse
Mounds and Hummocks	Flat to steep slopes	Drained, precipitation	Silt to fine sand	10–20%	Lenticular, Reticulate, Ataxitic	1s of m ²	0.2–1	NA
Nonpatterned	Flat to steep slopes	Drained, precipitation	Sand and gravel	0–10%	Lenticular, Pore	NA	<0.2	NA

Study Areas

The pilot scale analyses were conducted for the three national park units within the CAKN network. A small test area (10 x 10 km) was chosen for each park unit by NPS personnel. The test area for the unit in Denali National Park and Preserve is located in the north Toklat River basin, and is roughly centered at 63° 49' 30" N, 150° 07' 00" W. This study area falls within the Yukon Tanana Upland Ecoregion (Nowacki et al., 2001); the ecoregion narrative description is from Nowacki et al. (2000):

‘These dissected mountains of moderate height are underlain by the metasedimentary Yukon-Tanana terrane sandwiched between the Tintina and Denali Faults. This terrane is a composite of transported crust blocks that includes former volcanic island arcs and continental shelf deposits. The topography of smooth-topped ridges deeply incised by narrow valleys is indicative of a lack of glaciation in the past. Most surfaces are comprised of bedrock and coarse rubble and underlain by discontinuous permafrost. Surface deposits consist of colluvium (gravity-transported materials) due in large part to soil creep and debris flows. Permafrost is discontinuous but widespread, and is particularly abundant on moist lower slopes and valley bottoms. Climate is strongly continental with warm summers and very cold winters. There a slight rainshadow affect from the towering Wrangell and St. Elias Mountains to the south. This area straddles treeline with vegetation ranging from alpine tundra on ridges and upper slopes to boreal forests on lower slopes and valleys. Stunted black spruce woodlands occur on cold, north-facing slopes whereas mixed forests (spruce, aspen, birch, poplar) occur on warm south-facing slopes. This area includes the highest incidence of lightening strikes in the Yukon and forest fires are consequently frequent. Caribou, moose, snowshoe hares, marten, lynx, black bear, and wolverine are abundant mammals.’

The test area for the unit in Yukon-Charley Rivers National Preserve is located on the right bank of the Yukon River, and is roughly centered at 65° 22' 00" N, 142° 51' 24" W. This study area falls within the North Ogilvie Mountains Ecoregion (Nowacki et al., 2001); the ecoregion narrative description is from Nowacki et al. (2000):

‘This terrain consists of flat-topped hills and eroded remnants of a former plain. This area represents the western extent of the North America stable platform onto which terranes radiating from the Pacific and Arctic oceans have attached. Sedimentary rocks, especially limestone, underlie most of the area. Ridgetops and upper slopes are often barren with angular, frost-shattered rock outcrops (resembling castellations) surrounded by long scree slopes. These are characteristics of an unglaciated area that has undergone long periods of erosion. Shallow soils have developed in rocky colluvium on mountainsides where landslides, debris flows, and soil creep frequently occur. On lower slopes, soils are deeper, moister, and underlain by extensive permafrost. Low shrub tundra of willow, alder, and birch and aspen and spruce woodlands occur

at lower elevations. These mountains are the source of many streams that eventually feed the Porcupine, Yukon, and Peel rivers. Lakes are relatively rare. A strong continental climate prevails, with prolonged frigid winters lasting from October to May and cool, short summers. Brown bears, wolverine, Dall sheep, caribou, lemmings, and pikas are common inhabitants of these mountains.'

The test area for the unit in Wrangell-St. Elias National Park and Preserve is located adjacent to the Chetaslina River, and is roughly centered at 61° 51' 00" N, 144° 40' 00" W. This study area falls within the Copper River Basin Ecoregion (Nowacki et al., 2001); the ecoregion narrative description is from Nowacki et al. (2000):

'This mountain basin lies within the former bed of Glacial Lake Ahtna on fine-textured lacustrine deposits ringed by coarse glacial tills. The basin is a large wetland complex underlain by thin to moderately thick permafrost and pockmarked with thaw lakes and ponds. A mix of low shrubs and black spruce forests and woodlands clothe the wet organic soils. Cottonwood, willow, and alder line rivers and streams as they braid or meander across the basin. Spring floods are common along drainages. Arctic grayling, burbot, and anadromous sockeye salmon are common fishes. Black and brown bears, caribou, wolverines, and ruffed grouse are present throughout these wetland habitats. The climate is strongly continental, with steep seasonal temperature variation. The basin acts as a cold-air sink and winter temperatures can get bitterly cold.'

Methods

Co-Registration of Images

For each test area the airphotos and satellite image were co-registered to facilitate comparison. The positions of the Landsat TM images were accepted as accurate and all other products were registered to the Landsat image. For the photography, the small-scale photos were initially orthorectified with ERDAS Imagine software using camera model information, fiducial marks, and distinct landmarks (usually small ponds with distinct shoreline features). Once one photo was co-registered to the satellite image, all other photos were rectified to the first set of photos because of higher resolution of control points. The old B&W airphotos, however, were not orthorectified due to lack of fiducial marks. Five to ten control points were used for each rectification.

Photo-Interpretation

Thermokarst features were delineated on airphotos for small test areas in DENA (1987 1:6,000 scale true color), WRST (1957 1:40,000 scale B&W, 1997 1:40,000 CIR), and YUCH (1984 1:63,360 scale CIR) based on manual photointerpretation. Thermokarst features were identified based on their shape (typically round), landscape position (lowland depressions or basins), topographic relief around the margins (banks),

contextual position of water, and spectral characteristics diagnostic of various vegetation types associated with thermokarst (e.g., dwarf birch-ericaceous shrub bogs, wet meadows, herbaceous meadows). The delineation was done on-screen. After delineation, the thermokarst features were classified according to degradation stage based on degree of vegetation establishment (Table 4).

Table 4. Classification and description of permafrost-degradation stages. The stages are most evident in ice-rich soils with high thaw-settlement characteristics.

Class	Description
Frozen	Areas with permanently frozen soils that show no signs of permafrost degradation. These areas frequently have stunted vegetation (black spruce, dwarf birch, tussocks) and thermokarst features in the surrounding area. This class is difficult to differentiate in upland areas with sandy or rocky soils that lack periglacial or thermokarst features.
Unfrozen	Areas with perennially unfrozen soils associated with newly deposited material or southern exposures in the discontinuous permafrost zone, and where permafrost has not been present for centuries. This class is difficult to differentiate in upland areas with sandy or rocky soils that lack periglacial or thermokarst features. Collapse features are absent.
Degrading, Initial	The initial stage of permafrost degradation shows the first indications of thaw settlement or changes in vegetation growth or composition. Settlement generally is less than 0.5 m in ice-rich soils. Water is usually absent at the surface.
Degrading, Advanced	Advanced degradation has undergone substantial thaw settlement. Water is usually present at the surface (at least during the snowmelt period) and the original vegetation usually has been killed. Thermokarst features include thermokarst lakes, collapse-scar bog, pits and polygonal trough networks, high-centered polygons, gullies, and sink holes. Degradation is difficult to determine in ice-poor areas.
Degradation, Morainal	Degradation of ice-cored moraines is a special type of degradation where the glacial ice has thawed and the surface has collapsed into kettle basins. In moraines deposited by the last major glaciation, the degradation occurred mostly during the early Holocene. There are areas of recent glacial retreat, however, where degradation of subsurface glacial ice is still active.
Stabilization, Initial	Initial stabilization occurs when the ground has entirely thawed or revegetation processes are starting to affect the radiation balance and heat flux. Vegetation usually has early successional species that are colonizing the recently changed soil or water environment. Water is often present in the center of the thermokarst features, but the margins of the features are vegetated.
Stabilization, Advanced	Advanced stabilization differentiates the stage when ground ice has totally thawed or when permafrost starts regrading in areas where the permafrost was not totally thawed. Vegetation is characterized by late-successional species. Water is absent due to the infilling of vegetation.

Point-sampling was used to determine the abundance of thermokarst on the WRST airphotos (1957 B&W, 1997 CIR) by determining terrain characteristics at 100 systematically distributed points. At each point for each year, the geomorphic unit, surface form (macrotopograph), vegetation (Viereck Level IV), and degradation stage were classified. Each point represented 1% cover and the percent cover of thermokarst features were cross-tabulated by year. The classification of 100 point took about 2 hours.

Spectral Classification

After thermokarst areas were manually delineated and classified, spectral signatures for each thermokarst class were generated using region-growing software (ERDAS 8.6) for use in supervised classification. Five to ten signatures were created for initial and advanced stabilization classes for all images. Fewer signatures were acquired for advanced degradation regions because they occurred much less frequently in study areas. After signatures were generated, each signature was evaluated using a signature mask. Parallelepiped limits were revised for each signature to emphasize thermokarst features and reduce misclassified pixels. Some signatures were deleted because they were not spectrally distinct from other landscape features leaving a reduced set of signatures for classifying each image. Classifications were run nonparametrically using revised parallelepiped limits with overlapping signature assignments resolved by parametric (maximum likelihood) analysis, and non-assigned pixels left unclassified.

Results and Discussion

We found large differences in the ability of various remote imagery products to detect thermokarst presence and stage. A summary of the areal extent of various classifications of permafrost degradation within the three pilot-scale test areas by park, year, and analytical technique is found in Table 5. Imagery overlays from the test evaluations of the photo-interpretation, point sampling and spectral classification methods are found in Appendix A, and are referenced in the discussion below.

Photointerpretation of Aerial Color Photography

Photointerpretation of high resolution color photography was used successfully in all three study areas to delineate permafrost degradation. Photointerpretation has the advantages of being able to detect thermokarst based on vegetation characteristics, micro-topographic differences evident in stereoscopes, and the shape of the feature associated with various types of thermokarst.

Wrangell-St. Elias

Photointerpretation at WRST was complicated by the presences of morainal kettle basins which appear similar to some low-lying thermokarst features. By using a stereoscope with paired aerial photography, we were able to discern the larger topographic relief of the kettle basins which was differentiated from the thermokarst associated with flat, low-lying terrain. The delineation of the 1997 CIR photography is shown in Figure 3.

Table 5. Areal extent of permafrost degradation within three pilot-scale test areas by park, year, and analytical technique. Degradation stages were classified as degradation-moraine (DM), degradation-active (DA), stabilization-initial (SI) and stabilization-advanced (SA).

Park	Year	Image Type	Analysis	Percent Area of Degradation Stage					Accuracy of Spectral Classification (%)
				DM	DA	SI	SA	Total	
Wrangells-St Elias	1957	BW Photo	PI	1.5	0	2.0	0.7	4.2	
	1957	BW Photo	Point Sampling	1	0	0	1	2	
	1997	CIR Photo	PI	1.5	0	0.4	1.3	3.3	
	1997	CIR Photo	Point Sampling	1	0	0	1	2	
	1997	CIR Photo	Spectral	ND ^a	1.4	2.3 ^b	0.4 ^b	3.9	22
	2002	Landsat	Spectral	ND	0.2	2.0	2.1	4.3	31
Denali	1987	Color Photo	PI		0.0	0.8	0.8	1.6	
	1987	Color Photo	Spectral		0.4	3.9	-	4.3	4
	1996	SPOT	Spectral		0.0	1.0	1.3	2.3	11
Yukon-Charley	1980	CIR Photo	PI		0.7	1.0	5.1	6.9	

^a Degradation of glacier ice in moraines lumped with SA.

^b Denotes that the SI and SA categories overlap

Denali

Photointerpretation was used to delineate permafrost degradation using the 1987 DENA color photography. Thermokarst features and degradation states were delineated (Figure 4), with the exception of an active degradation stage, which was not discerned in the study area. The 1987 photointerpretation was used as an overlay for comparison to other image types. Photointerpretation in this area was complicated by the presence of bog vegetation in prevalent swales in the area. For this area, only features with distinct rims were differentiated as collapse-scar features. In addition, this area was unique in that a few small patches had high-centered polygons that indicate the thawing of ice-wedges.

Yukon-Charley

Photointerpretation was used to delineate permafrost degradation using the 1984 YUCH photography. Thermokarst features and degradation states were delineated (Figure 5), and the 1984 photointerpretation was used as an overlay for comparison to other image types. Thermokarst lakes and collapse-scar bogs formed distinct features on the colluvial and abandoned floodplain terrain. Both distinct vegetation and the round shape of the features contribute to the distinct photo-characteristics. This area also had a few patches with mixed thermokarst pits and polygons.

Photointerpretation of Aerial Black and White Photography

Wrangell-St. Elias

Photointerpretation was used to delineate permafrost degradation using the 1957 WRST black and white photography. Thermokarst features and degradation states were delineated (Figure 6), and compared well when overlain with the boundary delineation of water and collapse scar features from the 1997 color photography. Comparisons of the degradation stages from 1957 and 1997 show very little active degradation during that 40-year period (Figure 7). The B&W photography was more difficult to interpret because of the poor contrast of the photographs. Many features were resolved only because they were first delineated on the 1997 photography so we knew where to look for the features on the 1957 photography.

Denali

We were not able to use the DENA digital orthographic quads for photointerpretation of permafrost features, due to the extremely low quality of the photographs. The lack or correlation between the 1987 photo delineation and the 1955 black and white photos is seen in Figure 8.

Yukon-Charley

Thermokarst features on the 1954 photography were examined visually by overlaying the thermokarst delineations from the 1984 photography over the 1954 photography (Figure 9). Boundary delineations were not done. The visual examination revealed that the thermokarst features were distinctly evident on the 1954 photography and that there has been only minor change over the 30 year period. Only at one thermokarst lake was active thermokarst evident with 7–11 m of bank erosion on one side over the 30 year period (~3 m/yr). This is only slightly larger than the co-registration accuracy.

Point Sampling of Aerial Color Photography

Wrangell-St. Elias

Point-sampling was used to determine the abundance of thermokarst on the WRST airphotos. Figure 10 displays the location of 100 systematically distributed points for the 1997 CIR photography. Point-sampling resulted in a significant underestimation of the areal extent of all four types of degradation stage; in fact, areas of active degradation and initial stabilization were not detected at all using the point sampling method.

Point sampling of Black and White Photography

Wrangell-St. Elias

Point-sampling was also used to determine the abundance of thermokarst on the 1957 WRST black and white airphotos, using 100 systematically distributed points. As with the color photography, point-sampling resulted in a significant underestimation of the areal extent of all four types of degradation stage; areas of active degradation and initial stabilization were not detected at all using the point sampling method.

Spectral Classification of Aerial Color Photography

Wrangell-St. Elias

Figure 11 presents the results from a spectral analysis of the 1997 WRST CIR photography. The accuracy of the CIR spectral analysis was 22% when compared to the photointerpretation with the 1997 photography. The low accuracy was reflected in an overestimation of percent area of active degradation and initial stabilization stages, and an underestimation of the percent area of the advanced stabilization stage. The occurrence of similar bog vegetation in the kettle bogs and old meltwater channels contributed to the large overestimation of the areal extent of the thermokarst.

Denali

Figure 12 presents the results from a spectral analysis of the 1987 DENA CIR photography. The accuracy of the CIR spectral analysis was 4% when compared to the photointerpretation with the 1987 photography. While thermokarst basins were consistently classified, the spectral classification also erroneously identified many spruce forests as having active degradation (waterbodies) and many other low-lying bogs and tussock-dominated areas as having thermokarst. The lack of differentiation of topography and contextual analysis and the lack of distinct spectral characteristics associated with thermokarst all contributed to the low accuracy. A significant factor in the poor accuracy was the late date (14 Sept) of the photography, which was taken after the vegetation had senesced.

Visual Interpretation of Landsat

Denali

The Landsat products were of limited value in being able to delineate thermokarst features, either through photointerpretation or spectral analysis. In Figure 13, the boundary delineations of water and collapse scar features from the 1987 DENA color airphoto photointerpretation are overlain onto the 2000 DENA Landsat image. Correlation between the known features on the overlay and the underlying Landsat image is essentially non-existent, due to the low resolution and relatively poor quality of the Landsat image.

Yukon-Charley

In Figure 14, the boundary delineations of water and collapse scar features from the 1984 YUCH color airphoto photointerpretation are overlain onto the 1999 YUCH Landsat image. Though large waterbodies are apparent in the Landsat image, the low resolution prevents the identification of the permafrost degradation stage of those features. Smaller features cannot be resolved at all on the Landsat image.

Spectral Classification of Landsat

Wrangell-St. Elias

In Figure 15, the boundary delineations of water and collapse scar features from the 1997 WRST color airphoto photointerpretation are overlain onto the 2002 WRST Landsat image. Again, the low resolution of the Landsat image prevents any identification of most thermokarst features identified on the aerial photography.

Figure 15 also presents the results from a spectral analysis of the 2002 WRST Landsat image. Though some permafrost-degradation stages are identifiable using spectral analysis, the accuracy is low. This is because the spectral characteristics of the thermokarst feature often extend beyond those features in other areas not underlain by permafrost. For example, spectral analysis may be used to detect dwarf birch-ericaceous shrub vegetation in bogs; however, the same signal is prevalent across much of the rest of the photograph, forcing the analyst to rely on pattern and shape to discriminate between types of features. With the low visual resolution of the Landsat product, such resolution of topographic patterns related to collapse is extremely difficult or impossible.

Spectral Classification of SPOT

Denali

The SPOT satellite imagery was unable to provide a delineation of thermokarst features, either through photointerpretation or spectral analysis. In Figure 16, the boundary delineations of water and collapse scar features from the 1987 DENA color airphoto

photointerpretation are overlain onto the 1996 DENA SPOT image. Correlation between the known features on the overlay and the underlying SPOT image is essentially non-existent, due to the low resolution, large pixel size, and relatively poor quality of the SPOT image.

Figure 17 presents the results from a spectral analysis of the 1996 DENA SPOT image. The accuracy of the SPOT spectral classification was about 11% when compared against the photointerpreted classification. Though better than the DENA CIR spectral classification, it was poor when compared to the WRST Landsat spectral classification accuracy of 22%. Such low accuracy precludes the use of SPOT spectral data for analysis of permafrost degradation. Interestingly, the spectral classification of the Landsat TM and SPOT satellite imagery was better than that of the color photography, presumably due to the better spectral resolution and the presence of a near-infrared band.

Photointerpretation of Radarsat

Denali

We were unsuccessful in delineating thermokarst features in the Radarsat imagery of the DENA test area. In Figure 18, the boundary delineations of water and collapse scar features from the 1987 color airphoto photointerpretation are overlain onto the 2003 Radarsat image. Correlation between the known features on the overlay and the underlying radar image is essentially non-existent. Though a few large black objects are discernible in the radar image as large waterbodies, the low resolution and noise speckling inherent in the radar return prevent the delineation of smaller features or patterns.

Other Satellite Imagery Not Evaluated

Though the satellite imagery (Landsat, SPOT, Radarsat) tested in our pilot-scale evaluations did not provide adequate resolution, other satellite platforms and products with high resolution are currently operational. The resolution of these satellites will provide imagery that can be used for boundary delineation of permafrost features.

Pan-sharpened multi-spectral color imagery is available from the IKONOS satellite with a resolution of 1 m (Spaceimaging, n.d.). The Quickbird satellite can provide 61-centimeter class panchromatic and 2.5-meter multispectral data (DigitalGlobe, n.d.). Both satellites provide stereo imagery. Based on the results from this study for resolution requirements and our previous experience with satellite imagery on other projects, it is apparent that satellite-based, high resolution, multispectral platforms such as IKONOS are capable of providing the imagery necessary for long-term monitoring of permafrost and detection of related biophysical landscape change.

Recommendations for CAKN Network

We developed a series of recommendations that provide the experimental design and technical approach necessary to monitor changes in the nature, abundance, distribution, stability, and ecological consequences of permafrost degradation under a warming climate. The recommendations are based on the review of the literature, the pilot-scale evaluation of several remote sensing techniques, and on our experience in monitoring permafrost degradation across both tundra and boreal ecosystems. Accordingly, we recommend three main components to the program that include: (1) an initial assessment of the risks of permafrost degradation, (2) establishment of a network of field monitoring sites in high risk areas, and (3) remote sensing to quantify changes in the regional abundance and distribution of thermokarst. These components are described below.

Assessment of Potential for Permafrost Degradation

The assessment for future thermokarst in the CAKN should be assessed either through one of three approaches or a combination of the three approaches listed below.

- Use photo-interpretation at 500 points per park to establish current abundance of thermokarst and to classify the terrain characteristics that are susceptible to thermokarst.
- Use the existing ecological subsection maps as the basis for qualitatively characterizing the susceptibility of the terrain to thermokarst.
- Develop spatially explicit thermal models of ground temperature distribution, coupled with a surficial geology map to identify areas at highest risk for thermokarst.
- In addition to these map-based strategies, a field inventory should be made of the varying modes of permafrost degradation that occur in each park and the nature and ice contents associated with permafrost-affected ecosystems. This would entail descriptions and sampling from shallow cores and bank exposures at 20–30 sites per park.

Field Monitoring

- A network of 3–5 monitoring toposequences (1–2 km long) should be established within each park to document thermal, physical, and biological processes associated with thermokarst. The monitoring transects should be oriented across topographic gradients, include thermokarst features, and cross as many ecotypes as possible. The monitoring transects should be located in areas of high risk for thermokarst (typically lowland areas with ice-rich, fine-grained soils) that already have some thermokarst features, have little potential for future disturbance by humans, and easy access for monitoring. Sampling should be done every three years, which would allow a three-year rotation among the parks in the network.
- Along each toposequence, thermal monitoring should be done with inexpensive temperature data loggers to record shallow (–5 cm) and deep (1.5 m) soil temperatures in each of the 5–8 dominant ecosystem types. Ground elevations,

surface and groundwater elevations, and thaw depths should be measured at close intervals. Initially, shallow coring (2–3 m) should be done within each ecotype to document ground ice morphology and volume to calculate thaw settlement properties. Optionally, vegetation plots should be established along environmental gradients within the collapse-scar bogs to monitor plant succession after initial collapse. The soil temperature and ground ice data could be used for modeling responses across larger areas.

- A deep borehole for temperature monitoring should be established at each park to document deep thermal changes in collaboration with the USGS and UAF borehole monitoring program. In addition, the active layer should be instrumented with temperature sensors every 10 cm to allow measurement of active layer dynamics. Preferably the borehole would be established near one of the monitoring transects. These should be monitored every 1-3 years.
- Official designation as a GCOS/GTOS site can lead to substantial advantages for research groups or national agencies when requesting funding. By participating in an international network of sites, the significance and impact of measurements are greatly increased. The CAKN should consider becoming a contributing member of the international organizations that have established long-term permafrost monitoring networks.

Remote Sensing

- A network of 10–20 monitor sites (10 x 10 km) should be established for monitoring changes in the abundance and distribution of thermokarst using remote sensing.
- High-resolution (1–2 m) multi-spectral satellite imagery of the sites should be acquired every 10 years. If rapid changes become evident, the interval should be shortened to 5 years. Alternatively, digital aerial photography (1:10,000 to 1:20,000 scale, >1,000 dpi) can be substituted, depending on cost and reliability. Imagery should be acquired in mid-summer to the extent possible.
- Permafrost degradation should be delineated through photointerpretation of imagery because accurate mapping of thermokarst features is dependent on both pattern recognition, micro-topographic differences evident in stereoscopes (advantage of airphotos), and vegetation patterns. The mapping should classify the thermokarst mode (e.g. thermokarst lake, collapse-scar bog), degradation stage (e.g., Initial Stabilization), microtopography, and vegetation type of the thermokarst features. If future improvements in software for spectral analysis and pattern recognition allow automation, this can be considered.
- LIDAR (light detection and ranging) imagery should be evaluated at several test sites. This technology has the potential for providing data for analyzing vertical and volumetric changes.
- The initial classification and mapping of thermokarst requires expertise in permafrost science, geomorphology, soils, hydrology, and vegetation. Once the initial network is mapped, mapping of subsequent changes can be done with less technical expertise.

References

- AeroMap U.S. (n.d.). Lidar. Retrieved May 6, 2004, from <http://www.aeromap.com/lidar.htm>.
- Bockheim, J.G., and K.J. Hall. 2002. Permafrost, active-layer dynamics and periglacial environments of continental Antarctica. *South African Journal of Science*, 98, January/February, pp. 82-90.
- Brown, J. 1998. Active layer monitoring: Circumpolar Active Layer Monitoring (CALM) Program Network: Description and data. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital Media.
- Burgess, M.M., D.W. Riseborough, and S.L. Smith. 2000. Permafrost and glaciers/icecaps monitoring networks workshop; report on the permafrost sessions. Geological Survey of Canada, Ottawa. January 28-29, 2000.
- Chapman, B. 1995. Basic principles of SAR interferometry: SAR interferometry and surface change detection. Retrieved April 1, 2004, from <http://southport.jpl.nasa.gov/scienceapps/dixon/report2.html>.
- Drozдов, D.S. 2004. Information and cartographical modeling of natural and technogenic geological objects in geocryology. Ph.D dissertation abstract. Institute of Siberian Branch of Russian Academy of Sciences. In Russian.
- DigitalGlobe. (n.d.). Basic imagery, retrieved April 15, 2004, from http://www.digitalglobe.com/product/basic_imagery.shtml
- Gillespie, A.R., D. H. Clark, E.J. Steig, and N. Potter. 1997. The geomorphic and climatic significance of rock glaciers: an AGU Chapman Conference Report. *EOS* 78 (20), 208-209.
- GTN-P. (n.d.). A Strategy for the Global Terrestrial Network for Permafrost (GTN-P) of the Global Climate Observing System (GCOS) and Global Terrestrial Observing System (GTOS). Retrieved April 1, 2004, from http://www.geography.uc.edu/~kenhinke/CALM/gtn_p_calm.html.
- Heginbottom, J.A. 2002. Permafrost mapping: a review. *Progress in Physical Geography*, 26:4. pp. 623-642.
- Hoelzle, M., D. Vonder Muhll, and W. Haeberli. 2002. Thirty years of permafrost research in the Corvatsch-Furtschellas area, eastern Swiss Alps: a review. *Norwegian Journal of Geography*, Vol. 56, 137-145. Oslo.
- Keller, F. et al. 1998. Permafrost map of Switzerland. 7th International Conference on Permafrost. Yellowknife, June 23-27, 1998. Proceedings.

Lewkowicz, A.G., and C.R. Duguay. 1999. Detection of permafrost features using SPOT panchromatic imagery, Fosheim Peninsula, Ellesmere, N.W.T. *Canadian Journal of Remote sensing*, 25, 34-44.

Lillesand, T.M., and R.W. Kiefer. 2000. *Remote sensing and image interpretation*. Fourth edition. John Wiley and Sons, Inc. New York.

Jorgenson, M.T., C.H. Racine, J.C. Walters, and T.E. Osterkamp. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. *Climate Change*, Vol. 48, 551-579.

MacCluskie, M., and K. Oakley. 2002. Central Alaska Network vital signs monitoring plan, Phase 1 report. National Park Service, Fairbanks, AK. 115 pp.

McGinnis, L.D. 1981. Dry Valley drilling project. American Geophysical Union, Antarctica Research Series, Vol. 33.

Melnikov, E.S. 1998. Catalog of boreholes from Russia and Mongolia. In International Permafrost Association Standing Committee on Data Information and Communication (comp.). 2003. Circumpolar Active-Layer Permafrost System, Version 2.0. Edited by M. Parsons and T. Zhang. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. CD-ROM.

Melnikov, E.S., and M.A. Minkin. 1998. On the strategy of the development of electronic geoinformation systems (GIS) and databases in geocryology. *Earth's Cryosphere*. Vol. 2, No. 3, pp. 70-76.

Morrissey, L.A. 1988. Predicting the occurrence of permafrost in the Alaskan discontinuous zone with satellite data. In *Proceedings, Fifth International Conference*. August 2-5, 1988. Trondheim. Tapir Publishers, 1988, pp. 213-217.

NASA. (n.d.). Landsat program. Retrieved April 1, 2004, from <http://geo.arc.nasa.gov/sge/landsat/landsat.html>.

Nolan, M., and P. Prokein. 2003. Evaluation of a new DEM of the Putuligayuk watershed for arctic hydrologic applications. In: *Proceedings Eighth International Conference on Permafrost*. Zurich, Switzerland 21 - 25 July 2003. pp. 833-839.

Nowacki, G., P. Spencer, T. Brock, M. Fleming, and T. Jorgenson. 2000. Narrative descriptions for the ecoregions of Alaska and neighboring territories. Final draft. Companion report to U.S. Geological Survey Open-File Report 02-297 (map).

Nowacki, G., P. Spencer, M. Fleming, T. Brock, and T. Jorgenson. 2001. Ecoregions of Alaska: 2001. U.S. Geological Survey Open-File Report 02-297 (map).

- Odegard, R.S., K. Isaksen, M. Mastervik, L. Billdal, M. Engler, and J.L. Sollid. 1999. Comparison of BTS and Landsat TM data from Jotunheimen, southern Norway. *Norsk Geogr. Tidsskr.* Vol. 53, 226-233. Oslo. ISSN 0029-1951.
- Osterkamp, T.E. 2003. Establishing long-term permafrost observations for active layer and permafrost investigations in Alaska: 1977-2002. *Permafrost and Periglac. Process.* 14: pp. 1-13.
- Osterkamp, T.E., D.C. Esch, and V.E. Romanovsky. 1998. Permafrost, in Weller, G. and P.A. Anderson (eds.), *Implications of global change in Alaska and the Bering Sea Region*. Center for Global Change and Arctic System Research, University of Alaska, pp. 115-127.
- Osterkamp, T.E., L. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle, and R. D. Boone. 2000. Observations of thermokarst and its impact on boreal forests in Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research*. Vol. 32, No. 3, pp. 303-315.
- Pavlov, A.V. 1997. Permafrost-climatic monitoring in Russia: methodology, observation results, and forecasting. *Earth's Cryosphere*. Vol. 1, No. 1, pp. 47-58.
- Sjogren, D.B., B.J. Moorman, and P.W. Vachon. 2003. The importance of temporal scale when mapping landscape change in permafrost environments using interferometric synthetic aperture radar. In: *Proceedings Eighth International Conference on Permafrost*. Zurich, Switzerland 21 - 25 July 2003. pp. 1057-1062.
- Smith, S.L. and Burgess, M.M. 2000. Ground temperature database for northern Canada; Geological Survey of Canada Open File Report #3954, 57 p.
- Smith, S.L. and Burgess, M.M. 2002. Permafrost thickness database for northern Canada Geological Survey of Canada Open File Report 4173.
- Spaceimaging. (n.d.). IKONOS, retrieved April 15, 2004, from <http://www.spaceimaging.com/products/ikonos/>.
- SPOT. (n.d.). SPOT image technical information, retrieved March 1, 2004, from http://www.spotimage.fr/html/_167_.php.
- SPRI. (n.d.). Scott Polar Research Institute, Russian information transfer program, retrieved April 10, 2004, from <http://www.spri.cam.ac.uk/resources/russian/>.
- Streletskaia, I.D., M.O. Leibman, L.A. Gerhart, C.D. Haggerty, and A.M. Brennan. 1998. Russian Permafrost Map Bibliography And Index, 1998. In: *World Data Center-A for Glaciology/National Snow and Ice Data Center (NSIDC)*, Boulder, Colorado, USA.
- UAF. (n.d.). Permafrost laboratory, Geophysical Institute, UAF. Retrieved April 1, 2004, from <http://www.gi.alaska.edu/snowice/Permafrost-lab/index.html>.

UAF. (n.d.). Bonanza Creek long-term ecological research. Retrieved April 20, 2004, from http://www.lter.uaf.edu/publications/lter2004/lter4_files/methods/bg3-1.html.

USGS. 1996. Permafrost map of Alaska. U.S. Geological Survey EROS Alaska Field Office. Anchorage. Source map is from Ferrians, O.J., 1965, Permafrost map of Alaska, USGS Miscellaneous Investigations Map I-445.

USGS. (n.d.). Eros data center. Retrieved April 1, 2004, from <http://edc.usgs.gov/products/aerial/mapping.html>.

Van Everdingen, R.O. 1998. Multi-language glossary of permafrost and related ground ice terms. Editor. International Permafrost Association.

Vonder Muhll, D., C Hauck, and H. Gubler. 2002. Mapping of mountainous permafrost using geophysical methods. *Progress in Physical Geography* 26, 4, pp. 643-660.

Appendix A- Imagery overlays from the pilot-scale test evaluations.

Figure 3. 1997 photo delineation over 1997 CIR airphoto.

Figure 4. 1987 photo-delineation over 1987 color airphotos.

Figure 5. 1984 photo-delineation over 1984 CIR airphoto.

Figure 6. 1957 photo-delineation over 1957 black and white photo.

Figure 7. 1957 photo-delineation over 1997 CIR air photo.

Figure 8. 1987 photo-delineation over 1955 black and white photo.

Figure 9. 1984 photo-delineation over 1954 black and white air photo.

Figure 10. 1997 permafrost point samples on 1997 CIR air photo.

Figure 11. 1997 spectral analysis and 1997 photo-delineation over 1997 CIR air photo.

Figure 12. 1987 spectral analysis and photo-delineation over 1987 color air photo.

Figure 13. 1987 photo-delineation over 2000 Landsat image.

Figure 14. 1984 photo-delineation over 1999 Landsat image.

Figure 15. 2002 spectral analysis and 1997 photo-delineation over 2002 Landsat image.

Figure 16. 1987 photo-delineation over 1996 SPOT image.

Figure 17. 1996 spectral analysis and 1987 photo-delineation over 1996 SPOT image.

Figure 18. 1987 photo-delineation over 2003 radar image.

