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RESEARCH ARTICLE

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Taliks, cryopegs, and permafrost dynamics related to channel migration, Colville River Delta, Alaska

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Abstract

Talik and cryopeg development related to channel migration has been observed in arctic deltas, but our knowledge on the configuration, properties, and rate of freezeback has remained limited. Along a main channel of the Colville River Delta (Alaska), we integrated subsurface data from 79 boreholes with a remote sensing analysis to measure channel changes in 1948–2013. We found that closed taliks occurred under the active channel and extended into intrapermafrost cryopeg layers under the riverbed/riverbar and active floodplain. Cryopegs as isolated small pockets were also identified at depths in older terrain units. In the study corridor, we estimated that the likelihood of talik and cryopeg occurrence was predominantly (42.2% of area) low, yet a high likelihood was also identified (27.0% of area). Permafrost growth occurred at a rapid rate in the land exposed following channel migration, likely due to the low and delayed release of latent heat as the freezing front progresses downward in the coarse-grained soils of increasing salinity but decreasing temperatures. As the deposits keep cooling, ground ice will continue forming therefore increasing furthermore the salinity of the remaining unfrozen soil pore-water and likely prevent the complete freezeback of the cryopegs developed in relation to channel migration.

KEYWORDS
cryopeg, epigenetic permafrost, landscape, salinity, talik

1 | INTRODUCTION

Arctic deltas are complex and dynamic environments characterized by a variety of landforms and subsurface conditions,[1,2] and are affected by the presence of cold climate and permafrost that restrict water flow in winter and influence geomorphology and landscape change.[3] Deltaic landforms evolve with time mainly as a result of channel migration and lake drainage,[4] with most morphologic changes occurring during high flood periods in spring and summer.[5] Subsurface conditions vary laterally, according to the contemporary landform spatial distribution,[1] and with depth as they reflect the past terrain conditions and sedimentation processes.[6] The abundance of and variability in surface water bodies increase the complexity of subsurface conditions due to the heat storage effect of the surface water that may cause taliks to develop. Some specific variability in subsurface conditions may be especially challenging to predict, including the presence of isolated cryopegs.

In the continuous permafrost zone, surface water bodies (e.g., lakes and rivers) that do not freeze to the bottom in winter typically have an underlying talik that may be open (through-talik) or closed[7,8]; an open talik penetrates the permafrost entirely connecting suprapermafrost and subpermafrost groundwater, while a closed talik refers to unfrozen soils forming a depression in the permafrost table.[8] Cryopegs are layers of perennially cryotic (<0°C) soils, which remain unfrozen due to high salinity decreasing the freezing point of soil pore-water.[8] Soils with high pore-water salinity may also be poorly bonded or unbonded at temperatures below 0°C.[9-12] The degree of bonding of soils refers, qualitatively, to the strength of bonds between soil grains cemented together by ice; it is a common visual and qualitative measure used by engineers in North America to describe frozen ground.[13,14]

Some direct observations on the geometry and properties of taliks and cryopegs are available in the literature,[15-34] with most of them focused at shallow depths and/or obtained from limited data, implying that conclusions may have been partially based on assumptions rather than mainly on field measurements. Thorough field assessments that include drilling, soil sampling, laboratory testing, and measuring ground temperatures and groundwater levels at depths greater than tens of meters are typically challenging and expensive. More accessible methods to estimate talik occurrence, configuration, properties and/or temporal changes include measuring bottom water temperatures in lakes and channels[19,35-37] for subsequent analytical calculations,[16,35,36] numerical modeling,[18,19,38-46] and geophysical surveying.[15,47-57] These methods typically do not provide much information on cryopegs, although the use of ground-penetrating radar combined with direct current resistivity surveys may help to differentiate brine from freshwater.[52]

The heterogeneity and changes in surface and subsurface conditions in arctic deltas can be challenging for land planning and engineering applications, such as route selection and design of linear infrastructure (e.g., roads, bridges, and pipelines). Engineered structures are somewhat static features in a very dynamic natural system that experiences changes at various spatial and temporal scales. Hence, there are potentially significant changes expected in the natural terrain and subsurface conditions within the lifetime of infrastructure. Understanding the heterogeneity and rate of changes in arctic deltas, including the potential spatial distribution and properties of taliks and cryopegs, becomes essential to successfully design infrastructure while also mitigating risk to the infrastructure and reducing future maintenance and operation costs in these remote environments. Estimating the potential occurrence and properties of taliks and cryopegs at the landscape scale may also be helpful in assessing groundwater resources, as talik configuration is an important factor controlling surface drainage and groundwater storage in Arctic watersheds.[58,59] In the Colville River Delta of Alaska, Jorgenson et al.[1] and Shur and Jorgenson[60] established a conceptual model of floodplain development that allows estimation of near-surface permafrost properties at the landscape scale by terrain units specific to the floodplain development stages. This model focused on syngenetic and quasi-syngenetic permafrost that aggrades as sedimentation progresses, the permafrost table moves upward, and the ground ice accumulates below the active layer, therefore increasing the overall permafrost thickness and ground-ice content. In addition to this upward aggradation of syngenetic and quasi-syngenetic permafrost, epigenetic permafrost aggradation occurs in taliks exposed by channel migration; however, to our knowledge, the rates of this process have been little studied.

2 | STUDY OBJECTIVES

The overarching goal of our study was to advance the conceptual model of floodplain development[1,60] in the Colville River Delta by integrating an assessment of the subsurface conditions, at greater depths, that relate to channel migration along the Nigliq channel (Figure 1). We focused primarily on the talik and cryopeg conditions that have resulted from channel migration and the subsequent epigenetic aggradation of permafrost following terrestrial land exposure. Our specific objectives were to: (a) assess, up to depths of ~55 m below the ground surface (bgs), the response of permafrost to channel migration, including its post-degradation recovery; and (b) estimate the likelihood of talik and cryopeg occurrence at the landscape scale along the channel.

3 | STUDY SITE

The Colville River Delta is located on the Arctic Coastal Plain in northern Alaska, ~90 km west of the Prudhoe Bay oilfield. It covers an area of ~600 km^2 and drains roughly one-third of the North Slope.[5] The delta is located entirely in the continuous permafrost zone with mean annual ground temperature (MAGT) measured at 20 m depth in 2007 of −9.4°C at Drew Point, −9.2°C at Atigaru, and −7.6°C at South Harrison.[61] Permafrost thicknesses are ~200–600 m[62] with an active-layer depth that varies from ~0.15 m in peat to ~ 2 m in bare mineral soils.[63] Ground ice content in the Colville River Delta typically varies with the stage of floodplain development, with ice-poor coarse-grained soils within younger terrain units and ice-rich fine-grained soils with massive ice (ice wedges) that develop at the later stages of landscape development.[60] The delta comprises a variety of specific ecosystems that host a large concentration of wildlife critical to the local subsistence economy.[64] The Nigliq channel, also referred to as the western or Nechelik channel, is the second largest distributary of the Colville River, as it carries about 20% of the total discharge.[5] Climate normal data (1981–2010) at Nuiqsut, a community located in the southern part of the Nigliq channel, gave a mean annual air temperature of −10.3°C, with maximum and minimum annual averages of −6.6 and −13.9°C, respectively.[65] The delta remains in a quasi-static state in winter as water bodies shallower than about 1.5–2 m deep are frozen,[2] thus restricting water flow as an eroding, transporting, and/or depositing agent, while the snow cover also limits wind erosion.[5] This period may also contribute to talik development. The greatest morphological changes occur in spring and early summer with breakup and extreme flooding events, and with most of the annual discharge.[66] Changes in water salinity occur on a seasonal basis; at freeze-up, seawater typically migrates into the delta's channels, up to ~55–60 km upstream, while at breakup the seawater is flushed by freshwater.[67,68] In winter, salinity also increases due to ice cover growth from freshwater and subsequent concentration of solutes in the unfrozen water.[67,68] As part of oil development in the National Petroleum Reserve Alaska

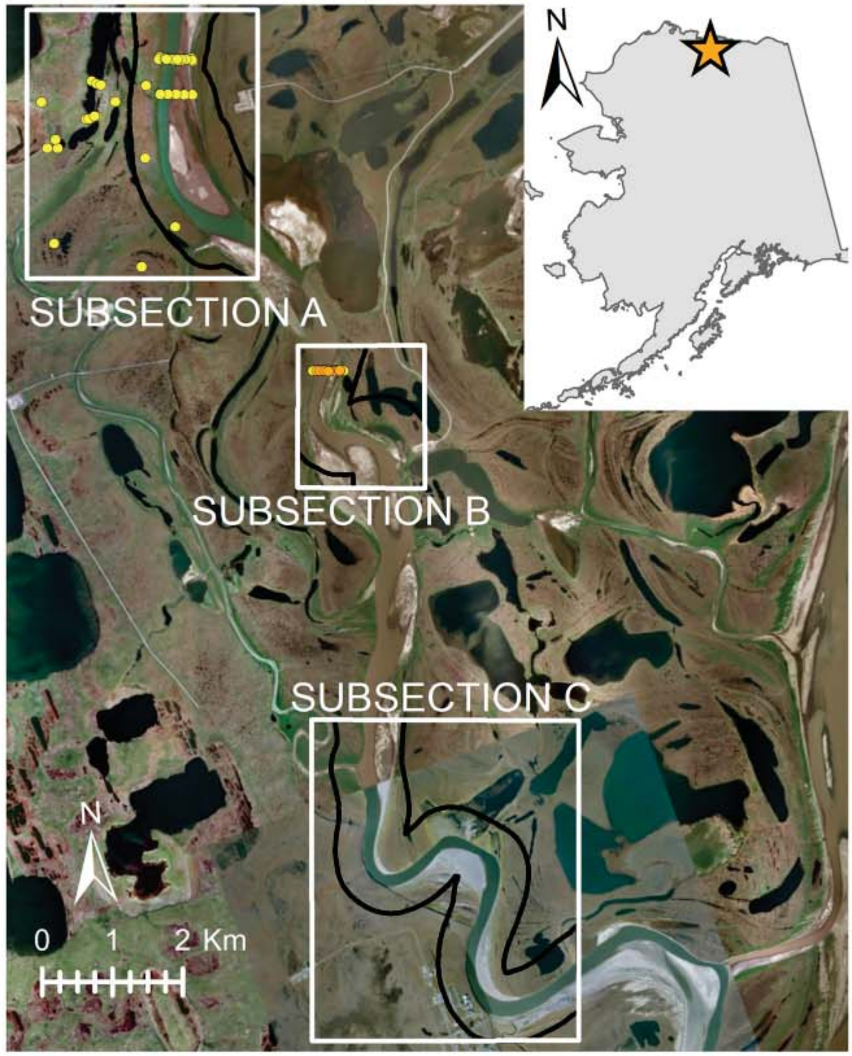

FIGURE 1 Location map. Orange star shows the Colville River Delta on the North Slope, Alaska. Black lines show the study corridor. Yellow and orange dots show locations of boreholes drilled in 2004–2009 and in 2013, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

(NPRA), Duane Miller Associates LLC (DMA; now Golder Associates, Inc.) and Golder Associates, Inc. drilled several geotechnical boreholes in the delta in support of bridge and pipeline crossings.[9-12,69] These unique data provide rare observations on subsurface conditions up to depths of several tens of meters in an arctic deltaic environment, including on talik and cryopeg characteristics associated with channel migration and permafrost dynamics.

4 | METHODOLOGY

4.1 | Subsurface assessment

In February–March 2013, we conducted a geotechnical study across the channel to supplement a previous assessment performed at the same location in 2009.[10] These data,[69] as well as data collected in previous geotechnical assessments[9,11,12] to support oil development in the Colville River Delta area, form the basis of this study (Figure 1). Here, we present the results of detailed fieldwork conducted in 2013 (12 boreholes), but we draw our study conclusions based on the larger dataset (79 boreholes up to 58.2 m deep).

4.1.1 | Drilling and soil sampling

We used a penetrometer (154.2 kg autohammer) over the active channel to determine comparable parameters for driving piles during infrastructure construction; however, in the context of this study, we used these data mainly to detect the boundary between unfrozen and frozen soils. We drilled 12 boreholes (Figure 2) that advanced to depths ranging between ~14 and 55 m bgs. We used a CME-75 drill rig with a combination of hollow stem auger (HSA), and cased borehole with rotary wash tri-cone and bi-cone bits, depending on subsurface conditions. We collected soil samples using a 50.8 mm O.D. split-spoon sampler (with 63.5 kg hammer) and a 76.2 mm O.D. heavy duty split-spoon sample (with 154.2 kg hammer) at the ground surface and at depths of 0.75 m and 1.5 m, and generally at 1.5 m intervals thereafter, or with changes in drilling conditions. We visually classified the samples in the field; permafrost soils and ground

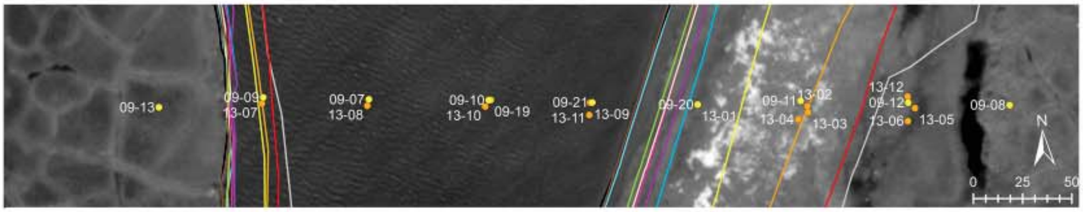

FIGURE 2 Borehole locations at the 2009/2013 drilling alignment across the Nigliq channel. Yellow and orange dots show locations of boreholes drilled in 2009 and in 2013, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

ice content were described according to ASTM 4083–89[13] and the cryofacies method applied for engineering purposes.[70] The number of blows required to drive the sampler, penetrometer and casing were recorded. However, there is not a direct correlation with corrected N-values (standard penetration resistance) for permafrost soils; rather, blow counts provide a relative value for estimation of soil/ice bonding, as well-bonded soils are significantly more resistant to penetration than unfrozen, unbonded or poorly bonded soils.

4.1.2 | Ground temperatures

We installed a sealed 2.54 cm diameter PVC casing in four boreholes to measure ground temperatures under the active channel (borehole #13-11), in the riverbed/riverbar (borehole #13-03), and in the active-floodplain (boreholes #13-05 and #13-06). We measured ground temperatures ~37 days after drilling completion by inserting a beadedstream digital temperature cable (DTC) in each casing for at least 1.5 h before recording the measurements. The DTC was ice-bath-calibrated before use; sensors have an accuracy of ±0.1°C.

4.1.3 | Groundwater

We installed a standpipe piezometer, consisting of a 5.08 cm diameter PVC casing with a screened section, and a pressure transducer (PT) in three boreholes (#13-02, #13-04, #13-12) for groundwater monitoring at 1 min intervals between February 19 and April 11, 2013. We backfilled the annulus of boreholes #13-02 and #13-04 with soil cuttings, and we left borehole #13-12 opened to manually measure, and monitor, the groundwater levels in the standpipe piezometer and opened borehole annulus twice per day for 8 days following drilling completion. We installed a barometric data logger in borehole #13-02 for corrections of the PT measurements; it measured atmospheric pressure and temperature every minute. We took some manual measurements of groundwater levels with an optical sounder in each borehole to calibrate our PT readings and obtained tidal data for the NOAA Deadhorse station. We monitored the groundwater level in borehole #13-02 in real-time while drilling nearby boreholes #13-03 and #13-04 to evaluate the groundwater connectivity between these locations. We installed a heat trace to temporarily maintain an unfrozen water column in the piezometer as we observed the real-time PT measurements in borehole #13-02, and we logged subsurface conditions (e.g., bonding, lithology, groundwater) and drilling operations (e.g., lowering rods) in boreholes #13-03 and #13-04. We also collected water samples for salinity measurements at depths of 1.8 and 2.7 m below the ice cover in the active channel upstream and downstream of the 2009/2012 drilling alignment.

4.1.4 | Laboratory testing

We re-examined and visually classified all soil samples in the laboratory to confirm the field classification. We measured gravimetric moisture content[71] and pore-water salinity on all samples. We conducted additional tests on selected samples, including: grain size distribution,[72,73] Atterberg limits,[74] organic content by ignition,[75] and fines content by means of a U.S. Number 200 Sieve wash test.[76]

4.2 | Likelihood of talik and cryopeg occurrence at the landscape scale

Our general approach to estimate the likelihood of encountering taliks and cryopegs at the landscape scale was based on a thorough assessment of surface and subsurface conditions in the terrain units of the floodplain development stages, followed by an extrapolation of our findings to similar surface conditions observed along the channel in remote sensing data. In ESRI ArcGIS (version 10.4.1), we manually identify the temporal changes in the active channel positions occurring at the 2009/2013 borehole alignment using a combination of historical aerial photography (1948, 1955, 1979, 1982) and high-resolution satellite imagery (Quickbird-2/WorldView-1, 2, 3: 2007–2008, 2010–2013, 2015–2016) taken in summer (June–August). The year of land exposure was estimated from the closest channel position line. We used equation (1) developed by Smith[16] and presented in Ensom[35] and Burn[36] to evaluate the temperature profile below the 2009/2013 drilling alignment in order to compare it with the ground temperatures measured in April 2013 below the active channel. This equation is for the stable thermal state:

$$T_z = T_g + \frac{z}{I} + \frac{T_p - T_g}{\pi}\left(2tan^{-1}\frac{H_p}{z}\right) \tag{1}$$

where T_z is temperature (°C) at depth z (m); T_g the mean annual surface temperature of the surrounding ground (−6.4°C for northern

Alaska[77]); T_p the mean annual bottom water temperature (°C); l the geothermal step (40 m °C^{-1}); and H_p is the half-width of the disturbance (~103 m). Given our lack of bottom water temperature measurements to establish the annual mean value (T_p), we tested a range of values determined by others in the Mackenzie Delta.[35-37] We also used the Stefan equation to estimate depths of the newly aggraded permafrost in order to compare them with our field data:

$$X = \sqrt{\frac{2k_f T_s}{\rho l} t} \tag{2}$$

where X is depth, k_f is frozen soil thermal conductivity (751 W°C^{-1} m^{-1}), ρ is density (1601 kg m^{-3}), l is latent heat of fusion (334,000 J kg^{-1}), T_s is applied constant surface temperature (~−6.5°C) and t is time. We calculated freezing depths at the borehole positions located on land only, although freezeback of the talik may have started when the water depth was about 1 m, and therefore before the land was exposed.

Within a 400 m wide corridor along the Nigliq channel, Stephani et al.[78] manually digitized terrain units mapped in the 1990s[64,79] and updated their boundaries based on changes observed in the 2013 high-resolution imagery, 2015 ArcticDEM[80] and 2013 LiDAR[81] data. The active channel position observed in the 1948 aerial imagery and 2013 satellite high-resolution imagery were manually mapped in ArcGIS; land changes that occurred between 1948 and 2013 were classified, by terrain units, as land eroded or exposed[78] (Figure 3). We classified areas with potential of finding taliks and cryopegs based on the integration of results from this channel migration analysis,[78] from our 2013 drilling program in subsection B (12 boreholes up to 54.1 m deep), and from previous drilling programs by DMA/Golder in subsection A (57 boreholes up to 58.2 m deep) and subsection B (10 boreholes up to 57.6 m deep). The specific rationales to attribute the likelihood levels are presented in the Results section. We estimated the area covered by each likelihood level in the study corridor using the "calculate geometry" function in ArcGIS.

5 | RESULTS

5.1 | Subsurface conditions

5.1.1 | Sedimentary horizons

At the 2009/2013 drilling alignment, the soil conditions observed in the 2013 geotechnical study were consistent with those documented in 2009,[10] as well as with those reported at other locations along the channel in previous drilling campaigns.[9,11,12] We identified four distinct sedimentary horizons across the channel (Figures 4–6, Table 1); for the purpose of this paper, we decided not to link them to regional deposition history.

Unit 1 (~6–9 m thick; absent under active channel) was composed of organic silt, silt and peat soils with rootlets and wood (Figures 4 and 5a). It was entirely frozen, with gravimetric moisture contents of 25–79% (Table 1, Figure 6a). The porous visible cryostructure was dominant in mineral soils with some ice lenses, and reticulate and microlenticular cryostructures; in peat it was mainly an organic-matrix cryostructure. The typically ice-rich intermediate layer characterized by a suspended (ataxitic) cryostructure was probably missed between sampling intervals while drilling the older terrain units; this layer is generally found within the upper 2 m of permafrost and acts as a buffer between the active layer and long-term permafrost due to its important ice content that increases the latent heat needed for thawing.[82,83]

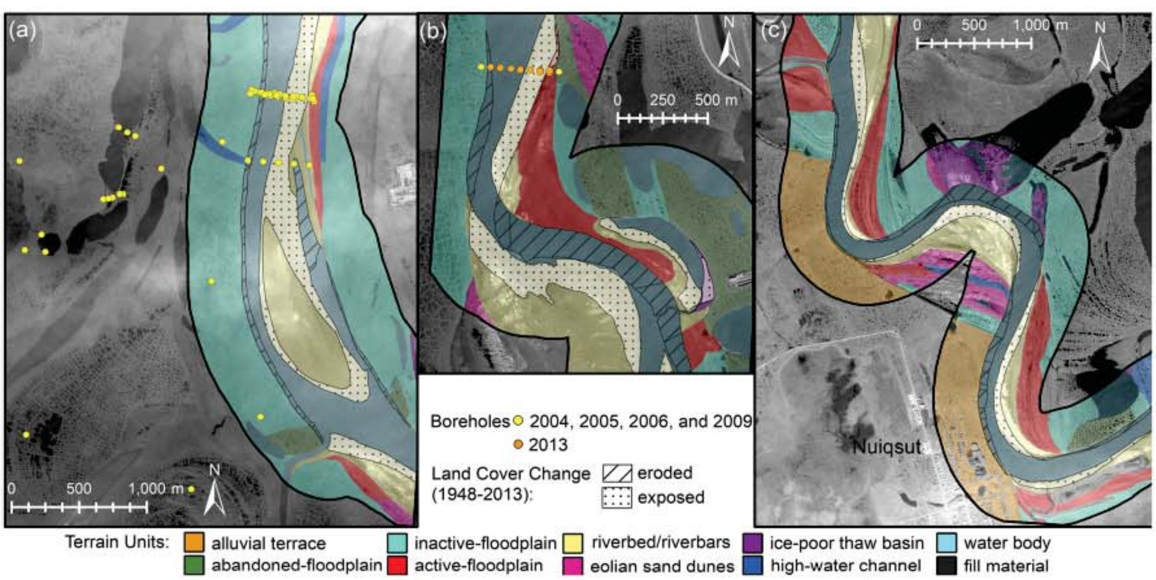

FIGURE 3 Terrain units and land cover changes from 1948 to 2013 along the Nigliq channel. (a) Section A; (b) section B; and (c) section C [Colour figure can be viewed at wileyonlinelibrary.com]

Unit 2 (~5–11 m thick) consisted primarily of sand and silty sand, interbedded with silt layers and some interbeds of gravel, organic silt, and peat with wood (Figures 4 and 5b). These deposits were entirely frozen under the riverbed/riverbar and active-floodplain, except at the westward edge of the riverbed/riverbar deposits (boreholes #13-01, #09-20). Gravimetric moisture contents were 12–48% (Table 1, Figure 6a) with mainly porous visible and invisible cryostructures.

Unit 3 (~5–16 m thick) consisted mainly of clean sandy gravel and gravelly sand with some silty lenses (Figures 4 and 5c). It

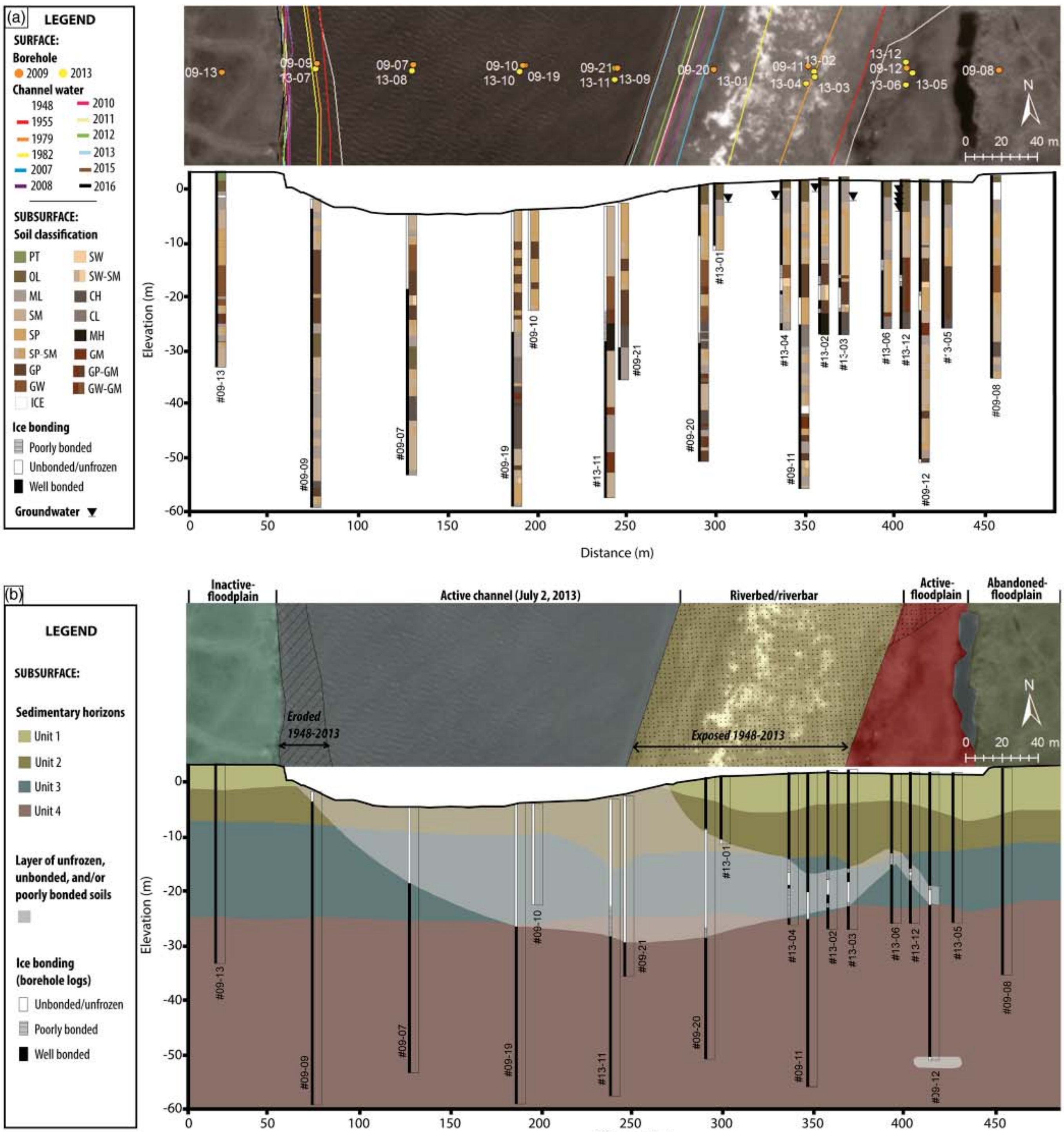

FIGURE 4 (a) Surface and subsurface data at the 2009/2013 borehole alignment: temporal variations of the active channel position, soils with their thermal and bonding state, and groundwater. (b) Data interpretation at the 2009/2013 borehole alignment: terrain units, land cover changes in 1948–2013, cryostratigraphic units, and configuration of the talik and cryopeg (background imagery: WorldView-2, July 10, 2013) [Colour figure can be viewed at wileyonlinelibrary.com]

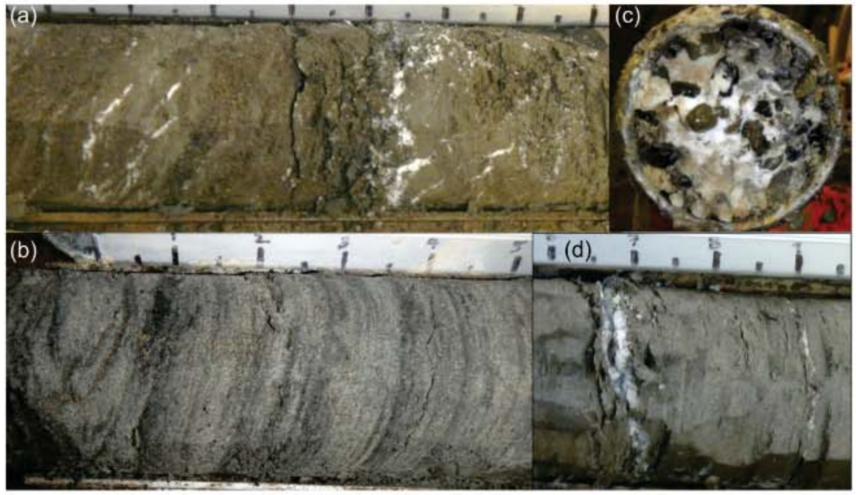

FIGURE 5 Samples from (a) unit 1: reticulate and porous cryostructures in silt; (b) unit 2: porous cryostructure in interbeds of sand, silty sand and silt; (c) unit 3: suspended cryostructure in sandy gravel; and (d) unit 4: layered cryostructure in silt. Scale bar is in inches [Colour figure can be viewed at wileyonlinelibrary.com]

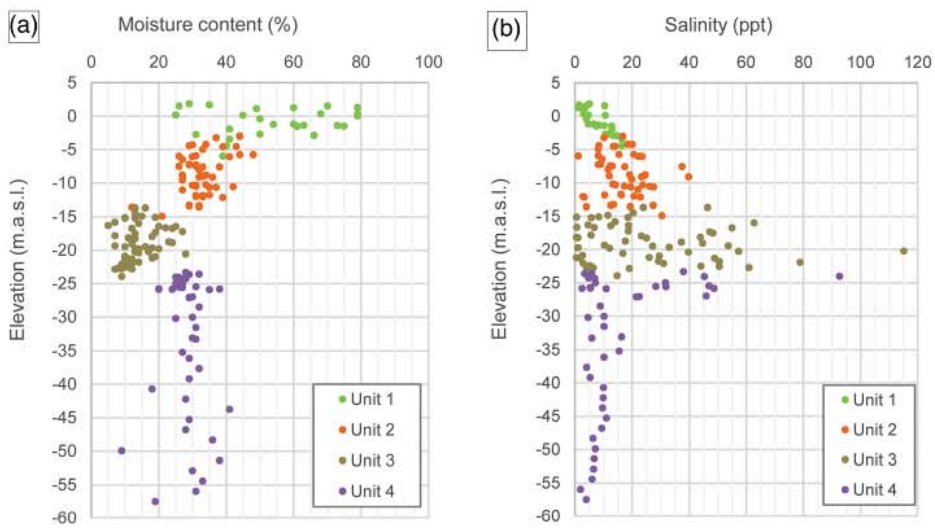

FIGURE 6 Variations in gravimetric moisture content (a) and pore-water salinity (b) with elevation [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Soil properties of the sedimentary horizons

		Unit 1	Unit 2	Unit 3	Unit 4
Unified soil classification system (USCS)[a]		OL, ML, PT	SP-SM, SP, SM	GP-GM, GP, GM	CH, ML, SM
Organic content (%)	Average	8	7	NA	5
	Minimum	6	6	NA	2
	Maximum	9	7	NA	7
Gravimetric moisture content (%)	Average	53	33	14	28
	Minimum	25	12	5	9
	Maximum	79	48	28	41
Salinity (ppt)	Average	8	11	26	16
	Minimum	1	1	1	2
	Maximum	23	40	115	93

[a]CH = fat clay; GM = silty gravel; GP = poorly graded gravel with sand; GP-GM = poorly graded gravel with silt; ML = silt; OL = organic silt; SM = silty sand; SP=poorly graded sand; SP-SM = poorly graded sand with silt; PT = peat.

included a mix of unfrozen, unbonded, poorly bonded zones, and frozen well-bonded soils (Figures 4, 7 and 8). Gravimetric moisture contents were 5–28% (Table 1, Figure 6a) with porous visible and invisible cryostructures, although some samples were ice-rich with a suspended cryostructure. We measured salinities of 8–19 ppt in the upper parts of the poorly bonded zone, and 18–115 ppt in the underlying poorly bonded, unbonded and/or unfrozen soils (Figure 6b).

Unit 4 was at least 33 m thick; we did not reach the bottom extent (Figure 4). These deposits were characterized by layers of clay and silt interbedded with silty sand, gravelly sand, sandy gravel and organic layers with wood (Figure 5d). The deposits were mostly frozen, in a well-bonded state, with a few exceptions in the upper parts of the deposits underlying the active channel and riverbed/riverbar (Figures 4, 7 and 8). Gravimetric moisture contents were 9–41% (Table 1, Figure 6a) with porous visible and invisible cryostructures and some ice lenses. We measured salinities of 2–93 ppt (Table 1, Figure 6b).

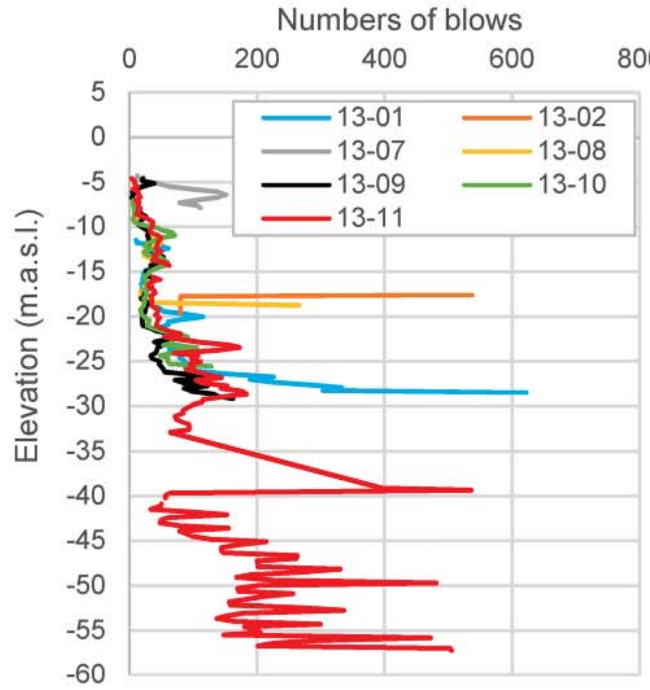

FIGURE 8 Penetrometer blow counts (#13-07 terminated with 110 blows in 0.2 m) [Colour figure can be viewed at wileyonlinelibrary.com]

5.1.2 | Ground thermal regime

In spring, a period when we could expect the lowest ground temperatures (or close) to occur, we measured temperatures above freezing (up to ~1.7°C) at depths of 0 to ~14.9 m below the active channel floor (elevations: 0.4 to −14.5 m) (borehole #13-11), therefore indicating the presence of a talik under the active channel. We measured ground temperatures below 0°C under this talik and in the adjacent (eastward) riverbed/riverbar (borehole #13-03) and active-floodplain (boreholes #13-05 and #13-06) (Figure 7). However, during drilling and soil sampling we observed unfrozen, unbonded and/or poorly bonded soils at depths of ~14.9–25.3 m (elevations: −14.5 to −24.9 m) below the active channel floor (borehole #13-11), ~18.3–25 m bgs (elevations: −16.5 to −23.3 m) in the riverbed/riverbar (borehole #13-03) and ~14.6–16.8 m bgs (elevations: −13.1 to −15.2 m) in the active-floodplain (borehole #13-06) (Figure 4a). These cryopeg soil conditions that exist below the 0°C freezing temperature due to high pore-water salinity are not detected just from temperature measurements. We observed only well-bonded soils and measured negative ground temperatures below this cryopeg layer located at depths of 14.9–25.3 m below the active channel floor and extending within the riverbed/riverbar and active-floodplain. These field data confirmed that the active channel is not underlain by an open talik but, rather, by a closed talik and cryopeg that extend into an intrapermafrost layer eastward at depths of ~9–29 m bgs under a former channel position (Figure 4b). The temperature profile estimated with equation (1) did not fit the conditions observed in the field, as the analytical solution suggested the occurrence of a through-talik underlying the active channel. Similarly, significant disparities were observed between the freezing depths estimated with the Stefan equation (2) and our field data (Table 2).

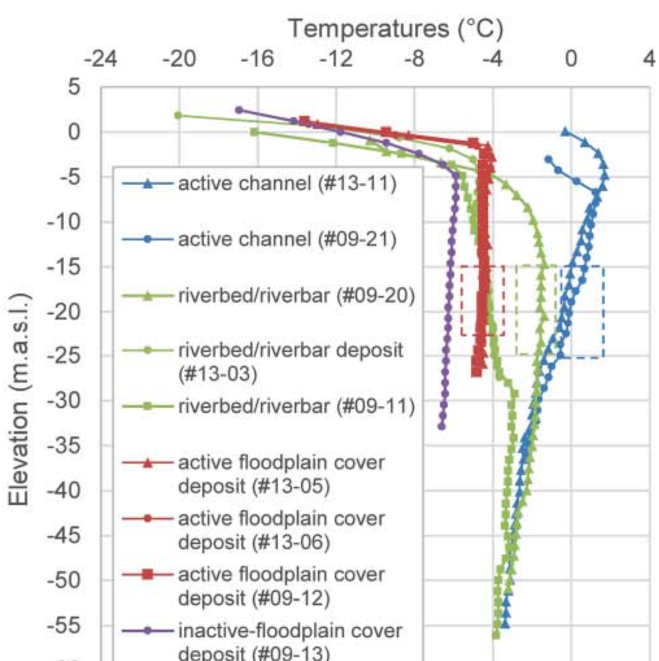

FIGURE 7 Ground temperatures measured in spring 2009 and 2013 (dashed boxes show cryopeg depths) [Colour figure can be viewed at wileyonlinelibrary.com]

5.1.3 | Groundwater

We encountered groundwater in the boreholes penetrating the cryopeg layer under the riverbed/riverbar (boreholes #13-01,

TABLE 2 Summary of freezeback rates per location

Terrain unit	Borehole ID	Depth to cryopeg (m)[a]	Freezing depth (m)[b]	Time elapsed from land exposure (years)
Riverbed/riverbar	13-01, 09–20	~11	8	>6
Riverbed/riverbar	13-02, 13–03, 13–04, 09–11	~19	19	~34
Active-floodplain	13-06, 13–12, 09–12	~19	27	>65

[a]Field data.
[b]Stefan equation.

#13-02, #13-03, #13-04), and the active-floodplain (borehole #13-12) (Figure 4a). This sandy and gravelly layer had a hydraulic connection to the channel. In the riverbed/riverbar, groundwater levels monitored in real time in borehole #13-02, while drilling boreholes #13-03 and #13-04, varied sharply in response to drilling activity after we reached the cryopeg and stabilized shortly (<12 h) after drilling completion (Figure 9); it confirmed the groundwater connectivity between these locations. Within the active channel, we measured salinity values of 11–22 ppt in the water at depths of 1.8 and 2.7 m under the ice cover near the 2009/2013 drilling site.

5.2 | Likelihood of talik and cryopeg occurrence

We classified the terrain with three likelihood levels (low, medium, and high) of finding taliks and/or cryopegs by extrapolating, at the landscape scale, the typical subsurface conditions obtained in specific terrain units and time elapsed since land exposure. A low likelihood level was attributed if the soils observed in the same terrain units elsewhere along the channel were entirely frozen and well bonded during drilling, except for isolated pockets. Older terrain units in the floodplain development stages were typically attributed to the low likelihood level, as our data suggest a likelihood of full freezeback given the substantial time frame (thousands of years) required to develop these terrain units compared to the much shorter freezeback time frame. Similarly, terrain units developed not as a direct result of channel migration and not related to surface water (e.g., eolian sand dunes) were also attributed a low likelihood level. The low likelihood level characterized a total area of 42.2% within our study corridors, including such terrain units as alluvial terraces, abandoned floodplains, inactive floodplains, and eolian sand dunes (Table 3, Figure 10). We attributed a medium likelihood level to terrain units in which we find, while drilling in similar terrain units elsewhere in the study area, a mix of boreholes with entirely frozen soils and boreholes containing layers of unfrozen, unbonded, and/or poorly bonded soils. The medium likelihood level was attributed to 29.2% of the study area, including the riverbed/riverbar exposed before 1948, active floodplains, thaw-lake basins (ice-poor), high-water channels, and smaller water bodies (Table 3, Figure 10). Finally, we attributed the high likelihood level if: (a) we observed unfrozen, unbonded and/or poorly bonded soils conditions in all the boreholes drilled in similar terrain units elsewhere in the study area, and (b) the ground surface became exposed after 1948. We considered in our rationales whether the land was exposed before or after 1948, as it was the oldest imagery available for our study area and, therefore, it could be used as a temporal baseline to evaluate permafrost aggradation following channel migration. The likelihood level was high in riverbed/riverbar exposed after 1948, the active channel, and larger lakes; it covered 27.0% of the area within the study corridor (Table 3, Figure 10).

6 | DISCUSSION

6.1 | Talik and cryopeg development in dynamic conditions

Along the Nigliq channel, which migrates at relatively low rates compared to other arctic deltas,[78,84] our field data, combined with

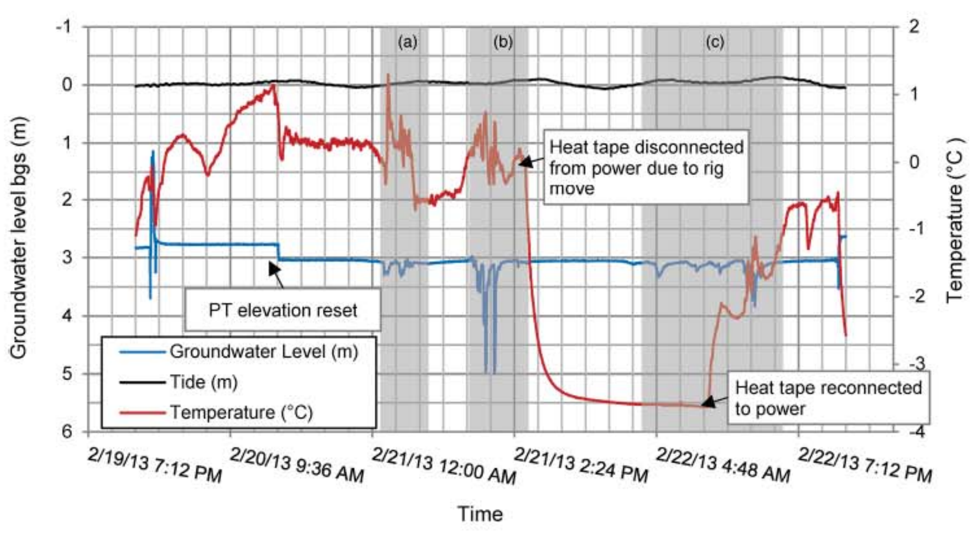

FIGURE 9 Real-time monitoring of groundwater conditions in borehole #13-02 with a pressure transducer (PT) while drilling boreholes #13-03 and #13-04. The gray shaded areas show periods of drilling activity after reaching cryopeg depths in the boreholes: (a) #13-03, (b) #13-03 and (c) #13-04 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Areas covered by occurrence level

Occurrence level	Terrain unit	Area (m^2)	Portion of total area (%)[a]
High	Riverbed/riverbar	1,239,081	8.3
	Large water bodies and active channel	2,773,212	18.6
Medium	Riverbed/riverbar	1,805,429	12.1
	Active-floodplain	1,366,756	9.2
	High-water channel	267,829	1.8
	Ice-poor thaw basin	282,102	1.9
	Water bodies (relatively medium)	626,971	4.2
Low	Alluvial terrace	1,243,698	8.4
	Abandoned-floodplain	571,784	3.8
	Inactive-floodplain	4,100,014	27.6
	Eolian sand dunes	363,006	2.4

[a]Excludes fill material area to sum 100%.

previous drilling work,[9-12] indicated that closed taliks have developed under this main distributary of the Colville River Delta, rather than through taliks as estimated by an analytical solution developed for the stable state (Equation (1)). As channels migrate in arctic deltas, even at the low long-term rate of 1 m yr^{-1} measured at the 2009/2013 drilling site,[78] the boundary conditions change very rapidly compared to the time needed to reach ground thermal equilibrium. Smith[16] estimated that the steady-state configuration, under a laterally stable channel 100 m wide located in the east central modern Mackenzie Delta, was reached after ~500 and 750–1000 years at depths of 30 and 60 m, respectively. He estimated that a through-talik would underlie this 100 m wide channel section within 200–300 years, while the critical channel width above which through-taliks develop in similar conditions was estimated at ~70–80 m. However, the channels would need to be significantly wider for through-taliks to develop under channels migrating, even at low rates of 1 and 3 m yr^{-1}.[16,34] Burn[36] estimated that it may take 3,500–9,000 years to establish a through-talik under deep lakes (>4 m deep) in areas where permafrost thicknesses range from 400 to 700 m, such as on Richards Island in the outer Mackenzie Delta. He found that approximately one-quarter of the total number of lakes on this island developed through-taliks, while most lakes deeper than 4 m had through-taliks. Ensom et al.[35] found based on bottom water measurements and analytical solution that through-taliks are underlying nearly the entire channel network in the Mackenzie Delta, identifying a channel critical width of 62.6 m for a through-talik to develop. Also in the Mackenzie Delta, a study using a one-dimensional heat-flow equation (Neuman solution), with a limited number of oil development boreholes for ground-truthing, estimated the predominance of through-taliks under major channels and closed taliks under secondary channels.[34] The various findings in the Mackenzie Delta contrast with our field observations along the Nigliq channel where we identified only closed taliks along this main distributary. Besides channel sizes and other properties, this important difference in talik type may be partially explained by the permafrost thicknesses, which vary from less than 100 m thick in the modern Mackenzie Delta to 663 m thick in the Tuktoyaktuk coastlands,[85] compared to thicknesses of ~200–600 m in the Colville River Delta.[62]

Taliks identified under migrating channels and rivers in the Arctic have shifted in response to these surface changes.[29,31,34] Similarly, the talik configuration at the 2009/2013 borehole alignment indicated that it shifted according to channel migration. However, the former talik that established under past channel positions was characterized by ground temperatures well below 0°C, yet some of the deposits at depths remained unfrozen, unbonded and/or poorly bonded due to high pore-water salinity. This cryopeg layer was part of an open-system as it connected to the talik underlying the active channel. Some cryopegs that developed below arctic lake taliks have been reported,[22,23] but, to our knowledge, there is no detailed description

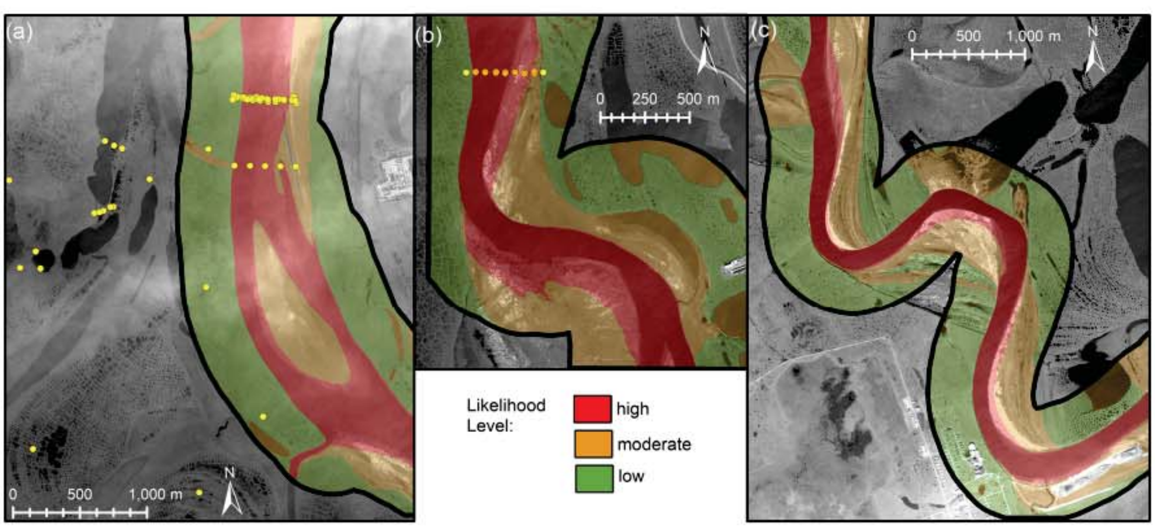

FIGURE 10 Likelihood levels of encountering taliks and cryopegs along the Nigliq channel. Yellow and orange dots show locations of boreholes drilled in 2004–2009 and in 2013, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

of cryopeg layers occurring below active and former channel positions in arctic deltas. The main assessment methods may explain the lack of such observations. In the Mackenzie Delta, there may also be fundamental differences relative to the Colville River Delta such as depositional history and hydrology, including seasonal seawater and freshwater interactions. In the Colville River Delta, the seawater intrusion in winter[67,68] may contribute to an increase in the salinity of the deposits, while the Mackenzie Delta remains a freshwater body throughout the year. In winter, it becomes an important freshwater body due to the considerable water volume flowing from the Mackenzie River that is captured in the delta by the bottom-fast ice acting as a dam in the outer delta.[86] Nevertheless, an effective comparison of our study findings with other deltas remain difficult given the limited data availability of detailed subsurface conditions at depths.

6.2 | Permafrost aggradation with channel migration

The occurrence of unfrozen soils associated with channel migration in an arctic delta has been established as a transient condition that reflects the ground thermal adjustment following a change in boundary conditions, including the disappearance of surface water bodies and subsequent vegetation succession[87]; in the Mackenzie Delta, these findings on near-surface permafrost (NSP) conditions (permafrost within 3 m of the ground surface) confirmed that it is part of the continuous permafrost zone rather than the discontinuous zone suggested by others.[88,89] Freezeback of terrestrial land exposed by channel migration along the Nigliq channel reached depths well beyond NSP aggradation, yet some cryopegs at depths may or may not freeze back entirely depending on factors such as pore-water salinities. In the conceptual model of arctic river floodplain development,[1,60] the authors established that syngenetic permafrost aggrades as accumulation of floodplain deposits progress, the permafrost table moves upward, ice accumulates in the upper permafrost and the ground surface rises, therefore decreasing the flooding frequency. According to this model, the active-floodplain phase may last 100–300 years, while an important transition in permafrost development occurs during 1,500–2,500 years in the inactive-floodplain phase.[1] The final stage of floodplain development, the abandoned-floodplain stage, lasts for 2,000–4,000 years. Therefore, it takes thousands of years after terrestrial land exposure to develop the ice-rich syngenetic permafrost,[1] which may reach heights of ~4 m above the water level at the final stage of floodplain development.[78] Our findings indicate that during an extremely short period (~6–34 years) compared to thousands of years for this upward aggradation, epigenetic permafrost developed, up to depths of ~11–19 m below the water line, in the terrestrial land exposed by channel migration. Ground temperatures in the riverbed/riverbar measured at nearly the same location in 2009 and 2013 showed that the soils, already frozen in 2009, cooled further in the subsequent 4 year period (by up to 4°C at ~15 m depth) (Figure 7). According to the Stefan equation (2), we would expect that a talik would remain for a longer duration at depths, but ground temperatures well below 0°C indicated that freezeback of the deposits had progressed at a much faster rate than expected in a simple conductive heat transfer model. At Illisarvik Lake on Richards Island in the outer Mackenzie Delta, Mackay[22] measured a rapid freezeback rate (30 m in 5 years) of the talik that was associated with convective heat transfer of groundwater flow from pore-water expulsion during the freezing of saturated sands in an open hydrologic system, and the occurrence of intrapermafrost groundwater of increasing salinity but decreasing temperature. Under these conditions, Mackay[22] identified the need for a three-dimensional conductive–convective heat transfer approach. Similar convective heat transfer may have played a role in the rapid freezeback rate at the Nigliq site; however, we explain the rapid rate mainly due to a much lower and delayed release of latent heat in the cryopeg compared to the significant latent heat released during freezing of soils with fresh pore-water.[90]

The configuration of the talik and cryopeg at the 2009/2013 borehole alignment indicated that freezing has mainly been occurring downward. Shallower depths of the bottom extent of the cryopeg in the eastward area suggest that, as the area of disturbance and ground temperatures decrease, some limited upward and horizontal freezeback may have begun. Similar freezing trends were observed at the Illisarvik Lake; Mackay[22] determined that, following lake drainage, permafrost aggradation occurred downward, upward and horizontally in nearshore areas while at distal and central locations, where the talik was deeper than 20 m, freezeback was primarily downward. Downward freezing of the deposit with heat conduction has changing surface boundary conditions as the floodplain develops and permafrost changes from a climate-driven permafrost (e.g., riverbed/riverbar) to a climate-driven, ecosystem-modified permafrost (e.g., active- to abandoned-floodplain). According to the conceptual model of permafrost aggradation and degradation developed by Shur and Jorgenson,[91] climate-driven permafrost is a simple system with a barren surface and a ground thermal regime mainly controlled by air temperatures. The cryostratigraphy is also simple, mainly formed by a homogeneous cryofacies with a porous cryostructure that has very little or no excess ice. At the 2009/2013 borehole alignment, the configuration and properties of the talik, cryopeg and newly frozen soils in relation to terrain units indicate that downward aggradation of epigenetic permafrost in terrestrial land exposed by channel migration has occurred predominantly as a climate-driven system. The subsequent vegetation succession, significant ground ice accumulation and landscape changes transform the initially simple permafrost model into a complex one; it is referred as a climate-driven, ecosystem-modified permafrost. The system becomes far more complex with the development of surface modifiers (e.g., vegetation), a decrease in the active-layer depth, and accumulation of large amounts of ground ice in the upper permafrost. This corresponds to the syngenetic and quasi-syngenetic permafrost that aggrades upward in the floodplain development model,[91] yet some freezeback of cryopegs at depths may still be progressing concurrently. In the active-floodplain (borehole #09-12), unfrozen sandy gravels were observed at depths of ~52 m bgs with down-hole heaving sand conditions and high pore-water salinity (89 ppt; for reference, seawater salinity is ~35 ppt). It is unlikely that such pockets of highly saline soils may ever entirely freeze back in our contemporary climate, as salt is expelled during permafrost aggradation,[66] and therefore also increasing the salinity of the pore-water below the freezing front. In these complex systems, the surface and subsurface conditions can be highly variable vertically and horizontally. This includes a cryostratigraphic profile with multiple layers that typically comprises ice-rich cryostructures in the upper permafrost and massive ice as a polygonal network of ice wedges. At depths, the epigenetic permafrost developed in the terrestrial land exposed by channel migration is typically ice-poor. At the surface, the thickness of the organic cover generally increases with the stage of floodplain development. The vegetation may also vary horizontally throughout the area as it reflects ages of the floodplain terrain units and local variations in hydrologic conditions, such as observed in ice-wedge polygon centers and troughs. Furthermore, degradation and subsequent stabilization of ice wedges change the surface and near-surface conditions.[92] All these changes in boundary conditions evolve at variable temporal and spatial scales, resulting in a highly complex system. As changes in the landscape progress and permafrost conditions evolve, this permafrost becomes less sensitive to changes in air temperatures, yet its thaw sensitivity to surface disturbances increases due to high ice content that can lead to thermokarst development if thawing is initiated.[91]

6.3 | Estimating talik occurrence at the landscape scale

Our review of the available literature indicated that the occurrence, geometry and properties of taliks and cryopegs under water bodies throughout arctic deltas and coastal regions vary significantly but without clear trends that allow for prediction. Nevertheless, our findings, based on direct measurements at depths of tens of meters, suggest the existence of such trends within the Colville River Delta. Our likelihood analysis was based on detailed subsurface data collected specifically in the context of geotechnical investigations for foundation design. However, the consistency in our findings throughout the study area suggests that our likelihood analysis could now be used as a reconnaissance tool for future studies along this channel to identify potential areas of taliks and cryopegs with high pore-water salinities. These subsurface conditions may influence infrastructure routing and foundation design. An assessment of the potential occurrence of such soil conditions at the landscape scale would be very valuable as a risk analysis tool for land planning purposes and engineering projects in arctic deltas, as well as for other applications such as assessing potential groundwater resources and release of greenhouse gases.

Our likelihood estimation of encountering of taliks and cryopegs at the landscape scale has its limitations. The analysis relies on the availability of historical imagery; therefore, it covers a very small temporal scale compared to the time needed (hundreds to thousands of years) to reach steady-state conditions or develop the various terrain units from the floodplain development model.[1,60] This also implies that the 1948 temporal limit in our analysis, which represents the oldest imagery available, consists of an arbitrary threshold compared to some timescales of the surface and subsurface processes occurring within our study area. Similarly, temporal coverage in images between the initial and final position of the channel influences the robustness of a likelihood analysis such as the one we have developed. Our analysis also requires a thorough understanding of permafrost dynamics in an arctic deltaic environment. To name just a few topics, this includes: interrelations between terrain and subsurface conditions, and how they may change spatially and temporally; permafrost aggradation and degradation mechanisms; and a cryofacies approach applied at the landscape scale. Our findings based on a thorough analysis of surface and subsurface conditions imply that a significant amount of work must be conducted to support a robust likelihood analysis, which is likely to be expensive in the context of land planning but a strong tool for sustainable development. The great disparities in subsurface conditions with channel migration found in other regions, namely the Mackenzie Delta, question whether our approach to assess the likelihood of finding taliks and cryopegs may be expanded to other regions.

6.4 | Cryofacies approach for assessing changes occurring at variable spatial and temporal scales

Our holistic assessment of permafrost conditions and channel migration showed that surface and subsurface conditions along the Nigliq channel change at highly variable spatial and temporal scales. For instance, surface changes in the landscape may occur within a relatively small time frame, from annual to decadal, yet terrain units may take hundreds to thousands of years to develop.[1,64] Channel migration may result in changes in the thermal state of the deposits and in whether they are frozen or unfrozen, which can vary significantly both spatially and temporally. Permafrost aggradation after terrestrial land exposure may take several decades and still not be completed due to remaining pockets of soils with high pore-water salinity (Figures 4, 6b and 7). The type and spatial distribution of ground ice in all terrain units may also change relatively rapidly after thawing and subsequent freezeback that occurs with channel migration. The syngenetic permafrost that aggraded during floodplain development[60] tends to be ice-rich while the epigenetic permafrost, which developed in the thawed and consolidated riverbed/riverbar under a past channel, is generally ice-poor with a predominantly porous cryostructure. Understanding the typical properties of syngenetic and epigenetic permafrost, and the subsequent changes that may be triggered by channel migration, will help to estimate at the terrain unit scale the spatial variation of key parameters for land planning and engineering purposes.

A high variability in the spatial and temporal scales of changes stresses the need to use adapted investigation methods to measure changes in surface and subsurface conditions in arctic deltas to detect this variability. It also emphasizes the need for routing and design of linear infrastructure to understand the evolution of past and current conditions, so we can estimate how these conditions may also change in the lifetime of infrastructure due to anthropogenic and natural processes, and from effects of climate change (e.g., snow cover, air temperature, ice cover thickness, vegetation). The cryofacies approach, which applies to all types of permafrost,[6] can be combined with complementary methods to give a comprehensive assessment of surface and subsurface conditions. Some geotechnical studies[70,93-95] have used the cryofacies approach to establish the link between cryostructures and physical properties to estimate the excess ice content and thaw susceptibility of soils at the terrain unit scale. Here, a geotechnical investigation and channel migration analysis combined with terrain analysis allowed us to identify areas recently exposed along the channel where permafrost may now be aggrading while some layers of unfrozen, unbonded, and/or poorly bonded soils with high pore-water salinity may remain at depths. Additional data, such as flooding frequency and climate data, could be integrated into our analysis to give a more comprehensive assessment of changes in permafrost conditions with channel migration; this is because, according to a geosystems approach, the climatic, terrain and subsurface components closely interact with consequences that may be of interest for engineering applications.[36] According to the geosystems approach, these components (including infrastructure) operate as a complex system and, thus, changes in one component can trigger a series of feedback effects in the overall system.[96]

7 | CONCLUSIONS

We identified the typical configuration and properties of taliks and cryopegs along the Nigliq channel of the Colville River Delta, as well as subsequent epigenetic permafrost growth that are related to channel migration and floodplain development. Our study was based on data from 79 boreholes that included soil sampling with index testing, measurements of channel water and soil pore-water salinity, groundwater and ground temperatures, and temporal changes in channel positions from 1948 to 2013. We found that the active channel was underlain by closed taliks, rather than through-taliks, and thus did not penetrate the entire layer of permafrost connecting supra- and sub-permafrost groundwater. Cryopeg layers connected to the taliks under the active channel were identified under terrain units exposed and developed following channel migration, namely the riverbed/riverbar and active-floodplain. Cryopegs as isolated small pockets were also identified at depths in older terrain units (e.g., inactive-floodplain). The cryopeg layer that was thoroughly assessed in the geotechnical drilling programs in 2009 and 2013 appeared to have reached ground temperatures below 0°C at a faster rate than expected with a simple conductive heat transfer model. We explained this rapid rate mainly by the low and delayed release of latent heat as the freezing front progresses downward in the sandy and gravelly soils of increasing salinity but decreasing temperatures. As the deposits keep cooling, ground ice will continue to form, further increasing the salinity of the remaining unfrozen soil pore-water and probably preventing complete freezeback of the cryopeg developed in relation to migration of the Nigliq channel.

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