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Authors: Pullman, Erik R., Torre Jorgenson, M., and Shur, Yuri

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# Thaw Settlement in Soils of the Arctic Coastal Plain, Alaska

*Erik R. Pullman*‡*
*M. Torre Jorgenson*§ and*
*Yuri Shur†*

*ABR, Inc.—Environmental Research and Services, P.O. Box 80410 Fairbanks, Alaska 99708
†University of Alaska Fairbanks, Civil and Environmental Engineering, University of Alaska Fairbanks, P.O. Box 755900 Fairbanks, AK 99775-5590
ffys@uaf.edu
‡epullman@abrinc.com
§tjorgenson@abrinc.com

## Abstract

On the Beaufort Coastal Plain of northern Alaska, thaw settlement in permafrost soils occurs whenever natural or human disturbances result in an increase in the depth of seasonally thawed soil (the active layer). Knowledge of the potential magnitude of thaw settlement is important for assessing the long-term recovery of disturbed land and for developing rehabilitation plans and performance standards. To address this need, we analyzed thaw strain and thaw depth data from soil cores distributed across the central Beaufort Coastal Plain to evaluate potential thaw settlement at landscape (e.g. terrain units) and regional (e.g. ecodistricts) scales in connection with various oilfield studies during the period 1998–2003.

Mean thaw strain values ranged from 1% for meander active channel deposits to 55% for delta inactive overbank deposits, and tended to be highest at 1–2 m below the ground surface. The potential thaw settlement of specific terrain units was evaluated based on thaw strain of soils and the range of changes in active layer depths typically found after disturbance. Mean estimates for potential thaw settlement for an active layer adjustment to 110 cm after disturbance varied from ~0 cm in sandy soils with thick active layers associated with meander active channel and overbank deposits to 86 cm in very ice-rich silty soils with thin active layers associated with delta inactive overbank deposits. Potential thaw settlement also varied by region, with values for terrain units tending to be higher in the central Beaufort Coastal Plain (Prudhoe Bay and Kuparuk Oilfield areas) than in the western Beaufort Coastal Plain. The highest estimate for potential thaw settlement was 103 cm for delta inactive overbank deposits on the Colville Delta. The thawing of ice wedges will further contribute to thaw settlement and effect local hydrology and topography following thermokarst.

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## Introduction

Natural or human-caused disturbance increases the active layer depth and causes thaw settlement of ice-rich permafrost soils. The magnitude of thaw settlement is directly related to the nature and abundance of ground ice as well as severity of a disturbance. While naturally occurring thermokarst is fundamental to terrain diversity and ecological processes on the arctic lowlands (Britton, 1957; Billings and Peterson, 1980; Walker et al., 1980; Carter et al., 1987), human-induced thermokarst is usually a concern for land development in the Arctic because of its unwanted effects on infrastructure, hydrology, soils, and vegetation (Brown and Grave, 1979; Jorgenson, 1986; Lawson, 1986; Walker et al., 1987). Off-road and seismic trail disturbances associated with oil development activities have led to thermokarst in some circumstances (Walker et al., 1987; Emers and Jorgenson, 1997), although modern exploration equipment and winter-only exploration have greatly reduced the impacts on terrain and the development of human-induced thermokarst. Other disturbances, such as road dust, oil spill cleanups (Jorgenson et al., 1991, 1992), closeout and rehabilitation of reserve pits (Burgess et al., 1999), and gravel removal after site abandonment (Jorgenson and Kidd, 1991; Kidd et al., 1997) still require the mitigation of thermokarst-related processes. Little work has been done, however, to quantify the amount of thaw settlement that potentially could occur from severe disturbances across a region with highly variable geomorphic, soil, and ground ice characteristics.

In the studied area (Fig. 1) between the Sagavanirktok River and the northeastern area of the National Petroleum Reserve–Alaska (NPRA), permafrost is continuous and its temperatures at 20-m depth typically have ranged from −6 to −10°C over the last three decades (Osterkamp, 2003) and have risen 1–1.5°C over the last two decades. Massive ice is common in the form of ice wedges, and less common as ice cores in pingos and thin subsurface ice sheets (Rawlinson, 1993; Jorgenson et al., 1996). The volume of ice wedges in the upper 2 m of permafrost ranges from 0% in recently exposed channel deposits to 20% or more in 2000- to 4000-year-old, fine-grained abandoned floodplain deposits (Jorgenson et al., 1996). The ice wedges in particular are very sensitive to disturbance and climate change (Jorgenson et al., 2006). The patterns and abundance of segregational ice formed within a soil matrix is even more complex and typically ranges in volume from 40% in sandy channel deposits to 80% in deltaic abandoned floodplain deposits (Shur and Jorgenson, 1998). The permafrost is protected by a seasonally thawed active layer that adjusts in thickness to summer temperatures, vegetation, and organic matter accumulation (Shur, 1988; Jorgenson et al., 1996). Under undisturbed conditions, late-summer mean thaw depths ranged from 26 cm for upland tussock tundra with organic-rich soils to 133 cm for riverine moist tall willow shrub on well-drained sandy soils (Jorgenson et al., 2003a).

In this paper, we quantify the thaw settlement associated with melting of segregational ice in the upper permafrost in response to increases in active layer depth that occur after severe disturbances



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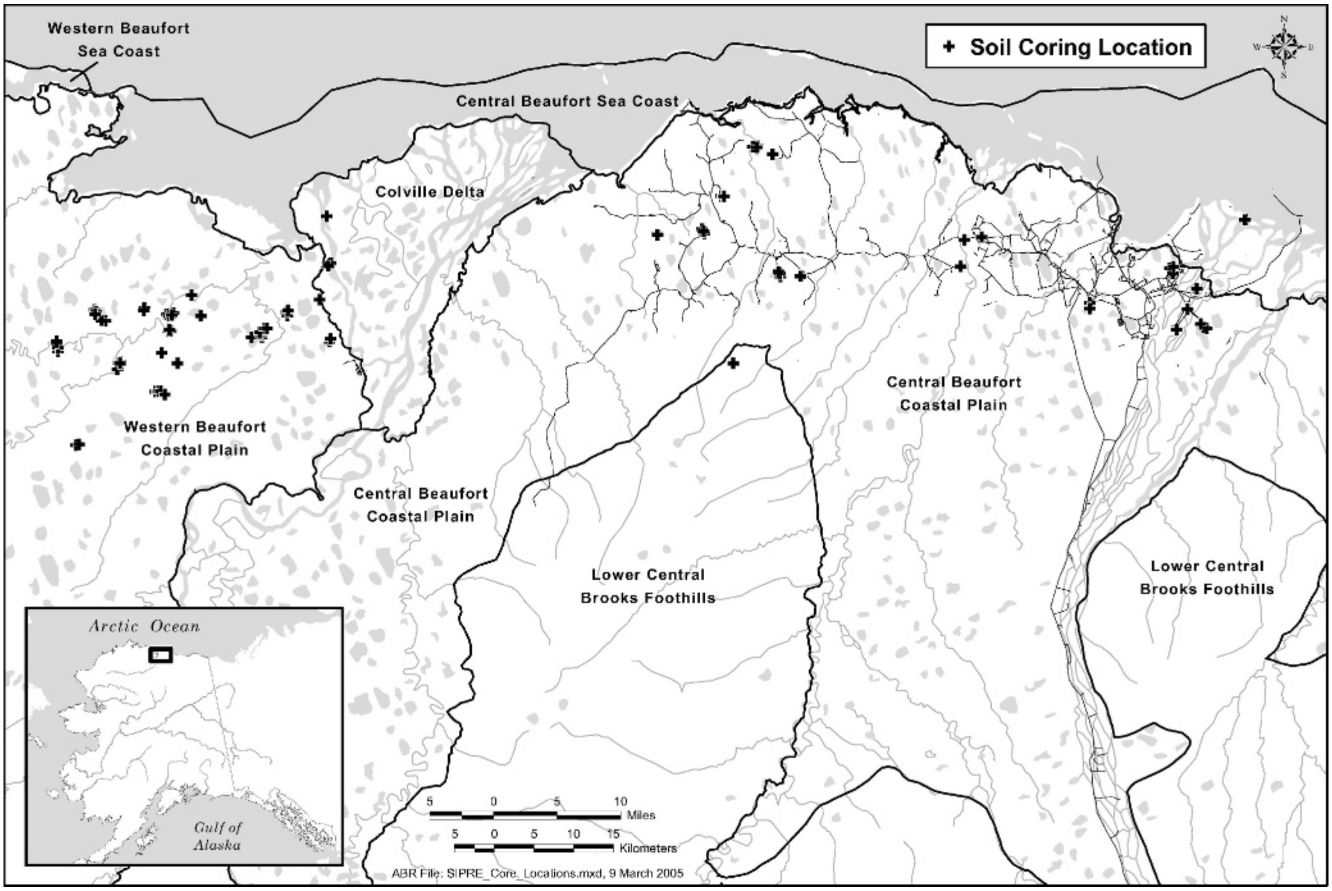


**FIGURE 1. Map showing the location of the sample sites.**

of vegetation on the soil surface. These data are needed to improve prediction of impacts of disturbances of the soil surface and develop appropriate rehabilitation strategies. To address the spatial variability of ground ice (both massive and segregational) across the landscape we analyzed the core sample data at both local and regional scales, based on the terrain unit approach. At the local scale, we used terrain units, which correspond to depositional units related to a specific sedimentation process (fluvial, lacustrine, marine, eolian, etc.). At the regional level, we grouped coring locations by ecodistricts (e.g., central Beaufort Coastal Plain) and ecosubdistricts (e.g., Prudhoe Bay Coastal Plain) that were defined primarily by topography and soil parent material (Jorgenson et al., 1997).

Thaw settlement, associated with disturbances of the soil surface, has been studied on a local scale at specific sites around the world's permafrost regions (e.g. Burgess, 2003b; Johnston, 1969; Olovin, 1979; Shur, 1988). The data in this paper can be applied to estimate thaw settlement across approximately 7000 km$^2$ of the Beaufort Coastal Plain.

## Methods

### *EVALUATION OF ICE CONTENT*

Soil cores were collected in connection with several studies conducted in 1998–2003 (Burgess et al., 1999; Jorgenson et al., 2002; ABR and BP, 2002a, 2002b, 2002c; ABR, 2003a, 2003b, 2003c; Jorgenson et al., 2003b, 2004). The number of cores and their location are listed in Table 1. At each site, the stratigraphy of the soil in the active layer was described from soil pits to assess surface organic thickness and mineral characteristics of soil. Samples of active layer soils were collected to determine the bulk density of unfrozen sediments. A 3-in.-diameter (7.6-cm-diameter) SIPRE (Snow, Ice and Permafrost Research Experiment group) corer with a portable power head was used to obtain permafrost cores from 1 to 2.7 m in length below the active layer. Several bank exposures of undisturbed frozen sediments were described and sampled. Descriptions included the texture of each horizon, the depth of organic matter, depth of thaw, and visible ice volume and cryogenic structure. In the field, soil texture was classified

**TABLE 1**

**Data sources used in compiling summary of thaw settlement.**

| Source | Study area | Stations |
|---|---|---|
| Burgess et al. (1999) | Prudhoe Bay and Kuparuk Oilfields | 24 |
| Jorgenson et al. (2001) | NPRA Exploration Area | 15 |
| Jorgenson et al. (2002) | NPRA Exploration Area | 31 |
| Jorgenson et al. (2003) | NPRA Exploration Area | 20 |
| ABR (2003a, 2003b, 2003c) | Exploratory Well Sites West Sak 1, West Sak 11, and West Sak B10 | 9 |
| ABR and BP (2002a, 2002b, 2002c) | Exploratory Well Sites Sag Delta 2, MPU-N Pad, and WS-25 | 9 |

**TABLE 2**

**Density of soils in the contemporary active layer (mean ± standard deviation).**

| Lithofacies | Code | Mean bulk density (g/cm$^3$) |
|---|---|---|
| Organic, massive | Om | 0.3 ± 0.2 |
| Organic, layered | Ol | 0.7 ± 0.4 |
| Organic, layered turbated | Olt | 0.41 (n = 1) |
| Fines, limnic | Fa | 0.6 ± 0.4 |
| Fines with organics, massive | Fom | 0.7 ± 0.4 |
| Fines with organics, turbated | Fot | 1.0 ± 0.5 |
| Fines, layered | Fl | 1.3 ± 0.4 |
| Fines with clay, laminar | Fcl | 1.4 ± 0.2 |
| Fines, massive | Fm | 1.4 ± 0.5 |
| Sands with organics, inclined | Soi | 1.5 ± 0.1 |
| Sands, rippled | Sor | 1.2 ± 0.5 |
| Sands, layered | Sl | 1.3 ± 0.2 |
| Sands with organics, turbated | Sot | 1.3 ± 0.1 |
| Sands, inclined | Si | 1.4 ± 0.2 |
| Sands, massive | Sm | 1.5 ± 0.2 |
| Sands with gravel, turbated | Sgmt | 1.5 ± 0.4 |

according to the Soil Survey Manual (1993). Cryogenic structure of permafrost soils was described according to Shur and Jorgenson (1998).

Soil samples were taken from each borehole or an exposure at 20- to 30-cm intervals, or within each stratigraphic soil section (whichever interval was smaller). Samples were photographed and subsequently analyzed for volumetric and gravimetric water content. Volume of each sample was determined in the field by measuring a sample length at three points and three circumferences along each collected core section.

## *THAW SETTLEMENT*

Thaw strain was determined for each core sample, and mean thaw strain was calculated for each of the sampled terrain units. Potential thaw settlement was estimated as the decrease in volume a frozen soil sample undergoes when thawed for individual soil horizons and the potential change in the active layer thickness caused by surface disturbance.

Thaw strain ($\delta$) for each soil sample was calculated from the equation (USSR Building Code, 1960; Crory, 1973)

$$\delta = [(\gamma_{dt} - \gamma_{df})/\gamma_{dt}], \tag{1}$$

where $\gamma_{df}$ is the dry density of the soil sample (g cm$^{-3}$) in frozen state, and $\gamma_{dt}$ is the dry density of thawed and overburden soil (g cm$^{-3}$). Data on $\gamma_{dt}$ for studied lithofacies are shown in Table 2.

Figure 2 shows active layer depths before ($H_1$) and after ($H_2$) disturbances on the soil surface. Increase in the active layer depth triggers melting of ice-rich upper permafrost and thaw settlement ($S$). The thaw strain of soil is $\delta$ (fraction of 1). If the active layer depth after surface disturbance is measured from the initial surface, it would be equal to ($S + H_2$). Thaw settlement ($S$) is equal to

$$S = [(S + H_2) - H_1]\delta, \tag{2}$$

from which

$$S = \frac{(H_2 - H_1)\delta}{1 - \delta} \tag{3}$$

Shur (1988) derived a similar equation as the limit of accumulating settlement with time. Figure 3 shows dependence

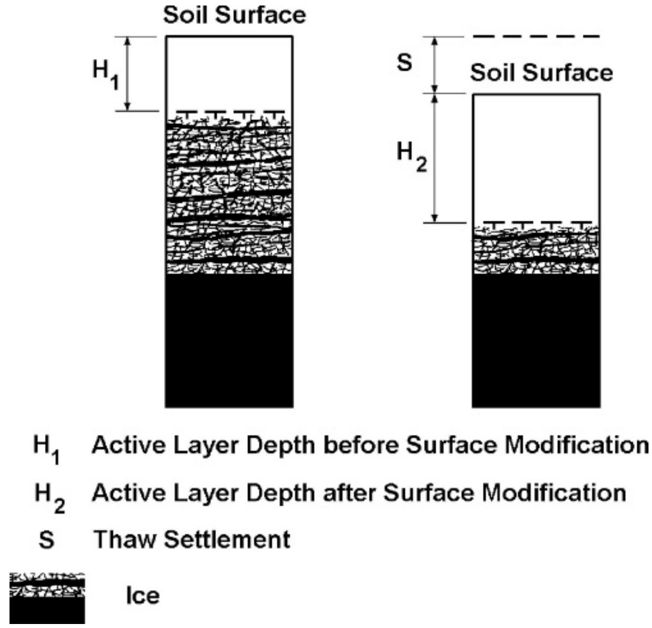


**FIGURE 2. Illustration showing the development of thaw settlement associated with an increase in the active layer depth.**

of thaw settlement on change in the active layer depth for four thaw strains. This figure also shows that for ice-rich soils with thaw strain greater than 0.5, thaw settlement is greater than an increase in active layer depth measured from soil surface (not from a fixed reference point).

Equation (3) is derived for homogeneous soil or for soil that can be represented by averaged thaw strain. For the sequence of upper permafrost with highly variable thaw strain

$$\Delta S_i = h_i\delta_i \text{ and } \Delta H_i = h_i - h_i\delta_i, \tag{4}$$

where $h_i$ is a sublayer with uniform thaw strain, $\delta_i$ is the thaw strain for this layer, and $\Delta H_i$ is the thickness of the sublayer $h_i$ after its thawing and settling. Thaw settlement stops when the

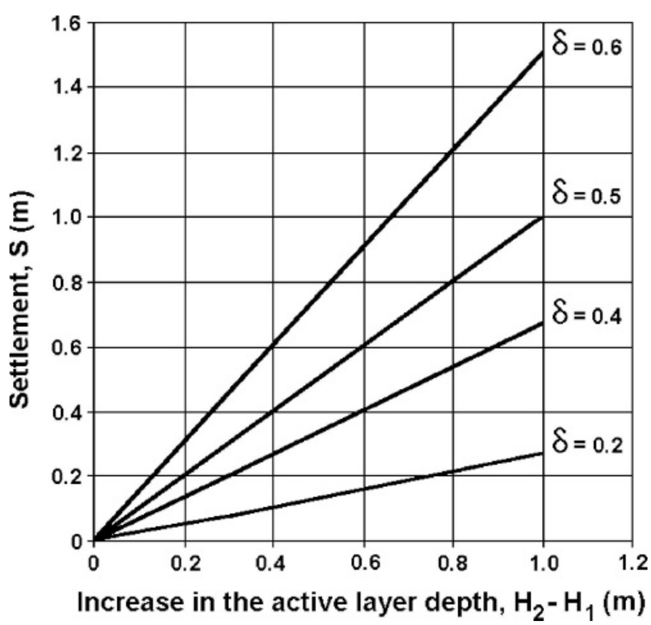


**FIGURE 3. The relationship of thaw settlement ($S$) to increases in the active layer depths ($H_2$-$H_1$) in uniform soils with various thaw strains ($\delta$).**

**TABLE 3**

**Description of ecodistricts in the Beaufort Coastal Plain where soil samples were collected for thaw settlement estimates.**

| Ecodistrict | Description |
|---|---|
| Central Beaufort Coastal Plain | This area extends from the Canning River west to the Colville Delta. The coastal plain extends inland and encompasses the Sagavanirktok and Kuparuk river floodplains on the east and the Colville River and Itkillik River floodplains to the west. The region consists of a flat terrain underlain by alluvial marine deposits, floodplain deposits, and eolian sand and loess. Drained lake basin features such as shallow wind-oriented lakes, pingos, and wet meadows comprise a significant portion of the landscape. |
| Central Beaufort Sea Coast | This ecodistrict encompasses the outer delta deposits of the Sagavanirktok, Kuparuk, and Colville rivers along with the nearshore shallow waters and barrier islands off the central Beaufort Coastal Plain. The region is strongly affected by marine processes (storm surges, wave erosion, sea ice, and tidal fluctuations). |
| Colville Delta | The Colville Delta begins inland at the confluence of the Colville and Itkillik rivers and extends into the Beaufort Sea. This ecodistrict defines the area influenced by the deposition of deltaic sediments. The region consists of very flat terrain divided by a series of distributaries of the Colville River and underlain by thick, ice-rich fluvial deposits. |
| Lower Central Brooks Foothills | This ecodistrict consist of gently rolling terrain that rises from the central Beaufort Coastal Plain. The terrain is dominated by thin loess deposits over ice-rich pebbly sands. Thaw basins are uncommon. |
| Western Beaufort Coastal Plain | The ecodistrict is similar to the central Beaufort Coastal Plain but is somewhat more rolling and lacks an extensive loess cap. Floodplain deposits are limited to narrow, meandering stream corridors. The terrain is dominated by eolian sands, alluvial marine deposits, and thaw basin deposits. |

combined thickness of sublayers affected by melting and settling reaches the difference between old and new equilibrium depths of the active layer. Calculation for the summation of settlement of sublayer is represented by the equation

$$\sum_{i=1}^{n} (h_i - h_i\delta_i) = H_2 - H_1 \tag{5}$$

For homogeneous soil ($i = 1$) or for soil, which is represented by averaged thaw strain, Equation (5) is equivalent to equation (3).

Equations (3) and (5) were used to evaluate thaw settlement for each sampling site across a range of equilibrium thaw depths ranging from 60 to 110 cm. Mean thaw settlement values ($\pm$SD) were grouped by terrain unit and by terrain unit within ecodistricts across the study area.

### *EQUILIBRIUM THAW DEPTH*

We define an equilibrium thaw depth as the depth of the active layer measured from the soil surface after settlement following surface disturbance has stabilized. In the continuous permafrost such stabilization can occur in a few years after removal of the vegetation cover of the soil surface (Shur, 1988). Based on our field observations in the region (ABR and BP, 2002a, 2002b, 2002c; ABR, 2003a, 2003b, 2003c; Kidd and Rossow, 1998; Burgess et al., 1999; Jorgenson et al., 1997, 2002, 2003a), the thaw depth after disturbance of moist organic-rich soils varies from 60 to 110 cm and the equilibrium thaw depths of 60, 80, and 110 cm were chosen to represent low, medium, and high disturbance levels (respectively).

### *TERRAIN CLASSIFICATION*

Investigation sites were assigned to ecodistricts based on their geographic location (Jorgenson et al., 2003a). Ecodistricts are regional-scale terrestrial and nearshore areas with similar surficial geology and soils (Table 3). Each site was also associated with a terrain unit (local surficial deposit) based on the soil characteristics and landform patterns. The terrain-unit classification system that we used is our further development of approaches proposed by Kreig and Reger (1982) and the Alaska Division of Geology and Geophysical Surveys (Carter and Galloway, 1985) for their engineering-geology mapping scheme. The terrain units used in this study are described in Table 4. Many terrain units had a 10- to 15-cm-thick cap of loess in the active layer. This loess layer did not directly affect thaw settlement and was too thin to justify a subclassification of terrain units.

## Results and Discussion

### *THAW STRAIN FOR DOMINANT TERRAIN UNITS*

Mean thaw strain varied among 12 terrain units from nearly 0% at the surface of meander active channel and active overbank deposits with ice-poor sandy soils to 55% for the intermediate layer of meander abandoned overbank and delta inactive overbank deposits with ice-rich, interbedded silts and organics (Fig. 4). The values are variable within a terrain unit due to the range of textures and ages of the soils at the various depths.

Variation in the mean thaw strain values are closely related to geomorphic processes and can be partitioned into six main groups. (1) The inactive eolian sand deposits have an ice-rich, organic and silty intermediate layer below the active layer and overly uniformly ice-poor, sandy soils. (2) Floodplains with active channel deposition and erosion have ice-poor soils due to the predominance of sandy soils and the rapid sediment accumulation that precludes significant ice development in the upper permafrost. (3) Overbank deposits on braided and meandering have interbedded organics, sands, and silts that are intermediate in ice content. (4) Meander abandoned overbank and delta inactive overbank deposits are extremely ice rich due to the high organic and silt content of the soils and the long period that ice has been allowed to develop below the aggrading surface. (5) Drained basins with ice-poor margins have high ice contents immediately below the active layer, but become very ice poor in the underlying sandy materials that develop along wave washed shorelines. The drained basins with ice-poor centers, ice-rich margins, and ice-rich centers have intermediate ice contents due to the accumulation of limnic and organic material in the soils. Note that the ice-poor and ice-rich basins are differentiated on the basis of ice-wedge polygonization evident on aerial photography, and not necessarily on the amount of segregated ice. (6) The alluvial marine deposits are very ice rich because they are the oldest undisturbed deposits across the landscape.

**TABLE 4**

**Description of terrain units on the Beaufort Coastal Plain where soil samples were collected for thaw settlement estimates.***

| Terrain unit | Description |
|---|---|
| Eolian inactive sand deposits | Fine to very fine, well-sorted sand containing abundant quartz with minor dark minerals. Sand is stratified with large-scale cross bedding in places. 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. Inactive dunes occur both on the coastal plain and adjacent to river channels. |
| Delta inactive overbankdeposits | 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 organic horizons is a thick layer (0.3–2 m thick) of silty cover deposits overlying channel deposits. Surface forms range from non-patterned to disjunct and low-density, low-centered polygons. Lenticular and reticulate forms of segregated ice, and massive ice in the form of ice wedges, are common. |
| Meander sandy active channel deposits | Sand and mud deposited as lateral accretion deposits in active river channels by fluvial processes. Occasional sub-rounded to rounded pebbles may be present. Frequent deposition and scouring from flooding usually restricts vegetation to sparse pioneering colonizers. The channel has a meandering configuration characterized by point bars. |
| Meander active overbank deposits | Thin (0.5–1 ft; 0.15–0.3 m), fine-grained cover deposits (primarily silt) that are laid down over sandy or gravelly riverbed deposits during flood stages. Deposition occurs with enough frequency (probably every 3–4 years) to prevent the development of a surface organic horizon. This unit usually occurs on the upper portions of point and lateral bars and supports riverine willow vegetation. |
| Meander inactive overbank deposits | Interbedded layers of peat and silty, very-fine sand material (0.5–2 ft thick; 0.15–0.61 m thick), indicating a low frequency of flood deposition. Cover deposits below this layer generally consist of silt but may include pebbly silt and sand and usually are in sharp contact with underlying channel deposits. This unit has substantial segregated and massive ice, as indicated by the occurrence of ice-wedge polygons. |
| Meander abandoned overbank deposits | Sediments are a mixture of peat, silt, or fine sand. Surface organic horizon is free of fluvial deposits, 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 silt-loam or fine-sand alluvium. Low center polygons and small ponds are common. |
| Braided inactive overbank deposits | Interbedded layers of peat and silty very fine sand material (0.5–2 ft thick; 0.15–0.61 m thick), indicating a low frequency of flood deposition. Cover deposits below this layer generally consist of sand and pebbly sand and usually are in sharp contact with underlying gravelly sand channel deposits. This unit is generally ice poor due to the prevalence of sand in the soil matrix. |
| Alluvial–marine deposits | The moderately thick (3–10 m) sand sheet is widespread across the Beaufort Coastal Plain and is comprised of poorly sorted, slightly pebbly loamy sands. The material is non-stratified but usually has large cryoturbation or deformation features that extend several meters below the surface, is non-fossiliferous, and is slightly saline. The origin of the sand sheet is problematic and has been variously attributed to be eolian (Rawlinson 1993), alluvial, and marine (Cater and Galloway, 1985). The deposits occur in upland situations between lake basins and represent some of the oldest deposits on the coastal plain. |
| Drained lake basin, ice-poor margins | The sandy margins of lacustrine deposits exposed in drained lake basins typically have soils that are fine-grained and organic-rich, with stratigraphy re-formed by subsidence. The presence of non-patterned ground or disjunct polygonal rims indicates that ground ice content is low and that lake drainage has recently occurred. Ponds in these basins typically have irregular shorelines and are highly interconnected. Sandy margins and silty centers are differentiated when micro-topographic features are distinct. |
| Drained lake basin, ice-poor centers | The centers of lacustrine deposits exposed in drained lake basins typically have a thin to thick surface horizon of fibrous peat underlain by a thick accumulation of algal-rich limnic silts. Ice-poor basins are differentiated by the lack of low-centered polygons caused by ice wedge development. |
| Drained lake basin, ice-rich margins | The sediments are similar to those of ice-poor margins of drained lake basins 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, have smooth, regular shorelines, and be poorly interconnected. |
| Drained lake basin, ice-rich centers | The sediments are similar to those of ice-poor centers of drained lake basins but have much more ground ice, as indicated by the development of low-centered or high-centered polygons. The centers of basins usually have organic-rich, silty sediments that have high potential for ice segregation and often are raised by ice aggradation. Surface morphology ranges from low-center polygons at early stages of development to high-centered polygons on distinctly raised domes. |

* Modified from Carter and Galloway (1985) and Krieg and Reger (1982).

### *THAW SETTLEMENT FOR DOMINANT TERRAIN UNITS*

Thaw settlement is a function of the original thickness of the active layer, the increase of the active layer as it adjusts to disturbance at the surface, and the thaw strain of the underlying permafrost. Mean thaw settlement values were calculated from the cumulative loss of volume associated with the thaw strain values for the many layers within a profile. Potential mean thaw settlement for an active layer adjustment to 110 cm varied from ~0 cm in sandy soils with thick active layers associated with meander active channel and overbank deposits to 86 cm associated with delta inactive overbank deposits that typically have thin active layers over very ice-rich silty soils (Fig. 5). Variability in estimated thaw settlement also is due to the high variability in soil materials and ice contents through the soil profiles. Note that the thaw settlement values are for soils with segregated ice and do not

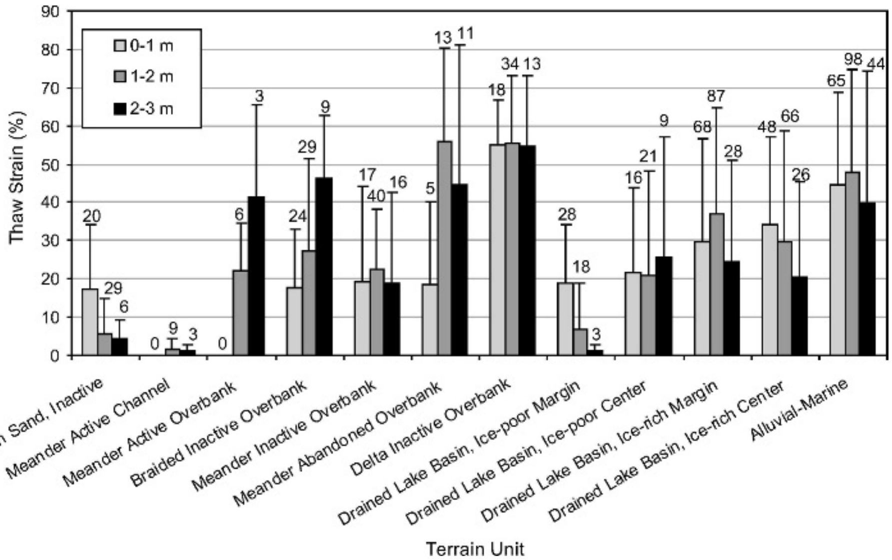


**FIGURE 4. Mean thaw strain (±SD) for permafrost samples obtained from 12 terrain units on the Beaufort Coastal Plain, northern Alaska. Values are summarized by depth from the ground surface and sample number is given above bars.**

include estimates of the potential settlement associated with ice wedges.

Observations based on aerial photographs, exposures on lakeshores, and soil cores suggest that this analysis may have underestimated the thaw settlement in ice-rich thaw basin centers. At four of seven of sampling locations in this terrain unit, we did not encounter the underlying sand sheet, due to the thickness of ice-rich, drained-lake deposits. Therefore, some portion of ice-rich soil may not have been sampled. The development of secondary thaw lakes, and the subsequent thermal erosion of ice-rich centers of drained-lake basins observed on aerial photographs and in the field, suggest that a total subsidence of 2–4 m is possible following a severe surface disturbance in ice-rich thaw basin centers.

### *THAW SETTLEMENT BY REGION*

Thaw settlement estimates for the various terrain units varied across the region, however, as indicated by differences among ecodistricts (Table 5). Most of studied sites (Fig. 1) were in the central Beaufort Coastal Plain ecodistrict (35 samples in 6 terrain types) and the western Beaufort Coastal Plain ecodistrict (52 samples in 10 terrain types). The remaining 9 sites were distributed across the central Beaufort Sea Coast (2 sites), the Colville Delta (3 sites), and the lower central Brooks Foothills (3 sites). Mean thaw settlement values between the central Beaufort Coastal Plain (Prudhoe Bay and Kuparuk Oilfields) and the western Beaufort Coastal Plain (site of new oil developments) were similar for alluvial marine deposits (74 vs. 62 cm) and ice-rich margins of drained-lake basins (34 vs. 31 cm) when calculated for an active-layer adjustment to 110 cm. Sample sizes (8–13) used for these estimates were fairly high. In contrast, the respective values for the ice-rich centers of drained-lake basins (76 vs. 41 cm) and ice-poor margins of drained-lake basins (69 vs. 16 cm) varied widely, in part due to the low sample sizes for these terrain units. The highest mean thaw settlement for 110-cm active-layer adjustment occurred in delta inactive overbank deposits (103 cm) in the Colville Delta.

These results indicate that when estimating potential thaw settlement for a specific location, the estimates are most reliable when calculated for the terrain unit level within the associated ecodistrict. However, for some sites this is not possible because not all terrain units have been sampled in every ecodistrict. For such cases, the regionwide mean for that terrain unit would be the best available estimate of thaw settlement.

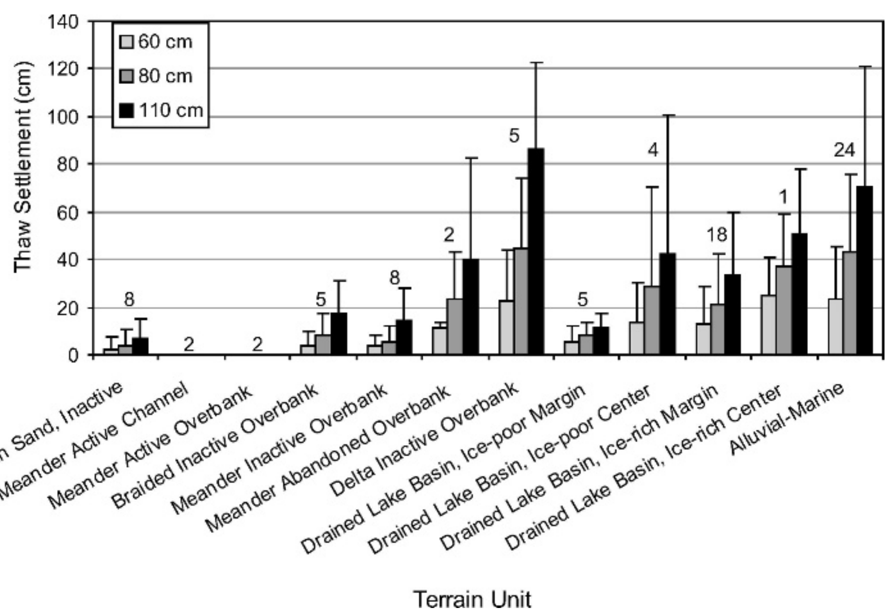


**FIGURE 5. Estimated mean thaw settlement (±SD) after surface disturbance for 12 terrain units on the Beaufort Coastal Plain, northern Alaska. The estimates were calculated for three magnitudes of readjustment of the active layer. An active layer depth of 110 cm is typical for severely disturbed tundra. Sample sizes are given above bars, and each sample represents one core.**

TABLE 5

**Mean thaw settlement (±standard deviation) summarized by terrain units within five ecodistricts for equilibrium thaw depths representing low (60 cm), medium (80 cm), and high (110) disturbance impacts, Beaufort Coastal Plain, northern Alaska.**

| | | Thaw settlement (cm) | | | |
|---|---|---|---|---|---|
| | Disturbance level: | Low | Medium | High | |
| Ecodistrict terrain unit | Equilibrium thaw depth: | 60 cm | 80 cm | 110 cm | Samples (*n*) |
| Central Beaufort Coastal Plain | | | | | |
| Alluvial-marine | | 29.8 ± 26.4 | 42.7 ± 29.4 | 74.1 ± 58.8 | 13 |
| Braided inactive overbank | | 3.9 ± 5.5 | 8.1 ± 9.7 | 17.1 ± 13.8 | 5 |
| Drained lake basin, ice-rich center | | 22.0 ± 14.6 | 53.5 ± 15.1 | 76.1 ± 15.4 | 3 |
| Drained lake basin, ice-rich margin | | 9.1 ± 9.0 | 20.9 ± 17.4 | 34.2 ± 26.4 | 11 |
| Drained lake basin, ice-poor, center | | 18.6 ± 26.3 | 44.6 ± 63.1 | 68.8 ± 84.2 | 2 |
| Central Beaufort Sea Coast | | | | | |
| Delta inactive overbank | | 0 ± 0 | 12.5 ± 0.2 | 61.6 ± 55.4 | 2 |
| Colville Delta | | | | | |
| Delta inactive overbank | | 37.2 ± 10 | 65.9 ± 2.6 | 102.9 ± 9.3 | 3 |
| Lower Central Brooks Foothills | | | | | |
| Alluvial-marine | | 20.1 ± 15.3 | 58 ± 15.4 | 79.1 ± 20.4 | 3 |
| Western Beaufort Coastal Plain | | | | | |
| Alluvial-marine | | 15.2 ± 11.3 | 39.0 ± 42.0 | 61.8 ± 47.3 | 8 |
| Eolian inactive sand | | 2.5 ± 5.1 | 4.1 ± 6.2 | 6.7 ± 8.2 | 8 |
| Meander active riverbed | | 0 ± 0 | 0 ± 0 | 0 ± 0 | 2 |
| Meander active overbank | | 0 ± 0 | 0 ± 0 | 0 ± 0 | 2 |
| Meander inactive overbank | | 3.7 ± 4.7 | 5.4 ± 6.6 | 14.3 ± 13.6 | 8 |
| Meander abandoned overbank | | 11.6 ± 2.2 | 23.8 ± 19.1 | 40.3 ± 42.5 | 2 |
| Drained lake basin, ice-rich center | | 26.0 ± 17.6 | 31.4 ± 20.7 | 40.9 ± 25.5 | 8 |
| Drained lake basin, ice-rich margin | | 18.9 ± 22.5 | 22.3 ± 27.3 | 31.2 ± 29.9 | 7 |
| Drained lake basin, ice-poor center | | 8.3 ± 8.6 | 12.2 ± 14 | 15.6 ± 18.9 | 2 |
| Drained lake basin, ice-poor margin | | 5.2 ± 7.1 | 8.2 ± 5.7 | 11.3 ± 5.9 | 5 |

### *VARIABILITY IN THAW SETTLEMENT*

Potential thaw settlement after disturbance was highly variable both within a terrain unit (as indicated by high SD) and among terrains units across the studied region (Table 5). Much of the variability in thaw settlement reflects natural differences in ground ice content across the landscape, at both large and small spatial scales. However, some of the variability in our estimates reflects the limits on the accuracy with which thawed bulk density of permafrost soils [$\gamma_d$ in Equation (1)] can be estimated. Natural variability due to the former were reduced by grouping study sites by terrain units (Jorgenson et al., 2002), grouping terrain units by ecodistrict, and sampling in the center of polygons to avoid wedge ice. Most of the variability with terrain units reflects the heterogeneous distribution of segregation ice across the landscape and with depth in a soil profile.

Some variance arises from the accuracy in measuring the thawed bulk density of frozen soil, $\gamma_d$. For this study, the mean bulk densities of active layer soils were used to estimate the bulk densities of permafrost soils (based on the lithofacies classification) after thawing, with the difference in bulk density attributed to the volume occupied by excess ice. Some of the variability due to differing proportions of organic material among samples within the same lithofacies class can be eliminated by measuring total carbon content of the sample (Jorgenson et al., 2002). However, this value was only available for a minority of the samples included in this study.

### *MELTING OF ICE WEDGES AND THERMOKARST DEVELOPMENT*

The preceding discussion of thaw settlement represents calculations for soils within the central parts of ice-wedge polygons. Thaw settlement for massive ice bodies, such as ice wedges, however, is very different. If seasonal thaw depth reaches the top of massive ice some time during summer, massive ice will melt during the rest of summer. Field studies of such process and evaluation of a thickness of melting ice in this case were described by Shur (1988). Conditions that can lead to terminating of this potentially continuous process were discussed in Jorgenson et al. (2006).

There usually is a thin transient layer of frozen soil between the active layer and the ice wedges (Shur, 1988; Shur et al., 2005), which helps protect ice wedges from small disturbances and climatic fluctuations. Disturbance of the soil surface causes an increase of the active layer and degradation of ice wedges. The ponding of water in deep troughs in the thawing ice wedges causes a complete or nearly complete loss of the ice within months to a few years. Water drainage is often channelized through the deepening trough network. Our observations show that in some terrain units, ice wedges melt at least to a depth of 2 m, leaving a highly polygonized surface. The loss of volume due to thawing of ice wedges is about 20% for alluvial marine deposits, 15% for ice-rich thaw basin centers with well-developed low-centered polygons, and negligible for ice-poor thaw basins.

The degradation of both segregated and wedge ice results in a mosaic of polygonal troughs and high-centered polygons. The prominence of such a network is different in different terrain units. In alluvial marine deposits, which have the highest volumes of both segregated ice and wedge ice, the topography that develops as a result of thermokarst is highly irregular, with deep and shallow troughs and prominent high-centered polygons. Because these terrain units generally occupy slopes and gently rolling uplands between thaw basins, surface drainage and lowering of the water table is often associated with thermokarst. In most cases, these changes result in most of the polygon centers being above the water table. In ice-poor thaw basins, where segregated ice volumes are much lower and wedge ice is negligible, thaw settlement is moderate. However, the surface can remain flooded because this terrain unit occurs in the lowest portions of the basins, and minor settlement could result in the development of shallow ponds.

Such thermokarst topography has been observed at numerous sites. At sites on alluvial marine deposits, such as the Sinclair Exploratory Well Site (Bishop et al., 1998) and S. E. Eileen State No. 1 (Cater and Jorgenson, 1993), thermokarst settlement and partial drainage have resulted in highly irregular surfaces, with deep and shallow water in troughs and patches of wet and moist tundra in the polygon centers. At a site in an ice-rich thaw basin (undifferentiated) near the Prudhoe Bay Operations Center, where ~20 cm of gravel was left after gravel removal in 1988, thermokarst has resulted in shallow water over the polygon centers and deep water in the troughs (Kidd and Rossow, 1998). At the S. E. Eileen Exploratory Well Site (Bishop et al., 1999), on a meander inactive overbank deposit of the Kuparuk River, thermokarst has resulted in mostly moist and wet high-centered polygons with only limited presence of shallow water in troughs. This site is somewhat unusual in being located next to the river bank, so drainage is better than on many flat inactive overbank deposits (floodplains). At sites in ice-poor thaw basins (undifferentiated), such as the abandoned access road to Drill Site 3K in the Kuparuk Oilfield (Cater and Jorgenson, 1993) and the abandoned access road to the Operations Storage Pad in Prudhoe Bay (Kidd and Rossow, 1998), where thick gravel was removed from the tundra surface, thermokarst has resulted in level flooded topography with shallow ponds or wet meadows, depending on water depth.

## Conclusions

The potential for thaw settlement associated with surface disturbance varies across the Arctic Coastal Plain from near zero in active riverine deposits and inactive eolian sand deposits to more than one meter in alluvial marine deposits. These differences in thermokarst susceptibly of terrain units have important implications for land management, facility planning, and development of site-specific rehabilitation strategies. Knowledge of the thermokarst susceptibility of a site can help to ensure integrity of structures and the long-term success of rehabilitation efforts. Evaluation of permafrost responses to specific impacts on the soil surface should also consider the melting of massive ice and the potential for water impoundment associated with thaw settlement.

Thermokarst is a natural process that is integral to development of the landscape on the Arctic Coastal Plain. Human-induced thermokarst can be incorporated into rehabilitation planning to increase habitat diversity and productivity. However, minimization of thermokarst propagation beyond the disturbed site is usually an important objective.

At sites where the gravel base of temporal roads is removed, thermokarst greatly affects the outcome of any rehabilitation effort. Sites on eolian inactive sand and alluvial marine deposits will likely become diverse mosaics of well-drained, high-centered polygons and flooded troughs. Over time, areas in ice-rich thaw basin margins probably would become large shallow ponds; while areas in ice-rich thaw basin centers would likely become large deep ponds. Areas in ice-poor thaw basins would likely become shallow ponds (in poorly drained areas), or uniform wet or moist meadows (in better drained areas).

Effective land management on permafrost-dominated terrain requires site-specific predictions of thermokarst following disturbance. Knowledge of the likely extent of thaw settlement across the landscape is essential for effective rehabilitation planning, including the choice of surface preparation and selection of appropriate plant materials.

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