PERMAFROST DATABASE DEVELOPMENT, CHARACTERIZATION, AND MAPPING FOR NORTHERN ALASKA

Final Report

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

Permafrost is a unique characteristic of polar regions and high mountains and is fundamental to geomorphic processes and ecological development in permafrost-affected environments. Because permafrost impedes drainage and ice-rich permafrost settles upon thawing, degradation of permafrost in response to climate change will have large consequences for tundra and boreal ecosystems (Osterkamp 2005, Jorgenson and Osterkamp 2005, Shur and Osterkamp 2007, Jorgenson et al. 2010, 2013). Thawing permafrost affects surface hydrology by impounding water in subsiding areas and enhances drainage of upland areas. Changes in soil drainage alter soil carbon dynamics, habitats for vegetation and wildlife, and emissions of greenhouse gases (Ping et al. 2002, Grosse et al. 2011), but the magnitude of these changes is highly dependent on the type and amount of ground ice, surficial materials, and thaw-settlement characteristics (Shur 1977, 1988, Shur and Osterkamp 2007, Pullman et al. 2007, Jorgenson 2008a). Despite the critical importance of permafrost to ecosystem responses to climate change, permafrost characteristics of Alaska have been mapped in only generalized regional maps (Ferrians 1965, Jorgenson et al. 2008b), and site-level terrain unit maps for engineering design and impact assessments (Kreig and Reger 1982, Jorgenson et al. 2004). An intermediate-level map is needed to improve landscape-level assessments, regional climate impact modeling and prediction, and as an intermediate step toward developing a larger scale surficial geology/permafrost map for Alaska. In turn, progress in improving permafrost maps will depend on compilation and acquisition of field data that form the basis for photo-interpretation and spatial extrapolation.

Permafrost has been mapped through correlation with mapping of terrain units (Kreig and Reger 1982), airborne electromagnetic (AEM) surveys (Minsley et al. 2012), and modeling of soil temperatures from terrain conditions (Marchenko et al. 2008). The terrain-unit approach, with permafrost properties summarized for each terrain unit, has been used for mapping permafrost along the Trans-Alaska Pipeline System (Kreig and Reger 1982), predevelopment terrain analysis for oil development on the Colville Delta (Jorgenson et al. 1997) and the National Petroleum Reserve in Alaska (NPRA) (Jorgenson et al. 2004), and for statewide permafrost mapping (Jorgenson et al. 2008b). AEM surveys provide reliable delineation of permafrost boundaries, but are not effective at quantifying ground ice conditions and high costs make it suitable for only small areas (Minsley et al. 2012). Mapping permafrost distribution through numerical modeling can reliably predict permafrost boundaries and subsurface temperatures, but also does not provide information on ground-ice characteristics. For region-wide characterization and mapping of permafrost, we used the terrain-unit approach for mapping landscape-level units (1:1,000,000 scale), attributing the map polygon with dominant geomorphic units, and characterizing those units through compilation and analysis of borehole data available from government agencies, industry, literature, and our own studies.

Specific objectives of the project are to:

(1) Compile existing soil/permafrost data into a region-wide permafrost database;
(2) Develop detailed descriptions of permafrost characteristics by geomorphic units;
(3) Develop thematic permafrost maps through revision and attribution of an existing landscape-level map;
(4) Produce a 1:250,000 scale map of geomorphic units for a small area to evaluate methods and costs;
(5) Develop maps of permafrost vulnerability to climate change through rule-based modeling; and
(6) Distribute the database and maps through the GINA website.

STUDY AREA

The area covered by this project (Figure 1) was primarily the Beaufort Coastal Plain, Brooks Foothills, Northern Brooks Range, Southern Brooks Range ecoregions, which were already covered by existing landscape-level (subsections) mapping (Jorgenson et al. 2003, 2009). The mapping, however, extends beyond these ecoregions into the southern Arctic National Wildlife Refuge, Gates of the Arctic National Park, and Kotzebue Sound Lowlands.

METHODS

PERMAFROST DATA COMPILATION

Data on permafrost stratigraphy and physical characteristics were compiled from 11 available sources and entered into an Access database called the NoAK Permafrost Database (Table 1). These data come from a wide range of permafrost studies involving intensive soil sampling from cores and pits, descriptions of soil profiles and exposures, surficial geology mapping surveys, and geotechnical and geophysical exploration for development. Conoco Phillips Alaska generously gave permission for use of data from the Colville Delta and Fish Creek environmental studies but we are still working on a formal agreement for public access to the data. Other data compiled here are already open to public access.

Table 1. Sources of permafrost-soils data.

Project	Source/Owner	Reference	Sites (n)
FWS AWNR Long-term monitoring	ABR/FWS	Jorgenson et al. 2003a	5
CPAI NPRA Environmental Study	ABR/CPAI	Jorgenson et al. 2004	113
NSF ARCSS Coastal Dynamics	UAF-ABR/NSF	Ping et al. 2013, Kanevskiy et al. 2013, Dou et al. 2009; Lynn 2008, 2009, Michaelson et al. 2008	166
NSF Permafrost Dynamics	UAF-ABR/NSF	Kanevskiy et al. 2011, Unpublished	30
EPSCOR Permafrost Vulnerability	UAF-Alaska Ecoscience/NSF	Unpublished	20
NSF ARCSS Thermokarst	Alaska Ecoscience/NSF	Bowden et al. 2012	43
ADOT Arctic Transportation Planning Geophysics	UAF/ADOT	Schnabel et al. 2012	16
NSF Ice-wedge degradation	UAF-Alaska Ecoscience/NSF	Unpublished	199
ARCO/CPAI Environmental Study	ABR/ARCO	Jorgenson et al. 1997	74
ADGGS Surficial Geology	ADGGS	Rawlinson 1993 (lacks ground ice)	102
Palmer Research Center Soils	PRC-UAF	NRCS Statsgo	93
		Total	861

The data were compiled into an Access database that includes tables for site information, soil stratigraphy, soil physical laboratory data (particle-size distribution, bulk density, moisture), and soil chemical data. Because of the volume and inconsistency of the data, data compilation for many of the fields was incomplete. The database is publically available through a web-based interface developed by GINA. The site information includes 77 fields with information on source, observers, location, geomorphology, hydrology, chemistry, soil, and vegetation. The soil stratigraphy table includes fields for horizon depths, texture, coarse fragments, and ice morphology and volume. When available, site and soils photographs and drawings were compiled and subsets of images were selected for web distribution.

GEOMORPHIC UNITS

CLASSIFICATION

For permafrost characterization and mapping for northern Alaska we used a terrain-unit approach. Geomorphic units were distinguished on the basis of geomorphology and surficial geology according to the terrain-unit classification system developed by Kreig and Reger (1982) and modified by Jorgenson et al. (1997, 2004, 2009). This approach assumes that ground ice volume and distribution and other permafrost characteristics have a close correlation with geomorphic units, because the process of ground-ice accumulation is controlled by soil texture and properties, surface topography, vegetation, geologic history, and conditions of permafrost formation. Such correlations have been demonstrated by several permafrost studies in various areas of northern Alaska (Jorgenson et al. 1997, 1998, 2004, 2011; Shur and Jorgenson 1998; Pullman et al. 2007; Kanevskiy et al. 2011, 2013).

Permafrost characteristics were quantified by geomorphic units from the database and used to assess ground-ice distribution with depth. Short summaries of the main characteristics of the geomorphic units were provided in tabular form.

MAPPING

A prototype map was developed at 1:250,000 scale to better differentiate geomorphic units, because the 1:1 M scale mapping typically includes complexes of geomorphic units. Because of the large effort and cost uncertainties involved in mapping geomorphic units at 1:250,000 scale across the entire North Slope, the prototype mapping evaluated mapping methods, the classification system, and hour requirements for mapping a small test area. The prototype area was the Umiat Quadrangle because it ranges from the coastal plain to the lower and upper foothills, and includes older glaciated terrain. The area already has an engineering geology map by Carter and Galloway (1986), which is one of the latest engineering geology maps available for the region. In addition, most of the area is covered by higher-resolution orthorectified SPOT imagery available from GINA. The Umiat engineering geology map, however, was not available digitally and used the USGS Quadrangle as a base map, so the accuracy of its alignment with modern georectified imagery needed improvement. The mapping involved several steps: (1) georectification of the scanned engineering geology map for the Umiat Quandrangle; (2) manual digitizing and modification of the original polygons as necessary during digitizing through manual image interpretation to better match satellite imagery; and (3) coding of the polygons with a region-wide terrain-unit classification (adapted from Kreig and Reger 1982 and ADGGS

1983). Minimum polygon size was 0.2 km^2 (2 mm diam. at published scale) for waterbodies and 0.5 km^2 for all other geomorphic units. During prototype mapping, several issues were evaluated, including: (1) whether to use old USGS hydrography from the 1950s or digitize new waterbody boundaries on the recent satellite imagery; (2) how much modification of the old mapping is needed because of the use of better base imagery; (3) whether additional modifications need to be made to the classification system to better represent permafrost conditions; and (4) what is the effort per unit area of the new mapping. For this effort, the goal was to map the entire quadrangle, but the actual area mapped was smaller based on allocated funds. Development of a more precise estimate of the effort per unit area allows better estimation of the cost of covering the entire North Slope. The map was done within an ESRI geodatabase in UTM, NAD83 projection.

PERMAFROST-SOIL LANDSCAPES

CLASSIFICATION

The classification of permafrost-soil landscapes was based on the ecological landscapes map of Jorgenson and Grunblatt (2013). The ecological landscapes are an integration of climate, physiography, geology, and unconsolidated lithologies. It incorporates the bedrock geology classification of the Natural Resources Conservation Service (Schoenberger 2012) and the upper levels of the engineering geology classification of Kreig and Reger (1982).

MAPPING

A new landscape-level (1:1,000,000 scale) permafrost map was developed by: (1) revising an existing landscape-level map; (2) attributing the map units with permafrost characteristics; and (3) developing thematic maps of permafrost distribution and properties. We used the existing landscape-level mapping (subsections), which was compiled and modified from maps developed for oil development impact analysis (Jorgenson et al. 2003b), ecoregional planning (Jorgenson and Heiner 2003), and the national park inventory and monitoring program (Boggs 2001, Swanson 2001, Jorgenson et al. 2009). While the Natural Resource Conservation System (NRCS) has developed a new statewide soil landscapes map, the northern portion of the map was based on the northern Alaska subsection map (Jorgenson et al. 2003, 2009) with minor revisions that included deleting upper floodplains and differentiating upper mountain crests. We used the northern Alaska subsection map because it already underwent substantial revision for a previous ALCC-supported effort by Jorgenson and Grunblatt (2013), and the use of this map did not require coordination and approval with NRCS on the revision of their map.

The issue of scale and the extreme heterogeneity of permafrost characteristics, even at the micro-scale is a difficult problem for mapping. Although it would be more reliable to partition variability of ground ice by mapping geomorphic units (similar to engineering geology, surficial geology) at a large scale, this is a large undertaking beyond the scope of this effort. Our approach to dealing with this variability is to map landscape-level units (subsections) and describe the dominant geomorphic units comprising each landscape. These repeating patterns of dominant geomorphic units were grouped by regional or physiographic differences.

The map focused on the top 5 m of permafrost, where permafrost can be more readily mapped from surface features, determined by simple field observations, and where ground ice usually is most abundant. Attribution of the map units was the major focus of the mapping effort.

The polygons on the existing map already were attributed with geographic locality, physiography, generalized geology, generalized lithology (soil texture or rock type), and detailed geology (lithology as described by original reference geology maps). The revised map included new fields for permafrost extent, massive ice volume (classes), maximum potential thaw settlement, thermokarst landforms (primary and secondary), mean annual air temperature (MAAT), and slope (degrees). Permafrost extent was classified as continuous (>90%), discontinuous (50-90%), sporadic (10-50%), or isolated (<10%). MAAT for each polygon was calculated from gridded climate data (PRISM, Oregon State Univ.).

PERMAFROST CHARACTERISTICS AND VULNERABILITY

Permafrost characteristics were assigned to ecological landscapes to provide the basis for assessing the potential response of permafrost to climate warming. First, a tabular listing of permafrost and thermokarst characteristics associated with the generalized geology and ecological landscape classes was developed to categorically rank attributes for slope, segregated and wedge ice volume, maximum potential thaw settlement, and dominant thermokarst landforms (thaw lakes, thaw-lake basins, thermokarst pits and troughs, thaw slumps, active-layer detachment slides). Second, the attributes in the ranking table were linked to the landscape map for thematic presentation of characteristics affecting permafrost vulnerability.

WEB-BASED DATA DISTRIBUTION

Permafrost field data, products and documentation produced by this project (Microsoft Access database, ArcMap geodatabase, final reports) that have no distribution restrictions were provided to UAF-GINA for public discovery and download through the web-based North Slope Science Catalog that is maintained by UAF-GINA. Metadata for these products were compiled by investigators and shared by UAF-GINA with other repositories as appropriate.

A web-based visualization of the field data and map products also was developed by UAF-GINA. The geographic locations of field data collection sites were displayed over user selectable backgrounds that include the landscape-level permafrost map developed under this project. This Access database of permafrost data was converted by UAF-GINA to ESRI shapefiles to allow a subset of the data to be linked to the individual field sites locations in the web-based application. Functionality and display templates were developed by UAF-GINA to allow a user to click on individual field site locations and display the associated field site data. The associated field site information included site and collection information, site photos, soil stratigraphy, and source and citation information.

RESULTS AND DISCUSSION

PERMAFROST DATA COMPILATION

Permafrost soil data were compiled from nine primary sources (Table 1). Data from a total of 861 sites from 11 projects (Figure 1) were compiled into an Access relational database. Most of the site data were obtained from the Beaufort Sea Coast (249), Beaufort Sea Coastal Plain (416), and the Brooks Foothills (140), with lesser numbers of sites from the Northern Brooks Range (28), Southern Brooks Range (15), and Kotzebue Sound Lowlands (12)(Figure 2). For geomorphic units, most of the data were from Coastal Plain (317), Loess, Ice-rich (73), Delta Inactive Overbank (40), Organic Fen (36), Thaw Basin, Ice-rich Center (35), and Drained-lake Basin, Ice-rich Center (28) deposits (Table 2) using the classification in Table 3. There were very few data for colluvium and bedrocks in the Brooks Range. The most complete ground-ice data were from the NSF Coastal Dynamics, NSF Permafrost Dynamics, and NSF Ice-wedge Degradation studies, while other studies often lacked data for many permafrost attributes.

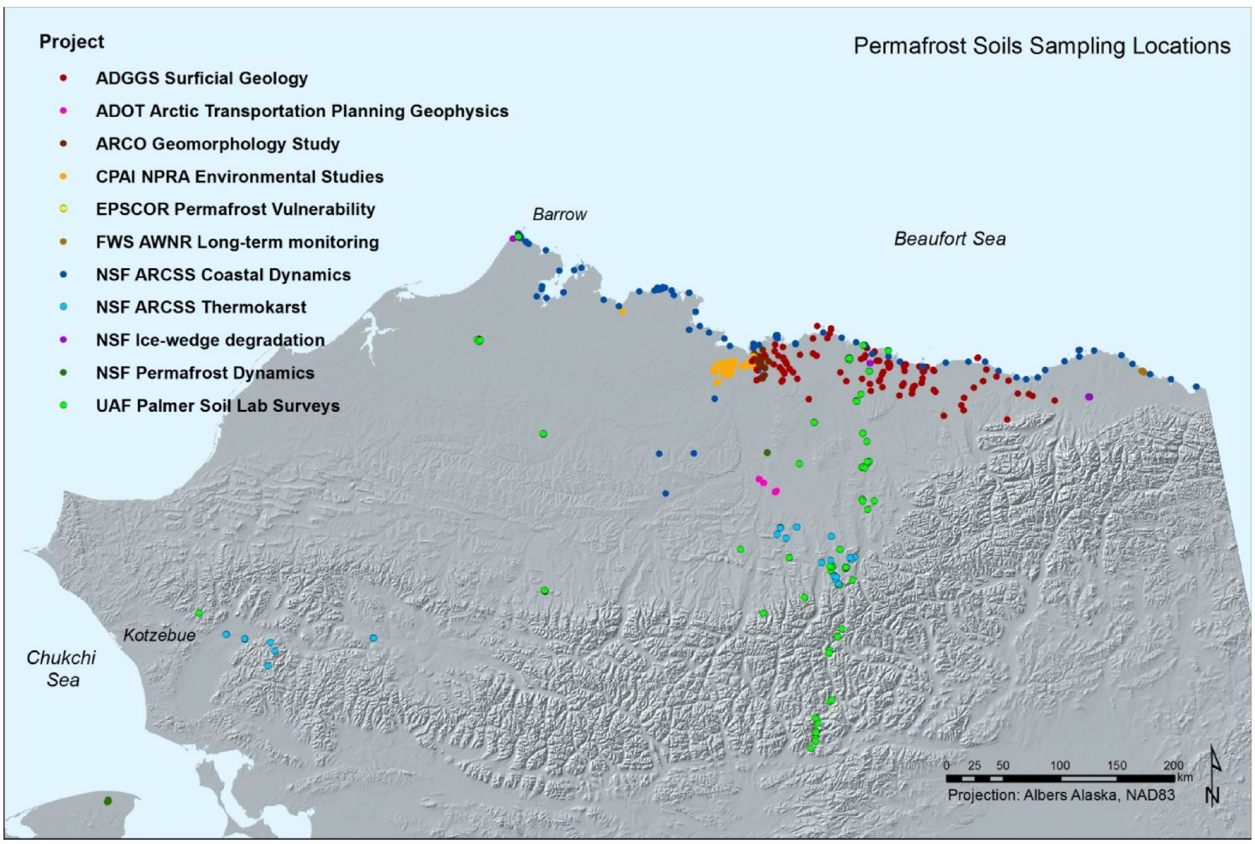

Figure 1. Map of 861 permafrost-soils sampling locations by project, northern Alaska.

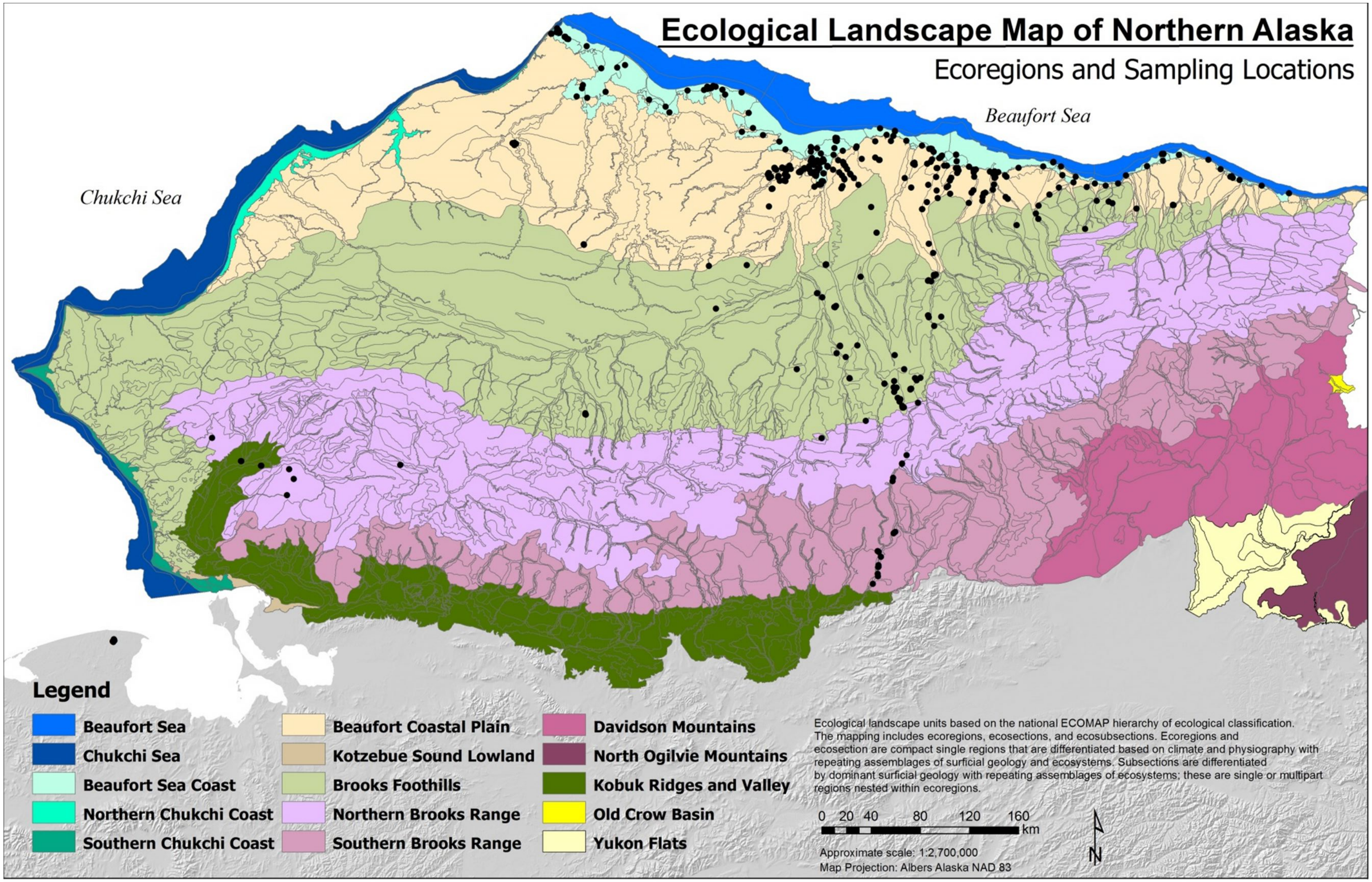

Figure 2. Map of sampling locations in relation to ecoregions (modified from Nowacki et al. 2002).

Ground-ice characteristics were available for the most common geomorphic units in the database, which allows comparisons of the vertical distribution of ice volumes among geomorphic units (Figure 3). A few geomorphic units were generally ice-poor (<50% ice volume, including pore, segregated, and massive ice), such as Eolian Sand that is abundant on the western Beaufort Coastal Plain (Carter 1981) and Floodplain Active Meander Deposits, but most were ice-rich (50–90% ice volume) because of the occurrence of massive ice (mostly ice wedges) and development of quasi-syngenetic permafrost which resulted in formation of the extremely ice-rich intermediate layer of the upper permafrost permafrost (Shur 1988, French and Shur 2010). The extreme variation in ground-ice characteristics is evident in drawings of the soil cores (Figure 4). The extremely ice-rich ataxitic (suspended) cryostructure (cryostructure – a pattern formed by ice inclusions in the frozen soil) was abundant in Coastal Plain, Glaciolacustrine, and Upland Loess deposits, whereas, only pore ice (usually not visible with a naked eye) was commonly found in sandy soils associated with Eolian Sand and Delta Active Channel deposits.

This database will continue to evolve and improve over time. In this initial development, there has been a substantial effort to standardize measurement units and nomenclature. But there is still more effort needed to ensure better consistency in site and stratigraphy classifications and terminology. This is a common issue with soils, permafrost, and vegetation databases compiled from numerous sources reporting work done in differing time periods. Second, there are still numerous sources of data that can be standardized and compiled into the database, though not all of them contain detailed information on ground ice. These include soils data from: Barrow and Okpilak (Brown 1968, 1969); Atkasook, Prudhoe Bay, and Dalton Highway (Everett and Parkinson 1977, Everett 1980, 1981, Bockheim et al. 1998), Chukchi Sea coast (Brigham 1985), deep boreholes in the NPRA (Lawson 1983), deep boreholes along the Trans-Alaska Pipeline System (Kreig and Reger 1982), drained-lake basins near Barrow by Hinkel and Bockheim (Hinket et al. 2003, Bockheim and Hinkel 2005, 2012); Noatak (Hamilton 2010); geophysical records of ice-bearing permafrost (Collett et al. 1989), and offshore permafrost drilling for geotechnical surveys (Bruggers and England 1982, Miller and Phillips 1996, 1998).

Table 2. Summary of sites (n) in permafrost database by geomorphic unit and ecoregion.

Geomorphic Unit	Beaufort Coast	Beaufort Coastal Plain	Kotzebue Sound Lowlands	Brooks Foothills	Northern Brooks Range	Southern Brooks Range	Grand Total
Alluvial Fan, Inactive	1				1		2
Alluvial Terrace, Old		10		4			14
Beach, Young	2						2
Beach, Old	2						2
Braided Abandoned Overbank Deposit	1	9		3			13
Braided Active Overbank Deposit				1			1
Braided Inactive Overbank Deposit		4				3	7
Coastal Beach, Old	2						2
Coastal Plain (alluvial-marine)	42	293					335
Colluvium (creep, solifluction, talus)				19	6	2	27
Delta Abandoned Overbank Deposit	15						15
Delta Active Channel Deposit	9						9
Delta Active Overbank Deposit	10						10
Delta Inactive Channel Deposit	2						2
Delta Inactive Overbank Deposit	41						41
Delta Thaw Basin, Ice-poor	1						1
Drained Lake Basin, Ice-poor Center	2						2
Drained Lake Basin, Ice-poor Margin	2	1					3
Drained Lake Basin, Ice-rich Center	10						10
Drained Lake Basin, Ice-rich Margin	38				1		39
Drained Lake Basin, ice-poor	1						1
Drained Lake Basin, ice-rich		22		1			23
Eolian Active Sand Dune	4						4
Eolian Inactive Sand Dune	6						6
Eolian Inactive Sand Sheet	3	12		1			16
Glaciolacustrine					4		4
Glaciomarine (w/ thin eolian cap)	13						13
Headwater Overbank Deposit, Moderately Steep				2	1	1	4
Lacustrine Deposit				1			1
Loess, Thin				5			5
Loess, Ice-rich (yedoma)	2	1	6	63			72
Meander Abandoned Overbank Deposit		3				1	4
Meander Active Overbank Deposit		1					1
Meander Fine Active Channel Deposit		4					4
Meander Inactive Overbank Deposit		11					11
Moraine, Older				6	6	1	13
Nearshore Water	21						21
not determined	5						5
Retransported Deposit				2	5	6	13
Sedimentary bedrock, noncarbonate				1			1
Thaw Basin, Ice-poor Center		4					4
Thaw Basin, Ice-poor Margin		2					2
Thaw Basin, Ice-rich Center		27	6	2			35
Thaw Basin, Ice-rich Margin	2	11		2			15
Thaw Basin, Pingo		1					1
Thaw Basin, undifferentiated				2			2
Tidal Flat, Active	8						8
Tidal Flat, Inactive	8						8
Till, Young				17	7	2	26
Till, Old				13	1		14
Total	250	416	12	140	28	15	861

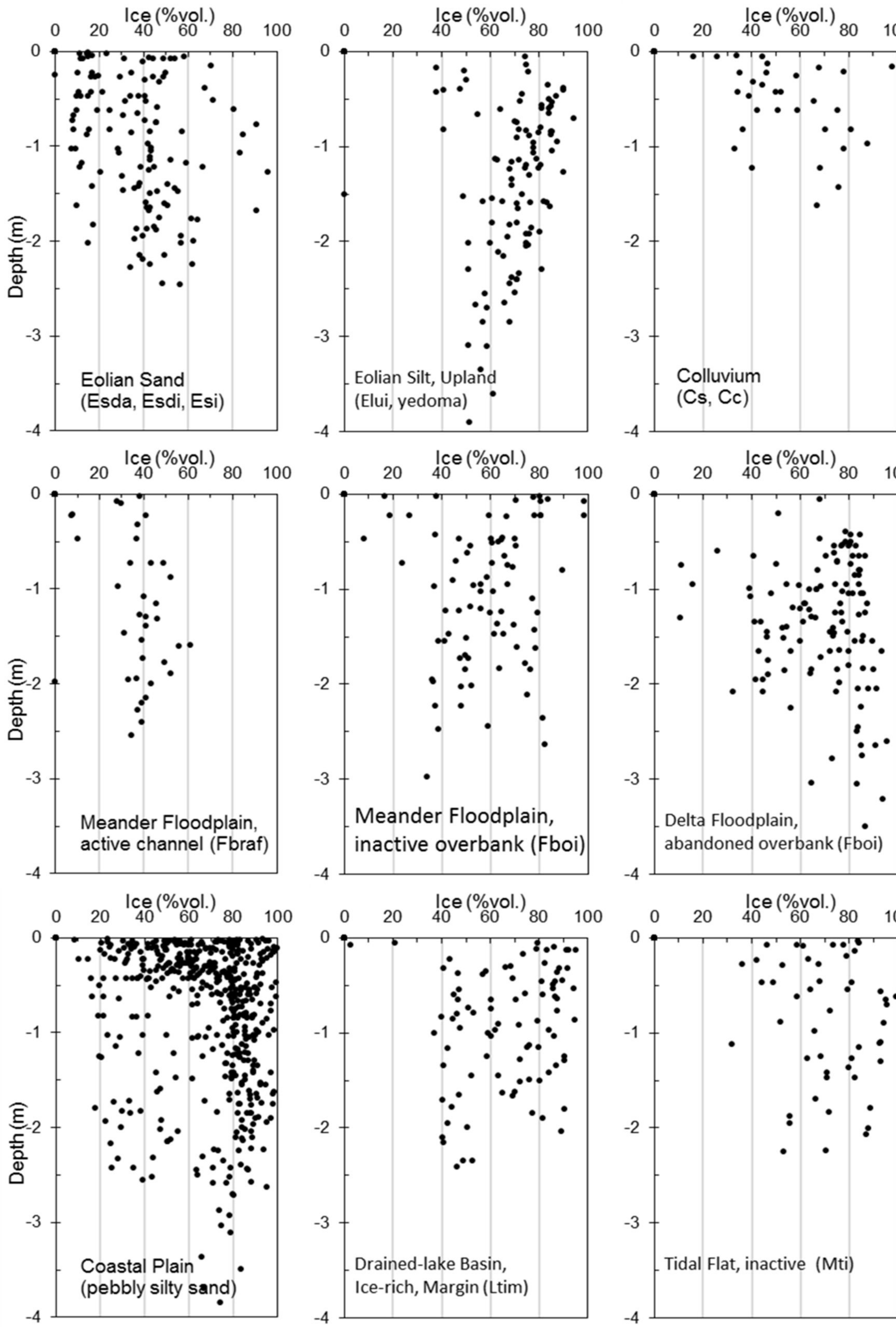

Figure 3. Volumetric moisture content by depth for common geomorphic units (excluding ice wedges), northern Alaska.

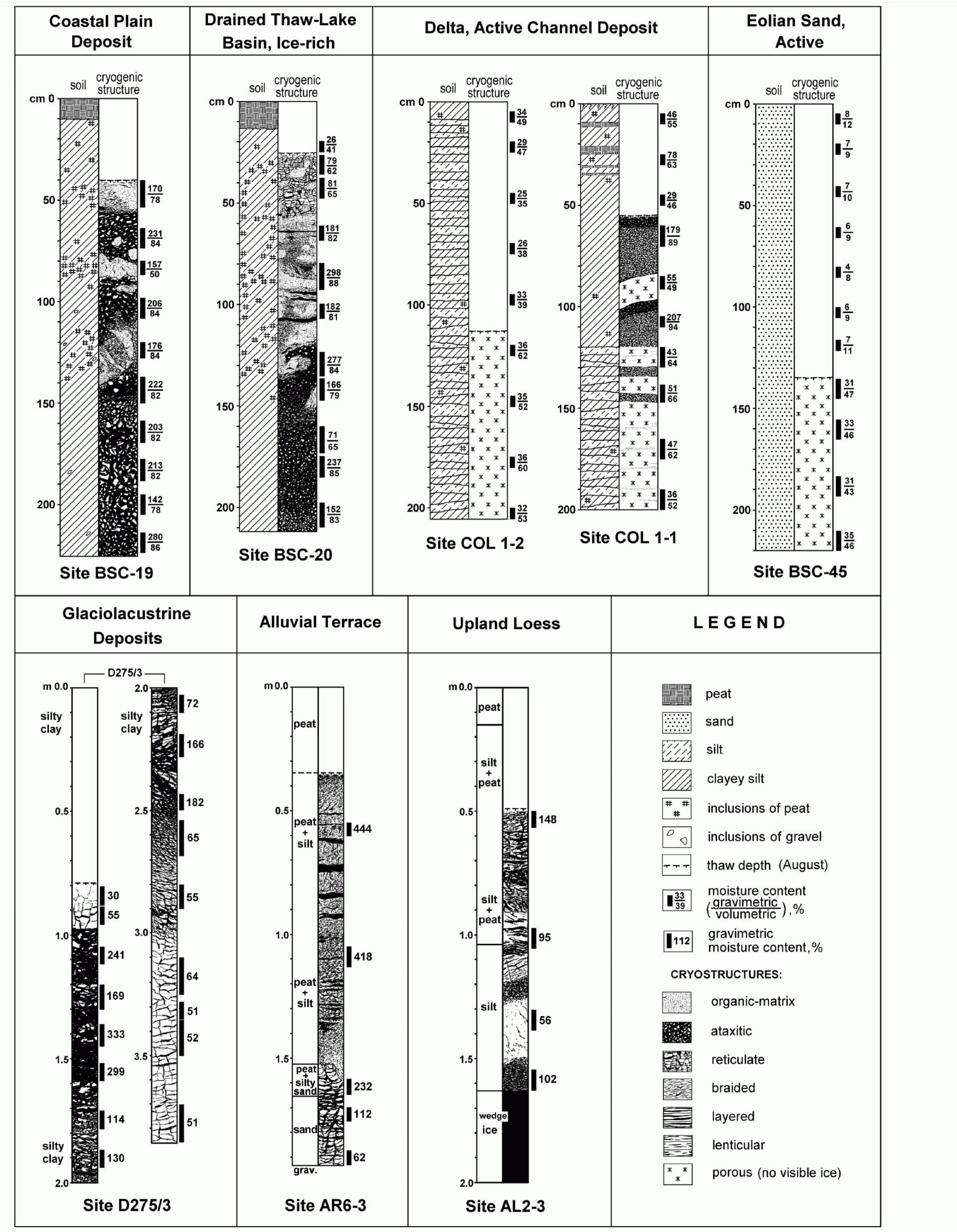

Figure 4. Representative drawings of cores illustrating the range in ice volumes and cryostructures (ice is black).

GEOMORPHIC UNITS

CLASSIFICATION AND DESCRIPTIONS

A geomorphic unit classification was compiled that is similar to the engineering geology classification of Kreig and Reger (1982), but differs in placing more emphasis of terrain age and surface soil development, characteristics that are important to permafrost development. The classification and descriptions include 74 of the most common geomorphic units, including 14 waterbody types (Table 3).

MAPPING

A prototype map of geomorphic units at 1:250,000 scale was developed for a portion of the Umiat Quandrangle (Figure 5). The mapping was based on the newly compiled and revised geomorphic classification, and new digitizing registered to the orthorectified SPOT imagery available from GINA. The existing engineering geology map of Carter and Galloway (1986) was used for reference. The map currently covers 1942 km^2 (10% of the Umiat Quad) and the dominant geomorphic units include ice-rich loess (yedoma, 951 km^2), abandoned braided overbank (198 km^2), inactive meandering overbank (157 km^2), thaw-lake plains (124 km^2), and ice-rich thaw-lake basins (102 km^2) deposits.

The new map is similar to the Carter and Gallowy map in terms of the distribution of loess, floodplains, thaw-lake basins, and lakes. There are several areas of improvement, however. First, the accuracy of the boundary delineation was improved by the use of geo-referenced, high-resolution (2.5 m) imagery, compared to the use of the old USGS topographic maps. Second, a more detailed classification was used for characterizing the terrain. This is particularly evident for floodplains, where channel and overbank deposits and floodplain morphologies were differentiated, and for drained thaw-lake basins, where ice-rich and ice-poor basins were differentiated. This higher-resolution classification better differentiates both surficial materials and ground ice contents that are important for characterizing permafrost. These improvements were mostly attributable to availability of higher quality remote sensing products and accumulation of field data over the intervening ~30-yr period. The quality of the earlier mapping is still impressive.

During prototype mapping, we also evaluated several other production issues to assess how well the methodology could be applied to a regional effort. First, our FWS collaborator Jennifer Jenkins digitized ~200 waterbodies in about 4 hours using the SPOT imagery to provide more accurate delineations compared to the existing NHD data. The NHD waterbodies were quite good, however, with only minor differences in shorelines due to image-base differences, water levels, and locational accuracy. In many cases a simple shift of the waterbodies was sufficient to improve co-registration with the SPOT imagery. Use of the existing NHD waterbodies are sufficient for this scale mapping. Overall, about 60 hours were required to complete the new mapping for the 1942-km^2 area.

Table 3. Description of geomorphic units (adapted from Kreig and Reger 1982). Classification emphasizes relative age of surficial deposit because of strong relationships with ground ice. Bolded units are most common.

Geomorphic Unit	Description
BEDROCK	
Weathered Bedrock (Bxw), undifferentiated	Highly fractured or weathered bedrock. The ground surface has abundance of exposed rock blocks. This unit was limited to alpine areas where soil formation is minimal.
Residual Soil over Weathered Bedrock (Bxr)	Soils have formed from completely weathered material formed from underlying bedrock and little or none of the original primary structures remaining. Typically, there is an increase in particle size at the base of the soil as it grades into weathered bedrock below.
Intrusive-felsic (If)	Felsic and meta- plutonic rocks that have mineral assemblages dominated by light-colored minerals, such as quartz, potassium feldspar, and muscovite. Acidic rocks include granite pegmatite (coarse crystals), granite (fine crystals), granite porphyry (few visible crystals), rhyolite porphyry, and rhyolite (micro-crystals). Soils generally are acidic and podzolization is more fully developed.
Intrusive-intermediate (Ii)	Intermediate composition plutonic rocks that have light to dark-colored mineral assemblages with significant amounts of potassium, calcium, sodium, aluminum, iron and magnesium. Rocks dominated by potassium and plagioclase feldspars include monzomite pegmatite, quartz monzonite, quartz monzomite porphyry, quartz latite, monzonite, monzonite porphyry, and latite. Soils tend to be neutral to alkaline.
Intrusive-mafic (Im)	Mafic plutonic rocks that have dark-colored mineral assemblages with significant amounts of calcium, sodium, aluminum, iron and magnesium. Mafic rocks dominated by pyroxene and plagioclase feldspars include diorite pegmatite; quartz diorite and diorite; quartz diorite, diorite, dacite, and andesite porphyrys; and dacite and andesite. Soils tend to be neutral to alkaline.
Intrusive-ultramafic (Iu)	Ultramafic rocks are rich in olivine and pyroxene and include hornblendite, pyroxenite, dunite, peridotite (olivine), and serpentine. Plant growth tends to be minimal due to lack of calcium and phosphorus and high heavy metal concentrations.
Metamorphic Bedrock, Noncarbonate (Nn)	A diverse group of metasedimentary, metapelitic, and metavolcanic rocks that lack carbonates. Metasedimentary include metaconglomerate, metagraywacke, phyllite, slate, quartzite, and schist (K, Mg, Fe, Al rich), while marble may be a minor component. Metavolcanic rocks include greenschist, greenstones, schists, amphibolite, olivine, and phyllite. Soils tend to be acidic.
Metamorphic, carbonate (Nc)	Metacarbonate sedimentary rocks consisting essentially of calcite and/or dolomite. Rock is primarily marble. Soils tend to be alkaline
Sedimentary, carbonate (Sc)	Sedimentary rocks dominated by carbonate materials, primarily calcite ($CaCO_3$) and magnesite ($Mg\ CO_3$). Rocks include limestone (Ca-rich), dolostone (Ca, Mg-rich), and calcareous sandstone. Soils generally are alkaline and rich in humus. Phosphorus availability is reduced by fixation in various calcium phosphate compounds (hydroxyapatite, flouroapatite). In addition, at pH values above 7, excess calcium may hinder phosphorus absorption and utilization of plants.
Sedimentary, noncarbonate (Sn)	Noncarbonate sedimentary rocks include conglomerate (pebble-cobble rich), sandstone (sand-rich), greywacke, shale (clay-rich), argillite (clay minerals) and chert (SiO2). Generally low Ca and Na and high Al concentrations lead to acid soils.
Volcanic-mafic-older (Vmo)	Mafic and intermediate extrusive igneous rocks have dark-colored mineral assemblages with low silica content and high metallic bases, such as plagioclase feldspar, pyroxenes and olivine (high in Fe, Mg, Ca orthosilicates). Rock types include basalt, andesite, and dacite. The iron- and magnesium-rich minerals are more easily weathered than granites. Rocks were formed during the Tertiary or older periods.
COLLUVIUM	
Colluvium, Creep (Cc)	Apron-like, hillside deposits of loose silty to rubbly unsorted deposits derived directly from weathering of bedrock upslope and moved downslope by frost heave, gravity, and creep. It usually includes some sheet-wash deposits. Thickness often 0.5–2 m and usually vegetated. On mountain slopes downslope of bedrock.
Solifluction Deposits (Cs)	Saturated soil material and rock fragments formed by downslope, viscous flow of the active layer. The unit is identified by the distinct lobate surface mounds.
Talus (Ct)	Angular rubble or rock fragments that have accumulated by gravity at the base of bluffs and steep slopes. The talus makes a cone-shaped deposit, usually at the base of draws and chutes. Also loose, thin accumulations on the steep slopes of coastal and stream bluffs. Varies from pebbly silt and sand to large boulders; massive to poorly bedded, poorly sorted. Often unstable and partially vegetated.

Table 3 (cont.).

Geomorphic Unit	Description
EOLIAN	
Lowland Loess	Windblown silt deposited on poorly drained lowland locations in complex depositional environments near large river floodplains. The deposit may contain a mixture of eolian sand, retransported, and organic deposits in close association with the deposits of massive silt. Small hills generally have a thin cover of loess over eolian sand, whereas swales often contain retransported deposits with higher clay contents or thick organic deposits. In the flat and lowland portions of this unit, the soil is normally frozen with a high ice content. Small collapse-scar bogs are common in boreal.
Upland Loess (Elu)	Windblown silt deposited on well-drained upland slopes. Gully pattern associated with these easily eroded deposits is usually present. Massive silt lack horizontal stratification and coarse fragments. Deposit must be at least 40 cm thick for mapping. Unusually unfrozen on south-facing slopes in the boreal zone.
Loess, Thin (Elt)	Thin (<2 m) eolian silt caps on other deposits. Eolian silt covers large areas but can be highly variable. While not mappable, thin caps can greatly affect ground ice characteristics near the surface and are important for analysis of site specific data.
Upland Loess, Ice-rich (Elui)	Extremely ice-rich Pleistocene-age silt deposits. Also termed yedoma, although term can be used more broadly. The deposits have large syngenetic ice wedges that extend down through most of the deposit.
Eolian Sand, Active (Esa)	Unconsolidated, wind-deposited accumulations of primarily very fine to fine well sorted sand. Sand is stratified with large-scale cross bedding in places. Deposits are barren or partially vegetated and are undergoing active accretion and deflation, typically adjacent to exposed sandy channel deposits. Eolian sand dunes (Esda) is used to distinguished distinct ridge and swale dune forms.
Eolian Sand, Inactive (Esi)	Similar at depth to active eolian sand but often contains buried soils and peat beds in upper few meters. Inactive dunes are well vegetated, typically have thin to thick organic soil horizons at the surface, and are not subject to active scouring or movement. This unit is used for very large sand sheets.
ALLUVIAL	
Braided Active Channel(Fbra)	Sandy to gravelly floodplain materials deposited by rivers where the channels form a braided pattern due to the high sediment load. Due to the frequent disturbance associated with flooding and erosion and deposition, the surfaces are barren or vegetated with only scattered willows and herbaceous plants.
Braided Active Overbank (Fboa)	Silty to sandy fine-grained cover deposits (0.5-1 m thick) associated with a braided floodplain that are subject to frequent (every 1-2 years) flood deposition. Due to frequent deposition, organic material does not accumulate at the surface. Typically has early successional vegetation is dominated by alders and willows, although balsam poplar sapling also may be present.
Braided Inactive Overbank (Fboi)	Fine-grained cover or vertical accretion deposits (1-4 m thick) formed from infrequent (every 3-5 years or less frequent) overbank flooding events. Due to the infrequent deposition, organic matter accumulates at the surface and deposits have distinct interbedding of organic and mineral layers. Vegetation is typical of intermediate successional stages and is dominated by wet sedge meadows in tundra regions and balsam poplar and white spruce forests in boreal regions.
Braided Abandoned Overbank (Fbob)	Overbank, vertical accretion deposits with a mixture of peat, silt or fine sand occurring adjacent to braided rivers. Cover deposits tend to be thin (<1 m) over gravel, and typically have at least 20 cm of surface organics over silt-loam or fine sand alluvium. Surface organic horizon is free of fluvial layers, indicating the terrain is no longer affected by riverine processes. Typically, these areas occupy the highest position on the floodplain, and represent the oldest local terrain. In tundra regions, low-center polygons and small ponds are common; in boreal regions black spruce woodlands and low scrub are typical.
Meander Active Channel (Fmra)	Mud to gravel deposited as lateral accretion deposits in active river channels by fluvial processes. Gravel is subrounded to rounded. Frequent deposition and scouring from flooding usually restricts vegetation to sparse pioneering colonizers. Channels have sinuous to only slightly meandering curves and distinctive point bars. Surface is barren due to frequent scouring and deposition. Can be differentiated into sandy/muddy (Fbras) or gravelly deposits (Fbrag).
Meander Inactive Channel Deposits (Fmri)	Similar to active meander channel deposits, but flooded only during high-water events. Riverbed material often has a thin layer of fine-grained material over the coarse channel deposits and surface is usually vegetation. Can be differentiated into sandy (Fbris) or gravelly deposits (Fbrig).

Table 3 (cont.).

Geomorphic Unit	Description
Meander Active-floodplain Overbank Deposit (Fmoa)	Low portions of the overbank environment in close proximity to the river channel that are subject to frequent flooding. Sediments typically are composed of silts and fine sands and have a laminar, interbedded structure formed by changes in velocity and deposition during waxing and waning floods. Frequent deposition prevents organic matter accumulation. Fine-grained material must be >40 cm thick and organic layers comprise less than 10% of the thickness.
Meander Inactive-floodplain Overbank(Fmoi)	Higher portions of the overbank environment in close proximity to the river channel that are subject to infrequent flooding (approx. every 5-25 years). Sediments typically are composed of interbedded organic material, silts and fine sands. Cover material is >40 cm thick and organic layers comprise10–90% of the thickness.
Meander Abandoned-floodplain Overbank (Fmob)	Overbank, vertical accretion deposits with a mixture of peat, silt or fine sand occurring adjacent to meandering rivers associated with fluvial, eolian, and organic processes. Surface organic horizon is free of fluvial layers, indicating the terrain is no longer affected by riverine processes. Typically, these areas occupy the highest position on the floodplain, and represent the oldest local terrain. Abandoned floodplain deposits typically have at least 20 cm of surface organics over silts and sands. In tundra regions, low-center polygons and small ponds are common; in boreal regions black spruce woodlands and low scrub is typical.
Delta, Active Channel Deposit (Fdra)	Silty and sandy riverbed or lateral accretion deposits laid down from the bed load of a river in areas of channeled flow. This unit includes point bars, lateral bars, mid-channel bars, unvegetated high-water channels, and broad riverbed/sandbars exposed during low water. In general, texture of the sediments becomes finer in a seaward direction along the distributaries and in a bankward direction from the deepest portion of the channel (thalweg). Organic matter, including driftwood (mostly small willows), peat shreds, and other plant remains, usually is interbedded with the sediments. Only those riverbed deposits that are exposed at low water are mapped. Frequent flooding (every 1–2 yr.) prevents the establishment of permanent vegetation.
Delta, High-water Channel (Fdri)	Riverbed deposits in channels that are only flooded during periods of high flow. Because of river meandering, these channels are no longer active during low-flow conditions. High-water Channel deposits are similar to those described for Delta Riverbeds. Generally, there is little indication of ice-wedge development, although a few older channels have begun to develop polygon rims. Very old channels with well-developed low-centered polygons are not included in this unit.
Delta, Active-floodplain Overbank Deposit (Fdoa)	Thin (<0.5 m), fine-grained cover deposits (primarily silt) that are laid down over sandier riverbed deposits during flood stages. Relatively frequent (every 3–4 yr) deposition prevents the development of a surface organic horizon. This unit usually occurs on the upper portions of point and lateral bars, has moderately well drained soils and supports low and tall willow vegetation.
Delta, Inactive-floodplain Overbank Deposit (Fdoi)	Fine-grained cover or vertical accretion deposits laid down over coarser channel deposits during floods. The surface layers are a sequence (20–60 cm thick) of interbedded organic and silt horizons, indicating occasional flood deposition. Under the organics is a thick layer (0.3-2 m thick) of silt and fine sand overlying channel deposits. Surface forms range from nonpatterned to disjunct and low-density, low-centered polygons. In tundra regions vegetation is dominated by wet sedge meadows, while in boreal regions forests are common.
Delta, Abandoned-floodplain Overbank Deposit (Fdob)	Peat, silt, or fine sand (or mixtures or interbeds of all three), deposited in a deltaic overbank environment by fluvial, eolian, and organic processes. These deposits generally consist of an accumulation of peat 20-60 cm thick overlying cover and riverbed alluvium. Because these are older surfaces, eolian silt and sand may be common as distinct layers or as intermixed sediments. The surface layer, however, usually lacks interbedded silt layers associated with occasional flood deposition. Lenticular and reticulate forms of segregated ice, and massive ice in the form of ice wedges, are common in these deposits. The surface is characterized by high density, low-relief polygons and represents the oldest surface on the floodplain.
Headwater Floodplain, Lowland (Fhl)	Small, thin deposits formed in the headwaters of small creeks in lowland areas. The low stream gradients (<2%) are associated with bog streams and places where small streams originating from upland areas cross low-lying flat areas. Deposits usually range from gravelly sand to fine-grained and organic-rich silt.
Headwater Floodplain, Moderately Steep (Fhm)	Small, shallow deposits formed in the upland headwaters of small creeks with moderately steep (2–6%) stream gradients. Sediment depositional processes are limited and channel banks are composed of boulder and bedrock materials that limit floodplain development. Channel and overbank deposits are not differentiated.

Table 3 (cont.).

Geomorphic Unit	Description
Alluvial Fan (Ffi)	Gently sloping cone-shaped deposit of alluvium formed where a stream extends onto a relatively level plain such as where streams issue from mountains onto a lowland. Alluvial fans are composed predominantly sands and gravel, but also have varying quantities of silt.
Alluvial Fan, Abandoned (Ffb)	Similar to above, except material was deposited by early fluvial regime that no longer exists. Thus, gravelly deposits have substantial organic layers at the surface or well developed A horizons, indicating a long period since last depositional event.
Retransported Deposits (Fs)	Valley bottoms and lower slopes with fine-grained, organic-rich materials moved downslope by slopewash, solifluction, and piping. Loess also may be incorporated in these deposits. The surface of these areas typically has a feather pattern indicative of small-scale fluvial processes. The soils usually are underlain by ice-rich permafrost in tundra and boreal regions.
Alluvial Terrace (Fto)	Flat, elevated terraces above the current flooding regime composed of fluvial gravelly sand, sand, silty sand, and peat. Deposits usually are overlain by eolian silt and sand and thaw basin deposits. This unit has a high content of segregated and massive ice, as indicated by the presence of ice-wedge polygons and thaw ponds.
GLACIAL	
Moraine, Young (Gmy)	Relatively young moraines with steeper knob and basin topography with a poorly integrated drainage network. The deposits are composed of glacial till deposited at the terminal or lateral margins of a glacier that has since retreated or disappeared. Younger moraines have less basin filling. Sediments are highly variable ranging from poorly sorted sand and subangular gravel with some boulders to sorted coarser subrounded material. Moraine age is Holocene to Late Pleistocene.
Moraine, Old (Gmo)	Similar to above except older moraines have subdued topography with broader knobs and swales and more integrated drainage network. Soils show greater organic accumulation, more leaching and horizon development. Moraine age is mid to early Pleistocene.
GLACIO-FLUVIAL and GLACIO-LACUSTRINE	
Glaciofluvial Outwash, Old (GFo)	Sediments that have been deposited by glacial meltwater streams beyond the terminal glacial margin. The proglacial drift includes outwash fans, deltas, aprons, valley trains, and both pitted and nonpitted outwash plains. Sediments are composed of moderately to well-sorted, clean-washed bedload sand and gravel with some boulders.
Glaciolacustrine Deposits (GL)	Glacial lake deposits composed of interbedded stony silt to stony silty clay, with some silty fine sand, massive to faintly bedded. Contains sparse to abundant subangular to subrounded pebbles, cobbles, and boulders, commonly striated. Glaciolacustrine deposits are abundant in the Noatak region (Hamilton 2010).
LACUSTRINE	
Lacustrine (L)	Silt and clay materials deposited in both glacial and non-glacial lakes. Lake sediments generally are well stratified into very thin laminations, but may also include coarse-grained sediments associated with shorelines and fluvial sediments in deltas and fans.
Drained Thaw Lake Basin, Ice-poor (Ltn)	Drained-lake basins with fine-grained and organic-rich sediments. The stratigraphy of the original sediments has been deformed by subsidence or ice-wedge degradation. The presence of nonpatterned ground or disjunct polygonal rims indicates that ground ice content is low and that lake drainage has occurred recently. Ponds in these basins typically have irregular shorelines and are highly interconnected. Often related to thaw lake development, but drainage can also occur in lowland lakes not developed from thawing permafrost.
Drained Thaw Lake Basin, Ice-rich (Lti)	Distinct basins with sediments are similar to those of ice-poor thaw lake deposits, but have much more ground ice, as indicated by the development of low-centered or high-centered polygons. Waterbodies within these basins tend to be rectangular, to have smooth, regular shorelines, and to be poorly interconnected.
Thaw Lake Plain (Ltp)	The oldest stage of drained-lake basins, where the basin margins and ice-wedge polygons are indistinct. Basins are often overlapping but not separable forming broader plains. Peat and segregated-ice accumulation have smoothed the surface. Surface often has very shallow, small secondary lakes that are infilling.
Delta Thaw Lake Basin, Ice-Poor (Lddn)	Deposits in thaw lakes within deltaic deposits. They usually are connected to a river or to nearshore water (tapped lake) and influenced by changes in river level. During breakup, large quantities of sediment-laden water flow into the lake, forming a lake delta at the point of breakthrough. Sediments generally consist of fine sands, silts, and clays and typically are slightly saline.

Table 3 (cont.).

Geomorphic Unit	Description
MARINE	
Coastal Active Gravelly Beach (Mbga)	Unconsolidated sandy to gravelly coastal deposits in beach, bar, spit, and barrier island deposits, and other littoral and intertidal sediments. Surface is barren or partially vegetated due to active erosion and deposition. Material show stratification, often with crossbedding, indicative to varying depositional energy.
Coastal Old Gravelly Beach (Mbgo)	Older, stabilized beach deposits with subsurface stratigraphy similar to that of active beaches. The beach deposit is often covered with thin layers of eolian silt and sand, as well as organic soil. The deposits typically maintains elevated salinity at depth.
Coastal Lagoon Deposit (Ml)	Nearshore stratified silt and clay, with some sand and gravel, deposited in lagoon and estuarine environments. This deposit includes both recently emerged and subaerial deposits. Deposits are brackish to saline, with gravel fraction often derived from erosion of coastal bluffs.
Tidal Flat, Active (Mta)	Areas of nearly flat, barren mud or sand that are periodically inundated by tidal waters. Tidal flats occur on seaward margins of deltaic estuaries, leeward portions of bays and inlets, and at mouths of rivers. Tidal flats frequently are associated with lagoons and estuaries and may vary widely in salinity, depending on how exposed the flat is to salt-water incursion and the rate of influx of fresh water.
Tidal Flat, Inactive (Mti)	Similar to active tidal flats, but flooded only by during larger storm events. The sediments are only slightly brackish and the surface usually is well vegetated with halophytic plants. Soils have interbedded silts and organic layers indicating infrequent flooding and deposition.
Coastal Plain Deposit (Mp)	Coastal plains are flat regional features situated between coastlines and landward uplands. Deposits have complex interspersion of marine and alluvial deposits associated with past marine transgressions. Composition is variable, often including fluvial gravelly sand, silty sand, and organic silt and/or stratified layers of marine gravelly sand, silty sand, silt and minor clay that occur in some locations beneath the fluvial deposits. The deposits often are overlain by sand and silt and organic-rich lacustrine deposits. Terraces (Mpt) also can be differentiated.
GLACIO-MARINE	
MG	Complex areas composed of marine, glacially derived, and lacustrine deposits. Along the Beaufort Sea coast, the deposit is mostly sandy silt containing scattered pebbles and lenses of sand, clay, pebbly sand, gravel, and occasional erratic boulders up to ~1 m. Mapped as marine silt by NPRATF (1978). Fossil shells, bones of marine mammals, and organic beds are common. This deposit is mostly found between Barrow and Cape Halkett, but occurs in other isolated localities, such as Flaxman Island.
HUMAN-MODIFIED	
Fill and Embankments (Hf)	All forms of artificial fill or embankment materials, including road and foundation embankments, dikes, and other artificial earth fills. Fill is often composed of largely of sand and gravel. Can be differentiated into gravel fill (Hfg) used for roads and pads and peat fill (Hfp) occasionally used for temporary roads.
Excavations (He)	Man-made excavations includes large cuts, gravel removal sites, and other mine pits. Remaining unconsolidated or bedrock material is highly variable depending on local geology.
ORGANIC	
Fen (Of)	Areas with thick (>40 cm) organic deposits associated with minerotrophic ground or surface water movement. Deposits vary from thick fibrous sedge mats in tundra regions, to floating mats of live, fibrous roots and loosely consolidated poorly decomposed organic material in boreal regions. Soils are circumneutral to acidic.
Bog (Ob)	Wet depressions with thick (>40 cm) organic deposits associated with oligotrophic environments lacking groundwater input. Often formed from thermal degradation of ice-rich permafrost. The soils are composed of poorly decomposed sphagnum peat and permafrost is absent. The vegetation is dominated by Sphagnum, although sedges can be abundant in early successional stages.

Table 3 (cont.).

Geomorphic Unit	Description
WATERBODIES	
Brackish Shallow Lake (Wels)	Shallow (<1.5 m), coastal waterbodies that have been partially drained through erosion of banks by adjacent tidal river channels, and are connected to rivers by distinct, permanently flooded channels. The water typically is brackish and lakes generally have broad flat shorelines with silty clay sediments. Salt-marsh vegetation is common along the shores.
Tidal Lakes (Welt)	Coastal lakes and ponds that are flooded periodically with saltwater during high tides or storm surges. Salinity levels often are increased by subsequent evaporation of impounded saline water. The substrate frequently is silt with some clay and fine sand and occasionally contains peat. Connected and isolated ponds were not differentiated from each other.
Tidal River (Wert)	Permanently flooded channels that are affected by daily tidal fluctuations and have correspondingly variable salinity. The channels generally experience peak flooding during spring breakup and lowest water levels during mid-summer.
Deep Lakes, Bedrock (Wldb)	Deep (>1.5 m) ponds and lakes that do not freeze to the bottom during winter. These lakes are found in uplands and highlands and are bedrock controlled. Bottoms are rocky. Deep water prevents permafrost formation. Includes connected (Wldbc) and isolated lakes (Wldbi).
Deep Lakes, Morainal (Wldm)	Deep (>1.5 m) "kettle" ponds and lakes that do not freeze to the bottom during winter. The lakes develop from the melting of glacial ice in moraines, or are moraine damned, and typically have rocky bottoms. Includes connected (Wldmc) and isolated lakes (Wldmi).
Deep Lakes, Dunal (Wldd)	Deep (>1.5 m) ponds and lakes that do not freeze to the bottom during winter. These lakes occur in swales of sand dunes and undulating sand sheets. Bottoms are sandy.
Deep Lakes, Thaw (Wldt)	Deep (>1.5 m) ponds and lakes that do not freeze to the bottom during winter. The thaw lakes develop from the melting of ice-rich permafrost and typically have muddy, organic-rich bottoms. Includes connected (Wldtc) and isolated lakes (Wldti).
Deep Lakes, undifferentiated (Wldu)	Deep (>1.5 m) ponds and lakes that do not freeze to the bottom during winter. The lakes occur in undulating terrain and not attributed to a specific origin. Includes connected (Wlduc) and isolated lakes (Wldui).
Shallow Lakes, Riverine (Wlsr)	Shallow (<1.5 m) ponds or small lakes formed in abandoned river channels or in thaw lakes on floodplains subject to infrequent flooding. Water freezes to the bottom during winter, thaws by early to mid-June, and is warmer than water in deep lakes. Sediments are fine-grained silt and clay. Includes connected (Wldrc) and isolated lakes (Wldri) with or without emergent vegetation.
Shallow Lakes, Thaw (Wlst)	Shallow (<1.5 m) ponds or small lakes formed from thawing permafrost, with or without emergent vegetation. Sediments are fine-grained silt and clay. These ponds most commonly are found within Ice-rich Thaw Basins. Includes connected (Wlstc) and isolated lakes (Wlsti).
Shallow Lakes, Undifferentiated (Wlsu)	Shallow (<1.5 m) ponds and lakes that do not freeze to the bottom during winter. The lakes occur in undulating terrain and not attributed to a specific origin. Includes connected (Wlsuc) and isolated lakes (Wlsui).
Lower Perennial River, Non-glacial (Wrln)	Permanently flooded channels of freshwater rivers where the gradient is relatively low and discharge and water quality are not affected by glacial meltwater. Unusually associated with meandering river channels. Rivers generally experience peak flooding during spring breakup and late summer and lowest water levels during mid-summer.
Upper Perennial River, Non-glacial (Wrun)	Permanently flooded channels of freshwater rivers where the gradient is relatively low to moderate and discharge and water quality are not affected by glacial meltwater. Unusually associated with braided river channels.
Lowland Headwater Stream (Wrhl)	Permanently flooded channels of small headwater streams originating in lowland environments. Water is often brown with high concentrations of dissolved organic carbon.
Moderately Steep Headwater Stream (Wrhm)	Permanently flooded channels of small headwater streams with moderately steep gradients occurring in upland and mountain environments. Channel is often bedrock controlled or has substantial cobbles and boulders. Water typically is clear.

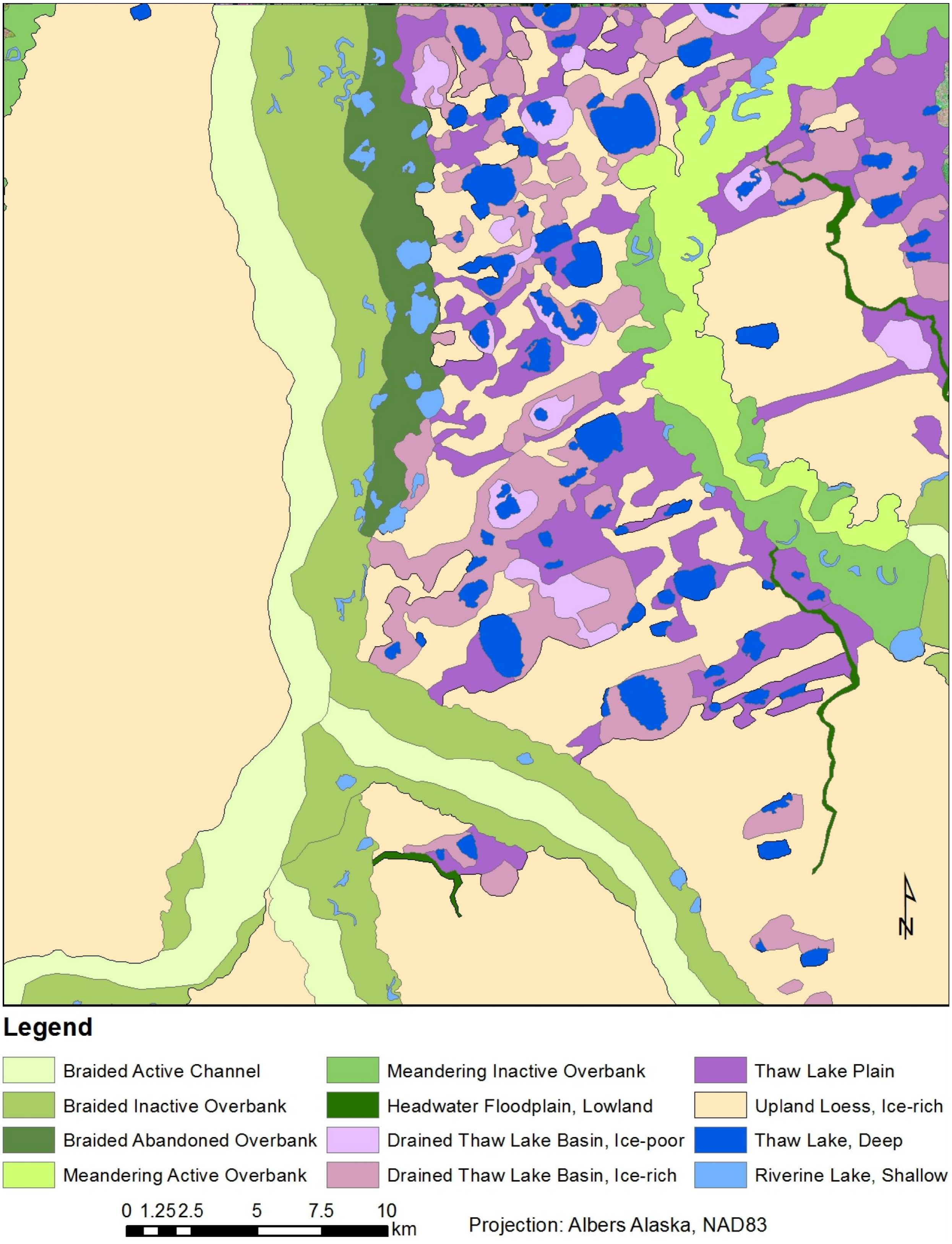

Figure 5. Prototype map of geomorphic units in the Umiat Quadrangle, northern Alaska, 1:250,000 scale.

PERMAFROST-SOIL LANDSCAPES

CLASSIFICATION AND DESCRIPTIONS

The generalized geology classification comprises 35 classes, including 17 surficial deposits and 18 bedrock classes (Table 4). The preponderance of bedrock types is due to the extent and complexity of the Brooks Range, although not all classes in the system were mapped. The classification emphasizes the differentiation of ages of many surficial deposits because of the importance to soil weathering, organic accumulation, and ground-ice development. Generalized geology formed the basis for partioning ground ice and thermokarst characteristics.

LANDSCAPE PROFILES

Each generalized geology class in the landscape-scale mapping comprises numerous geomorphic units that are closely associated with the patterns of geomorphic evolution and permafrost development within the various landscapes. Generalized landscape profiles were developed for some of the dominant geology classes/landscapes in northern Alaska where most of the permafrost studies have been conducted. The profiles show the relationships among geomorphic units, surface forms related to surface processes and ice wedge development, thermokarst, and near-surface stratigraphy (Figures 6–10).

Young and old fluvial deposits typically are associated with meandering floodplain deposits on the Beaufort Sea Coastal Plain, and usually include a sequence from rivers and active channel deposits to active and inactive overbanks deposits on the young portion of floodplains (Figure 6). Abandoned overbank deposits are associated with the older portion of floodplains because they are rarely flooded, have high organic and ground-ice contents, and round thermokarst lakes. Permafrost aggrades and degrades along with this floodplain evolution. Permafrost can be absent in near-surface sediments where the permafrost table is lowered under deeper river channels and usually starts to form near the surface when water depths are less than ~2m. In coarser sands and gravels, ice mainly fills the pores and ice contents are low. In overbank deposits, substantial segregated and wedge ice aggrades in the silty and organic-rich deposits. In abandoned overbank deposits, ice-wedge polygons are well developed and ice contents become sufficiently high that the surface becomes prone to thermokarst lake development. The lakes are occassionally tapped by channel migration, creating a new lower surface subject to high-water flooding and renewed permafrost aggradation.

Young and old fluvial deposits also occur on braided floodplains with steeper gradients and typically occur in the Brooks Foothills (Figure 7). They include a sequence from rivers and active channel deposits to active and inactive overbank deposits on the young portion of floodplains. The channel deposits are gravelly with larger clast sizes than deposits of meandering floodplains. Abandoned overbank deposits are associated with the older portion of floodplains because the are rarely flooded, have high organic and ground ice contents, as indicated by round thermokarst lakes. Inactive and abandoned overbank deposits tend to be much thinner that those on meandering floodplains because the braided floodplains are frequently reworked by more active channel movement. Permafrost tends to have lower contents of segregated and wedge ice because of the coarser textures, thinner overbank deposits, and shorter period of permafrost development because of the channel activity. Thermokarst lakes are uncommon; most lakes are formed in abandoned channels.

Table 4. Classification and description of generalized geology in northern Alaska.

Class	Description
Colluvium, (Cu)	Gravity-transported sediments related to slope movement on middle to upper slopes, including hillside colluvium, retransported deposits (some slope wash), and solifluction.
Colluvium, basin (Cb)	Gravity-transported sediments related to slope movement on lower slopes and basins. Fine-grained and organic-rich deposits formed from a varied of processes, including solifluction, creep, slopewash, and eolian deposition. This also includes retransported deposits that have a substantial fluvial component.
Fluvial, young (Fy)	Fluvially deposited sediments on active to inactive, braided to meandering floodplains formed during the mid-late Holocene. Includes both gravelly and sandy channel and fine-grained overbank deposits. Soils are affected by frequent to infrequent flooding and sedimentation. Primarily differentiates active and inactive floodplains with early to mid-late successional vegetation.
Fluvial, old (Fo)	Fluvially deposited sediments associated with terraces and abandoned floodplains that are no longer affected by the current fluvial regime. Typically has thick fine-grained overbank deposits over gravelly and sandy channel deposits. Retransported deposits are grouped with basin colluvium
Glaciers and Snowfields (Gg)	Areas with ice, firn, and semi-permanent snow. Glaciers have definite lateral limits and motion in a specific direction. Snowfields are covered with snow year-round and show no movement.
Glacial, young (Gy)	Sediments deposited either in direct contact with glacial ice or deposited by meltwater. Composed of Holocene to Late Pleistocene (Wisconsin) moraines or till with more pronounced topography and poorly integrated drainage network. The glacial terrain has highly heterogeneous slopes, soils, and hydrography, often with kettle lakes.
Glacial, old (Go)	Sediments deposited either in direct contact with glacial ice or deposited by meltwater. Composed of Holocene to Late Pleistocene (Wisconsin) moraines with subdued topography, advanced basin filling, and well-integrated drainage network.
Glaciofluvial, young (GFy)	Sediments that have been transported and deposited by meltwater streams which flow within or beyond the terminal margin of an ice sheet or glacier, and includes outwash, kames, and eskers. Sediments are well-stratified sand and gravel with some boulders. Young deposits occur in front of an active glacier.
Glaciofluvial, old (GFo)	Sediments that have been transported and deposited by meltwater streams which flow within or beyond the terminal margin of an ice sheet or glacier. Sediments are well-stratified sand and gravel with some boulders. Old deposits are associated with an earlier glacial activity.
Glaciolacustrine (GL)	Sediments deposited in a wide variety of environments associated with glacial lakes, including grounding-line fans, morainal banks, wedges beneath ice shelves, deltas, and distal environments related to ice-rafting. Sediments tend to be fine-grained, with some sand and occasional striated boulders.
Glaciomarine (MG)	Sediments deposited in a wide variety of environments associated with shallow marine or estuarine waters, including grounding-line fans, morainal banks, wedges beneath ice shelves, deltas, and distal environments related to ice-rafting. Sediments tend to be fine-grained, with some sand and occasional striated boulders.
Eolian silt (El)	Wind-deposited sediments composed of homogeneous, non-stratified, non-indurated silt and very fine sand, with minor amounts of clay. Pleistocene-aged deposits in permafrost areas can be extremely ice-rich and are termed “yedoma”.
Eolian sand (Es)	Wind-deposited sediments composed of very fine to fine sand. Stratification and cross-bedding is common. Eolian sand can form a variety of dune landforms or sand sheets. Soils are generally ice poor.
Lacustrine	Fine-grained mineral and organic sediments deposited in both glacial and non-glacial lakes. Sediments are generally well stratified with very thin laminations, but coarser deposits, such as beaches, bars, deltas, and fans can also be present.
Marine (My)	Sediments deposited within oceans and estuaries and are high in halites (NaCl). Sediments can vary widely in particle size. Deposits include beaches, bars, spits, lagoon bottoms, and tidal flats.
Coastal Plain (Mp)	Complex interspersion of marine and alluvial deposits on coastal plains associated with past marine transgressions. Composition variable, often including stratified gravelly sand, silty sand, and organic silt.
Organic (O)	Thick (>40 cm) deposits of peat, muck, and interbedded fine-grained mineral material in low-lying areas. Organic deposits can be differentiated into ombrotrophic bogs and groundwater fed fens.
Sedimentary, carbonate (Sc)	Sedimentary rocks dominated by carbonate materials, primarily calcite ($CaCO_3$) and magnesite ($Mg CO_3$). Rocks include limestone (Ca-rich), dolostone (Ca, Mg-rich), and calcareous sandstone. Soils formed from these rocks generally are alkaline and rich in humus. Phosphorus availability is reduced by fixation in various calcium phosphate compounds (hydroxyapatite, flouroapatite).

Table 4 (cont.).

Class	Description
Sedimentary, noncarbonate (Sn)	Sedimentary rocks other than limestone, including conglomerate (pebble-cobble rich), sandstone (sand-rich), greywacke, shale (clay-rich), argillite (clay minerals) and chert (SiO_2). Generally low Ca and Na and high Al concentrations lead to acid soils. High soluble aluminum concentrations can lead to plant growth problems. Phosphorus is fixed in large amounts as aluminum and iron phosphates in acid soils.
Sedimentary, mixed (Sm)	Sedimentary assemblage of both carbonate and noncarbonate rocks.
Volcanic-felsic-younger (Vfy)	Felsic extrusive igneous rocks that have light-colored mineral assemblages rich in silica content, such a quartz (SiO2, highly resistant to weathering), orthoclase feldspar (KalSi3O8), and muscovite mica (sheet silicates, Kal3Si3O10). Rocks include rhyolite, felsite, rhyocacite, trachyte, and quartz trachyte. Soils are absent to very thin and acidic.
Volcanic-felsic-older (Vfo)	Similar to above, except rocks formed during Tertiary or older periods and are more highly weathered. Weathering forms acidic soils.
Volcanic-intermediate-younger (Viy)	Intermediate extrusive igneous rocks have dark-colored mineral assemblages with minor silica content and high metallic bases, such as amphiboles (Ca, Na, Mg, Fe rich silicates), biotite mica (sheet silicate rich in Fe and Mg), plagioclase feldspar (NaAlSi3O8, CaAl2Si2O8), and minor potassium feldspar (K). Intermediate rocks include quartz latite and latite
Volcanic-inter.-older (Vio)	Similar to above, except rocks formed during Tertiary or older periods and are more highly weathered. Weathering forms circumneutral soils.
Volcanic-mafic-younger (Vmy)	Mafic and intermediate extrusive igneous rocks have dark-colored mineral assemblages with low silica content and high metallic bases, such as plagioclase feldspar, pyroxenes and olivine (high in Fe, Mg, Ca orthosilicates). The iron- and magnesium-rich minerals are more easily weathered than granites. Mafic rock types include basalt, andesite, and dacite. Soils on the Quaternary age rocks, are absent or thin.
Volcanic-mafic-older (Vmo)	Similar to above except rocks were formed during the Tertiary or older periods and, therefore, are more highly weathered.
Volcanic-pyroclastics-Vp	Detrital volcanic materials that have been explosively or aerially expelled from a volcanic vent. Deposits include pyroclastic flows, volcanic breccia, tuffs, ash, ash-flow, and all other tephras.
Intrusive-felsic (If)1	Felsic and meta- plutonic rocks that have mineral assemblages dominated by light-colored minerals such as quartz, potassium feldspar, and muscovite. Acidic rocks include granite pegmatite (coarse crystals), granite (fine crystals), granite porphyry (few visible crystals), rhyolite porphyry, and rhyolite (micro-crystals). Intermediate acidic rocks lacking quartz include syenite pegmatite, syenite, syenite porphyry, and trachyte. Soils generally are acidic and podzolization is more fully developed.
Intrusive-intermediate (Ii)	Intermediate composition plutonic rocks that have dark-colored mineral assemblages with significant amounts of potassium, calcium, sodium, aluminum, iron and magnesium. Intermediate rocks dominated by potassium and plagioclase feldspars include monzomite pegmatite, quartz monzonite, quartz monzomite porphyry, quartz latite, monzonite, monzonite porphyry, and latite. Soils tend to be neutral to alkaline.
Intrusive-mafic (Im)	Intermediate and mafic plutonic rocks that have dark-colored mineral assemblages with significant amounts of calcium, sodium, aluminum, iron and magnesium. Mafic rocks dominated by pyroxene and plagioclase feldspars include diorite pegmatite; quartz diorite and diorite; quartz diorite, diorite, dacite, and andesite porphyrys; and dacite and andesite. Soils tend to be neutral to alkaline.
Intrusive-ultramafic (Iu)	Ultramafic rocks are rich in olivine and pyroxene and include hornblendite, pyroxenite, dunite, peridotite (olivine), and serpentine. Plant growth tends to be minimal due to lack of calcium and phosphorus and high heavy metal concentrations.
Metamorphic, carbonate (Nc)	Metacarbonate sedimentary rocks consisting essentially of calcite and/or dolomite. Rock is primarily marble.
Metamorphic, noncarbonate (Nn)	A diverse group of metasedimentary, metapelitic, and metavolcanic rocks that lack carbonates. Metasedimentary include metaconglomerate, metagraywacke, phyllite, slate, quartzite, and schist (K, Mg, Fe, Al rich), while marble may be a minor component. Metavolcanic rocks include greenschist, greenstones, schists, amphibolite, olivine, and phyllite.
Metamorphic, mixed (Nm)	A mixture of interspersed carbonate and noncarbonated metamorphic rocks that cannot be mapped separately.
Bedrock Complex (BC)	Complex mixtures of highly interspersed patches of rocks with widely varying lithologies.

[1] Intrusive igneous bedrock classification from NRCS (2002).

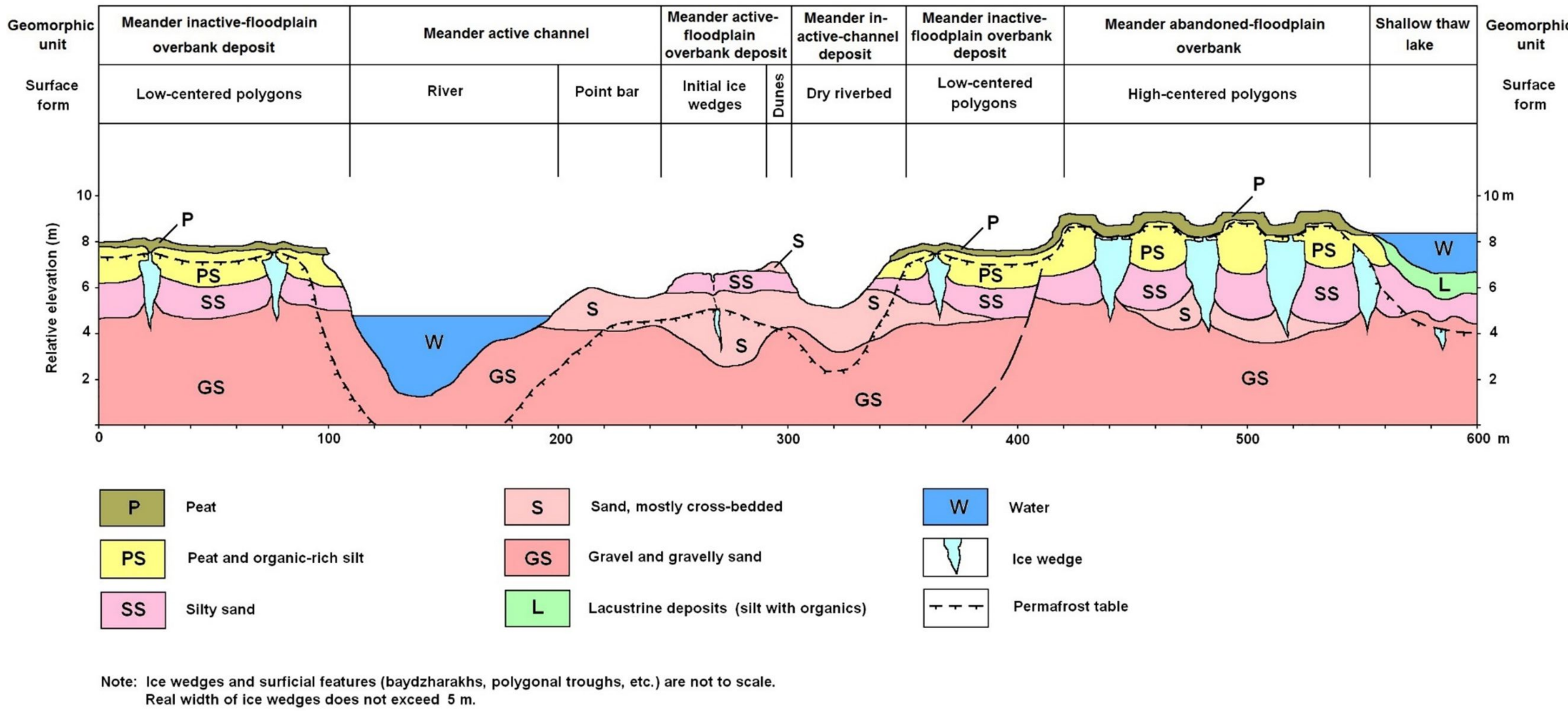

Figure 6. Landscape profile of soil and permafrost features of young and old fluvial deposits on meandering floodplains typical of the Beaufort Sea Coastal Plain.

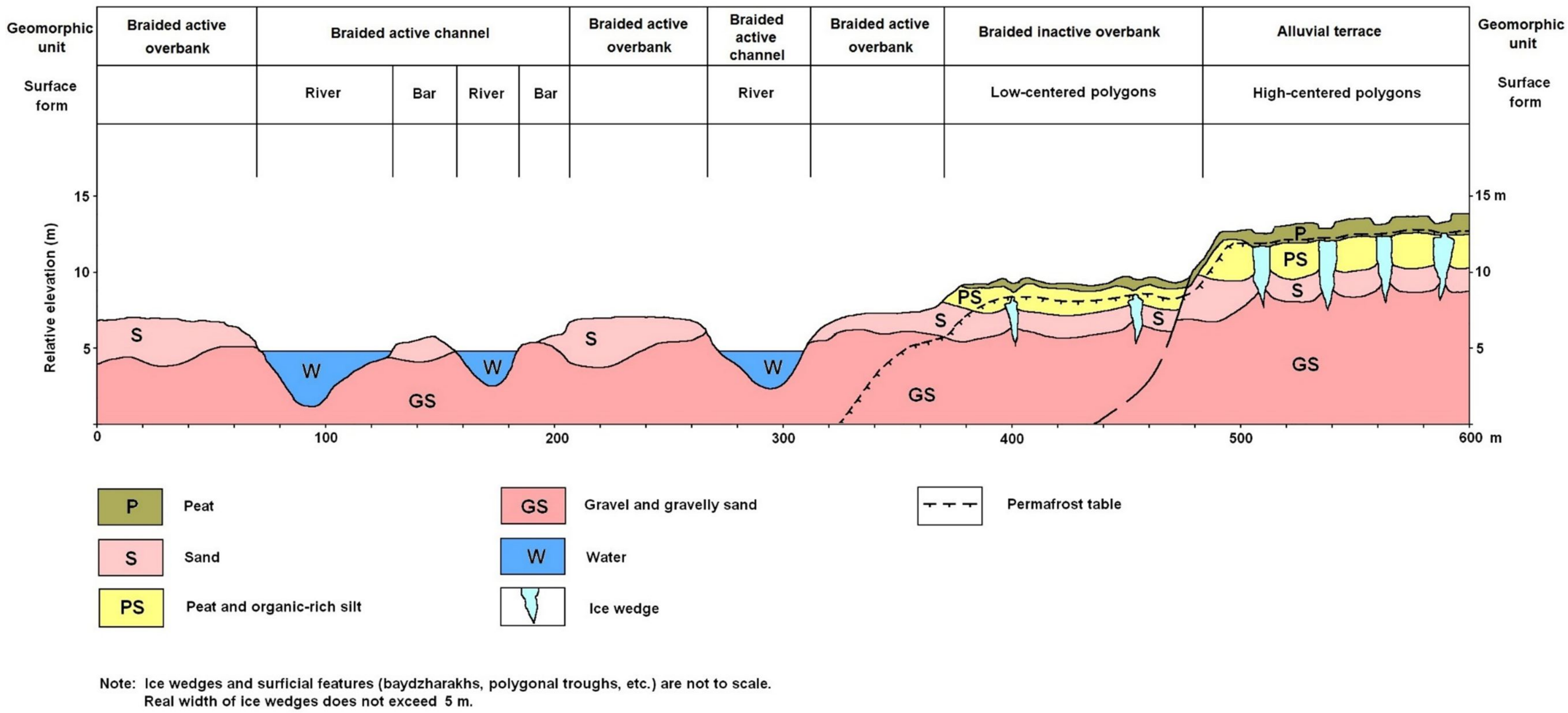

Figure 7. Landscape profile of soil and permafrost features of young and old fluvial deposits on braided floodplains typical of the Brooks Foothills.

Coastal plains have complex interspersion of marine and alluvial deposits associated with past marine transgressions. In the central and eastern parts of the Beaufort Coastal Plain, the highest and older portions of the landscape have surficial materials characterized by slightly pebbly loamy sands, that are slightly brackish, have high intermixing of organic materials at substantial depth, and lack stratification (Figure 8). Due to the odd nature of these deposits, they have been variously described as alluvial-marine deposits by Carter and Galloway (1985), eolian sands by Rawlinson (1992) who termed them Beechey Sands, and as sandy diamicton associated with glaciation of the coastal plain from the continental shelf by Jorgenson and Shur (2008). Deposits range from older coastal plain deposits to ice-rich and ice-poor lake basins. The loamy sands of the coastal plain deposits have moderately high ice contents, but are insufficient for thermokarst-lake development. Thus, the lakes are attributed to the accumulation of water in low-lying areas in an undulating sand sheet instead of thaw depressions related to thermokarst (Jorgenson et al. 2005). During the mid-Holocene, many of the lakes drained as stream networks became better integrated over time leaving an abundance of drained-lake basins. Younger drained basins are ice-poor due to the insufficient time for wedge-ice development, although segregated ice can accumulate rapidly near the surface in the newly emerged sediments. Older basins are ice-rich from abundant ice-wedge development, with the sandy margins typically having lower ice contents than the organic-rich limnic sediments in the centers (Jorgenson et al. 2004). Often the centers are domed from accumulation of ground ice. In some basins, tall pingos develop from formation of intrusive ice during freezeback of the previously unfrozen sediments associated with taliks that had developed under deeper lakes in sandy or gravelly deposits.

Coastal plain deposits in the coastal area between Barrow and Cape Halkett are a complex mixture of brackish silt and slightly pebbly loam sand deposits in the older, primary surfaces (Figure 9). They have been described as marine silt and clay (NPRATF 1978, Carter and Galloway 1985) because of the high silt and clay content, presence of marine mammals, molluscs, foraminifera, and ostracods. They have scattered ice-rafted pebbles, cobbles, and boulders of red granite, pink quartzite, dolomite and other exotic rocks that originated from Canada (MacCarthy 1958, Roedick 1979) as ice-rafted debris. This combination of silty clay, ice-rafted sediments, and marine fauna can also be characterized as a glaciomarine sediments deposited in a distal environment from the glacier. In our mapping we used the term glaciomarine to differentiate these extremely ice-rich deposits from the ice-poor marine silts of tidal flats. Because of the high silt and clay content, the deposit is extremely ice-rich to depths of 6 m or more. The landscape has abundant large, deep, elliptical, oriented thermokarst lakes. Many lakes have drained and are susceptible to seawater flooding during storm surges, up to 15 km inland from the coast. Once drained, they have similar drained-lake basin deposits described for the central and eastern portions of the Beaufort Coastal Plain. The glaciomarine deposits, however, are frequently inspersed with old beach ridge and coastal plain deposits, and frequently capped with thin eolian silt, indicating a complex depositional environment.

Eolian silt deposits in the lower Brooks Foothills and portions of the upper coastal plain are extremely ice-rich with tall syngenetic ice wedges and are of Late Pleistocene age (Carter 1988, Kanevskiy et al. 2011) (Figure 10). The deposits (as well as similar deposits of other genesis) are known in the Russian literature as yedoma (Kanevskiy et al. 2011a). At one world class exposure along the Itkillik River the eroding bluffs are up to 35 m high and have total volumetric ice contents more than 85%. Because of the extremely high ice content, thermokarst lakes and thaw-lake basins are abundant (Figure 10), and partially degraded areas can have a unique surface form with tall, conical thermokarst mounds termed “baydzherakhs” in the Russian literature.

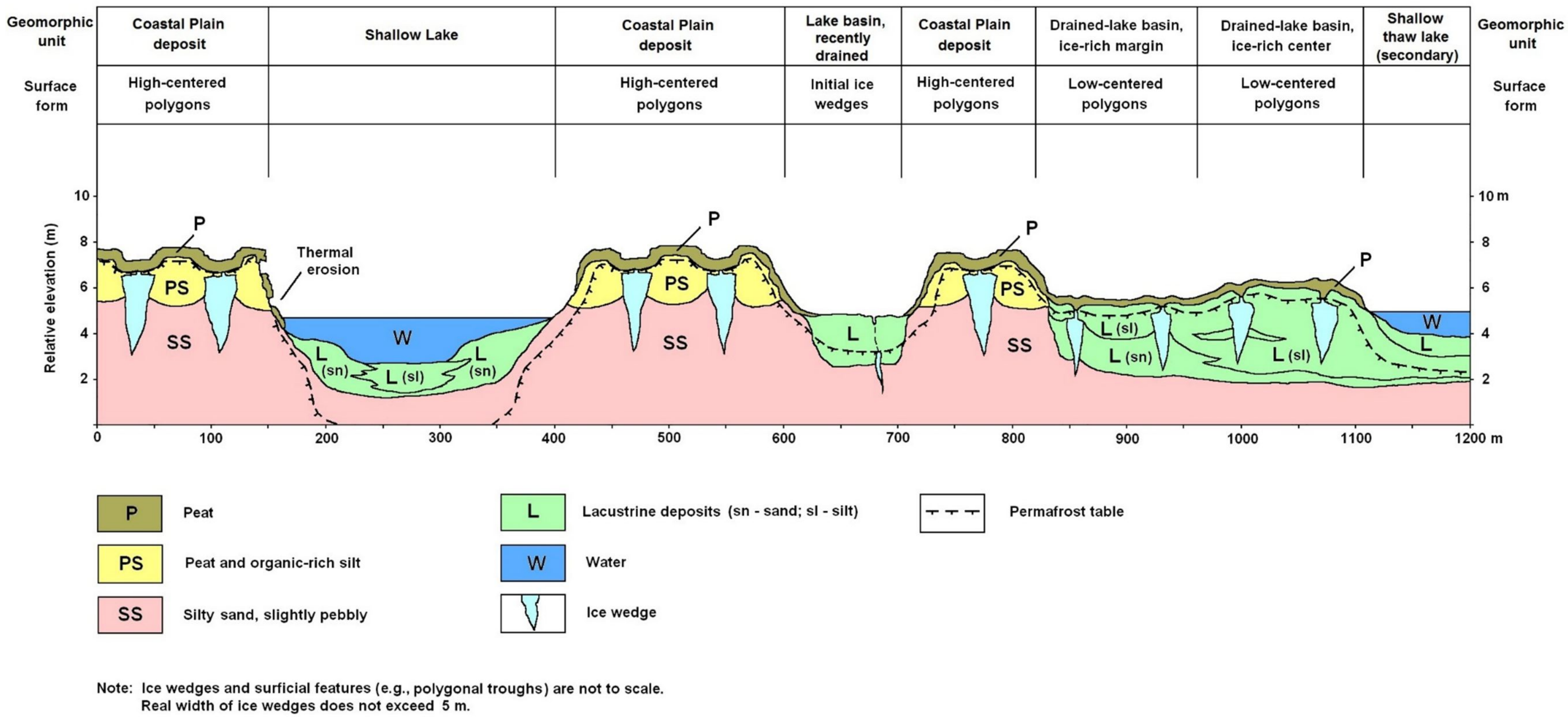

Figure 8. Landscape profile of soil and permafrost features associated with lake-basin development on coastal plain deposits with moderate ice contents on the Beaufort Coastal Plain.

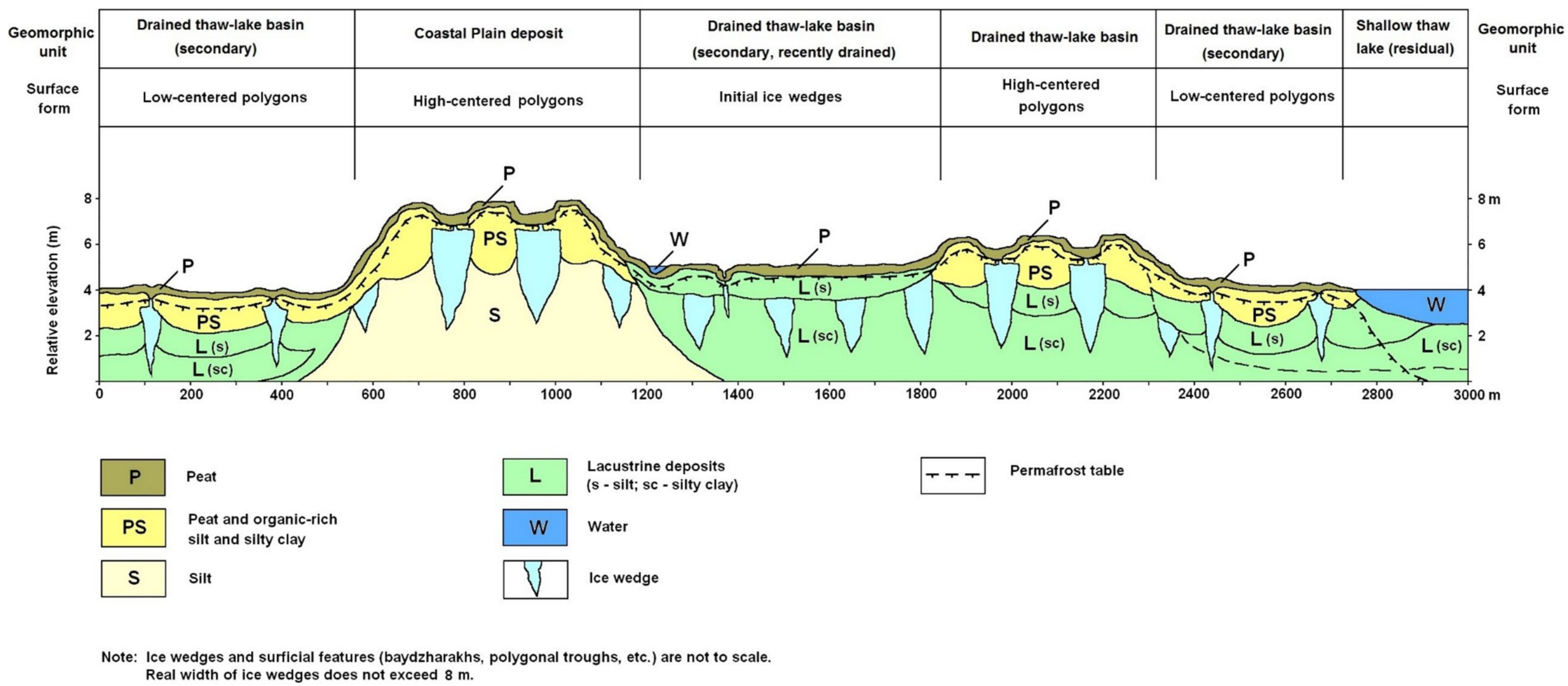

Figure 9. Landscape profile of soil and permafrost features associated with thaw-lake-basin development on old coastal plain deposits with high ice contents on the Beaufort Coastal Plain.

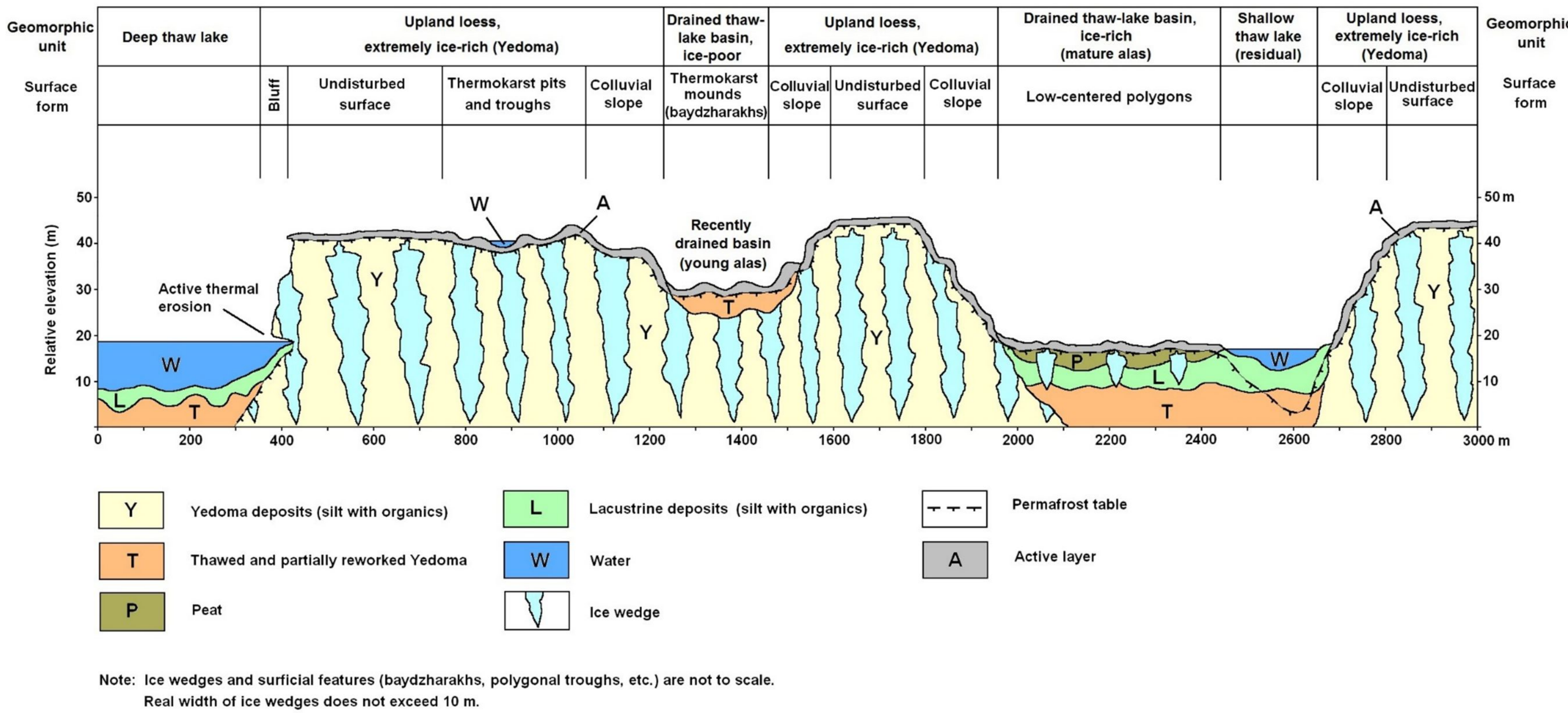

Figure 10. Landscape profile of soil and permafrost features associated with thermokarst lake development on ice-rich loess (yedoma) in the lower Brooks Foothills.

The drained thaw lake basins have three distinctive stages, including young, recently drained basins lacking low-centered polygons associated with wedge-ice development, intermediate ice-rich basins with distinctive low-centered polygons and distinguishable rims, and very old thaw-lake plain-like surfaces among the yedoma remnants where basin rims are indistinct and the surface has been modified by organic accumulation and ice aggradation and degradation.

MAPPING

The ecological landscape mapping covers 413,072 km^2, or about one-fourth of Alaska (1,518,800 km^2), but includes substantial areas of deeper marine and shallower coastal waters (Table 5). Attribution of the map polygons included: (1) the hierarchical regionalization of biomes, ecoregions (Figure 2), sections, and subsections included in the original mapping by Jorgenson and Grunblatt (2013); (2) generalized geology that groups closely related geomorphic units and is characterized by the dominant geomorphic unit (Figure 11); and (3) ecological landscapes that differentiate areas with differing biomes, physiography, generalized geology, and lithology or soil texture (Figure 12). These attributes in the geodatabase were cross-tabulated to differentiate and assign general permafrost characteristics, including permafrost extent (Figure 13), segregated ice volume in the top 3 m, massive ice volume in the top 5 m (Figure 14), maximum potential thaw settlement (Figure 15), and thermokarst landforms (Figure 16).

Generalized geology mapping at the landscape scale is useful to differentiate and visualize areas with properties important to permafrost development, but there are several limitations to the broad classification and small-scale mapping. First, all classes represent complexes of geomorphic units that often have very different properties. For example, Coastal Plain and Eolian Sand areas have abundant lakes and drained-lake deposits that are lost in the mapping. Fluvial and Glaciofluvial areas typically have evolutionary sequences from ice-poor gravelly and sandy channel deposits to organic- and ice-rich abandoned overbank deposits that can have abundant thaw lakes. Glacial, Glaciolacustrine, and Glaciomarine classes also reflect highly complex depositional environments. These could be mapped as complexes, but this can lead to a large number of complexes that have differing percentages of the constituent geomorphic units. Second, surficial deposits typically have complex stratigraphy associated with changes in depositional environments over time. This is particularly problematic for eolian deposits. Much of the region below 300 m elevation has a surficial cap of eolian silt of widely varying thickness. Even thin caps of <1 m can greatly affect soil properties in the active layer and ground ice near the permafrost table. Most of what is mapped as Eolian Silt is probably thicker than 10 m, but data are sparse. In addition, some lower slopes in bedrock controlled areas mapped as Colluvium Upland have thick ice-rich silt deposits. The older Glacial, Glaciofluvial and Glaciolacustrine deposits usually are covered by substantial silt caps with highly variable thickness.

The ecological landscape map (Figure 13), based in part on the generalized geology map, differentiates several characteristics important to ground ice. First, the colder classes in the Arctic biome tend to have higher abundance of ice wedges and higher frequencies of extremely ice-rich cryostructures below the permafrost table. Second, classes with coarse-textured soils tend to have lower contents of both segregated and wedge ice. While we have differentiated peat-rich classes, typically associated with older and wetter landscapes, we recognize peat thickness can be highly variable and there are limited supporting data. Third, physiography affects surface water runoff and impoundment and thus affects thermokarst potential.

Table 5. Areal extent of geological and ecological landscapes in northern Alaska.

General Geology	km²	Ecological Landscapes	km²
Marine water	21069	Arctic Marine Water	21069
Coastal water	7202	Arctic Coastal Water	7202
Freshwater	989	Arctic Freshwater	891
Marine, young	1611	Arctic Gravelly Coast	637
Fluvial, young	20834	Arctic Sandy Coast	974
Fluvial, old	8269	Arctic Gravelly Riverine	9210
Glaciofluvial, old	5979	Arctic Peaty Silty Riverine	1166
Coastal Plain	27216	Arctic Sandy Riverine	3693
Eolian sand	14669	Arctic Peaty Silty Lowland	10898
Eolian silt	34326	Arctic Peaty Sandy Lowland	27216
Colluvium, basin	2518	Arctic Peaty Gravelly Lowland	8943
Colluvium, upland	74793	Arctic Sandy Lowland	13956
Glaciomarine	2625	Arctic Silty Lowland	7083
Glaciolacustrine	3501	Arctic Silty Upland	21446
Glacial, young	25291	Arctic Peaty Glaciated Upland	11708
Glacial, old	22518	Arctic Rocky Glaciated Upland	13405
Sedimentary, noncarbonate	66413	Arctic Rocky Acidic Alpine	56713
Sedimentary, carbonate	36152	Arctic Rocky Acidic-Alkaline Alpine	3879
Sedimentary, mixed	4291	Arctic Rocky Alkaline Alpine	20716
Metamorphic, noncarbonate	20115	Arctic Rocky Circumneutral Alpine	827
Metamorphic, mixed	184	Arctic Rocky Ultramafic Alpine	1304
Intrusive, felsic	3717	Arctic Rocky Upland	50335
Intrusive, mafic	7136	Boreal Freshwater	99
Intrusive, ultramafic	1388	Boreal Gravelly Riverine	5831
Volcanic, mafic-older	268	Boreal Sandy Riverine	934
Total Area	413072	Boreal Peaty Silty Lowland	1860
		Boreal Peaty Gravelly Lowland	1190
		Boreal Silty Lowland	5797
		Boreal Sandy Upland	713
		Boreal Rocky Upland	29888
		Boreal Peaty Glaciated Upland	10810
		Boreal Rocky Glaciated Upland	11886
		Boreal Rocky Acidic Alpine	33531
		Boreal Rocky Acidic-Alkaline Alpine	596
		Boreal Rocky Alkaline Alpine	15436
		Boreal Rocky Circumneutral Alpine	1147
		Boreal Rocky Ultramafic Alpine	84
		Total Area	413072

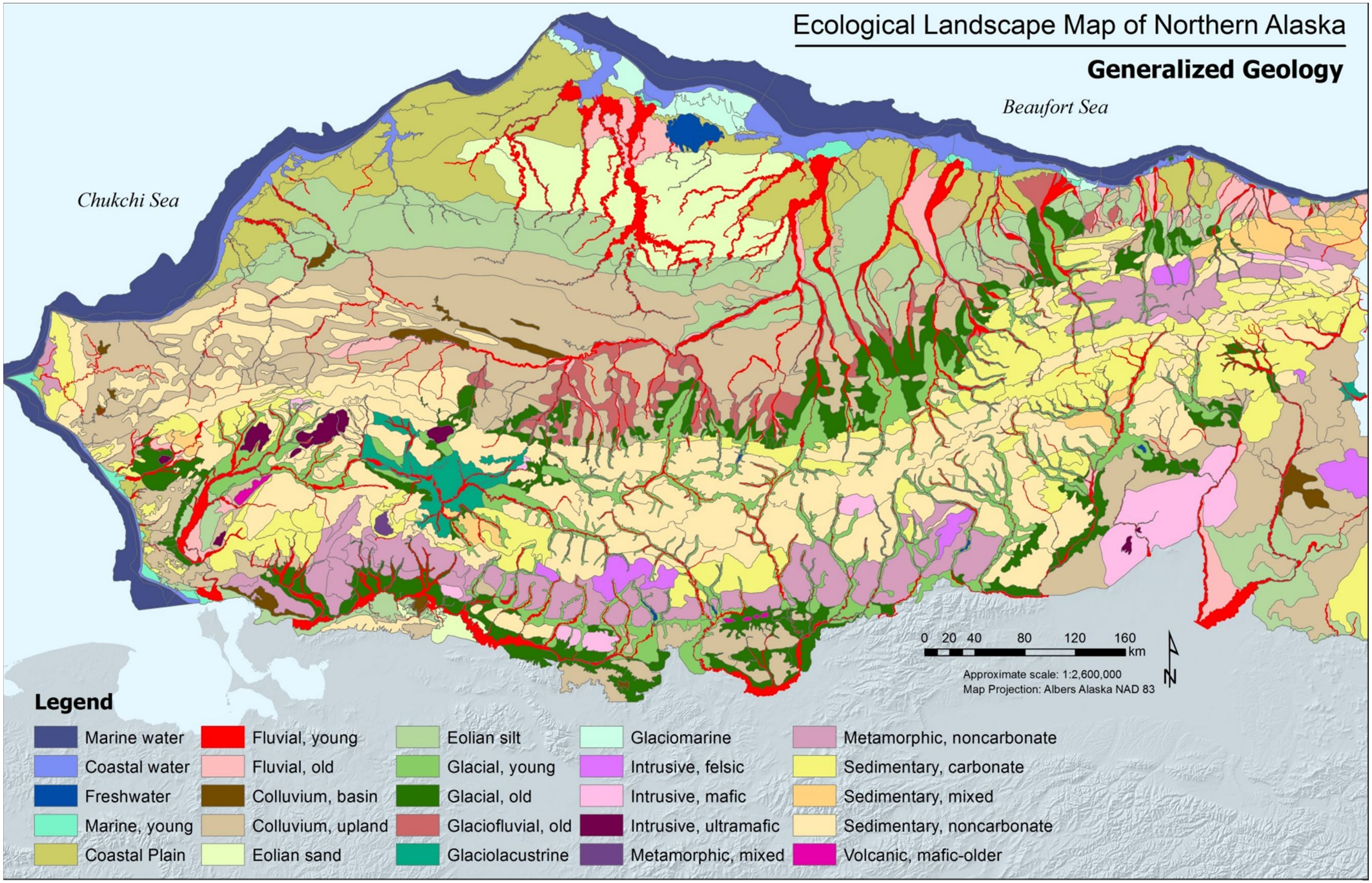

Figure 11. Map of generalized geology used for attributing permafrost characteristics.

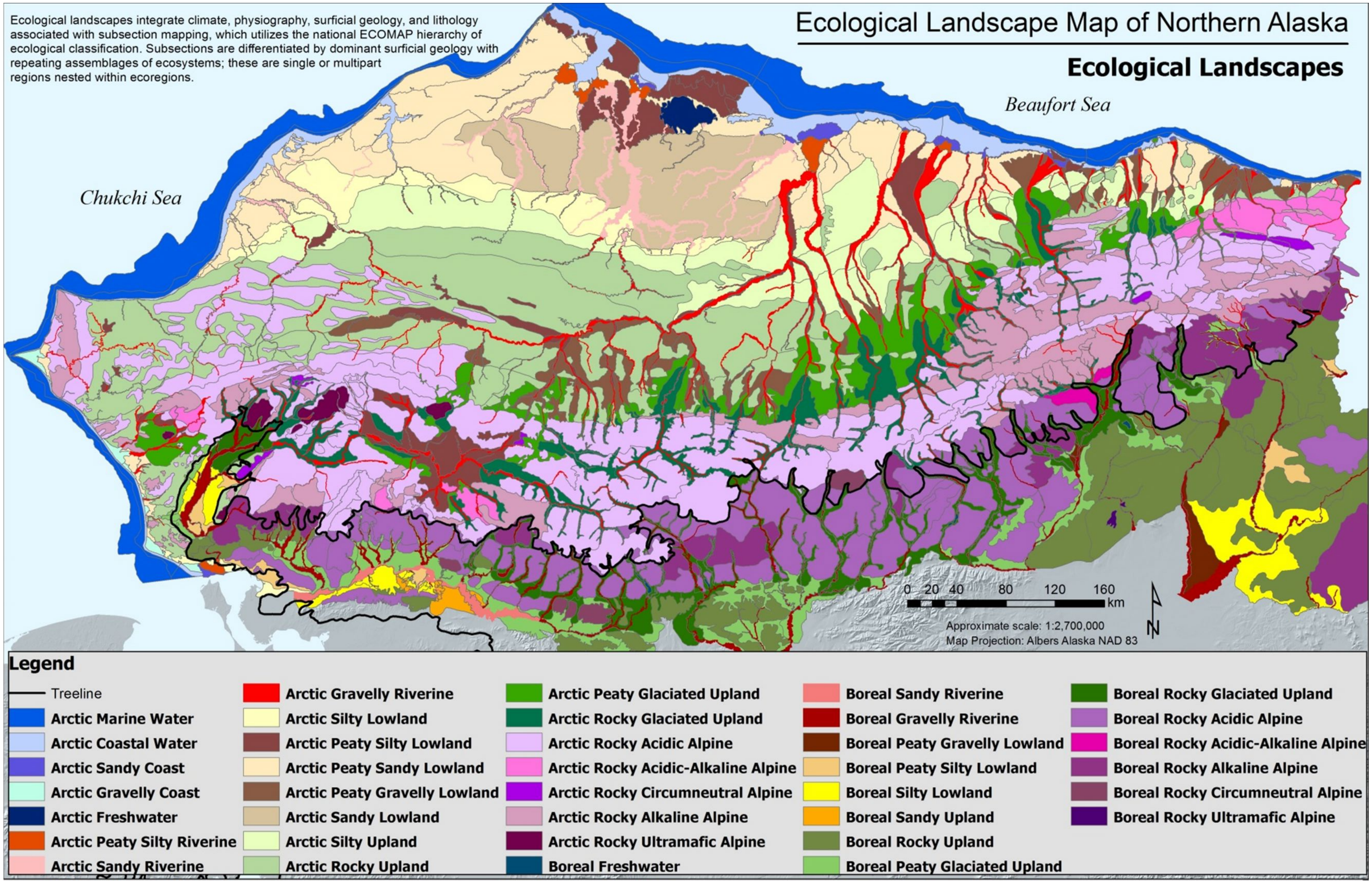

Figure 12. Map of ecological landscapes used for attributing permafrost characteristics.

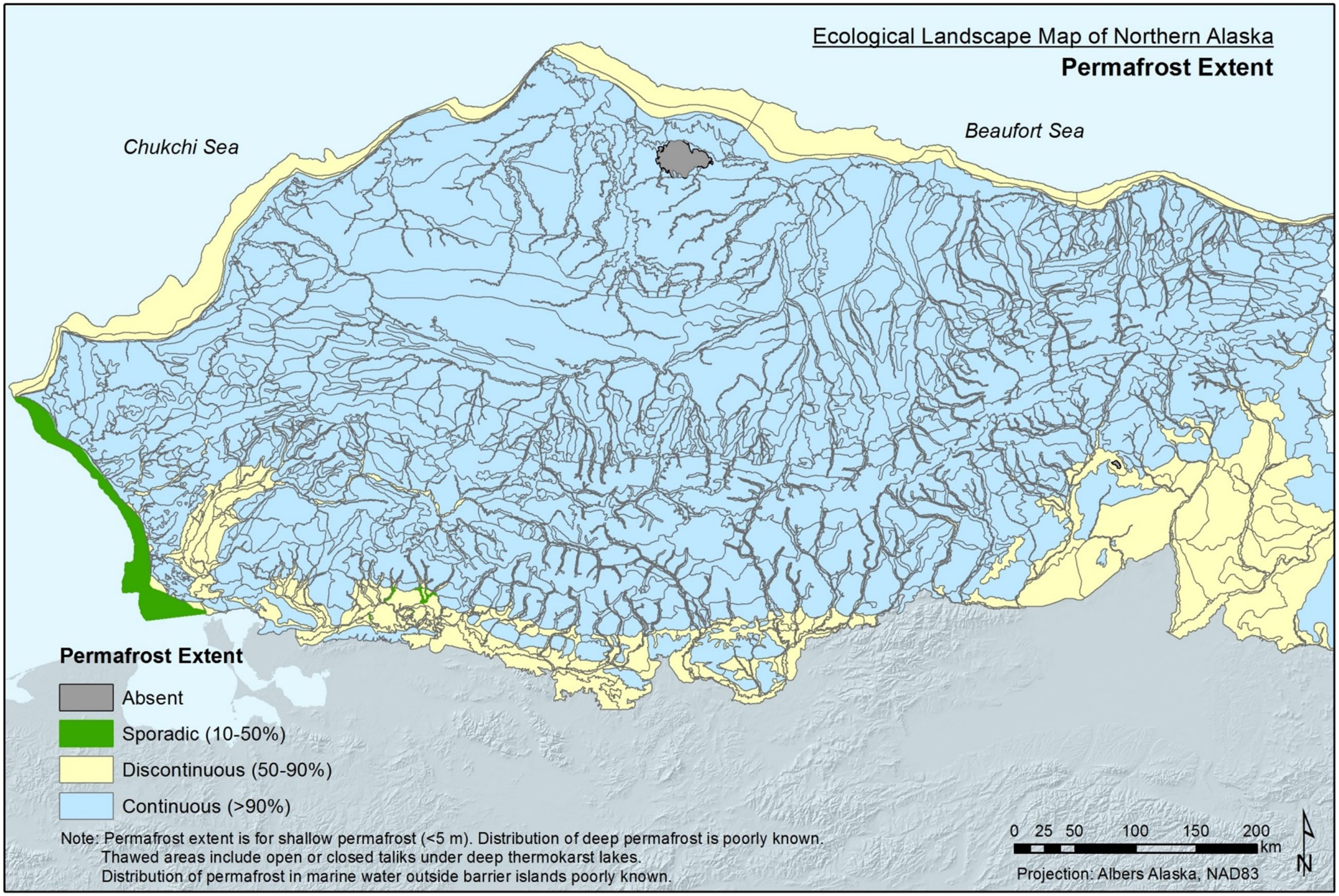

Figure 13. Map of permafrost distribution in northern Alaska.

Permafrost distribution was mapped as continuous (>90% of polygon area), discontinuous (50-90%), sporadic (10-50%), isolated (>0%-10%), or absent (0%). The extent was defined by a rule-based ranking based on the texture (silty to rocky) associated with the generalized geology and the mean annual air temperature (MAAT), similar to the approach by Jorgenson et al. (2008). For all areas where MAAT was <8 °C, permafrost extent was continuous, except under large lakes where the sediments near the surface were mapped as permafrost being absent (Figure 13). In deeper marine water, permafrost is mapped as discontinuous. Although numerous studies have documented offshore permafrost (Bruggers and England 1982, Osterkamp et al. 1987, Osterkamp 2001), data are sparse and distribution is poorly known. In marine water, the permafrost can lack ice-bonding because of sediment salinity. In the southern portion of the map where MAATs were -5 to -8 °C, young fluvial deposits, eolian sands, and rocky uplands with south-facing slopes were mapped as having discontinuous permafrost. Fluvial deposits were mapped as discontinuous because of the effects of groundwater movement through fluvial gravels (Kreig and Reger 1982).

PERMAFROST CHARACTERISTICS AND VULNERABILITY

Permafrost characteristics were assigned to the various combinations of the generalized geology and ecological landscapes to help assess the vulnerability of permafrost to degradation from disturbance and climatic change (Table 5). The assessment emphasizes ground ice and thermokarst characteristics, including volumes of massive and segregated ice, maximum potential thaw settlement, and thermokarst landforms, because they are fundamental to how permafrost degrades.

Massive ice mainly occurs as ice wedges, buried glacial ice in glacial deposits, and intrusive ice, mostly associated with pingos. Ice wedges can occur either as epigenetic or syngenetic wedges. Epigenetic wedges form after surficial deposition has ceased and typically occur within the top 3 to 5 m of the permafrost table. Syngenetic wedges form concurrent with sediment deposition and therefore can extend to depths as much as 30 to 40 m in loess (Shur et al. 2011, Kanevskiy et al. 2011a, b). The volume of ice wedges can be highly variable. The volume of epigenetic ice wedges in the Arctic can range from near zero in active channel and eolian deposits to 30% or more in older silty deposits (Kanevskiy et al. 2013). The volume of tall syngenetic wedges ranges from 30 to 70% in extremely ice-rich Pleistocene loess (Kanevskiy et al. 2011). Glacial ice, with its characteristic gravel and cobble inclusions and highly deformed bedding, has been observed in numerous thaw slumps in glacial moraines, but little is known about the volume of buried ice. We presume it is highly variable (10–80%);very high ice content is indicated by the frequent presence of new and old kettle lakes in glacial terrain, especially moraines of Little Ice Age and Wisconsinan age (Jorgenson 2013). Based on these characteristics, massive ice volumes were separated into six classes (Figure 14). Pingos were too small and random to map.

Segregated and pore ice have a wide range of morphologies that include pore, lenticular, porphyritic, organic-matrix, layered, braided, reticulate, and ataxitic cryostructures (French and Shur 2010, Kanevskiy et al. 2013). Reticulate and ataxitic cryostructures are commonly associated with the extremely ice-rich intermediate layer that occurs within the top 0.5–3 m of the permafrost (Shur 1988). This intermediate layer is found across most geomorphic units, although it is typically absent in young deposits lacking significant organic-matter accumulation. For now, we created only ice-poor (<50%) and ice-rich (≥50%) classes and did not develop a map for segregated ice volume. While we attempted to differentiate more volumetric classes, we were not able to identify distinct cutpoints for higher ice contents due to high variability by depth and among geomorphic units.

Maximum potential thaw settlement (Figure 15) was classified into five broad categories based on the ice contents, and our observations of thermokarst landforms (Figure 16). Maximum thaw settlement would occur if all segregated and massive ice were to thaw extending to the depth of the surficial deposit.

Thermokarst terrains were grouped into nine broad groups of associated landforms (Table 5, Figure 16). On flat areas, shallow and deep thermokarst lakes, drained-lake basins, and pits and troughs associated with ice-wedge degradation are common due to the impoundment of water, but differentiation of true thermokarst lakes from water impounded in low-lying swales on the coastal plain can be problematic (Jorgenson and Shur 2007). Eolian sand lacks sufficient ice for thermokarst lakes, but has sufficient wedge ice for thermokarst pits and troughs (Kanevskiy et al. 2013). While we attribute most of the lakes in sand dune deposits simply to impoundment in swales and subsequent bank erosion, the occurrence of deep centers in many lakes in the Ikpikpuk sand region indicates the origin is problematic and thawing of very deep ice may be a factor. Pleistocene aged eolian silt with large syngenetic ice wedges are prone to development of deep thermokarst lakes, drained-lake basins, and pits and troughs, but differ in the frequent occurrence of tall conical thermokarst mounds (baydzherakhs**)** that form from the thawing of the large ice wedges (Shur et al 2012). Glaciated areas with substantial buried glacial ice have deep thermokarst lakes and thaw slumps, with infrequent occurrence of thermokarst pits and troughs on top of degrading ice wedges. In some old glaciated areas, buried glacial ice is overlaid by the Late Pleistocene eolian silt (yedoma) with large syngenetic ice wedges (Swanson and Hill 2010). Ground ice and thermokarst landforms are poorly understood for bedrock-controlled areas. Small epigenetic ice wedges commonly form in weathered bedrocks (under very cold climate conditions), while larger syngenetic and epigenetic wedges may form in colluvium, alluvium, and especially in eolian silt, which can also accumulate within rocky landscapes. Sedimentary, noncarbonate bedrock areas (especially shale) are particularly susceptible to active-layer detachment slides due to the high silt content that facilitates substantial ice aggradation in the intermediate layer, but slides appear rarely on sedimentary, carbonate bedrock areas.

The vulnerability of permafrost to degradation depends on a complex interaction of surface changes with strong positive and negative feedbacks across a climatic gradient with differing permafrost characteristics (Shur and Jorgenson 2007, Jorgenson et al. 2010). While temperatures and ground ice volumes are important for assessing vulnerability, other important factors also control degradation. For example, ice wedges that form just below the active layer can easily degrade under cold temperatures due to the positive feedback of impounded water in sinking troughs (Jorgenson et al. 2006). On hillsopes burned by the Anaktuvuk River fire, detachment slides were particularly abundant presumably because the subsequent abrupt increase in thaw depths penetrated extremely-ice rich intermediate layer at the top of the permafrost, but most of ice wedges in well-drained areas were only slightly affected by thermokarst. In the warmer climate of central Alaska, yedoma can remain relatively stable due to the ability of the active layer to adjust to temperature changes, the elimination of massive ice during thawing episodes from past disturbance or climatic changes, and the effect of slopes minimizing surface impoundment (Kanevskiy et al. 2014). Surface peat and irregular subsurface distribution of organics from cryoturbation also affect thaw stability (Ping et al. 1998, 2008).

Table 6. Permafrost vulnerability to thermokarst related to generalized geology and ecological landscapes.

Generalized Geology	Ecological Landscapes	Massive Ice (%)	Segregated Ice (%)	Max. Settlement Potential	Thermokarst Landforms	Map Units (n)
Marine water	Arctic Marine Water	0	Unknown	0	Negligible	11
Freshwater	Arctic Freshwater	0	Unknown	0	Negligible	2
Freshwater	Boreal Freshwater	0	Unknown	0	Negligible	4
Coastal water	Arctic Coastal Water	0	<50%	<0.5 m	Negligible	23
Coastal water	Arctic Coastal Water	0	Unknown	0	Negligible	2
Marine, young	Arctic Gravelly Coast	<5%	<50%	<0.5 m	Negligible	8
Marine, young	Arctic Sandy Coast	<5%	<50%	<0.5 m	Negligible	20
Fluvial, young	Arctic Gravelly Riverine	<5%	<50%	<0.5 m	Negligible	208
Fluvial, young	Boreal Gravelly Riverine	<5%	<50%	<0.5 m	Negligible	116
Fluvial, young	Boreal Sandy Riverine	<5%	<50%	<0.5 m	Negligible	6
Fluvial, young	Arctic Sandy Riverine	<5%	<50%	<0.5 m	Pits and Troughs	19
Fluvial, young	Arctic Peaty Silty Riverine	10-30%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	11
Eolian sand	Arctic Sandy Lowland	5-10%	<50%	<0.5 m	Pits and Troughs	18
Eolian sand	Boreal Sandy Upland	<5%	<50%	<0.5 m	Pits and Troughs	16
Fluvial, old	Arctic Peaty Gravelly Lowland	5-10%	=>50%	0.5-2 m	Pits and Troughs	55
Fluvial, old	Arctic Peaty Silty Lowland	10-30%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	36
Fluvial, old	Boreal Peaty Silty Lowland	5-10%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	9
Fluvial, old	Boreal Peaty Gravelly Lowland	5-10%	=>50%	0.5-2 m	Pits and Troughs	7
Glaciofluvial, old	Arctic Peaty Gravelly Lowland	10-30%	=>50%	0.5-2 m	Pits and Troughs	2
Glaciofluvial, old	Arctic Peaty Gravelly Lowland	10-30%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	58
Glaciofluvial, old	Arctic Peaty Gravelly Lowland	5-10%	=>50%	0.5-2 m	Pits and Troughs	1
Coastal Plain	Arctic Peaty Sandy Lowland	10-30%	=>50%	0.5-2 m	Shallow Lakes, Drained-lake Basins, Pits and Troughs	45
Coastal Plain	Arctic Peaty Sandy Lowland	10-30%	=>50%	2-5 m	Shallow Lakes, Drained-lake Basins, Pits and Troughs	32
Colluvium, basin	Arctic Peaty Silty Lowland	10-30%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	8
Colluvium, basin	Boreal Peaty Silty Lowland	5-10%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	7
Glaciomarine	Arctic Peaty Silty Lowland	10-30%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	7
Glaciolacustrine	Arctic Peaty Silty Lowland	10-80%	=>50%	5-30 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	9
Glaciolacustrine	Boreal Peaty Silty Lowland	10-30%	=>50%	2-5 m	Deep Lakes, Drained-lake Basins, Pits and Troughs	3
Eolian silt	Boreal Silty Lowland	30-70%	=>50%	5-30 m	Deep Lakes, DLB, Conical Mounds, Pits and Troughs	20
Eolian silt	Arctic Silty Lowland	30-70%	=>50%	5-30 m	Deep Lakes, DLB, Conical Mounds, Pits and Troughs	15
Eolian silt	Arctic Silty Upland	30-70%	=>50%	0.5-2 m	Deep Lakes, DLB, Conical Mounds, Pits and Troughs	1
Eolian silt	Arctic Silty Upland	30-70%	=>50%	5-30 m	Deep Lakes, DLB, Conical Mounds, Pits and Troughs	54
Glacial, young	Arctic Rocky Glaciated Upland	10-80%	<50%	5-30 m	Deep Lakes, Slumps	125
Glacial, young	Boreal Rocky Glaciated Upland	10-80%	<50%	5-30 m	Deep Lakes, Slumps	93
Glacial, old	Arctic Peaty Glaciated Upland	10-80%	=>50%	5-30 m	Deep Lakes, Slumps, Pits and Troughs	65
Glacial, old	Boreal Peaty Glaciated Upland	10-80%	=>50%	5-30 m	Deep Lakes, Slumps, Pits and Troughs	66
Colluvium, upland	Arctic Rocky Upland	5-10%	=>50%	0.5-2 m	Detachment Slides, Pits and Troughs	119
Colluvium, upland	Boreal Rocky Upland	5-10%	=>50%	0.5-2 m	Detachment Slides, Pits and Troughs	5
Colluvium, upland	Boreal Rocky Upland	5-10%	=>50%	0.5-2 m	Detachment Slides	45
Sedimentary, noncarb.	Boreal Rocky Acidic Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	46
Sedimentary, noncarb.	Arctic Rocky Acidic Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	140
Metamorphic, noncarb.	Boreal Rocky Acidic Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	34
Metamorphic, noncarbon.	Arctic Rocky Acidic Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	16
Sedimentary, mixed	Arctic Rocky Acidic-Alk. Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	14
Sedimentary, mixed	Boreal Rocky Acidic-Alk. Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	2
Metamorphic, mixed	Arctic Rocky Acidic-Alk. Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	1
Volcanic, mafic-older	Boreal Rocky Upland	<5%	<50%	<0.5 m	Negligible	4
Volcanic, mafic-older	Arctic Rocky Circumneutral Alpine	<5%	<50%	<0.5 m	Negligible	1
Sedimentary, carbonate	Arctic Rocky Alkaline Alpine	<5%	<50%	<0.5 m	Negligible	84
Sedimentary, carbonate	Boreal Rocky Alkaline Alpine	<5%	<50%	<0.5 m	Negligible	29
Intrusive, felsic	Boreal Rocky Acidic Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	4
Intrusive, felsic	Arctic Rocky Acidic Alpine	<5%	=>50%	0.5-2 m	Detachment Slides	3
Intrusive, mafic	Boreal Rocky Upland	<5%	<50%	<0.5 m	Negligible	4
Intrusive, mafic	Arctic Rocky Circumneutral Alpine	<5%	<50%	<0.5 m	Negligible	8
Intrusive, mafic	Boreal Rocky Circumneutral Alpine	<5%	<50%	<0.5 m	Negligible	5
Intrusive, ultramafic	Arctic Rocky Ultramafic Alpine	<5%	<50%	<0.5 m	Negligible	6
Intrusive, ultramafic	Boreal Rocky Ultramafic Alpine	<5%	<50%	<0.5 m	Negligible	2
					Total	1754

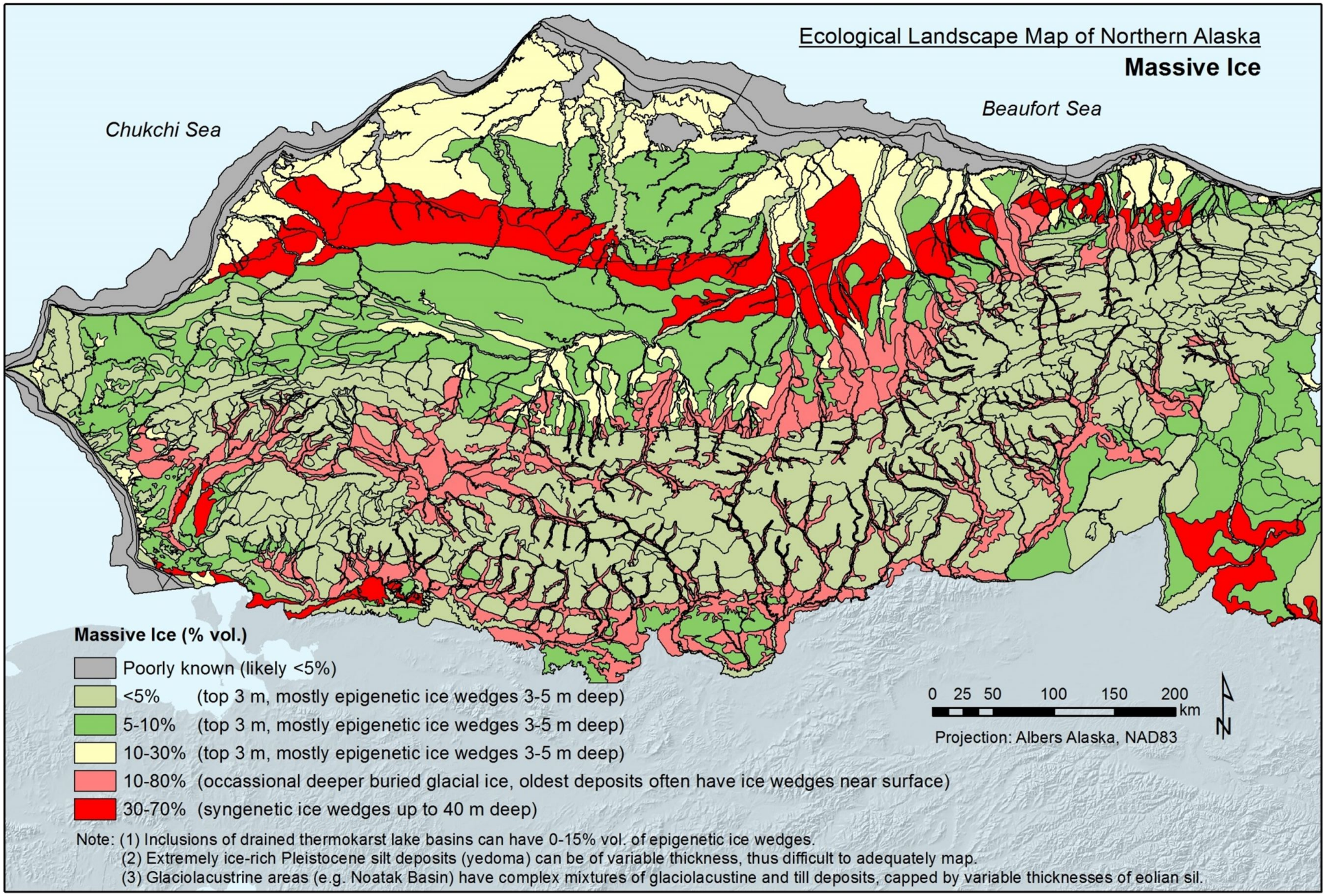

Figure 14. Map of massive ice (%vol.) distribution in northern Alaska based on ground ice associated with generalized geology.

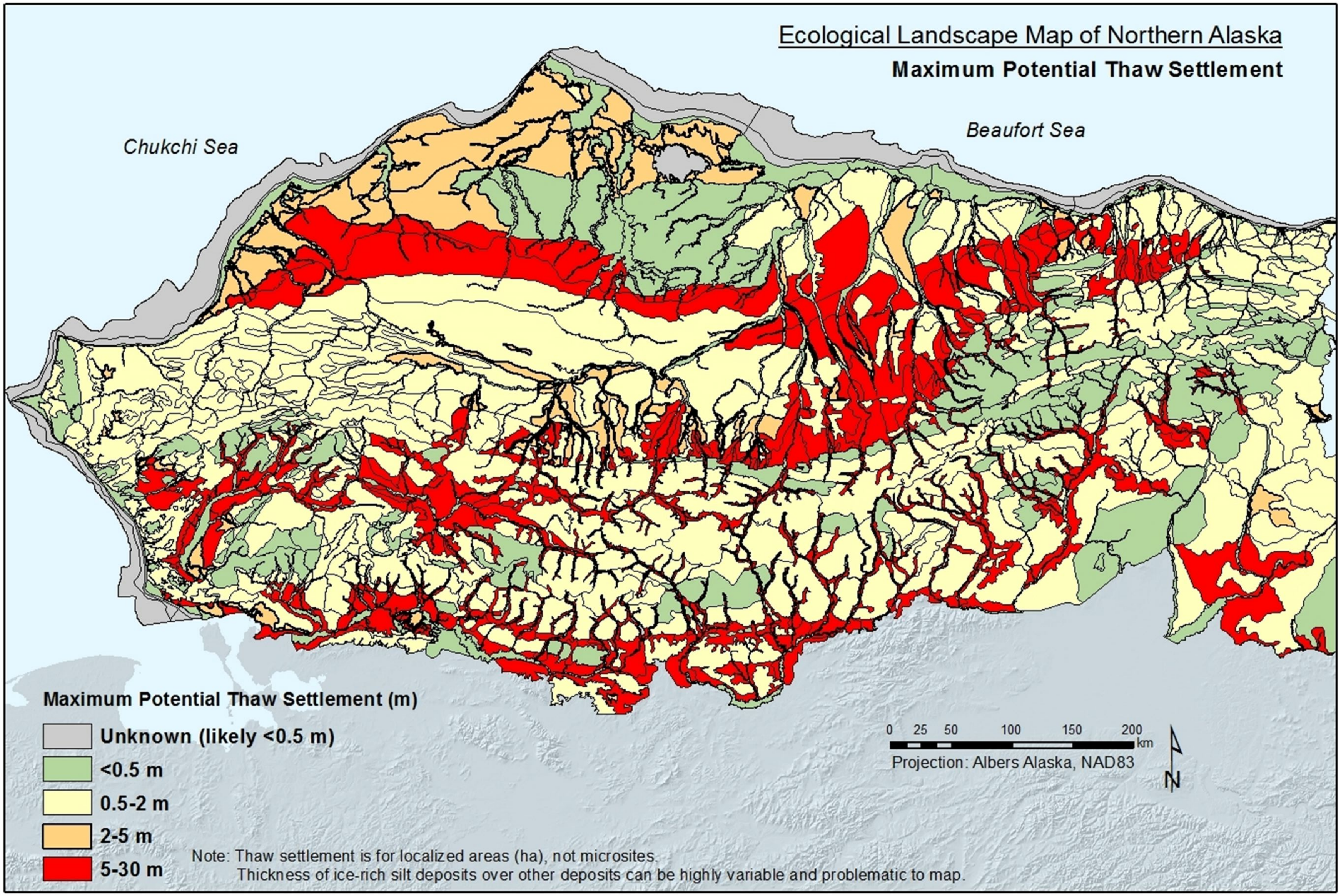

Figure 15. Map of maximum potential thaw settlement in northern Alaska based on ground ice associated with generalized geology.

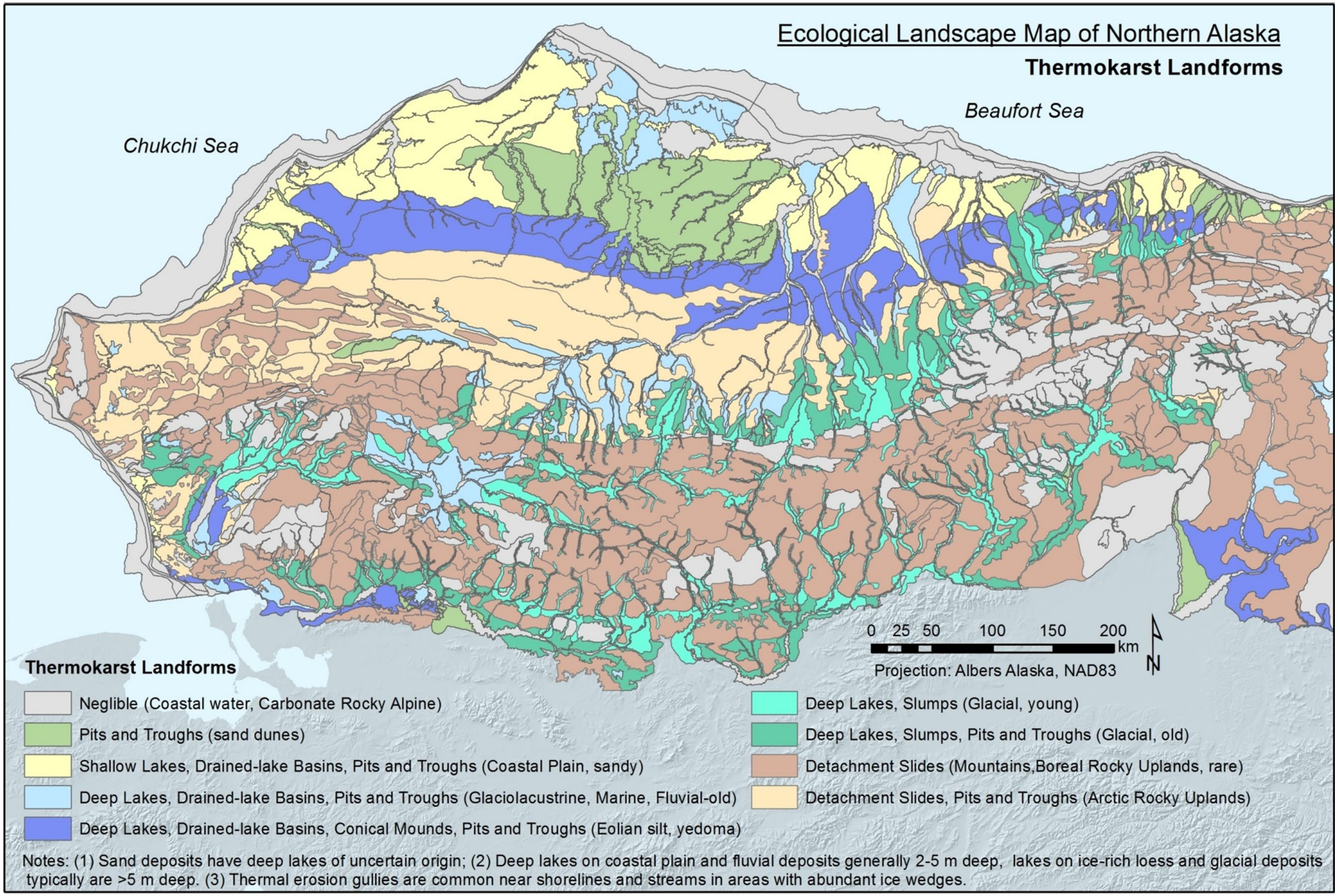

Figure 16. Map of thermokarst landforms in northern Alaska associated with generalized geology and ecological landscapes.

In addition to these spatial terrain factors, permafrost can degrade to differing degrees and over varying time periods. In the colder Arctic region much of the permafrost thawing is mostly related to ice-wedge thermokarst and limited to the upper several meters because of the cold ground temperatures, although formation of closed taliks under lakes is also common (Jorgenson et al. 2010). In the warmer boreal region, intermediate degradation, where closed taliks develop after disturbance (without formation of thermokarst lakes), is more common. Complete permafrost degradation and creation of open taliks under lakes and bogs also can be expected in the boreal region. Because of this complicated interplay of climate, surface topography, ecological processes and their positive and negative feedbacks, and varying disturbance regimes and recovery times, we were not able to develop simplified maps to rank permafrost vulnerability. Instead we highlighted the role of ground ice and the varying modes in which permafrost can degrade within different landscapes (Table 5).

WEB-BASED DATA DISTRIBUTION

Permafrost data from 861 sites and various map products derived from the landscape mapping have been made available on GINA's website for data discovery and delivery (Figure 17). A summary listing of site and permafrost characteristics are available as clickable points on a map. After clicking on a point, a tabular listing of site characteristics is displayed, along with a link to an image directory for each site that contains photographs of the site and soils, soil section drawing and description when available, and a table of soil stratigraphy and properties when available. The background maps are user selectable and include maps for topography, biomes, ecoregions, ecosections and subsections, generalized geology, ecological landscapes, permafrost characteristics, and mean annual air tempertures. From the website, the user also is able to download the report, GIS shapefiles, and the NoAK permafrost database.

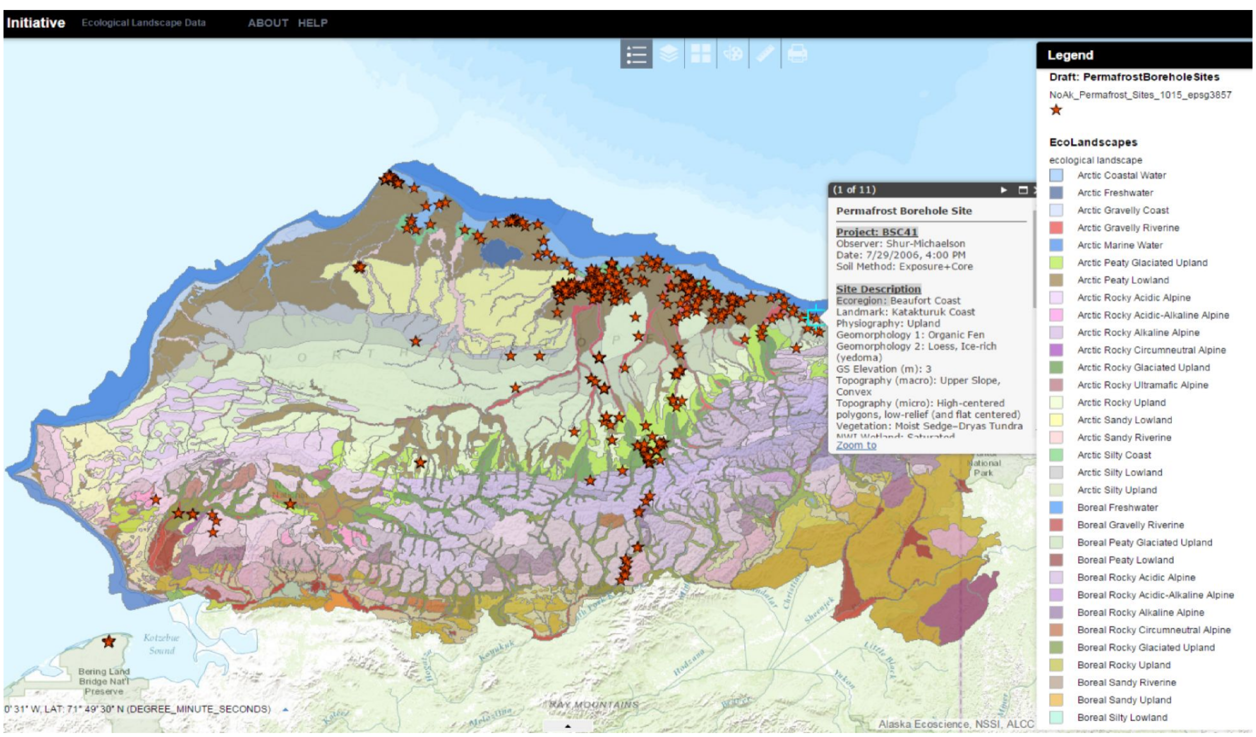

Figure 17. Screenshot of permafrost data available through the GINA website.

SUMMARY AND CONCLUSION

Permafrost and ground-ice characteristics in northern Alaska are extremely variable spatially due to differences in climate, topography, soil properties, cryogenic processes, and environmental history. To address this complexity, we used a multi-scale approach to: (1) develop a permafrost database for evaluating soil stratigraphy and ground-ice distribution at the microsite-scale; (2) synthesize data into site-scale conceptual models of ground-ice distribution associated with closely related geomorphic units across toposequences representative of dominant landscapes; and (3) to map broad ecological landscapes comprising closely related geomorphic units across the region. For the permafrost database, we compiled site characteristics, soil stratigraphy, and laboratory data on physical and chemical properties for 861 sites with mostly shallow (1 to 5 m) boreholes, pits, and exposures. For spatial analysis, we developed a region-wide classification of geomorphic units based on field studies and terrain mapping to provide a comprehensive framework for partitioning the variability in characteristics of the upper permafrost. For the landscape-scale mapping, we revised and recoded an existing ecological landscape map to develop regional maps of dominant permafrost characteristics. Finally, we made these data and map products available to the public over the internet through the Geographic Information Network of Alaska (http://www.gina.alaska.edu/projects/permafrost-database-and-maps-for-northern-alaska).

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