

Interactive comment on “Presence of rapidly degrading permafrost plateaus in southcentral Alaska” by B. M. Jones et al.

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Received and published: 6 July 2016

REVIEW

Benjamin M. Jones, Carson A. Baughman, Vladimir E. Romanovsky, Andrew D. Parsekian, Esther L. Babcock, Miriam C. Jones, Guido Grosse, and Edward E. Berg
PRESENCE OF RAPIDLY DEGRADING PERMAFROST PLATEAUS IN SOUTHCENTRAL ALASKA

GENERAL COMMENTS:

This manuscript is based on complex study of degrading frozen peat plateaus in the area of warm isolated permafrost. Such studies are very important because permafrost degradation strongly affects environment and infrastructure. Permafrost dynamics near

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the southern margin of the permafrost region is extremely complicated and has been studied very poorly, so this paper makes a significant contribution to permafrost science.

Thank you for the general praise Misha and for the very helpful and constructive review. We address each of your comments and suggested edits below in red bold text.

The manuscript contains unique information and is clearly written, and I strongly support its publication. Though I don't have any major concerns, I believe that this manuscript needs some minor revision. These are my main recommendations:

1. I recommend to add several more references:

Kuhry, P. 2008. Palsa and peat plateau development in the Hudson Bay Lowlands, Canada: timing, pathways and causes. *Boreas* 37(2): 316–327. DOI: 10.1111/j. 1502-3885.2007.00022.x

Sannel, A.B.K., Kuhry, P. 2008. Long-term stability of permafrost in subarctic peat plateaus, west-central Canada. The Holocene 18(4): 589–601.

Sannel, A.B.K., Kuhry, P. 2011. Warming-induced destabilization of peat plateau/thermokarst lake complexes. Journal of Geophysical Research 116, G03035, doi:10.1029/2010JG001635, 2011

Zoltai, S.C. 1993. Cyclic development of permafrost in the peatlands of northwestern Alberta, Canada. Arctic and Alpine Research 25(3): 240–246.

Riddle, C.H., Rooney, J.W., 2012. Encounters with relict permafrost in the Anchorage, Alaska, area. Proceedings of the Tenth International Conference on Permafrost, Salekhard, Yamal-Nenets Autonomous District, Russia, June 25–29, 2012, 1, pp. 323–328.

Jorgenson, T., Shur, Y.L., Osterkamp, T.E. 2008. Thermokarst in Alaska. In Proceedings of the Ninth International Conference on Permafrost, Vol. 1, June 29–July 3, 2008, Fairbanks, Alaska, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, Uni-

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iversity of Alaska Fairbanks; 869–876.

Jorgenson, T., Kanevskiy, M., Shur, Y., Osterkamp, T., Fortier, D., Cater, T., Miller, P. 2012. Thermokarst lake and shore fen development in boreal Alaska. In *Proceedings of the Tenth International Conference on Permafrost, Vol. 1 International contributions, June 25–29, 2012, Salekhard, Russia, Hinkel KM (ed.). The Northern Publisher: Salekhard, Russia; 179–184.*

Riordan, B., Verbyla, D., McGuire, A.D. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research* 111, G04002, doi:10.1029/2005JG000150, 2006

Nossov, D.R., Jorgenson, M.T., Kielland, K., and Kanevskiy, M. (2013) Edaphic and microclimatic controls over permafrost response to fire in interior Alaska. *Environmental Research Letters* 8 (3), 035013, doi:10.1088/1748-9326/8/3/035013.

Kanevskiy, M., Jorgenson, T., Shur, Y., O'Donnell, J.A., Harden, J.W., Zhuang, Q., Fortier, D. 2014. Cryostratigraphy and permafrost evolution in the lacustrine lowlands of West-Central Alaska. Permafrost and Periglacial Processes 25 (1): 14–34. DOI: 10.1002/ppp.1800

O'Donnell, J.A., Harden, J.W., McGuire, A.D., Kanevskiy, M.Z., Jorgenson, M.T., Xu, X. 2011. The effect of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior Alaska: implications for post-thaw carbon loss. Global Change Biology 17: 1461–1474. DOI: 10.1111/j.1365-2486.2010.02358.x

We appreciate the recommendations for incorporating additional references to these important research efforts and findings. We have incorporated a number of these references into the revised manuscript. These are highlighted above in red, italicized text.

2. I'm not satisfied with your explanations of low EIF values (0.09 to 0.13) calculated for your study sites (Pages 19-20, Lines 433-443). You wrote that "Lewkowicz et al. (2011) demonstrated that features with EIF values below 0.33 likely results from ice-

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poor permafrost and/or a high unfrozen water content of the permafrost,” but in the cited paper high unfrozen water content is supposed to explain low electrical resistivities, not low EIF. I’m not sure there is any correlation between low EIF values and high unfrozen water content, because you already mentioned (Line 440) that frozen peat contains a lot of excess ice. Even in warm permafrost, only a fraction of pore ice transforms into unfrozen water, while relatively large (clearly visible) ice lenses and inclusions remain frozen (according to your description, “. . . frozen peat . . . appears to be ice-rich, with a number of ice bands, ice lenses, and ice inclusions”). Probably low EIF values in your case result mainly from the nature of peat, which keeps its volume upon thawing pretty well in comparison with ice-rich mineral soil.

Besides, you didn’t provide any information on ice content of soils (except EIF). It will be good to compare ice content values obtained from frozen cores with EIF values. If you don’t have such data, you may find some information obtained from similar peat plateaus of boreal Alaska or Canada. For example, our team has published several papers with some ground-ice data: see Jorgenson et al., 2012, 2013; O’Donnell et al., 2012; Kanevskiy et al., 2014. I also recommend to add photos and descriptions of your frozen cores to Results.

During the initial submission of this paper we opted to indirectly estimate excess ice fraction based on previous research by Lewkowicz et al. (2011). We do understand the short-coming of such an approach for better describing the permafrost characteristics at our study sites in southcentral Alaska. Based on this comment and further discussion among coauthors, we asked our colleague Eva Stephani to contribute to this paper through analysis and incorporation of frozen core material that we had archived in freezers at the USGS Alaska Science Center. We now include material in the methods section on core prep and analysis, a paragraph in the results section describing the peat and ground-ice characteristics, and two new figures showing the cryostratigraphy and ice contents for a core collected in the Browns Lake wetland complex as well as photos of sections of the frozen cores prior to processing. We have also removed the material on EIF since we now directly quantify the icy nature of the permafrost deposits. We really appreciate this recommendation and we think that addition of this component makes the paper more well-rounded.

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SPECIFIC COMMENTS:

Page 1, Line 24. I recommend to add “at some locations” or “the minimum depth” after “but.”

Thanks for this suggestion. We have modified the text here.

Page 5, Lines 111-118. I recommend to move this text to Methods.

Thanks for this suggestion. We have opted to retain this text here in the final paragraph of the introduction to highlight our objectives and study design. We also go into further detail on each of these aspects in the methods section.

Page 7, Line 148. I recommend to replace “These features are...” with “Degradation of permafrost plateaus is...” I also recommend to move this sentence to Introduction.

Thanks for this suggestion. We have modified the text here.

Page 13, Lines 298-300. You are talking about hummocks and depressions but you didn't describe micro-topography in the paper. I recommend to add a short description to Chapter 2 (Study area).

Thanks for this suggestion. We have briefly described the microtopography in the methods section in the additional field surveys paragraph. We also show these results in Fig. 7b.

Page 19, Lines 422-431. You already presented these data in Results, so I recommend to shorten this paragraph.

Thanks for this suggestion. We have shortened this paragraph.

Page 22, Lines 489-499. Something is missing here.

Thanks for catching this mistake. We have fixed this sentence.

Page 22, Lines 495-496. I recommend to add several more references (see attached file).

Thanks for these suggestions. We have included these recommendations.

Page 23, Lines 520-522. I recommend to add several more references (see attached

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file).

Thanks for these suggestions. We have included these recommendations.

Page 24, Lines 545-546. I recommend to add one more reference (Shur and Jorgenson, 2007).

Thanks for this suggestion. We have included this reference here.

Page 47, Figure 7. I recommend to show expected permafrost boundary with dashed (or dotted) line (see attached file). Also it will be good to show the thickness of peat.

We appreciate this suggestion but have refrained from drawing the permafrost base boundary on Fig. 7b since we do not have the detailed information required to do this through our point measurements. We attempted to image this boundary continuously using GPR but were not able to resolve it. For these two reasons, we prefer to stick with our point data collection efforts in Fig. 7b. We now include a new figure that shows the thickness of peat and ground ice characteristics (Fig. 8).

More comments and suggestions (small edits mostly) are provided in the attached file.

Thanks for these additional minor edits Misha! We have incorporated all of them into the revised manuscript. You really helped us improve this paper.

Good luck!

Mikhail Kanevskiy, Institute of Northern Engineering University of Alaska Fairbanks

Please also note the supplement to this comment:

<http://www.the-cryosphere-discuss.net/tc-2016-91/tc-2016-91-RC1-supplement.pdf>

Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2016-91, 2016.

Interactive comment on “Presence of rapidly degrading permafrost plateaus in southcentral Alaska” by B. M. Jones et al.

A. Kääb (Referee)

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Received and published: 14 July 2016

I write a short review for this paper even if I am editor of it as it turned out impossible to find a 2nd referee due to holiday and fieldwork season. I have already given feedback to the paper before publication in TCD and the authors have adopted my recommendations.

Thank you for the previous feedback on the paper Andreas. We appreciated the comments and suggestions prior to publication in TCD. We have incorporated your further suggestions below in the revised version of the paper.

The paper is an interesting and nicely integrative (ground measurements, ground surveys, geophysical surveys, remote sensing) study about a little investigated but important topic. The paper is well written. I ask the authors to consider the following remaining comments:

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- some PF temperatures seem very little below zero, in the range of logger accuracy. Some more explicit discussion about the logger accuracy with respect to your temperature results could be helpful.

Thanks for this suggestion. We have addressed this potential issue further by incorporating this text in the methods section: The manufacturer-specified accuracy of the thermistors is ± 0.25 °C. Prior to deployment, we placed the data logger thermistors in a 0 °C ice bath for up to 45 minutes to estimate a calibration factor for post-processing of the data following download in the field. After calibration in a 0 °C ice bath, the precision of temperature measurements near 0 °C is limited only by the sensor-logger system sensitivity, which is 0.031 °C in this case. This means that the temperatures in our case were measured with the precision better than ± 0.02 °C and changes in soil temperature exceeding 0.03 °C can be recorded properly using this measuring system. This fact was established and demonstrated many times during our measurements in deeper boreholes using similar measuring systems when the annually measured temperature in some boreholes at deeper depths (50 m and deeper) will remain constant. These calibration techniques and measurement sensitivities are similar to improvements recorded for other measurement systems (Sannel et al., 2015; Cable et al., 2016).

- You don't mention much the role of snow depths, timing and distribution playing a role in the spatial pattern and temporal evolution of your PF. At least theoretically, also changes in snow cover could be in parts behind the spatio-temporal variations you found. You collect and show snow depth data for your field sites, but seem not to discuss these, and the role of snow in general in the phenomena and changes studied. Is snow in your study area too shallow to play an important role? Was this always the case for the time periods and time scales considered?

These are very good questions and a valid point to raise here. Unfortunately, we lack well distributed snow depth data for the study region and in particular on the permafrost peat plateaus over short as well as long time scales. Previous research on permafrost plateaus in colder regions indicate that preferential

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warming in the winter and increased snow accumulation leads to enhanced permafrost thaw in boreal peatlands (Camill, 2005; Osterkamp, 2007). Since the Kenai Peninsula lowlands experience a semi-continental climate due to the rain shadow produced by the Kenai Mountains, a lack of winter snow fall may have contributed to permafrost persistence in this region by allowing relatively cold winter air temperatures to propagate into the sub-surface. In table 1 we show that average end of winter snow depth declined over the three year ground temperature observation period, whereas ground temperatures have remained stable to slightly warmed in some instances. Permafrost loss on the Kenai Peninsula is likely associated with higher air temperature, particularly during the winter season, wildfires that remove the protective ecosystem cover, groundwater flow at depth, and lateral heat transfer from wetland surface waters in the summer. But the role of snow cover warrants further study in the region.

Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2016-91, 2016.

1 **Presence of rapidly degrading permafrost plateaus in**
2 **southcentral Alaska**

3

4 Benjamin M. Jones¹, Carson A. Baughman¹, Vladimir E. Romanovsky^{2,3}, Andrew D. Parsekian⁴,
5 Esther L. Babcock¹, Eva Stephani¹, Miriam C. Jones⁵, Guido Grosse⁶, and Edward E. Berg⁷

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15
16 *Correspondence to:* Benjamin M. Jones (bjones@usgs.gov)

17 **Abstract.** Permafrost presence is determined by a complex interaction of climatic, topographic,
18 and ecological conditions operating over long time scales. In particular, vegetation and organic
19 layer characteristics may act to protect permafrost in regions with a mean annual air temperature
20 (MAAT) above 0 °C. In this study, we document the presence of residual permafrost plateaus on
21 the western Kenai Peninsula lowlands of southcentral Alaska, a region with a MAAT of 1.5±1 °C
22 (1981–2010). Continuous ground temperature measurements between 16 September 2012 and 15
23 September 2015, using calibrated thermistor strings, documented the presence of warm permafrost
24 (-0.04 °C to -0.08 °C). Field measurements (probing) on several plateau features during the fall
25 of 2015 showed that the depth to the permafrost table averaged 1.48 m but at some locations was
26 as shallow as 0.53 m. Late winter surveys (augering, coring, and GPR) in 2016 showed that the
27 average seasonally frozen ground thickness was 0.45 m, overlying a talik above the permafrost
28 table. Measured permafrost thickness ranged from 0.33 m to >6.90 m. Manual interpretation of
29 historic aerial photography acquired in 1950 indicates that residual permafrost plateaus covered

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41 920 ha as mapped across portions of four wetland complexes encompassing 4,810 ha. However,
42 between 1950 and ca. 2010, permafrost plateau extent decreased by 60.0 %, with lateral feature
43 degradation accounting for 85.0 % of the reduction in area. Permafrost loss on the Kenai Peninsula
44 is likely associated with a warming climate, wildfires that remove the protective forest and organic
45 layer cover, groundwater flow at depth, and lateral heat transfer from wetland surface waters in
46 the summer. Better understanding the resilience and vulnerability of ecosystem-protected
47 permafrost is critical for mapping and predicting future permafrost extent and degradation across
48 all permafrost regions that are currently warming. Further work should focus on reconstructing
49 permafrost history in southcentral Alaska as well as additional contemporary observations of these
50 ecosystem-protected permafrost sites lying south of the regions with relatively stable permafrost.

51 1 Introduction

52 Permafrost is a major component of the cryosphere in the northern hemisphere, covering ~24 %
53 of the terrestrial landscape (Brown et al., 1998). Permafrost is defined as ground that remains at
54 or below 0 °C for at least two consecutive years (Van Everdingen, 1998). Four zones describe the
55 lateral extent of permafrost regions: continuous (90-100 %), discontinuous (50-90 %), sporadic
56 discontinuous (10-50 %), and isolated discontinuous (<10 %). This zonation typically represents
57 the north to south changes in spatial distribution for terrestrial permafrost in high latitudes. Mean
58 annual ground temperatures (MAGT) in the continuous permafrost zone can be as cold at -15 °C,
59 fall within a narrow range around -2 °C in the discontinuous permafrost zone, and can be warmer
60 than -1 °C in sporadic and isolated permafrost zones (Smith and Riseborough, 2002; Romanovsky
61 et al., 2010; Smith et al., 2010). In the absence of extensive ground temperature data, researchers
62 have estimated the southern limit of permafrost in northern high latitudes with continental-scale
63 patterns of air temperature isotherms (Brown, 1960, 1970; Ferrians, 1965; Brown et al., 1998).
64 However, in reality complex interactions between climatic, topographic, hydrologic, and ecologic
65 conditions operating over long time scales regulate permafrost presence and stability (Shur and

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70 Jorgenson, 2007). Due to these interactions, permafrost may persist in regions with a mean annual
71 air temperature (MAAT) above 0 °C, and it may degrade in regions with a MAAT below -10 °C
72 (Jorgenson et al., 2010). Thus, the extent and dynamics of permafrost and permafrost-related
73 landscape features remain poorly mapped and modelled at sufficiently fine resolution needed for
74 predicting the impact of climate change on specific local landscapes, which is necessary for many
75 decision makers.

76 Permafrost warming, degradation, and thaw subsidence can have significant implications
77 for ecosystems, infrastructure, and climate at local, regional, and global scales (Jorgenson et al.,
78 2001; Nelson et al., 2001; Schuur et al., 2008). In general, permafrost in Alaska has warmed
79 between 0.3–~~6.0~~ °C since ground temperature measurements began between the ~~1950–1980s~~
80 (Lachenbruch and Marshall, 1986; Romanovsky and Osterkamp, 1995; Romanovsky et al., 2002;
81 Osterkamp, 2007; Romanovsky et al., 2010). Warming and thawing of near-surface permafrost
82 may lead to widespread terrain instability in ice-rich permafrost in the Arctic (Jorgenson et al.,
83 2006; Lantz and Kokelj, 2008; Gooseff et al., 2009; Jones et al., 2015; Liljedahl et al., 2016) and
84 the sub-Arctic (Osterkamp et al., 2000; Jorgenson and Osterkamp, 2005; Lara et al., 2016). Such
85 land surface changes can impact vegetation, hydrology, aquatic ecosystems, and soil-carbon
86 dynamics (Grosse et al., 2011; Jorgenson et al., 2013; Kokelj et al., 2015; O’Donnell et al., 2011;
87 Schuur et al., 2008; Vonk et al., 2015). For example, in boreal peatlands, thaw of ice-rich
88 permafrost often converts forested permafrost plateaus into lake and wetland bog and fen
89 complexes (Camill, 1999; Jorgenson et al., 2001; Payette et al., 2004; [Sannel and Kuhry 2008](#);
90 [Sannel and Kuhry, 2011](#); Quinton et al., 2011; [Jorgenson et al., 2012](#); [Kanevskiy et al., 2014](#);
91 Swindles et al., 2015; [Lara et al., 2016](#)). Furthermore, the transition from permafrost peatlands to
92 thawed or only seasonally frozen peatlands can have a positive or a negative feedback on regional

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97 and global carbon cycles depending on permafrost conditions and differential effects of thaw on
98 net primary productivity and heterotrophic respiration (Turetsky et al., 2007; Swindles et al.,
99 2015), as well as on the degree of loss of the former deep permafrost carbon pool (O'Donnell et
100 al., 2012).

101 In Alaska, a variety of permafrost conditions shape roughly 80% of the landscape (Jorgenson
102 et al., 2008). Shur and Jorgenson (2007) proposed five classes of permafrost that describe the
103 interaction of climatological and ecological processes. Arranged from coldest to warmest, these
104 permafrost classes are as follows: climate-driven; climate-driven but ecosystem-modified;
105 climate-driven but ecosystem-protected; ecosystem-driven; and ecosystem-protected. Ecosystem-
106 protected permafrost is the warmest and most vulnerable of the five classes of permafrost and
107 characterizes the sporadic and isolated permafrost zones. It comprises residual permafrost that
108 persists due to favourable ecosystem factors under a climate that is not conducive to its formation.
109 Press disturbances, associated with warming air temperatures and increases in precipitation
110 (especially snow), and pulse disturbances, such as fire or human activities, can trigger immediate
111 ecosystem modification and permafrost thaw in these regions (Shur and Jorgenson, 2007).

112 Since permafrost acts as a sentinel, integrator, and regulator of climate change, improved
113 understanding of its distribution and dynamics is essential, particularly along the southern
114 permafrost boundary (Lunardini, 1996). Southcentral Alaska, a region with a MAAT ~ 2 °C, is
115 typically mapped as being within the permafrost-free zone (Ferrians, 1965; Brown et al., 1998;
116 Pastick et al., 2015). However, ecosystem-protected permafrost persists in southcentral Alaska in
117 regions with present-day climatic conditions that are no longer conducive to its formation (Shur
118 and Jorgenson, 2007). Isolated permafrost patches in southcentral Alaska exist on the western
119 Kenai Peninsula Lowlands (Berg et al., 2009; Hopkins et al., 1955; Jorgenson et al., 2008) and in

120 the vicinity of Anchorage (Jorgenson et al., 2003; [Riddle and Rooney, 2012](#); Kanevskiy et al.,
121 2013). Enhanced insight into the resilience and vulnerability of ecosystem-protected permafrost
122 is important due to its utility as a climate indicator and a forecaster of the environmental
123 consequences expected to arise from permafrost thaw elsewhere in the boreal forest where MAAT
124 is expected to warm beyond 0 °C in the coming decades (Beilman et al., 2001). Nevertheless, to
125 date, detailed studies of these southcentral Alaska ecosystem-protected permafrost deposits have
126 remained limited (Kanevskiy et al., 2013).

127 [This study documents](#) the presence of rapidly degrading permafrost plateaus on the western
128 Kenai Peninsula lowlands of southcentral Alaska (Fig. 1), a region with a MAAT of 1.5±1 °C (Fig.
129 2). In mid-September 2012, we conducted field studies at several black spruce plateaus located
130 within herbaceous wetland complexes. Continuous ground temperature measurements between
131 16 September 2012 and 15 September 2015 confirmed the presence and degradation of permafrost.
132 Probing, drilling, coring, and ground-penetrating radar surveys conducted in the summer, fall, and
133 winter seasons provided additional information on the geometry of the frozen ground below the
134 forested plateaus. [Historic](#) aerial photography and high-resolution satellite imagery from 1950,
135 1984, 1996, and ca. 2010 [were also used](#) to map decadal-scale changes in the aerial extent of the
136 residual permafrost plateaus in portions of four wetland complexes on the western Kenai
137 Peninsula. This study aims to document and incorporate the loss of ecosystem-protected
138 permafrost into the overall understanding of landscape dynamics on the western Kenai Peninsula
139 lowlands. More importantly, insights into its stability will enhance mapping and predicting current
140 and future permafrost extent along the southern fringe of the circumpolar permafrost region.

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144 **2 Study Area**

145 The western Kenai Peninsula lowlands are located in southcentral Alaska, between 59.6–61.0 °N,
146 and are generally less than 100 m [above sea level \(asl\)](#) (Fig. 1). The lowlands experience a semi-
147 continental climate due to a rain shadow produced by the Kenai Mountains to the east and the
148 presence of Cook Inlet to the west and north, and Kachemak Bay to the south (Jones et al., 2009).

149 Regional MAAT for 1981–2010 [was](#) 1.5 °C, with a mean annual precipitation of 441 mm
150 (<http://www.ncdc.noaa.gov/crn/observations.htm>) (Fig. 2). The lowlands represent a unique
151 landscape where two major glacial ice fields converged during the Late Wisconsin, 25,000–21,000
152 kya (Reger et al., 2007). The modern topography, composed of moraines, outwash fans, kettle
153 lakes, kames, and eskers, is indicative of this glacial history (Hopkins et al., 1955). During the
154 Holocene, the Kenai Peninsula lowlands have succeeded to boreal forest, muskeg, and wetlands
155 laced with rivers and creeks and dotted with lakes (Anderson et al., 2006; Reger et al., 2007).
156 Pastick et al. (2015) recently mapped this region as being permafrost-free in the upper one meter
157 of the ground surface.

158 The Kenai lowlands are situated in an ecotone between the coastal temperate rainforest and
159 interior boreal forest. Species assemblages depend on topography and disturbance history, as well
160 as their location relative to the rain shadow. Black spruce (*Picea mariana*), white spruce (*Picea*
161 *glauca*), Sitka spruce (*Picea sitchensis*), Lutz spruce (*Picea x lutzii*, hybrid of white and Sitka
162 spruce), paper birch (*Betula kenaica*), alder (*Alnus sp.*), black cottonwood (*Populus trichocarpa*),
163 and aspen (*Populus tremuloides*) all occur within various forest stand types. Herbaceous and
164 woody wetland complexes intermingle with these forests in low-lying areas and river corridors.
165 Within wetland complexes, elevated forested plateaus, primarily black spruce but with some paper
166 birch and cottonwood and an understory of dwarf shrubs, exist where the ground surface has been

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171 elevated above the regional water table. We suspected these features were associated with a
172 volumetric expansion of freezing peat, forming a permafrost plateau, an elevated permafrost
173 feature associated with frost heave (Zoltai, 1972, [Zoltai, 1993](#)). [Characterization of degrading](#)
174 [permafrost plateaus is](#) the focus of our studies on the Kenai Peninsula.

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175 3 Methods

176 In September 2012, we conducted field studies at a number of black spruce plateaus located within
177 herbaceous wetland complexes (Fig. [1](#), [Fig. 3](#)). These studies documented frozen ground below
178 an unfrozen layer with thicknesses ranging from 0, [49m](#) to >1.00 m. The plateau features tended
179 to have sharply defined scalloped edges, marginal thermokarst moats, and collapse-scar
180 depressions on their summits (Fig. 3). These traits were characteristic of the permafrost features
181 described by Hopkins et al. (1955) on the Kenai Peninsula and similar to permafrost plateaus across
182 colder boreal regions (Zoltai, 1972; Thie, 1974; Jorgenson et al., 2001; Camill, 2005; Sannel et al.,
183 2015). To answer whether the frozen [deposits](#) encountered at the black spruce plateaus were
184 indeed permafrost, we collected continuous ground temperature measurements for three years,
185 measured late-summer thaw depths, mechanically drilled and cored for the base of the frozen
186 ground, imaged the subsurface with ground-penetrating radar (GPR), and analysed a time series
187 of high-resolution remotely sensed imagery. [These](#) research efforts [are described](#) in more detail
188 below.

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189 3.1 Field Instrumentation and Surveys

190 To confirm the presence or absence of permafrost, [data loggers were installed](#) on 12 September
191 2012 at one ground temperature monitoring site in the Browns Lake and [at three sites](#) in the Watson
192 Lake area (Fig. 1). [A 5 cm diameter Kovacs Enterprise ice auger was used](#) to drill the boreholes

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200 and cased the holes with a 4.5 cm outer-diameter [polyvinyl chloride \(PVC\)](#) tube from the base of
201 the borehole to within 10 cm of the surface. [Each site was](#) instrumented with a [four](#) channel Hobo
202 data logger (Onset U12-008) buried below the ground surface (bgs). The data loggers recorded
203 hourly ground temperature at four depths from 0.10 [3.00](#) m bgs using Hobo TMC1-HD and
204 TMC2-HD thermistors (Table 1). The manufacturer-specified accuracy of the thermistors is [±0.25](#)
205 °C. Prior to deployment, we placed the data logger thermistors in a 0°C ice bath for up to 45
206 minutes to estimate a calibration factor for post-processing of the data following download in the
207 field. [After calibration in a 0°C ice bath, the precision of temperature measurements near 0 °C is](#)
208 [limited only by the sensor-logger system sensitivity, which is 0.031 °C in this case. Therefore, the](#)
209 [temperatures in our case were measured with the precision better than +/- 0.02 °C and changes in](#)
210 [soil temperature exceeding 0.031 °C can be recorded properly using this measuring system. This](#)
211 [fact was established and demonstrated many times during our measurements in deeper boreholes](#)
212 [using similar measuring systems when the annually measured temperature in some boreholes at](#)
213 [deeper depths \(50 m and deeper\) will remain constant. These calibration techniques and](#)
214 [measurement sensitivities are](#) similar to improvements recorded for other measurement systems
215 (Sannel et al., 2015; Cable et al., 2016). [All data were](#) post-processed prior to summarizing the
216 hourly ground temperature data into daily, monthly, and annual means.

217 Additional field surveys at each study site provided information on the geometry of the
218 frozen ground distribution and deposit types. [A tile probe was used](#) to measure the depth to frozen
219 sediments at each ground temperature monitoring location in mid-September 2015 (limited to 2.2
220 m bgs). At the two forested plateaus in the Watson Lake wetland complex, [tile probing locations](#)
221 [were selected](#) randomly and split between hummock and depression microtopography. At the
222 Browns Lake site, [this depth was recorded](#) at three points every meter along a 100 m transect across

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236 the plateau feature. In addition, a topographic profile of the primary Browns Lake plateau was
 237 collected using a Leica survey-grade differential GPS (dGPS) system (± 0.02 m vertical accuracy)
 238 on 09 October 2015 to adjust the probing measurements relative to the local topography. An
 239 additional dGPS profile was acquired on 19 February 2016 at an adjacent plateau to provide more
 240 relative feature height information in the wetland complex. At both the Browns Lake and Watson
 241 Lake locations, the frozen ground thickness was measured using the Kovacs Enterprise ice auger
 242 system powered by an 18V portable drill. At Browns Lake, (site PF-BL-6), a borehole was also
 243 core-drilled to a depth of 5.38 m using a SIPRE permafrost corer (5 cm diameter) with an engine
 244 auger head for analysis of the frozen ground deposit (Fig. 1). The frozen cores were described
 245 according to the cryofacies method (French and Shur, 2010) using cryostructure classification
 246 systems inspired from Murton and French (1994) and Kanevskiy et al. (2014). Gravimetric ice
 247 contents of eleven samples were measured by oven drying at 60 °C for 168 hours. Volumetric ice
 248 contents were measured from ten well-preserved samples.

249 Implementation of GPR allowed to image certain characteristics of the frozen ground along
 250 the primary Browns Lake plateau feature. A shielded 100 MHz Mala antenna was used in July
 251 2014 and Sensors & Software 100 MHz unshielded bi-static antennas in common-offset
 252 configuration in February 2016. The data were processed using commercially available Reflex-
 253 W processing software (Sandmeier, 2008). Basic processing steps included dewow, time-zero
 254 correction, removing bad traces, and bandpass filtering (40–67.2–128–369 MHz for Mala; 25–50–
 255 200–400 MHz for Sensors & Software). Additional processing steps included an average
 256 background subtraction with a running window of 20–100 traces to reduce noise from surface
 257 multiples, where applicable, and variable gain for viewing purposes. Care was taken during
 258 processing to preserve any flat-lying reflectors. Finally, the radargrams were corrected using the

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286 dGPS surface topography and converted two-way travel time to depth using an estimated average
287 subsurface velocity of 0.038 m ns⁻¹ calibrated to average direct probe depths.

288 3.2 Remotely Sensed Imagery and Change Detection

289 Historic aerial photography and contemporary high resolution satellite imagery acquired between

290 1950-ca. 2010 provided an estimated extent of forested plateaus centred on four wetland

291 complexes on the western Kenai Peninsula lowlands. Four change detection study areas (Fig. 1)

292 were selected based on the presence of forested-plateau features surrounded by herbaceous

293 wetland vegetation that likely indicated permafrost presence in the boreal wetlands on the Kenai

294 Peninsula (Hopkins et al., 1955). Arranged from north to south, these included portions of the

295 Mystery Creek, Watson Lake, Browns Lake, and Tustumena Lake wetland complexes (Fig. 1).

296 Mapping forested plateau features and their change over time is a common method for detection

297 of permafrost thaw in boreal wetlands. The land cover change associated with conversion of a

298 forested permafrost plateau to a lake or herbaceous wetland (i.e. bog or fen) is readily detectable

299 in high-resolution remotely sensed imagery (Thie, 1974; Camill and Clark, 1998; Osterkamp et

300 al., 2000; Jorgenson et al., 2001; [Jorgenson et al., 2008](#); Payette et al., 2004; Quinton et al., 2011;

301 Lara et al., 2016).

302 A 25 km² square study area was overlaid at each of the potential permafrost areas and

303 clipped the wetland extent as defined by the 2001 National Land Cover Dataset for Alaska

304 (<http://www.mrlc.gov/nlcd2011.php>) to define the mapping area. Panchromatic, Digital

305 Orthophoto Quadrangle (DOQs) images were produced at a spatial resolution of 1.0 m for the

306 entire Kenai Peninsula between July-August 1996. The DOQs provided the base upon which to

307 georegister the other remotely sensed image datasets that consisted of panchromatic aerial photos

308 collected in August 1950 (1:40,000 scale), color-infrared aerial photos acquired in 1984 (1:62,500

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315 scale), and panchromatic high-resolution satellite images (<1 m spatial resolution) acquired in ca.
316 2010. The mean RMS error associated with image georegistration was 1.82 m and ranged from
317 1.32–2.61 m. All images were sampled to a ground resolution of 1 m. Following image
318 registration, forested plateaus were manually digitized in a Geographic Information System
319 (ArcGIS v. 10.1) at a mapping scale of 1:1,000 (Fig. 4). The high-spatial resolution, georegistered
320 remotely sensed datasets allowed for the assessment of residual permafrost plateau extent in four
321 time slices (1950, 1984, 1996, ca. 2010) and change rates across three decadal-scale time periods:
322 (1) 1950–1984 (34 years), (2) 1984–1996 (12 years), and (3) 1996–ca. 2010 (14 years).

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323 3.3 Climate and Weather Data

324 Climate and weather data were compiled from two regional stations to provide context for
325 interpreting the ground thermal regime data and changes mapped in the remotely sensed data.

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326 Hourly air temperature data were compiled from Kenai Municipal Airport (KMA) (WBAN:
327 26523) for 1948–1971 and 1973–Present and sub-hourly air temperature data from the Kenai 29
328 ENE station (WBAN:26563) located at the Alaska Department of Fish and Game Moose Research
329 Center (MRC) from September 2010–Present. Since the MRC station is more representative of
330 the field study sites, the temperature record for MRC were reconstructed back to 1948 using a
331 linear regression function found between KMA and MRC daily mean temperatures as summarized
332 from hourly and sub-hourly measurements. The regression equation was calculated by comparing
333 daily mean temperature for 1 January 2012 to 31 December 2015, and validated against daily mean
334 temperatures at the MRC for 1 September 2010 to 31 December 2011. Lastly, daily snow depth
335 totals were acquired from September 2012–September 2015 from MRC records
336 (<http://wcc.sc.egov.usda.gov/nwcc/site?sitenum=966>).

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355 **4 Results**

356 **4.1 Ground thermal regime of southcentral Alaska permafrost**

357 Calibrated ground temperature records collected between 16 September 2012 and 15 September
358 2015 at one forested plateau near Browns Lake and two forested plateaus near Watson Lake
359 confirmed the presence of near-surface permafrost on the western Kenai Peninsula lowlands (Fig.
360 5a–5c). Over this time period, the MAGT of permafrost at 1.0 m bgs ranged from -0.04 °C to -
361 0.08°C (Table 1). At the Browns Lake PF1 and the Watson Lake PF2 sites, permafrost at 2.0 m
362 bgs had a MAGT between -0.06 °C and -0.08 °C. At the Browns Lake PF1 site, permafrost at 3.0
363 m bgs had a MAGT between -0.07 °C and -0.08 °C (Table 1). No permafrost was detected at a
364 black spruce forested, non-plateau site near Watson Lake between September 2012 and August
365 2014 (Fig. 5d).

366 During the three-year observation period, an increase in near-surface ground temperatures
367 was recorded at all three permafrost sites in response to increases in air temperature (Table 1, Fig.
368 5). The ground temperature at 0.5 m depth was substantially below 0 °C at all three sites during
369 the 2012–2013 winter with minimum temperatures between -1.33 °C (Browns Lake) and -2.50 °C
370 (Watson Lake PF2). In the 2013–2014 winter, the ground at 0.5 m depth was barely frozen at the
371 Browns Lake and Watson Lake PF1 sites (Fig. 5a and 5b), with minimum winter temperatures at
372 -0.32 °C and -0.20 °C, respectively. The increase in summer ground temperatures at 0.5 m depth
373 was also substantial. By the end of the 2012 warm period, this temperature was above 0 °C only
374 at the Browns Lake site (the maximum was at 0.40 °C). At the Watson Lake PF1 and PF2 sites
375 the temperature at 0.5 m depth was just below 0 °C and never exceeded the thawing threshold,
376 indicating that the maximum summer thaw (the active layer thickness) was just below 0.5 m during
377 2012. However, during the summer of 2013 and 2014, the active layer thickness was more than

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386 0.5 m at both of these sites and the maximum temperatures in 2014 exceeded 1 °C at the Watson
387 Lake sites (Fig. 5b and 5c). At the Browns Lake site the temperature at 0.5 m depth reached almost
388 2 °C before the thermistor malfunction. The ground temperature warming at 0.5 m depth continued
389 in 2015 (Fig. 5b and 5c).

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390 The increase in the shallow ground temperatures triggered warming in the near-surface
391 permafrost at all three permafrost sites (Fig. 6). This warming was strong enough to initiate top-
392 down permafrost thaw at the Watson Lake PF1 site in the fall of 2014 (Fig. 6b). Sensor failure
393 during the winter of 2014–2015 prevented further observations of ground temperature at this site
394 following thaw that winter. At the Watson Lake PF2 site bottom-up permafrost thaw was detected
395 at a depth of 2 m during the fall of 2015 and likely associated with groundwater flow or degradation
396 of the permafrost in the thermokarst moat that borders the plateau. At the Browns Lake site
397 permafrost persisted at the depths between 1.0–3.0 m bgs over the three-year observation period
398 (Fig. 6a). However, MAGT warmed by 0.02 °C to 0.01 °C at all three depths during the
399 observation period. The temperature at 1.0 m bgs is only -0.04 °C now.

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400 4.2 Depth to permafrost table and permafrost thickness

401 The thaw depth at the data logger observation sites, as measured with the tile probe on 16
402 September 2015, was 0.64 m for the Watson Lake PF1 site (n=3), 0.53 m for the Watson Lake PF2
403 site (n=6), and 0.57 m for the Browns Lake PF1 site (n=6). More systematic probing at all three
404 sites on 16 September 2015 showed that the average depth to the permafrost table where detectable
405 (max probe length=2.20 m) was 1.48 m (n=222). However, probing did not encounter frozen
406 ground in the upper 2.20 m of the ground surface at an additional 140 measurement points, mostly
407 associated with collapse-scar features and thermokarst moats. In general, depth to the permafrost
408 table depended on the local topographic conditions at each site. Hummocks (n=164) tended to

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420 have a shallower depth to the permafrost table where measurable (average of 1.12 m), while depth
421 to the permafrost table measurements in depressions (n=58) was larger (average of 1.53 m).

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422 The measurements of the depth to permafrost table were complemented with mechanical
423 augering, coring, and GPR surveys in July 2014, September 2015, and February 2016 to constrain

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424 permafrost thickness at the field observation sites. The most detailed measurements were collected
425 at the Browns Lake PF1 plateau feature (Fig. 7a). At this site, a topographic survey of the plateau

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426 feature was conducted to plot depth to permafrost table along with seasonally frozen depth and
427 constraints on permafrost thickness in relation to the relative ground surface elevation along a 100

428 m transect (Fig. 7b). The relative mean elevation of the plateau above the surrounding wetland
429 area and the collapse-scar bog in the center was 0.49 m, with a maximum along the transect of

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430 0.95 m, and a maximum across the feature of 1.30 m. A topographic survey on an adjacent plateau

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431 feature produced a mean relative height of 0.59 m and a maximum of 1.81 m. We measured
432 permafrost thickness at five locations and minimum-limiting permafrost thicknesses at another

433 five locations along the Browns Lake primary plateau feature, with one limiting thickness
434 measurement at an adjacent plateau feature using the Kovacs auger. The base of the permafrost at

435 the two marginal plateau measurement sites at the primary plateau feature indicated a permafrost
436 thickness of 0.45 m and 0.33 m (Fig. 7b). At the three interior plateau measurements points,

437 permafrost was 5.57-5.65 m thick. At one of these locations (0.98 m relative height), a core was
438 acquired. It consisted of frozen peat from 0.48-5.69 m bgs, overlying 0.25 m of unfrozen peat,

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439 with unfrozen mineral sediment at the base. At the other five locations where the bottom of
440 permafrost was not reached, drilling operations documented permafrost at least down to between

441 3.5-4.0 m bgs (Fig. 7b), and contained frozen peat as well.

Deleted: and 4.0 bgs (Fig. 7b), and contained frozen peat as well. The EIF for the three interior measurements points on the Browns Lake plateau, where we had information on relative height, depth to permafrost table, and depth of permafrost base, ranged from 0.09 to 0.13. At an adjacent plateau (not shown) the minimum permafrost thickness was 6.90 m bgs, at which point we ran out of auger flight extensions. At Watson Lake PF1, drilling efforts detected permafrost base between 1.30 and 1.50 meters bgs. At the Watson Lake PF2 site, the permafrost base was between 1.96 and 2.04 m bgs.

462 The permafrost core at the PF-BL-6 site was described as poorly decomposed peat with
463 well-developed organic-matrix cryostructures, except between depths of 3.32–3.65 m where a
464 layer of silt and peat with mainly microlenticular cryostructure was observed (Fig. 8 and 9). The
465 gravimetric and volumetric ice contents of the peat varied between 883–1873 % and 80–96 %,
466 respectively, while they were 379–447 % and 81 %, respectively, in the previously mentioned silt
467 and peat layer. The upper two meters of peat were characterized mainly by an organic-matrix
468 porphyritic cryostructure transitioning to an organic-matrix microlenticular cryostructure with
469 some layered ice lenses. Below two meters, the peat was characterized mainly by an organic-
470 matrix microlenticular cryostructure with some belt-like and suspended cryostructures.

471 GPR surveys conducted in July 2014 and February 2016 provided more continuous
472 information on the geometry associated with the permafrost table in the residual plateaus on the
473 primary Browns Lake plateau feature (Fig. 10). The topography-corrected radargrams show a
474 prominent reflector between 1–3 m depth that coincides with the permafrost table in both the
475 summer (Fig. 10a) and winter (Fig. 10b) survey. The center portion of both images is characterized
476 by moderately continuous and chaotic reflectors (Neal, 2004), as expected for records in unfrozen
477 peat sequences (Parsekian et al., 2010) associated with the collapse-scar bog. The areas underlain
478 by permafrost (i.e. 0–30 m, 60–90 m) show subdued reflection events deeper than the permafrost
479 table; however, we were unable to image the permafrost base. The interpretation of these
480 radargrams provides lateral subsurface information on the presence of a talik overlying the
481 permafrost table.

482 4.3 Remote identification of permafrost plateaus

483 In 1950, residual permafrost plateau extent accounted for 920 ha of the 4,810 ha (19.1 %) of
484 wetlands mapped within four change detection areas (Fig. 1, Table 2). Between 1950 and 1984,

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493 permafrost plateau extent decreased to 750 ha, at an average rate of 5.1 ha yr⁻¹ (Table 3). Between
494 1984–1996, permafrost extent dropped to 520 ha, at an average rate of 18.8 ha yr⁻¹, the greatest
495 rate documented in the study periods. Between 1996–2010, permafrost features continued to
496 degrade at a rate of 9.5 ha yr⁻¹ so that by 2010, only 370 ha of the permafrost features remained.

497 Thus, between 1950–ca. 2010, 60 % of the residual permafrost plateaus disappeared in the mapped
498 study areas (Fig. [11](#) and [Table 2](#)).

499 Assessment of change in the four wetland complexes showed differences in the extent and
500 change rate of residual permafrost plateaus overtime. The Mystery Creek study area had the most
501 extensive permafrost plateau coverage (32.8 % of the wetland area analysed) in the 1950s relative
502 to the Watson Lake (9.8 %), Browns Lake (11.1 %), and Tustumena Lake (15.8 %) study areas
503 (Table 2). By ca. 2010, permafrost plateau extent in each of the study areas diminished to a cover
504 of 14.8 %, 3.5 %, 3.8 %, and 5.2 %, respectively. Thus, there was a loss of 54.8 % of the plateau
505 extent in the Mystery Creek study area, 64.7 % in the Watson Lake study area, 65.5 % in the
506 Browns Lake study area, and 66.9 % in the Tustumena Lake study area between 1950–ca. 2010.

507 These changes equate to loss rates of 0.9 % yr⁻¹ for Mystery Creek and 1.1 % yr⁻¹ for the Watson,
508 Browns, and Tustumena Lake study areas (Table 3). Mean area loss for all four sites was 0.8 %
509 yr⁻¹ between 1950 and 1984. During this time, loss rate was greatest for Watson Lake and Brown
510 Lake and least for Mystery Creek. Mean loss rate for all four sites increased to 2.3 % yr⁻¹ between
511 1984 and 1996. During this time, loss rates were greatest in the north and least in the south with
512 Mystery Creek and Tustumena Lake losing 3.0 % yr⁻¹ and 1.2 % yr⁻¹, respectively. Average loss
513 rates decreased to 1.8 % yr⁻¹ between 1996 and 2010, with the three most northern sites losing
514 approximately 1.2 % yr⁻¹, while the Tustumena Lake study area lost 3.2 % yr⁻¹. In terms of plateau
515 area lost per year within the three time periods, Mystery Creek (13.8 ha yr⁻¹), Watson Lake (1.6 ha

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525 yr⁻¹), and Browns Lake (1.3 ha yr⁻¹) experienced the greatest areal loss rate during the 1984–1996
526 time period. At the Tustumena Lake study area, the greatest rate of plateau extent loss (4.6 ha yr⁻¹)
527 occurred between 1996–ca. 2010 (Table 3).

528 [This study](#) also assessed whether the permafrost degradation occurred along the perimeter
529 of the plateau (marginal), whether degradation was internal to the plateau, or if complete
530 degradation of a plateau occurred. Between 1950–2010, 85.0 % of the degradation occurred as
531 lateral thaw along the plateau margins, while internal thaw and complete loss of features accounted
532 for 1.5 % and 13.4 %, respectively. Lateral loss of permafrost was greatest in the Watson Lake
533 study area (90.9 %) and least (77.0 %) in the Browns Lake study area. Both Mystery Creek and
534 Tustumena Lake shared a lateral loss of 86.0 %. Mystery Creek saw the greatest percent of internal
535 collapse loss (3.3 %) compared to Tustumena (1.7 %) and Watson and Browns Lake (both <1.0
536 %). The complete loss of permafrost features was greatest in Browns Lake (22.4 %) and least in
537 Watson Lake (8.3 %). Mystery Creek and Tustumena Lake had 10.5 % and 12.3 %, respectively,
538 of their permafrost plateaus disappear in the form of complete feature loss. During the period of
539 remotely sensed observations complete feature loss increased from 6.7 % (1950–1984) to 21.0 %
540 (1996–ca. 2010) of the detected change, while lateral feature loss decreased from 91.0 % (1950–
541 1984) to 78.1 % (1996–ca. 2010) of the detected change, likely highlighting the role of
542 fragmentation promoting complete feature degradation.

543 4.4 Climate and Weather Data

544 The MAAT of the western Kenai Peninsula lowlands between 1981–2010 was 2.22 °C for the
545 [KMA station](#) and estimated to be 1.79 °C for the MRC station. There was significant correlation
546 between the [KMA and MRC](#) daily mean air [temperatures](#) for the 2012–2015 period ($r^2=0.97$). The
547 regression equation performed well during validation tests ($r^2=0.95$) and was therefore used to

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563 estimate daily temperature data for the MRC station back to July 1948. Mean annual air
564 temperature has increased by 0.4 °C since 1950, with a step increase occurring in 1976 associated
565 with the Pacific Decadal Oscillation (PDO) (Hartmann and Wendler, 2005) (Fig. 2). Between July
566 1948 and December 1976, MAAT was 0.83 °C and 0.29°C for [KMA](#) and MRC, respectively.
567 Following the PDO shift MAAT increased to 1.97 °C and 1.51_°C for [KMA](#) and the MRC,
568 respectively (Fig. 2). Prior to the PDO shift, 18 (MRC) and 6 ([KMA](#)) out of 27 years had a MAAT
569 below freezing and after the PDO shift, only 10 (MRC) and 0 ([KMA](#)) out of 39 years had a MAAT
570 below freezing. MAAT at the MRC station was 0.88 °C (2012), 2.58 °C (2013), and 3.24 °C
571 (2014) during our three-year ground temperature observation period of 16 [September](#) 2012 to 15
572 [September](#) 2015. Therefore, [the](#) observations during 2014_2015 occurred during a period with
573 anomalously high MAAT relative to the previous climate normal period, with more warming in
574 the winter than the summer months (Table 1). Additionally, between 1948_2015, warm season
575 (May-[September](#)) air temperatures increased by 0.02 °C yr⁻¹ for both the Kenai and MRC station,
576 while winter season ([October](#)-April) air temperature increased by 0.04 °C yr⁻¹ (Table 4).

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578 5 Discussion

579 5.1 Presence of ecosystem-protected permafrost in southcentral Alaska

580 [These](#) permafrost data for the residual permafrost plateaus on the Kenai Peninsula are the first such
581 observations for isolated permafrost bodies in southcentral Alaska (Osterkamp, 2007). Based on
582 the five classes of permafrost proposed by Shur and Jorgenson (2007), the permafrost present in
583 wetland complexes of the western Kenai Peninsula lowlands is ecosystem-protected. The
584 permafrost on the Kenai Peninsula is extremely warm, with a MAGT that ranges from [-0.04](#) to -
585 0.08 °C (Table 1; Fig. 6). Permafrost [ground temperatures](#) at all [monitoring sites](#) were near the

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602 phase-equilibrium temperature [at depths from 1.0–3.0 m](#). Latent-heat effects associated with
603 unfrozen water content in permafrost and with seasonal phase changes in the active layer can buffer
604 the ground thermal regime from changes in air temperature at warm permafrost sites (Romanovsky
605 and Osterkamp, 2000) and in part can explain the persistence of ecosystem-protected permafrost
606 on the Kenai Peninsula (Shur and Jorgenson, 2007; Jorgenson et al., 2010). Even though [all](#)
607 thermistors [were calibrated](#) prior to installation, the ability to resolve such warm permafrost
608 temperatures and their change over time using temperature alone is somewhat limiting. Thus,
609 future measurements at the residual permafrost plateau sites in southcentral Alaska will be
610 accompanied by the addition of soil moisture probes as well as borehole, nuclear magnetic
611 resonance (NMR) which provides a direct measure of liquid water content (Parsekian et al., 2013).

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612 Field surveys that included probing, [augering](#), coring and GPR provided additional
613 information on the vertical and spatial distribution of the warm permafrost on the western Kenai
614 Peninsula lowlands. The average active layer thickness at [the permafrost plateau ground](#)
615 temperature observation sites was 0.58 m. [These sites were chosen](#) for initial instrumentation in
616 September 2012 based in part on the relatively shallow depth to the frost table. More
617 comprehensive probing in September 2015 revealed that the average depth to the permafrost table
618 was 1.48 m (n=222) as averaged across three plateaus. At the Brown Lake plateau, a talik
619 overlying the permafrost table was present in February 2016. Average permafrost thickness at this
620 feature was 5.61 m thick, whereas at an adjacent feature it was more than 6.90 m, the maximum
621 depth of [the auger flights](#). GPR survey data confirmed the presence of a continuous surface talik
622 at the Browns Lake site (Fig. [10](#)); however, we were unable to image the base of the permafrost
623 using solely GPR, as similarly described by Lewkowicz et al. (2011). [Based on visual](#)
624 interpretation of the permafrost peat core acquired [at the PF-BL-6 site](#) in February 2016, the

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638 permafrost deposit consists mainly of ice-rich frozen peat with well-developed organic-matrix
639 porphyritic and microlenticular cryostructures and some layered ice lenses, belt-like, and
640 suspended cryostructures (Fig. 8 and Fig. 9). Laboratory analysis also revealed gravimetric and
641 volumetric ice contents up to 1873 % and 96 %, respectively (Fig. 8).

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Deleted: the flat-line ground temperature data suggest high unfrozen water content associated with degrading permafrost on the Kenai Peninsula.

642 5.2 Extent and change in residual permafrost plateaus since the 1950s

643 While previous reports of permafrost on the Kenai Peninsula exist (Hopkins et al., 1955; Jorgenson
644 et al., 2008), they were restricted to the wetland complex (Mystery Creek) north of Sterling (Berg
645 et al., 2009). Information on its dynamics here and elsewhere was lacking. The analysis of
646 remotely sensed imagery and field surveys identified residual permafrost plateaus in three
647 additional wetland complexes where it had not been previously identified (Fig. 1 and Fig. 11) and
648 indicated that the state of permafrost within the Kenai lowlands is highly dynamic. In 1950,
649 forested permafrost plateau extent accounted for 19.0 % of the land cover in the 4,810 ha of
650 wetland complexes analysed in the four change detection study areas. In each of the wetland areas
651 analysed, permafrost plateaus accounted for more than 10.0 % of the area in 1950. However,
652 inferred permafrost extent decreased by 60.0 % between 1950 ca. 2010, and its lateral coverage
653 dropped below 5.0 % in three of the four study areas (Table 2).

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654 The residual permafrost plateaus documented in this study share similar attributes to
655 features elsewhere in boreal peatlands for which permafrost degradation has been inferred due to
656 the ease of remotely detecting the conversion from forested permafrost plateau to non-permafrost
657 herbaceous wetland or waterbody (Jorgenson et al., 2001, 2008, 2012). Thie (1974) inferred a
658 permafrost plateau loss rate of 0.47 % yr⁻¹ between 1800 –1960 for a 130,000 ha area of southern
659 Manitoba. In Québec, Canada, a 13 ha peat bog lost 1.80 % yr⁻¹ between 1957 –2003 (Payette et
660 al., 2004). In the Northwest Territories, Canada, Quinton et al. (2011) reported a loss rate of 0.62

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675 % yr⁻¹ between 1947–2008 across a 100 ha study area. In Interior Alaska (Tanana Flats), Jorgenson
676 et al. (2001) reported a loss rate of 0.76 % yr⁻¹ for birch forested permafrost plateaus between
677 1949–1995 using a point sampling method within a 260,000 ha wetland area. Lara et al. (2016)
678 recently updated these numbers for the Tanana Flats by manually digitizing features with methods
679 similar to ours and demonstrated that birch forest plateaus decreased at a much slower rate of 0.12
680 % yr⁻¹, and that black spruce forested permafrost plateau features appeared to be stable. Thus, the
681 loss rate of 1.0 % yr⁻¹ that we report for the 4,810 ha mapped on the western Kenai Peninsula
682 Lowlands between 1950–ca. 2010 are the second fastest change rates reported thus far in boreal
683 peatlands.

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684 5.3 Drivers of permafrost loss

685 Permafrost on the Kenai Peninsula is likely degrading as a result of warming air temperatures (+0.4
686 °C decade⁻¹ since 1950), especially where warming during the winter season likely exacerbates
687 these effects (Table 4). During the three-year observation period as well as since the 1950s,
688 warming in the winter has been more pronounced than in the summer (Table 1 and Fig. 2) and
689 2014–2015 had a MAAT roughly double the 1981–2010 climate normal period. Storm systems
690 regularly bring warm air masses (>4 °C) to the region during the winter. Air temperature warming
691 during the winter months has decreased the number of freezing degree_days which means that the
692 ground freezes to a much lesser degree in the winter (Fig. 2 and Table 1). Therefore, ground
693 temperatures decreased less over the winter period (Fig. 5 and Table 1), potentially leading to talik
694 development. Previous research on permafrost plateaus in colder regions indicate that preferential
695 warming in the winter and increased snow accumulation leads to enhanced permafrost thaw in
696 boreal peatlands (Camill, 2005; Osterkamp, 2007). Since the Kenai Peninsula lowlands experience
697 a semi-continental climate due to the rain shadow produced by the Kenai Mountains, a lack of

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708 winter snowfall may have contributed to permafrost persistence in this region by allowing
709 relatively cold winter air temperatures to propagate into the sub-surface. Thus, talik formation and
710 permafrost degradation at the study sites in southcentral Alaska are likely being driven for the most
711 part by winter air temperature warming (Fig. 2).

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712 The increase in permafrost loss rate in southcentral Alaska following the 1980s is likely
713 due to the combined effects of forest fires and a shift in the PDO after 1976. The respective pulse
714 and press disturbances may have promoted large areas of permafrost already close to thawing, to
715 quickly thaw, leaving only colder permafrost and permafrost with intact peat and forest cover. Fire
716 can be an important driver of permafrost thaw (Yoshikawa et al., 2002) and thermokarst
717 development (Jones et al., 2015). The Kenai Fire of 1947 burned the majority of the Mystery
718 Creek study area, all of the Watson Lake study area, and the majority of the Browns Lake study

719 area. Evidence of this fire was seen at numerous sites in the Watson Lake and Browns Lake study
720 areas. Watson Lake and Browns Lake subsequently had the two greatest loss rates between 1950–
721 1984 which may be related to the 1947 fire. However, the presence of black spruce burn poles

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722 were not found on all permafrost plateaus visited indicating that the burning was likely relatively
723 patchy in the wetlands. At Browns Lake, permafrost islands that did not burn in 1947 exhibited
724 less degradation, had thicker permafrost, denser tree cover, and larger trees than the islands that
725 burned. Large portions of the Tustumena Lake study area burned in the 1996 Crooked Creek Fire
726 and 2005 Fox Creek Fire. These fires likely damaged, and partially removed the protective
727 ecosystem cover (black spruce forest and peat), and degraded several permafrost plateau features.
728 This resulted in the Tustumena study area having the highest change rate for the latter time period
729 and 77.0 % of the plateau loss that occurred between 1996–ca. 2010, did so in areas that burned in
730 the 1996 and 2005 fires.

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741 Bottom-up permafrost degradation was documented over the short period of direct
742 measurements between 2012–2015. The bottom-up permafrost thaw observed at the Watson Lake
743 PF2 site indicates that the flow of groundwater below the permafrost plateaus could be responsible
744 for degradation (Walters et al., 1998). In addition, analysis of the remotely sensed imagery for the
745 four select wetland complexes primarily documented lateral permafrost degradation since the
746 1950s, as inferred by the conversion of forested plateau margins to herbaceous wetland vegetation.
747 This type of feature loss accounted for 85.0% of the change between 1950–ca. 2010. This pattern
748 of loss was further observed in the field through the presence of thermokarst moats and drowning
749 black spruce trees along the margins of the permafrost plateaus (Fig. 3). This is similar to the
750 dominant processes documented in more northerly boreal peatlands with permafrost plateaus
751 (Thie, 1974; Camill and Clark, 1998; Osterkamp et al., 2000; Jorgenson et al., 2001; Payette et al.,
752 2004; Quinton et al., 2011; Jorgenson et al., 2012; O’Donnell et al., 2012; Lara et al., 2015). These
753 findings highlight the importance of groundwater flow and also the impact of saturated herbaceous
754 wetlands that absorb heat during the summer that likely degrades permafrost along the peat plateau
755 margins (Walters et al., 1998). It is possible that lateral permafrost degradation caused by these
756 processes is overwhelming the protection provided by the ecosystem cover for permafrost stability
757 on the Kenai Peninsula lowlands. Future research is required to more fully understand the role of
758 groundwater movement on permafrost instability in the study region.

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759 **5.4 Proposed history of permafrost on the Kenai Peninsula**

760 During the Last Glacial Maximum (LGM), northern hemisphere permafrost extended much further
761 south than present day (Lindgren et al., 2015). However, permafrost history in southcentral Alaska
762 is poorly constrained. Even though the western Kenai Peninsula lowlands were almost completely
763 glaciated during the LGM (Reger et al., 2007), the permafrost features identified in this study occur

769 in glaciolacustrine or glaciofluvial wetland complexes that were either not glaciated during the
770 LGM (Mystery Creek) or became deglaciated before 16,000 cal yrs BP (Reger et al., 2007).
771 Perhaps permafrost formed on the Kenai Peninsula during deglaciation or shortly thereafter during
772 the Younger Dryas 12,900–11,700 years ago (Jones et al., 2009). However, this permafrost would
773 have likely thawed during the Holocene Thermal Maximum (Zoltai, 1972; Kaufman et al., 2004).
774 As the regional climate became cooler and wetter, between 8,000–5,000 years ago, *Sphagnum*
775 accumulation and preservation on the western Kenai Peninsula lowlands may have promoted more
776 widespread permafrost aggradation (Jones et al., 2009). Following this period, the peatlands may
777 have progressively froze, heaving the permafrost plateaus above the water table, drying the peat-
778 rich soils, promoting growth of black spruce, and creating a buffer layer protecting the underlying
779 permafrost (ecosystem-protected) from the unfavourable climate for permafrost that currently
780 exists today (Zoltai, 1972, 1995; Payette et al., 2004; Camill, 2005; [Shur and Jorgenson, 2007](#)).
781 Growth of permafrost and heaving the peatland surface above the water table could explain low
782 peat accumulation rates calculated in many Kenai Peninsula peatlands between 3,300–2,000 years
783 ago (Jones and Yu, 2010; Jones et al., 2014). This also coincides with widespread neoglaciation
784 on the Kenai Peninsula 3,000–1,500 years ago (Wiles and Calkin, 1994, Barclay et al., 2009).
785 Alternatively, the Little Ice Age (365–165 years ago), promoted shallow permafrost formation in
786 areas that were predominantly unfrozen throughout the Holocene (Romanovsky et al., 1992;
787 Jorgenson et al., 2001), and thus, could account for the presence of residual permafrost on the
788 Kenai Peninsula. The widespread loss of permafrost plateaus in central Alaska may be a result of
789 degradation of Little Ice Age permafrost (Jorgenson et al., 2001). The age, history, and future
790 trajectory of permafrost on the western Kenai Peninsula lowlands require further study.

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798 **5.5 Landscape dynamics and permafrost thaw on the western Kenai Peninsula lowlands**

799 Previous and ongoing land cover change on the western Kenai Peninsula lowlands are primarily
800 in response to the interaction of climate change and human development. Increases in summer air
801 temperature and late-summer droughts, along with human disturbance, have been linked to the
802 massive spruce bark beetle (*Dendroctonus rufipennis*) outbreak of the late 1990s (Berg et al., 2006;
803 Sherriff et al., 2011), which led to subsequent timber salvage (Jones, 2008). Berg and Anderson
804 (2006) caution that overall drier conditions on the western Kenai Peninsula, combined with
805 standing dead spruce stands, may alter the future fire regime of this region. Wetland drying (Klein
806 et al., 2005) and establishment of woody vegetation in wetlands (Berg et al., 2009) may be
807 attributed to warmer air temperatures and decreases in precipitation. Furthermore, tectonic activity
808 associated with the Great Alaska Earthquake of 1964 caused the western Kenai Peninsula to lower
809 in elevation by 0.7–2.3 m (Plafker, 1969), while the northern portion of the peninsula subsequently
810 uplifted 0.8–0.9m (Cohen and Freymueller, 1997), potentially altering groundwater flow paths
811 (Gracz, 2011).

812 In this study, the loss of ecosystem-protected permafrost in the overall understanding of
813 landscape dynamics on the western Kenai Peninsula lowlands was documented and incorporated.
814 The degradation of permafrost can impact terrestrial and aquatic ecosystems, hydrology,
815 infrastructure, and carbon cycling on the Kenai Peninsula (Schuur et al., 2008; Grosse et al., 2011;
816 Jorgenson et al., 2013; Kokelj et al., 2015; Vonk et al., 2015). Permafrost degradation within the
817 wetlands is responsible for a shift from black spruce forest plateaus to fen and bog wetland
818 ecosystems at a mean rate of 9.2ha yr⁻¹ since the 1950s in the four change detection study areas.
819 Permafrost plateaus redirect surface and near-surface drainage in boreal wetlands (Quinton et al.,
820 2011), and the thaw subsidence of these features increases drainage network connectivity (Beilman
821 and Robinson, 2003), and alters the local hydrological cycle (Hayashi et al., 2007). Thus, the loss

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829 of permafrost and/or changes in seasonally frozen ground phenology could in part be aiding in
830 observations of terrestrial and aquatic changes that have occurred on the Kenai Peninsula during
831 the past several decades. Further work is required to better understand the past influence of
832 permafrost on the Kenai Peninsula as well as the future loss of these warm permafrost deposits.

833 6 Conclusions

834 Based on the ground data and remotely sensed observations, it was found that peatland permafrost
835 is currently more extensive than previously reported in southcentral Alaska, a region with a MAAT
836 of 1.5 °C. Warm permafrost (-0.04 °C to -0.08 °C) persists on the western Kenai Peninsula
837 lowlands in forested (black spruce), peat plateaus found in glaciolacustrine and glaciofluvial
838 wetland complexes. At the field study sites, the depth to permafrost table on the peat plateaus
839 averaged 1.48 m in September 2015, but was as shallow as 0.53 m at some locations. Permafrost
840 thickness ranged from 0.33 m to greater than 6.90 m. Field surveys conducted in February 2016
841 documented the presence of a surface talik overlying the permafrost table. In 1950, residual
842 permafrost plateaus covered 19.0 % of the 4,810 ha wetland area mapped in the study. Within the
843 changed detection study areas, 60.0 % of the permafrost plateaus present in 1950 had degraded by
844 ca. 2010. In most cases, permafrost degradation equated to the loss of forest and its replacement
845 by bog or fen vegetation, preferentially occurring along permafrost plateau margins. Permafrost
846 loss on the Kenai Peninsula is likely associated with a warming climate, particularly during the
847 winter season, wildfires that remove the protective ecosystem cover, groundwater flow at depth,
848 and lateral heat transfer from wetland surface waters in the summer. Future studies on the residual
849 permafrost plateaus on the Kenai Peninsula will provide further insight for mapping and predicting
850 permafrost extent across Boreal permafrost regions that are currently warming.

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857 **7 Data availability**

858 All data available upon request to the corresponding author.

859 **8 Author contribution**

860 B.M. Jones devised the study design and prepared the manuscript with contributions from all co-
861 authors. B.M. Jones, C.A. Baughman, V.E. Romanovsky, E.L. Babcock, A.D. Parsekian, M.C.
862 Jones, and E.E. Berg contributed to field instrumentation and field studies. B.M. Jones, C.A.
863 Baughman, and G. Grosse conducted and contributed to remote sensing analysis. C.A. Baughman
864 compiled and interpolated regional weather and climate station data. [E.Stephani conducted the](#)
865 [cryofacies analysis and laboratory testing.](#) All co-authors contributed substantially to this research.

866 **9 Acknowledgements**

867 Funding for this research was provided by the U.S. Geological Survey Land Change Science and
868 Land Remote Sensing programs. [Support also was provided by the Russian Science Foundation](#)
869 [\(project RNF 16-17-00102\).](#) We thank the Kenai National Wildlife Refuge for granting
870 permission to access field sites. We thank Kelly Harrell, Kobuk, Kashi, Lydia Zeglin, Josefine
871 Lenz, Emiline Ostlind, and Callie Zuck for help with fieldwork. We thank David Swanson, Eric
872 Klein, [Neal Pastick, Mikhail Kanevskiy, and Andreas Käab](#) for providing useful feedback [and](#)
873 [edits](#) on an earlier version of this paper. Any use of trade, product, or firm names is for descriptive
874 purposes only and does not imply endorsement by the U.S. Government.

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1149 **Tables**

1150 Table 1. Mean annual ground temperature (MAGT) data for four observation sites on the Kenai Peninsula lowlands. Browns Lake PF1,
 1151 Watson Lake PF1, and Watson Lake PF2 represent permafrost plateaus and the Watson Lake non-PF site a black spruce forested non-
 1152 plateau site. Sensor depths that were perennially frozen in a given year are in bold. Mean annual air temperature (MAAT), thawing
 1153 and freezing degree days (TDD and FDD), and average winter snow depth (MASD) are from the [he MRC station](#) (Kenai 29 ENE - AWS
 1154 702590).
 1155

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9/16/2012 - 9/15/2013

Browns Lake PF1		Watson Lake PF1		Watson Lake PF2		Watson Lake non-PF		KENAI 29 ENE AWS 702590 Met Station Data			
Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	MAAT (°C)	TDD Sums	FDD Sums	MASD (cm)
50	-0.02	10	0.34	10	0.05	25	0.94				
100	-0.06	25	-0.09	50	-0.30	50	0.42	0.88	1865.9	1544.3	19.3
200	-0.08	50	-0.20	100	-0.08	100	0.14				
300	-0.08	100	-0.08	200	-0.06	130	0.16				

9/16/2013 - 9/15/2014

Browns Lake PF1		Watson Lake PF1		Watson Lake PF2		Watson Lake non-PF		KENAI 29 ENE AWS 702590 Met Station Data			
Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	MAAT (°C)	TDD Sums	FDD Sums	MASD (cm)
50*	0.17	10	0.93	10	0.86	25	0.57				
100	-0.06	25	0.40	50	-0.07	50	0.32	2.58	2066.6	1123.4	8.3
200	-0.06	50	-0.02	100	-0.08	100	0.14				
300	-0.08	100	-0.06	200	-0.08	130	0.14				

*Thermistor failed on 24 August 2014

9/16/2014 - 9/15/2015

Browns Lake PF1		Watson Lake PF1		Watson Lake PF2		Watson Lake non-PF		KENAI 29 ENE AWS 702590 Met Station Data			
Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	MAAT (°C)	TDD Sums	FDD Sums	MASD (cm)
50*	---	10*	---	10	1.53	25*	---				
100	-0.04	25*	---	50	0.14	50*	---	3.24	2009.8	829.1	2.7
200	-0.06	50*	---	100	-0.07	100*	---				
300	-0.07	100 [#] *	---	200 [#]	-0.07	130*	---				

*Thermistor or data logger failure

[#]Permafrost thaw during observation period

1156

1158 Table 2. Permafrost plateau extent mapped in each study region in 1950, 1984, 1996, and ca. 2010. Analyzed wetland area for each
 1159 study region is given along with the number of features, total plateau area, mean plateau area, and plateau extent for each image
 1160 observation year. In ca. 2010, images were acquired in 2011 (Mystery Creek and Watson Lake), 2012 (Tustumena Lake), and 2013
 1161 (Browns Lake).
 1162

Study Region	Wetland Area (ha)	1950				1984				1996				ca. 2010			
		Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)	Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)	Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)	Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)
Mystery Creek	1562.0	212	511.5	2.4	32.7	237	457.7	1.9	29.3	335	292.6	0.9	18.7	321	232.3	0.7	14.9
Watson Lake	904.2	44	86.6	2.0	9.6	55	54.0	1.0	6.0	68	35.4	0.5	3.9	67	29.8	0.4	3.3
Browns Lake	1013.0	102	111.9	1.1	11.0	117	67.2	0.6	6.6	107	51.2	0.5	5.1	89	38.6	0.4	3.8
Tustumena Lake	1333.4	92	210.2	2.2	15.8	150	168.6	1.1	12.6	183	143.5	0.8	10.8	206	69.9	0.3	5.2
All Sites	4812.7	450	920.2	2.0	19.1	559	747.5	1.3	15.5	693	522.6	0.8	10.9	683	370.6	0.5	7.7

1163
 1164

1165 Table 3. Change in the extent of permafrost plateaus for each of the study regions between 1950
 1166 and ca. 2010, 1950 and 1984, 1984 and 1996, and 1996 and ca. 2010. Change is reported in aerial
 1167 units per year, proportional area change, percent change per year, and by the type of change.
 1168 Change type refers to whether the plateau loss occurred along the periphery of a feature (lateral),
 1169 in the centre of a feature (internal), or whether complete loss of a feature occurred. In ca. 2010,
 1170 images were acquired in 2011 (Mystery Creek and Watson Lake), 2012 (Tustumena Lake), and
 1171 2013 (Browns Lake).
 1172

Study Area	1950 to ca. 2010					
	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-4.6	-0.3	-0.9	86.2	3.3	10.5
Watson Lake	-0.9	-0.1	-1.1	90.9	0.8	8.3
Browns Lake	-1.2	-0.1	-1.0	77.2	0.3	22.4
Tustumena Lake	-2.3	-0.2	-1.1	86.0	1.7	12.3
All Sites	-9.2	-0.2	-1.0	85.1	1.5	13.4

Study Area	1950 to 1984					
	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-1.6	-0.1	-0.3	88.8	5.2	5.9
Watson Lake	-1.0	-0.1	-1.1	91.7	1.4	6.9
Browns Lake	-1.3	-0.1	-1.2	89.0	0.6	10.1
Tustumena Lake	-1.2	-0.1	-0.6	94.1	2.1	3.8
All Sites	-5.1	-0.1	-0.6	91.0	2.3	6.7

Study Area	1984 to 1996					
	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-13.8	-0.9	-3.0	87.1	1.8	11.2
Watson Lake	-1.6	-0.2	-2.9	88.7	0.6	10.7
Browns Lake	-1.3	-0.1	-2.0	84.0	0.1	16.0
Tustumena Lake	-2.1	-0.2	-1.2	85.1	2.9	12.0
All Sites	-18.7	-0.4	-2.5	86.2	1.3	12.5

Study Area	1996 to ca. 2010					
	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-4.0	-0.3	-1.4	82.7	3.0	14.3
Watson Lake	-0.4	-0.1	-1.1	92.2	0.5	7.3
Browns Lake	-0.7	-0.1	-1.4	58.7	0.1	41.2
Tustumena Lake	-4.6	-0.3	-3.2	78.7	0.2	21.1
All Sites	-9.5	-0.2	-1.8	78.1	1.0	21.0

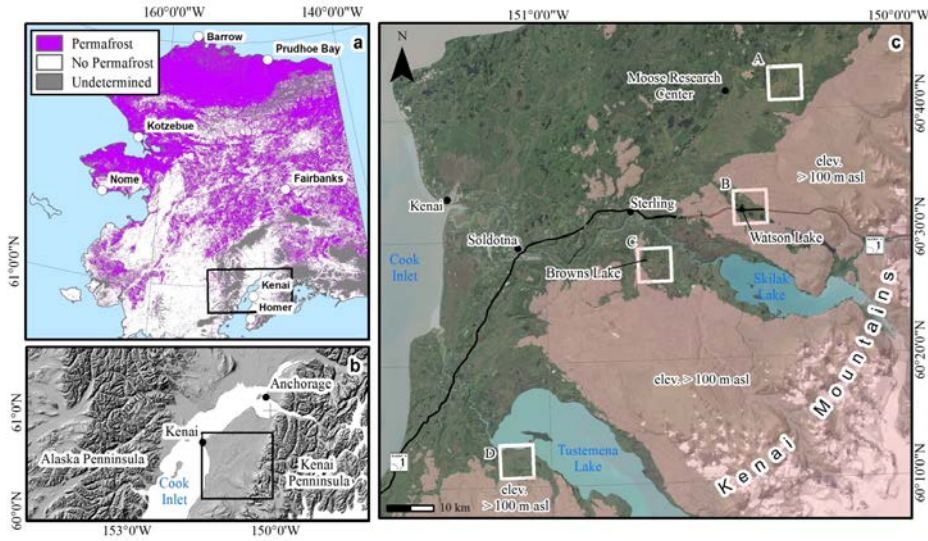
1173

1174 Table 4. Mean annual, mean summer (May to September), and mean winter (October to April) air
 1175 temperature for the three remotely sensed image observation periods compiled from the Kenai
 1176 Municipal Airport (WBAN 26523) and estimated from the MRC station (Kenai 29 ENE - AWS
 1177 702590).
 1178

Remote Sensing Time Period	Mean Annual Air Temperature (°C)		Mean Summer Air Temperature (°C)		Mean Winter Air Temperature (°C)	
	Kenai Airport	MRC	Kenai Airport	MRC	Kenai Airport	MRC
1950 to 1984	1.12	0.59	9.92	10.39	-5.29	-6.54
1984 to 1996	1.77	1.31	10.28	10.78	-4.37	-5.52
1996 to 2015	2.34	1.86	10.81	11.31	-3.77	-4.95

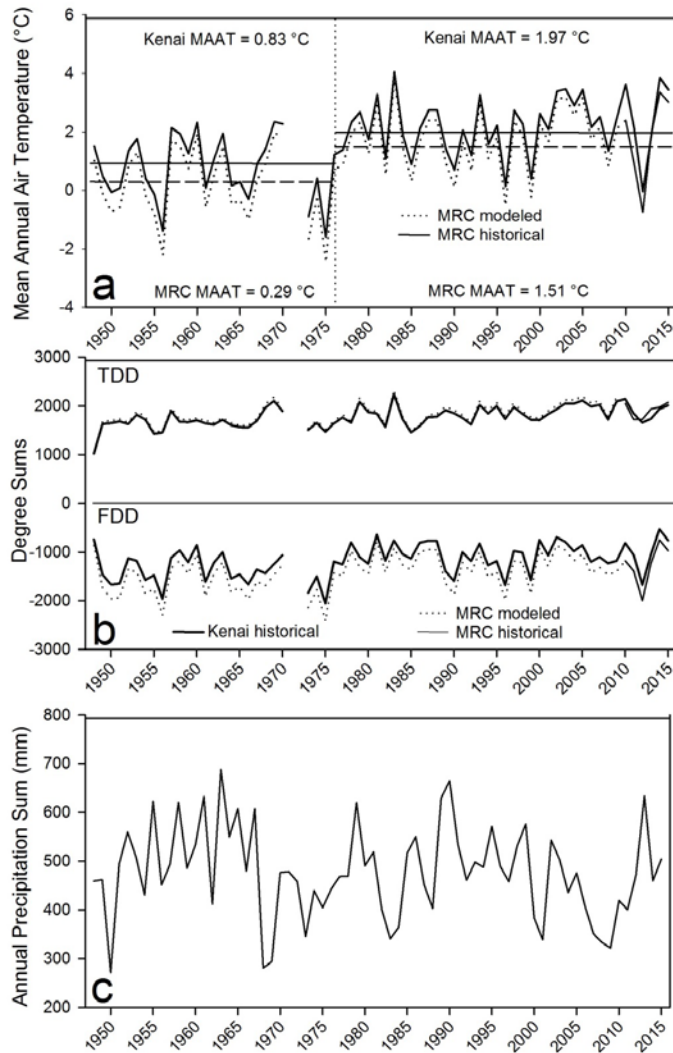
1179

1180 **Figures**



1181

1182 Figure 1: Study area figure. (a) Recent permafrost map of Alaska (Pastick et al., 2015) indicating
1183 permafrost presence (purple) and absence (white) in the upper one meter of the ground surface.
1184 (b) Hillshade relief image showing a portion of southcentral Alaska. The study region on the Kenai
1185 Peninsula lowlands is shown with the black box outline. (c) The portion of the Kenai Peninsula
1186 lowlands where field studies and remotely sensed observations were conducted. Ground
1187 temperature observations were collected at the Browns Lake and Watson Lake sites. The remote
1188 sensing change detection areas are shown with a white box: (A) Mystery Creek, (B) Watson Lake,
1189 (C) Browns Lake, and (D) Tustumena Lake wetland complexes.



1190

1191 Figure 2: a) Historical (1948-2015) mean annual air temperature compiled from Kenai Municipal
 1192 Airport (WBAN 26523) hourly surface data and interpolated (broken) and measured (solid) mean
 1193 annual air temperature for the MRC station (Kenai 29 ENE AWS 702590). b) Thawing degree
 1194 day (TDD) and freezing degree day (FDD) sums for 1948-2015 derived from historical and
 1195 interpolated daily mean temperature. c) Cumulative annual precipitation data from the Kenai
 1196 Municipal Airport (WBAN 26523) between 1948 and 2015.



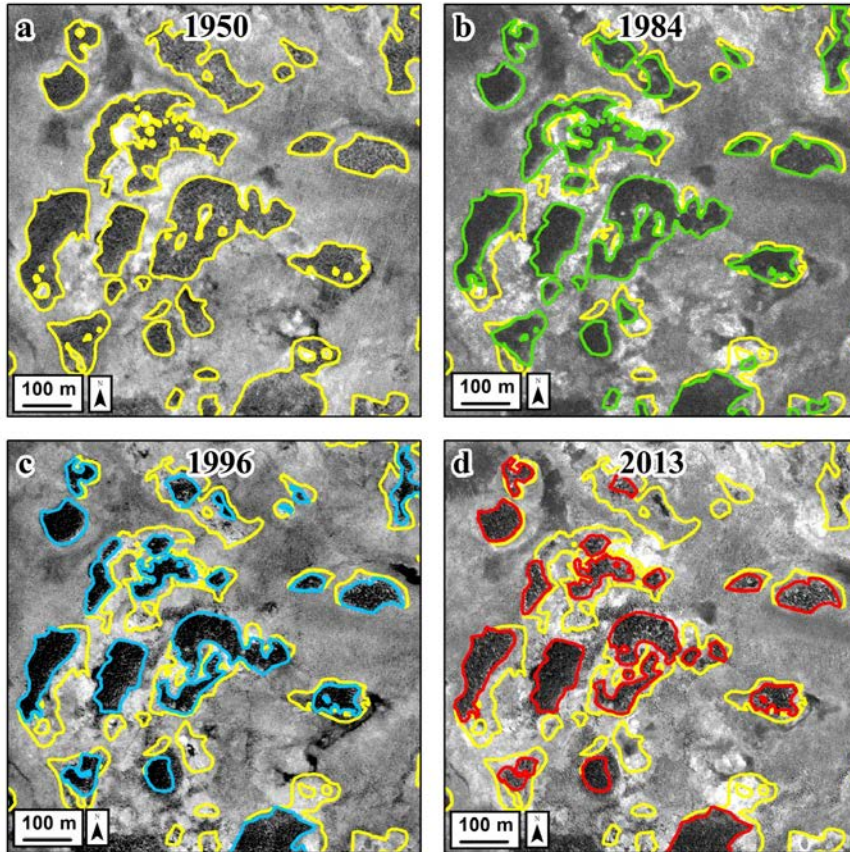
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1198

1199 Figure 3: Field photos of residual permafrost plateau landforms and thermokarst on the western
1200 Kenai Peninsula lowlands. (a) A forested permafrost plateau in the Browns Lake wetland
1201 complex. A thermokarst moat and drowning black spruce trees in the (b) Browns Lake and (c)
1202 Watson Lake wetland complexes.

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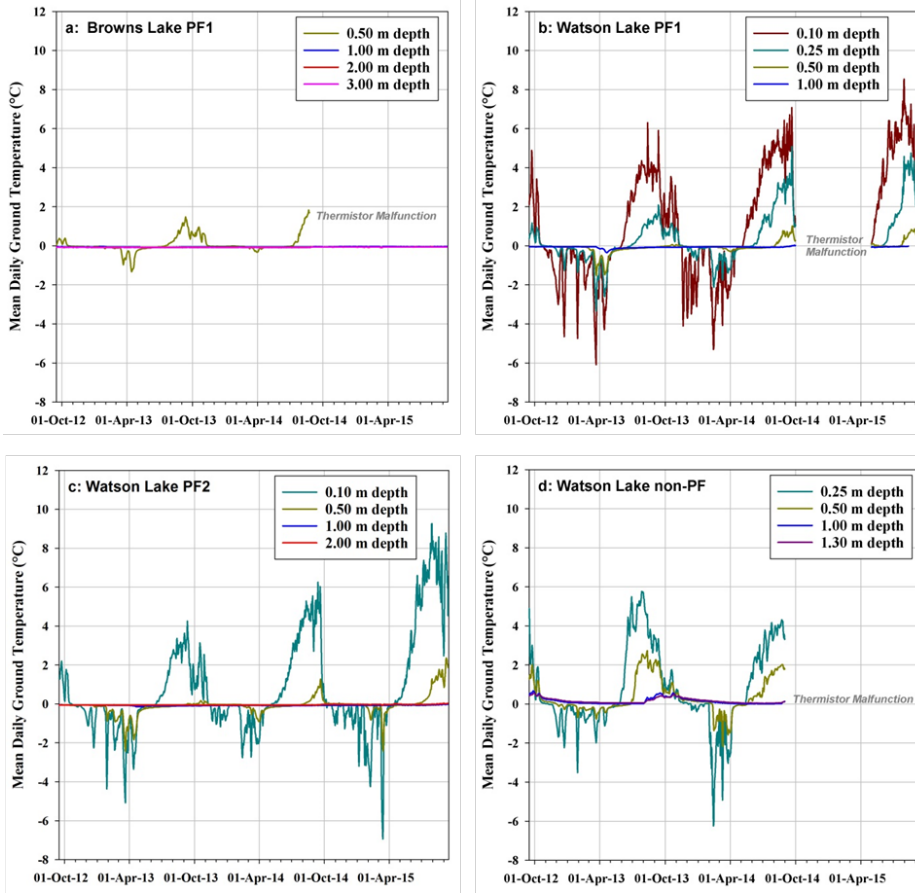
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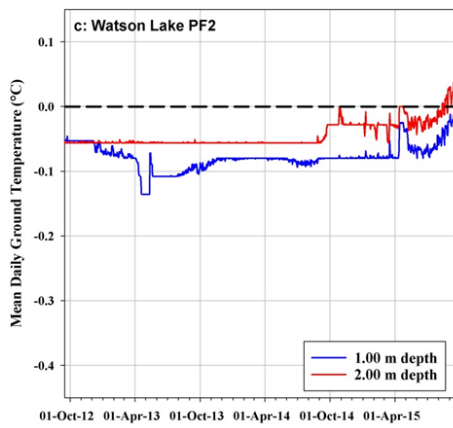
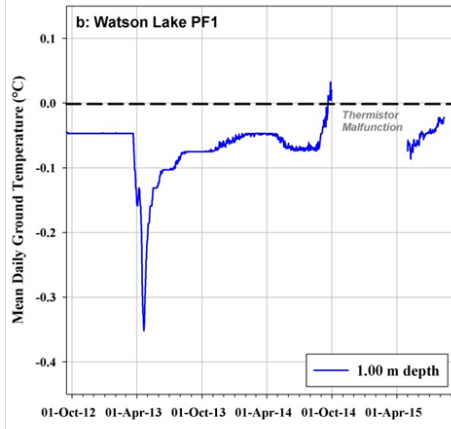
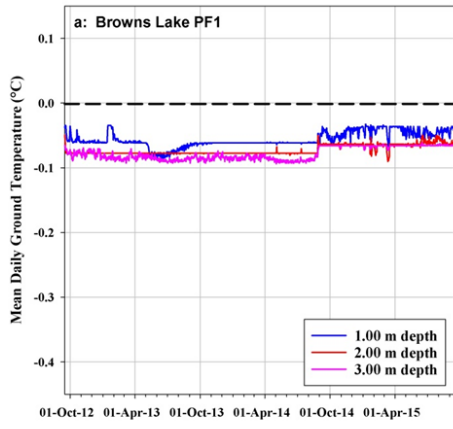
1206 Figure 4: Time series documenting the extent of a subset of permafrost features in the Browns
 1207 Lake wetland complex in (a) 1950, (b) 1984, (c) 1996, and (d) 2013. Permafrost plateau extent in
 1208 1950 is shown as a yellow polygon in each frame and other time slices outlined as green (1984),
 1209 blue (1996), and red (2013).

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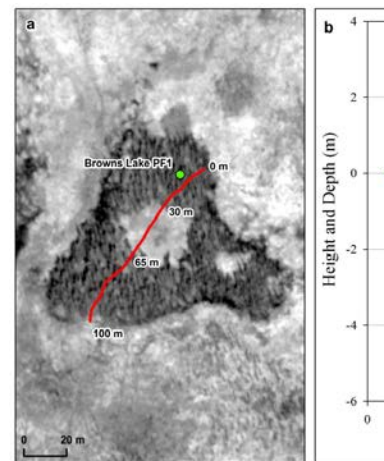
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1212 Figure 5: Mean daily ground temperature data plots for the four shallow boreholes on the western
1213 Kenai Peninsula lowlands for the period of 16 September 2012 to 15 September 2015: (a) Browns
1214 Lake PF1 site, (b) Watson Lake PF1 site, (c) Watson Lake PF2 site, and (d) Watson Lake non-PF
1215 site. All axes scales are the same but sensor depths vary among sites based on site characteristics.
1216 Missing data indicates sensor or thermistor failure.
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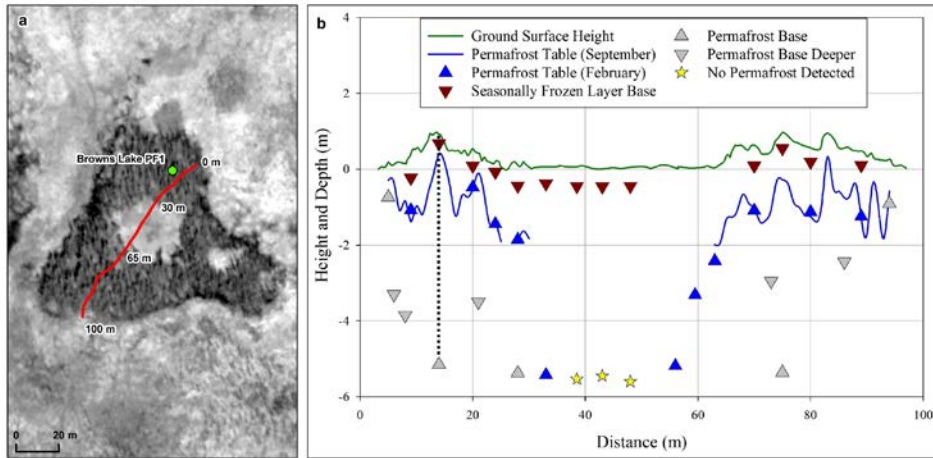
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1219 Figure 6: Mean daily ground temperature data plots indicating the presence of permafrost on the
 1220 western Kenai Peninsula lowlands for the period of 16 September 2012 to 15 September 2015: (a)
 1221 Browns Lake PF1 site, (b) Watson Lake PF1 site, and (c) Watson Lake PF2 site. Top-down
 1222 permafrost thaw occurred at Watson Lake PF1 during the fall of 2014 and bottom-up permafrost
 1223 thaw occurred at Watson Lake PF2 during the fall of 2015.
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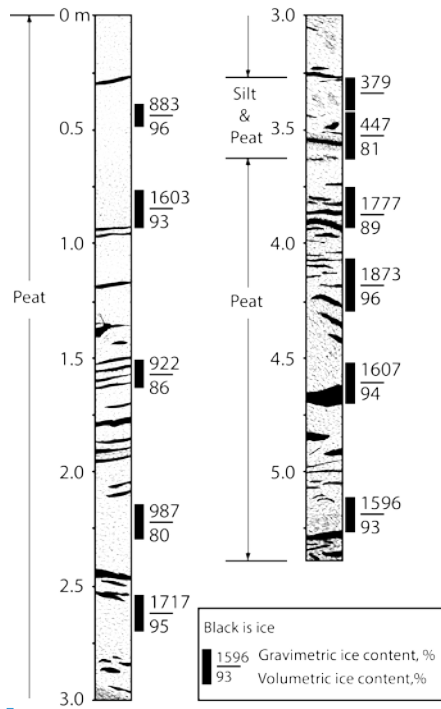


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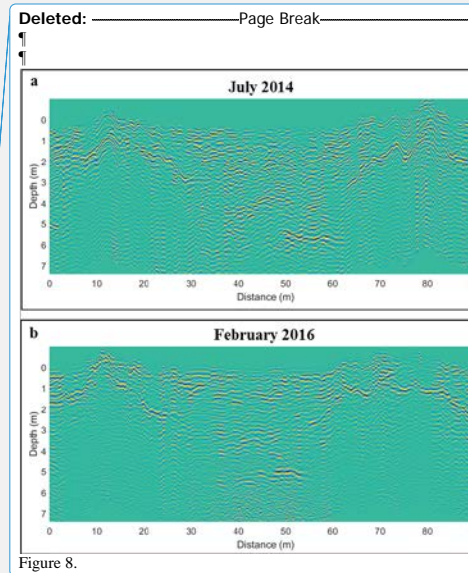


1227 Figure 7: (a) High-resolution satellite image showing the permafrost plateau in the Browns Lake
1228 wetland complex where detailed field surveys were conducted as well as the location of the Browns
1229 Lake PF1 data logger (green dot). (b) A ~100 m transect across the Browns Lake PF1 permafrost
1230 plateau site showing ground surface height above the wetland (green line), depth to the permafrost
1231 table (blue line and blue arrows), permafrost thickness constraints (grey arrows), seasonally frozen
1232 ground depth (maroon arrows), and lack of permafrost (yellow stars) as measured by probing,
1233 drilling, and coring. Locations where the permafrost table exceeded 2.2 m from the ground surface
1234 (limiting depth for September surveys) are indicated with a non-existent blue line. Locations
1235 where the base of the permafrost was encountered are indicated with an upward looking grey
1236 triangle and those locations where it was not encountered, a downward looking grey triangle. [The
1237 black dashed vertical line represents the location of the PF-BL-6 permafrost core.](#)



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Figure 8: Cryostratigraphy and ice contents from borehole PF-BL-6 (inspired by Kanevskiy et al., 2014). The gravimetric and volumetric ice contents of the peat varied between 883–1873% and 80–96%, respectively, while they were 379–447% and 81%, respectively, in the silt and peat layer located between 3.32 m and 3.65 m.





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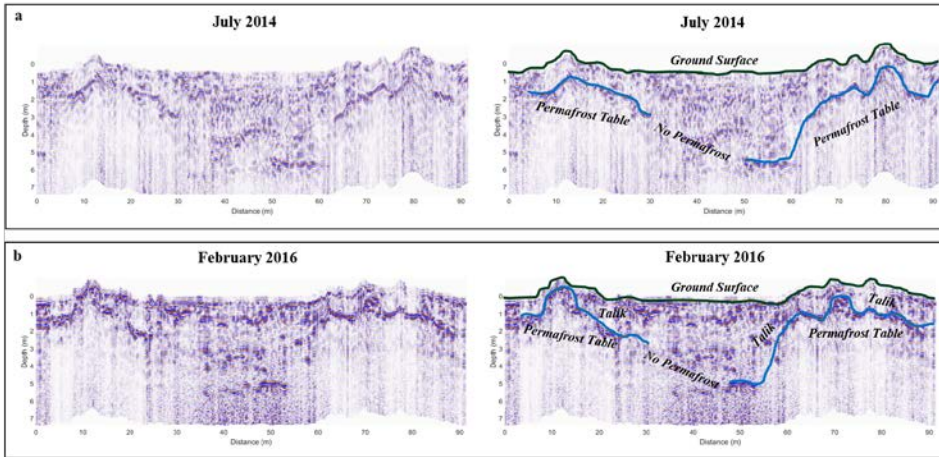
1250

1251 [Figure 9: \(a\) Stratigraphic contact between the base of the frozen silt and peat layer occurring at](#)

1252 [3.65 m and the underlying frozen peat. \(b\) Example of organic-matrix microlenticular to](#)

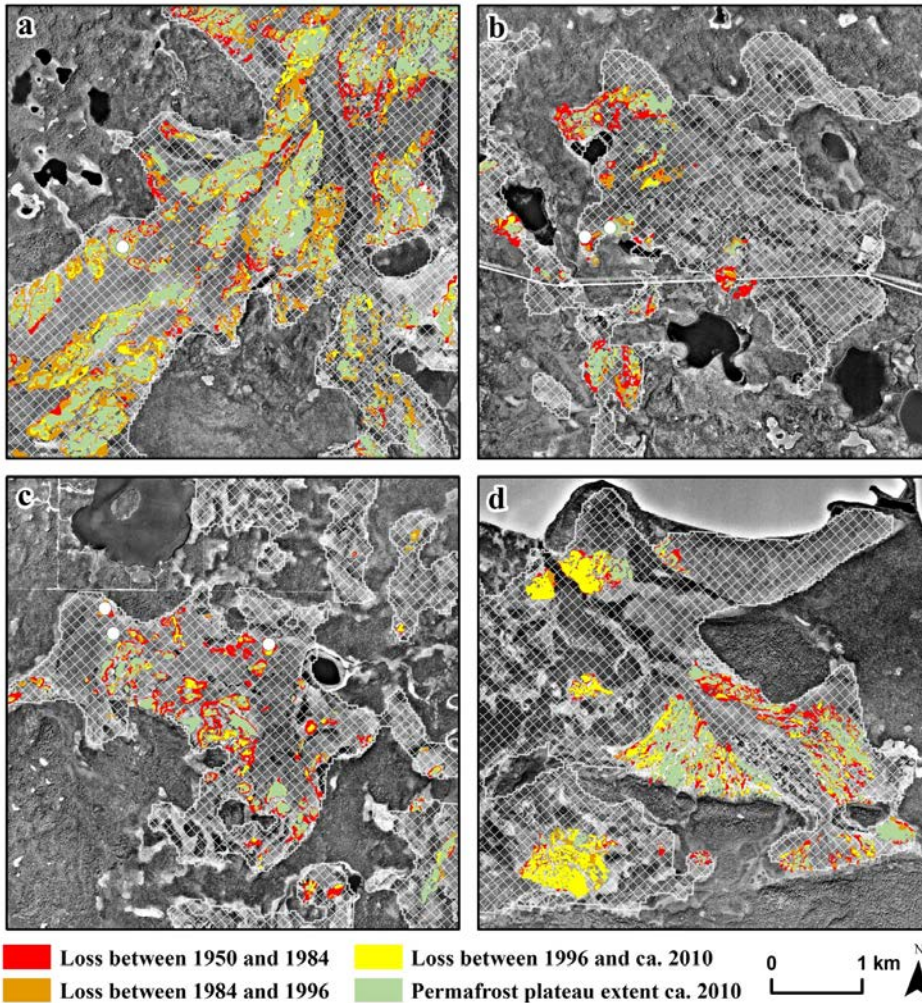
1253 [suspended cryostructures developed in the peat below the stratigraphic contact shown in \(a\).](#)

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1256 [Figure 10](#): GPR profiles at the intensive Browns Lake permafrost plateau (Fig. 7a) from a) late-
1257 July 2014 with Mala shielded 100-MHz antennas and b) mid-February 2016 with Sensors &
1258 Software unshielded bi-static 100-MHz antennas. Processed radargrams are on the left and
1259 processed, interpreted radargrams are on the right. Both summer and winter profiles clearly show
1260 reflectors associated with the permafrost table and in the case of (b) show the presence of a talik.
1261 However, we were unable to image the permafrost base using GPR. Note that the two GPR
1262 transects differ slightly in their orientation across the feature.
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1265 Figure 11: Spatial and temporal pattern of permafrost loss within four change detection areas: a)
 1266 Mystery Creek, b) Watson Lake, c) Browns Lake, and d) Tustumena Lake. Red indicates feature
 1267 loss between 1950 and 1980, orange is feature loss between 1984 and 1996, yellow is feature loss
 1268 between 1996 and ca. 2010, and green is ca. 2010 permafrost plateau extent. The white dots
 1269 indicate the location of field verified permafrost between 2009 and 2016. The hatched white
 1270 polygons indicate the wetland extent where plateau features were mapped in each study area.
 1271 Background imagery is the 1996 orthophotography.

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