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Geometry of oriented lakes in Old Crow Flats, northern Yukon

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ABSTRACT
Old Crow Flats is an interior basin with thousands of thermokarst lakes. These lakes have irregular shapes where they are surrounded by trees and tall shrubs that may remain rooted after bank subsidence and protect the underlying sediment from erosion. In polygonal tundra, the vegetation cover is easily removed and wave action can erode and redistribute bank sediment to form rectilinear shores. The majority of lakes with rectilinear shores are aligned parallel to dominant winds and expand most rapidly in this direction. This is contrary to the oriented lakes of the Arctic coastal plain and is due to the fine texture of glacio-lacustrine deposits in OCF, which contain very little sediment sufficiently coarse to accumulate near-shore along the leeward side of the lake, leaving the bank vulnerable to thermo-mechanical erosion caused by wave action.

RÉSUMÉ
La plaine d'Old Crow est un basin intérieur parsemé de milliers de lacs thermokarstiques. Ces lacs sont de forme irrégulière lorsqu'ils sont entourés de fardoche et d'arbres qui peuvent rester enracinés malgré l'affaissement des berges, et qui empêchent ainsi l'érosion des sédiments sous-jacents. Dans la toundra, où le couvert végétal est facilement rompu, les vagues érodent et redistribuent les sédiments pour former des rivages rectilignes. La plupart de ces lacs sont parallèles aux vents dominants et ont une croissance accélérée dans cette direction, ce qui est contraire à la configuration des lacs de la plaine côtière de l'Arctique. Cette différence est due à la granulométrie fine des dépôts glacio-lacustres de la plaine d'Old Crow: très peu de sédiments sont suffisamment grossiers pour s'accumuler près des berges exposées au vent, laissant ces dernières vulnérables à l'action thermo-mecanique érosive des vagues.

1 INTRODUCTION

Field evidence indicates that the orientation and shape of thaw lakes near the western North American Arctic coast reflect the effects of wave action and wind-generated currents on shore erosion and sediment transport (Mackay 1956; Rex 1961; Carson and Hussey 1962; Mackay 1963; Côté and Burn 2002). Oriented thaw lakes are also found in interior basins, such as Old Crow Flats (OCF), northern Yukon (Roy-Leveillee and Burn 2010), where little is known of the factors controlling their development and morphometry (Mackay 1956; Côté and Burn 2002). In this paper we discuss the distribution and characteristics of oriented lakes in OCF. We examine variations in lakeshore geometry within the Flats and use a combination of field observations and aerial photographs to discuss relations between patterns of lake expansion and lake orientation.

1.1 Background

Along the western North American Arctic coast, clusters of thermokarst lakes are oriented perpendicular to the dominant wind direction (Carson and Hussey 1962; Mackay 1963). This orientation has been attributed to longshore sediment drifting and wind-driven circulation patterns. Rex (1961) used hydrodynamic principles to show that longshore sediment drifting is greatest where the angle between the wave orthogonals and the normal to the shoreline is approximately 50º, and least where waves are parallel to shore. A prevailing wind direction results in the development of an elongated form with sediment accumulation near the centre of the leeward shore and maximum sediment transport near the ends of the lake, where shoreline curvature is often accentuated (Rex 1961). Carson and Hussey (1962) provided field observations supporting this model, and indicated that sediment accumulation on the leeward side of the lake protects the shore from wave action and is the key process for the initiation of lake elongation perpendicular to the prevailing wind direction. They also suggested that expansion perpendicular to the prevailing winds is accelerated in large lakes due to wind-driven circulation cells that create currents of sufficient strength to erode the lake ends. Recent remotely sensed images of gyres in oriented lakes of the Alaskan Arctic coastal plain support this circulation model, and confirm that the development of such currents increases with lake size and wind velocity (Zhan et al. 2014).

Oriented lakes can also develop parallel to the dominant wind direction, as observed in parts of the Lena River delta and in OCF (Morgenstern et al. 2011; Roy-Leveillee and Burn 2010), but information regarding the development of lakes with such an orientation is scarce.

1.2 Old Crow Flats

OCF (Fig. 1) is a 5600 km^2 wetland containing thousands of thermokarst lakes and ponds. It is within the forest-tundra ecotone of northern Yukon, and is in the continuous permafrost zone. The vegetation cover is a heterogeneous mosaic of woodlands, tall shrubs, low

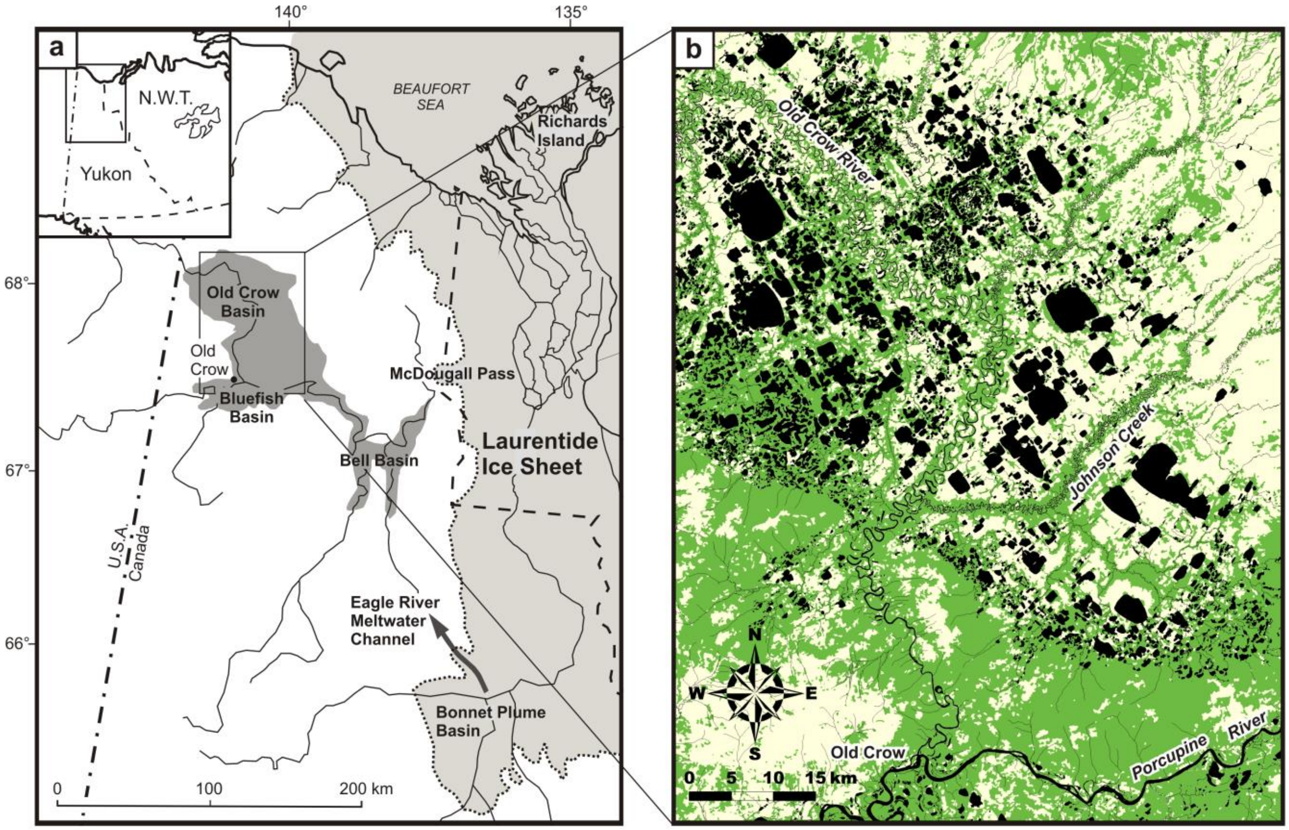

Figure 1 Location map of Old Crow Flats showing (a) northern Yukon with extent of Glacial Lake Old Crow in Bell, Bluefish, and Old Crow basins. The approximate maximum limit of the Laurentide Ice Sheet is shown in light grey (after Zazula et al., 2004, Fig. 1); and (b) a generalized map of land cover structure in OCF where lakes are in black, low shrubs, herbaceous vegetation, bryophytes and barren ground are in beige, and tall shrubs, woodlands and coniferous forest are in green (modified from Turner et al 2014, Fig. 4)

shrubs, and herbaceous communities (Turner et al. 2014). OCF was not glaciated during the Wisconsinan Stage but was submerged beneath a 13,000 km^2 glacial lake that drained catastrophically 15,000 years ago (Fig. 1a) (Zazula et al. 2004). The glaciolacustrine silts and clays are blanketed with peat. River-bank exposures indicate that excess ice in the upper 40 m of the ground is limited to the glaciolacustrine sediments, which are up to 9 m thick (Matthews et al. 1990). Permafrost temperatures at the depth of zero annual amplitude vary between -5.1ºC and -2.6ºC, depending primarily on snow cover (Roy-Léveillée et al. 2014).

The mean annual air temperature at Old Crow, the nearest community, is -8.3ºC (Environment Canada climate data are available at http://climate.weather.gc.ca/, accessed on May 23rd, 2015). The Old Crow wind record is short and incomplete, but wind speed and direction recorded during 1996 – 2014 indicate that winds are primarily from the NE during the open water season, which extends from June to October. Roy-Léveillée and Burn (2010) found a similar wind distribution in a tundra area near Johnson Creek in June to August 2008-09, with 68% of winds over 4 m/s from the NE and ENE (Fig. 2).

The lakes of OCF lack littoral shelves and are shallow, with a mean depth of 1 to 1.5 m. They exhibit key features

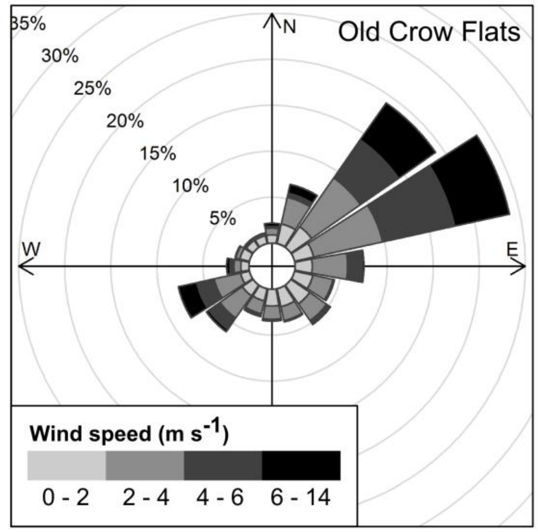

Figure 2. Frequency distribution of wind speed and direction during the 2008-09 open water seasons in OCF, modified from Roy-Leveille and Burn (2010) and adjusted to represent windspeed 10 m above the ground following Resio et al. (2002).

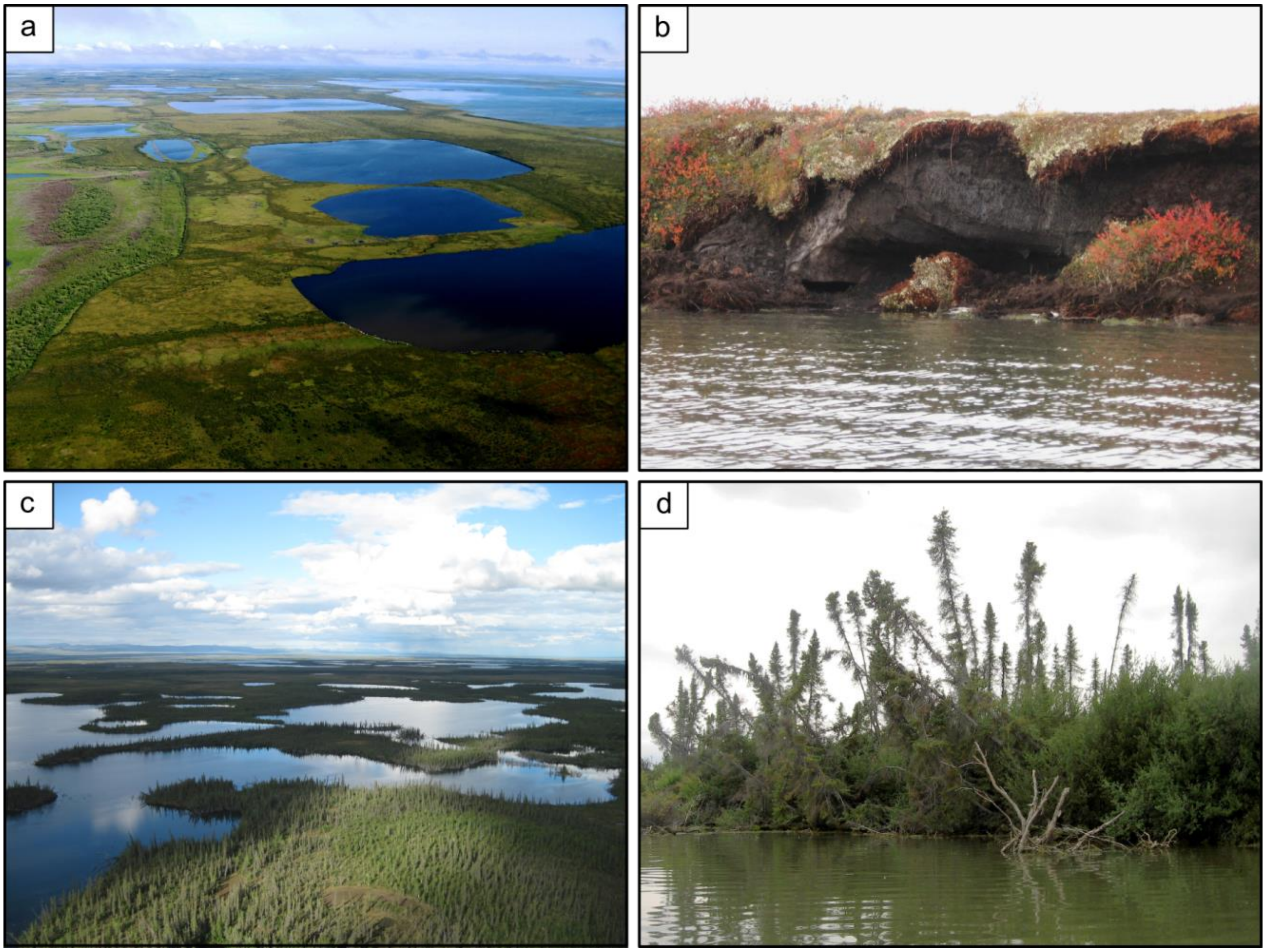

Figure 3. Lake geometry and shore erosion in tundra and taiga areas. a) Oriented lakes with rectilinear shorelines in an areas where the vegetation cover is dominated by low shrubs and grasses; b) shore section with overhanging peat curtains and thermo-erosional niche (bank height = 3 m); c) lakes with irregular shorelines in an area where the vegetation cover is dominated by taiga; d) shore section protected from thermo-mechanical erosion by partly submerged trees and tall shrubs (bank height = 2 m).

of the thermokarst lake cycle, such as lake expansion by thawing of ground ice and catastrophic drainage, followed by permafrost recovery and lake re-initiation. Drained lake basins are abundant throughout the Flats, commonly with deeply incised outlets. In parts of OCF, the lakes and drained basins have strikingly rectilinear shorelines whereas in other parts lakes tend to have irregular shapes. Morrell and Dietrich (1993) suggested that the orientation and morphology of OCF lakes may be controlled by underlying geology, but field observations of rapidly receding rectilinear shores suggest that geometrical control by static underlying features is unlikely (Roy-Leveillee and Burn 2010).

In order to discuss controls on lake geometry and orientation in OCF we (1) discuss field observations of shoreline conditions associated with different lake geometries; (2) compare the distribution of lake orientation to wind patterns during the open water season; and (3) investigate patterns of shore recession in lakes of different geometries, orientations, and sizes.

2 METHODOLOGY

2.1 Field conditions at thermokarst lakeshores

The distribution of lakes with irregular and rectilinear shores was examined on a map of OCF with land cover grouped into tundra and taiga (Turner et al. 2014). Several examples of lakes with irregular and rectilinear shores were examined in the field, and bank characteristics were described qualitatively and photographed.

Lake-bottom sediment samples were collected in a lake with rectilinear shores at distances of 0, 5, 10, and 20 m from a SW-facing shore with a 1600 m fetch. Twelve samples from the top 2 m of the surrounding area were used to represent the texture of bank sediment. Sediment texture between 0.4 and 2000 μm was determined using a Beckman Coulter LS 13 320 laser diffraction analyser (Neville et al. 2014). The samples were loaded into the machine until an obscuration level of 10 ±3% was reached and statistics were computed using the Fraunhofer diffraction model (Murray 2002; Neville et al. 2014). The mean particle size distributions for lake-bottom samples and for shore bank samples were used to build histograms. The littoral cut-off diameter represents the upper limit of particle sizes that are removed from the littoral zone by wave action (Limber et al. 2008). It was estimated as D_{10}, the grain size for which 90% of a sample is coarser and 10% is finer (Limber et al. 2008).

2.2 Lake orientation and shore recession

Lake orientation was determined using the ArcGIS bounding containers toolbox (http://arcscripts.esri.com/details.asp?dbid=14535) to provide a minimum area bounding rectangle and long axis azimuth for all lakes and ponds of OCF in the CanVec digital topographic dataset of the National Topographic System, and for two subsamples of 230 lakes each: lakes that were clearly rectangular or triangular in the first subsample, and lakes that did not have rectilinear shores, thus deemed ‘irregular’, in the second sample. Shore recession between 1951 and 1996 was determined for a subsample of 20 lakes using aerial photographs taken in 1951 and 1996. The images were superimposed and co-registered using ice-wedge networks around the lakes. Lakes shores were traced and total area of land eroded was calculated for each lake as the difference between the 1996 and 1951 lake polygons. Mean erosion rate was estimated by dividing the total area of land eroded by the perimeter of the 1951 lake polygon. Shore recession in specific locations was calculated along a normal to the 1951 shoreline. Where a strip of land was eroded due to shore recession on two sides (e.g. during the complete erosion of an island or the merging of lakes), recession rate was calculated based on the width of land eroded divided by two.

3 RESULTS

3.1 Field observations of shore conditions

3.1.1 Rectilinear and irregular shorelines

In OCF, lakes with rectilinear shores are generally in polygonal tundra, where the vegetation cover is dominated by low shrubs, grassy tussocks, and mosses (Fig. 1b and 3a). When examined, the vegetation cover was often ruptured at the top of the shore bank (Fig. 3b), ripped along the bank slope, or peeled back by the action of ice push, exposing the underlying unconsolidated sediment. The few beaches along oriented lakeshores were limited to shore sections sheltered from wave action or formed temporarily along leeward shores during calm periods.

Lakes with irregular shapes were generally expanding in areas where patches of trees and tall shrubs dominated the landscape (Fig. 1b and 3c, d). Standing trees and tall shrubs rooted in submerged ground were found along the shores. Live trees and shrubs were found closer to shore banks and some dead shrubs were occasionally present at the lakeward edge of the submerged vegetation. Water bodies with irregular shorelines in areas dominated by polygonal tundra were commonly remnant ponds within drained lake basins. Water bodies of ≤0.01 km^2 generally had irregular shorelines, particularly where they formed and expanded via degradation of ice wedges. In areas dominated by tall shrubs and taiga, small lakes had smoother shores.

3.1.2 Sediment texture

The sand fraction in near shore sediment was more than twenty times that in the bank sediment, and the clay fraction in near-shore sediment was reduced to 2% from 14% found in the banks. The mean littoral cut-off diameter was 42 µm. Less than 4% of the mineral fraction in shore bank sediment was coarser than 42 µm (Fig. 4).

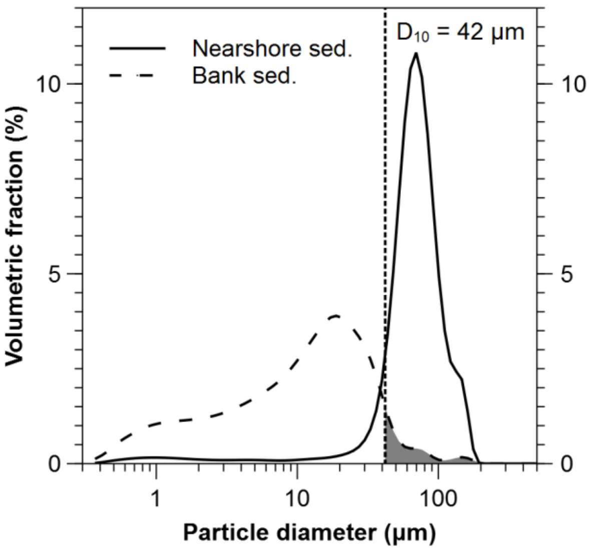

Figure 4. Mean particle-size distribution in nearshore lake-bottom sediment samples and bank samples. The littoral cut-off diameter, D_{10}, is shown with a vertical dashed line (Limber et al. 2008). The portion of the bank sediment distribution that is coarser than D_{10} is shaded.

3.2 Lake orientation

In OCF, the proportion of oriented lakes increases with lake size (Fig. 5a, b, c, d). Waterbodies ≤0.01 km^2 have no dominant orientation, but those between 0.01 km^2 and 1 km^2 are more often oriented NE-SW and ENE-WSW (Fig. 4a and b), i.e., parallel to dominant winds (Fig. 2). Beyond 1 km^2 the proportion of lakes oriented perpendicular to dominant winds increases and the distribution of lake orientations progressively becomes bimodal. Lakes larger than 10 km^2 are almost exclusively oriented perpendicular to prevailing winds (Fig. 5d). Only 13 water bodies fall in the latter size category, but they represent over 20% of the total lake area in OCF, making them, and their orientation, noticeable features of the Flats, as noted by Mackay (1956). Rectangular and triangular lakes are aligned either parallel or perpendicular to dominant winds in 90% of the cases (Fig. 5e). Lakes and ponds with irregular shapes do not have a dominant orientation overall (Fig. 5f), but lakes >1 km^2 are

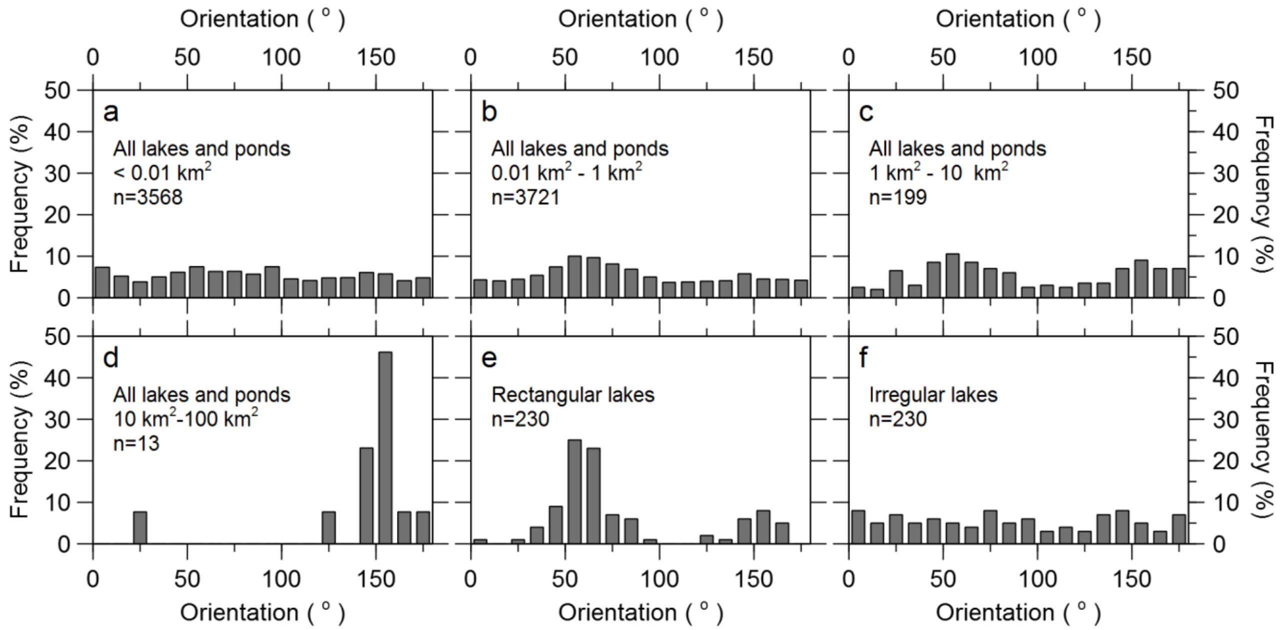

Figure 5. Distribution of lake and pond orientation for different size classes in OCF.

aligned parallel or perpendicular to dominant winds in approximately 60% of the cases, 10% more frequently than if lakes orientations were evenly distributed. The lakes of OCF are surrounded with paleoshorelines and drained basins outlines. Near Johnson Creek (Fig. 1b), where oriented lakes are abundant, numerous drained lake basin outlines are clearly visible. Similar to lakes, small basins are oriented parallel to prevailing winds and larger basins perpendicular. Triangular basins, similar to triangular lakes, are oriented perpendicular to prevailing winds and are at least 5 km^2 in area.

3.3 Shore erosion and lake expansion

During 1951-1996 lakes with rectilinear shores, including large lakes oriented perpendicular to prevailing winds, expanded most rapidly in a NE-SW direction (Fig. 6a, b, c, e). Rapidly eroding shore sections were irregular at the local scale (10 to 100 m), largely due to differences in erosion rates between ice wedges and polygon centres, but appeared smooth when considered at a larger scale. For this reason, water bodies smaller than 0.01 km^2 generally did not have rectilinear shores in polygonal tundra (Fig. 6g). However, water bodies larger than 0.01 km^2 developed increasingly rectilinear shores as they expanded (Fig. 6e). Lakes with irregular shores had no clear directional trend for expansion, but shore erosion proceeded fastest for islands and peninsulas, causing lakes to become less irregular as they expanded (Fig. 6d).

4 DISCUSSION

In order for sediment drifting to lead to the genesis of oriented thaw lakes as described for the North American Arctic coastal plain (Rex 1961; Carson and Hussey 1962), unconsolidated sediment must be available for redistribution and accumulation along the leeward shores. More specifically, two conditions must be fulfilled: 1) the thawing of lakeshore banks must yield unconsolidated sediment for transport in the littoral zone, which is facilitated if wave action, ice push, or mass-wasting processes result in the destruction of the vegetation cover to expose underlying sediment to erosion; and 2) long-shore sediment drifting must lead to sufficient sediment accumulation along leeward shores to impede thermo-erosional processes associated with direct contact between waves and the shore bank. These two conditions can be used to explain characteristics of lake geometry and orientation in OCF.

4.1 Rectilinear and irregular shorelines

Rectangular and triangular lakes are found in parts of OCF dominated by low shrub polygonal tundra. There, shore-bank vegetation cover is easily broken and removed by ice push and wave action, exposing unconsolidated sediment for erosion and transport. The combination of zones of erosion and accumulation along rectilinear shores indicates that ice push, solar radiation, or other processes pertaining only to shore erosion cannot be the fundamental mechanisms controlling lake geometry (Mackay 1963). Consistently with descriptions for lakes of the western North American Arctic coastal plain, the rectilinear shores of oriented lakes in OCF appear to result from differences in rates of sediment removal and accumulation along shore banks. Prominent shore features are exposed to more aggressive wave action whereas bays are sheltered and may accumulate sediment, resulting in a natural evening of the shoreline.

In parts of OCF where taiga and tall shrubs dominate the landscape, vegetation can remain anchored in the sediment after subsidence of the shore banks beneath water level, and form a barrier protecting the shore from wave action and ice push (Fig. 3c and d). With limited

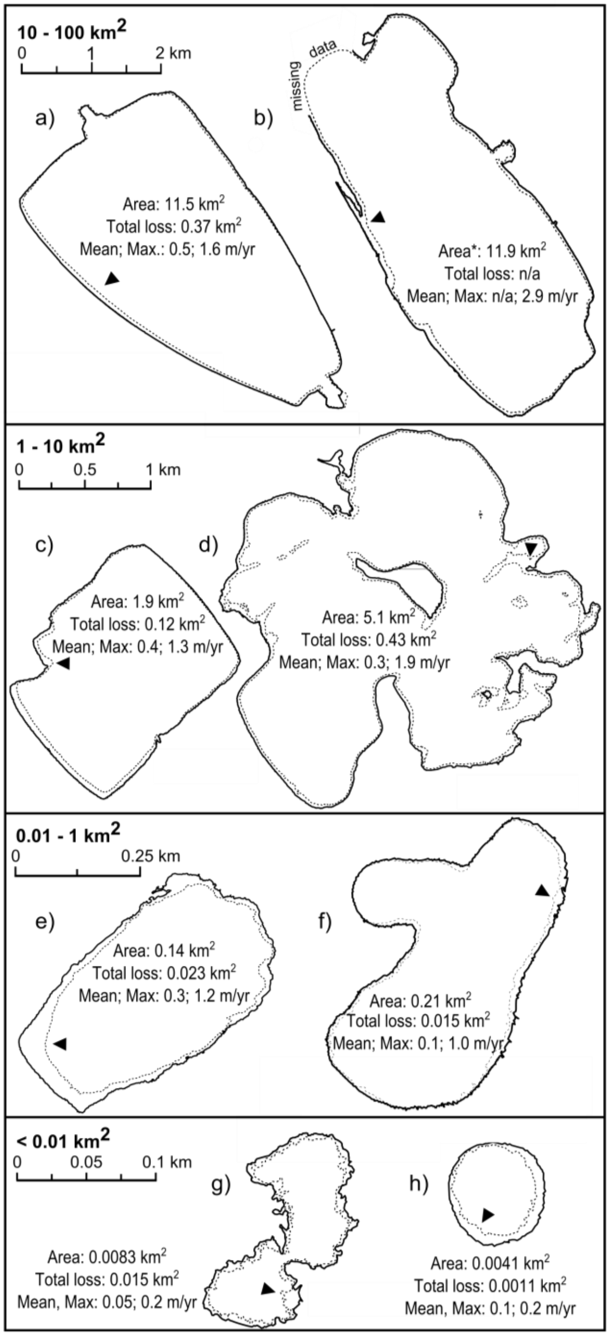

Figure 6. Shore recession patterns between 1951 (dotted line) and 1996 (solid line) in lakes of different sizes, orientation, and geometry. Lakes a), b), c), e), and g) are from areas dominated by low shrub tundra where lakes and basins generally are oriented and have rectilinear shores; lakes d), f), and h) are from areas dominated by tall shrubs and taiga, where lakes generally had irregular shapes. The location where the maximum rate of erosion was measured is marked with a black triangle. Lake area in 1996, total land loss to erosion and mean and maximum erosion rates during 1945-96, are indicated for each lake. *Lake area in 1945 is indicated for lake b).

removal of slumped sediment and no thermo-erosional action at the bank foot, heat conduction from the lake into the bank becomes the dominant process for permafrost thaw and lake expansion Sediment redistribution along the shore of these lakes is impeded by the persisting vegetation cover, resulting in irregular lake shapes (Fig. 3b and d). Along shore sections where the vegetation barrier is absent, thin, or exposed to very aggressive wave action, processes similar to those prevailing in polygonal tundra affect the shore bank.

This distribution of lakes with rectilinear and irregular shores within a forest-tundra ecotone is consistent with observations of thermokarst lake geometry north and south of treeline. The clusters of oval, ellipsoid, triangular, rectangular, and heart shaped oriented thaw lakes of the Alaskan Arctic coast, the Siberian north coast, and the Canadian western Arctic coast are limited to tundra environments (Carson and Hussey 1962; Mackay 1963; Morgenstern et al. 2008) whereas thermokarst lakes expanding in unconsolidated sediment south of treeline have irregular shorelines (e.g. Burn and Smith 1990; Marsh et al. 2009).

4.2 Orientation of lakes with rectilinear shores

4.2.1 Parallel to prevailing winds

The increase in the proportion of oriented lakes with increasing lake size indicates that the processes controlling lake orientation are associated with shore erosion and lake growth. The orientation and expansion of tundra lakes parallel to prevailing winds in OCF is contrary to reports on lakes of similar size on the Alaskan Arctic coastal plain and the Tuktoyaktuk Peninsula, where oriented lakes generally have their long axis approximately perpendicular to the prevailing summer winds (Mackay 1956).

However, Rex (1961) noted the importance of an abundant, sandy sediment input to allow sediment accumulation in the leeward littoral zone and, in OCF, sediment input to the littoral zone from eroding lake banks includes only a small fraction of fine sand (Fig. 4). When comparing the texture of lake-bottom sediment near a SW-facing shore to that of bank sediment, the majority of the input sediment is smaller than the littoral cut-off diameter and is apparently removed from the littoral zone by wave action (Limber et al. 2008). This leaves only a very small fraction of sediment available for longshore drifting and accumulation in the littoral zone. Hence, the textural characteristics of the sediment input impede accumulation in the near-shore zone and allows waves to reach the foot of the shore bank. Contact between waves and the bank foot accelerates erosion by mechanically removing slumped sediment and preventing a thawing bank from stabilizing. Where there is contact between water and permafrost, heat transfer into the bank is greater than through accumulated sediment. We suggest that this accelerated erosion of the leeward shores is responsible for the NE-SW orientation of the majority of lakes with rectilinear shores in OCF.

4.2.2 Perpendicular to prevailing winds

Large lakes and drained basins, particularly those that are >10 km^2 are almost exclusively oriented perpendicular to the dominant wind directions. Some of these lakes and basins have a triangular rather than a rectangular shape, similar to lakes of the Tuktoyaktuk Peninsula. The recent expansion of these large lakes in a direction opposite to their orientation (Fig. 6a and b), suggests that they are likely not in equilibrium with current conditions. The expansion pattern observed in 1951-1996 could not be sustained for thousands of years without resulting in a NE-SW orientation. Little information is available on past wind patterns in the area, but Lauriol et al. (2002) examined cliff-top aeolian deposits and report signs of vigorous summer winds from the SW for several thousand years after drainage of Glacial Lake Old Crow. There is insufficient information to resolve the cause of the NW-SE orientation of the lakes, but past increases in the intensity of summer winds may have led to the development of wind-induced circulation cells of sufficient strength to cause shore erosion and lake elongation perpendicular to prevailing winds, as observed on the Alaskan coastal plain (Carson and Hussey 1962). Near Barrow and Tuktoyaktuk, winds greater than 6 m/s are approximately twice as frequent as in OCF, and recent lake expansion patterns indicate that such erosion has not dominated the larger lakes of OCF since the 1950s.

5 CONCLUSIONS

This paper examined the distribution of lakes with irregular and rectilinear shores in relation to vegetation structure in OCF, and discussed differences between the oriented lakes of the OCF and lakes of the western North American Arctic coastal plain. Our main findings are that:

(1) In areas where trees and tall shrubs surround the lakes, the vegetation may remain rooted after bank subsidence, protecting the shore from erosion and impeding longshore sediment transport, leading to the development of lakes with irregular shapes;

(2) Lakes with rectilinear shores are concentrated in areas dominated by polygonal tundra, where the vegetation cover is easily torn by wave action or ice push to expose unconsolidated bank sediment to erosion and redistribution by wave action;

(3) Contrary to the western North American Arctic coastal plain, the majority of oriented lakes in OCF are oriented parallel to prevailing winds. This orientation develops as the glacio-lacustrine sediment of OCF is too fine to drift and accumulate along leeward shores as described by Rex (1961). Rather, the bulk of the sediment is suspended and removed from the near shore zone by wave action.

(4) Nearly all lakes > 10 km^2 are oriented perpendicular to dominant winds. Recent patterns of shore recession for these lakes indicate that their orientation is not in equilibrium with current conditions.

The oriented lakes of Old Crow Flats and those of the North American Arctic coastal plain are both shaped and oriented by wave action. However regional differences in environmental conditions, primarily textural differences between the sandy Pleistocene deposits of the coastal plain and the glacio-lacustrine deposits of OCF, result in contrasting responses to the dominant wind direction.

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