Mapping and Monitoring Activities in the Pingo Canadian Landmark, Tuktoyaktuk Area, NWT, 2004-2005

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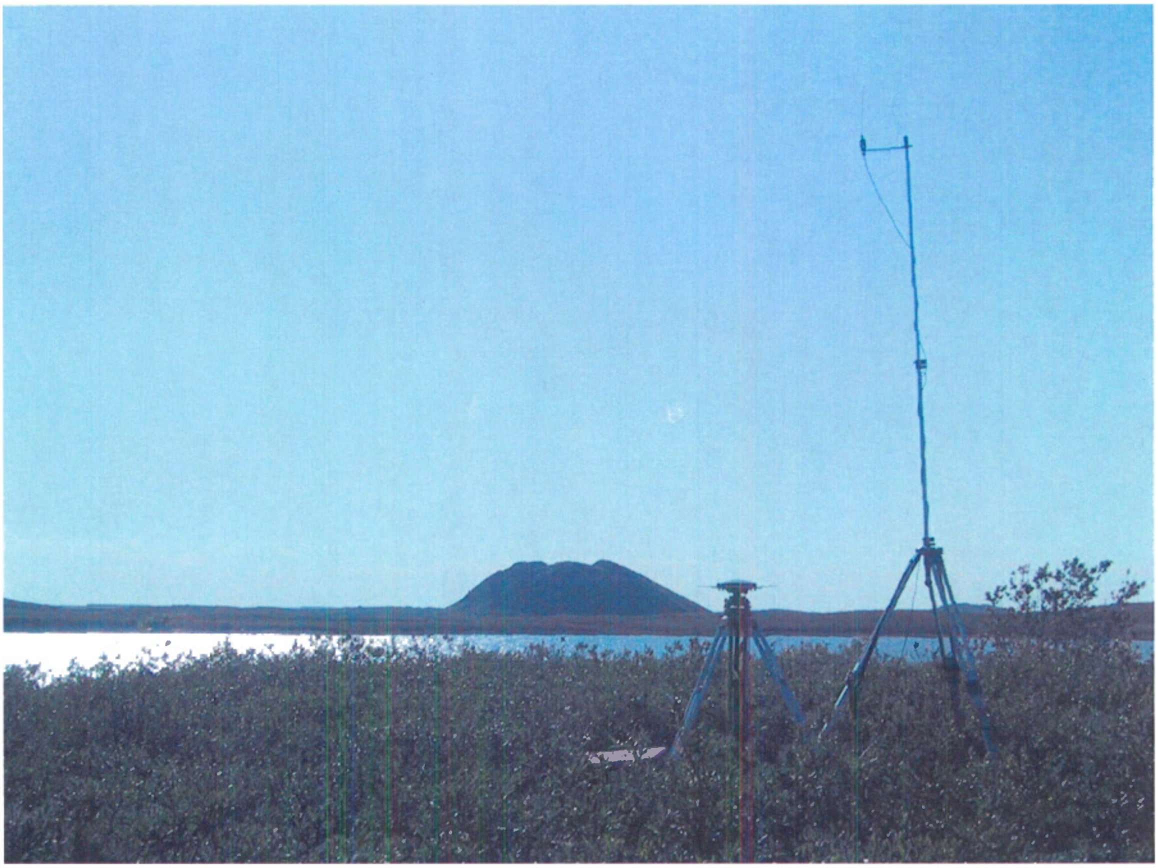

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1.0 Introduction

Located on the Tuktoyaktuk Peninsula adjacent to Kugmallit Bay (Fig. 1), the 16.4 km^2 Pingo Canadian Landmark (PCL) was identified as an area of national significance by Parks Canada in 1997. The PCL is jointly managed by Parks Canada, the Inuvialuit Land Administration, and various Tuktoyaktuk community organisations for the purposes of developing tourism in the vicinity of Tuktoyaktuk while maintaining the ecological integrity and stability of the landforms in the PCL. The Memorandum of Agreement between joint management organisations includes commitments to monitor elevation changes of Split and Ibyuk Pingos and the erosion and impacts of visitors on pingo slopes.

As part of Natural Resources Canada Earth Science Sector's Information for Other Government Departments project of the program Reducing Canada's Vulnerability to Climate Change, the Geological Survey of Canada (GSC) is collaboratiing with Parks Canada (PC) in monitoring landforms and coastal processes in the PCL. This monitoring focusses particularly on the morphologic mapping component and detection of changes in pingos and other coastal features, leading to an evaluation of landform stability.

This document summarises activities to date and presents preliminary results with recommendations for future collaborative monitoring.

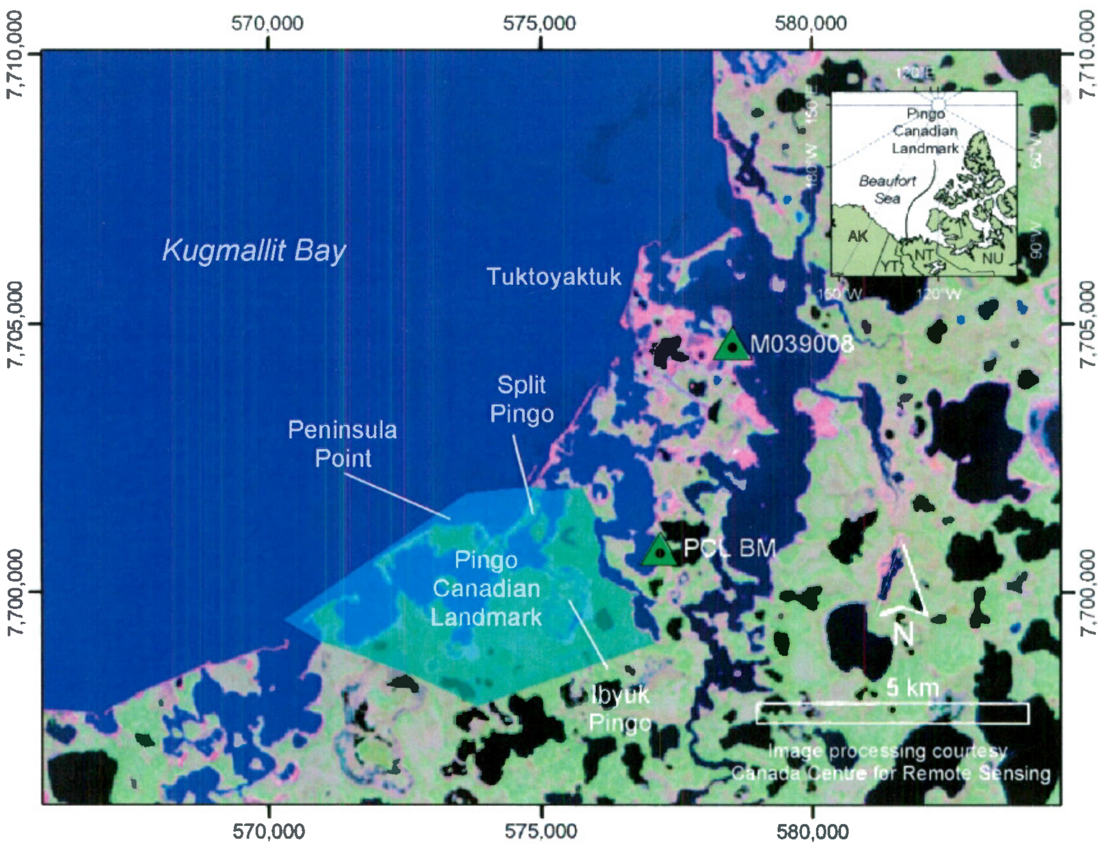


Figure 1. Location map showing Tuktoyaktuk, features within the PCL, and survey benchmark locations.

2.0 Methods

The PCL includes 8 pingos, including Ibyuk Pingo, the tallest in Canada and the second tallest known in the world (Mackay, 1986; Mackay, 1998; Parks Canada, 2005). Some of the pingos in the PCL have previously been intensively studied by J.R. Mackay (e.g. Mackay, 1962; Mackay, 1976; Mackay, 1979; Mackay, 1986; Mackay, 1998). A pingo is a conical ice-cored hill, usually growing in a drained lake bed. Notable pingo features include the summit (or summits), a summit pond in its crater, its base (taken here as the lakebed from which the pingo has grown), and they often have a moat (a depression commonly filled with water where the pingo slope meets the lakebed).

Because of the coastal location of the PCL and the presence of ice-rich sediments at the shoreline, areas of the PCL exposed to wave action in Kugmallit Bay are prone to erosion. One notable eroding feature is Peninsula Point which displays multiple retrogressive thaw failures resulting from wave attack at the failure toe and melting of frozen sediments in the headwall scarp. Airborne Light Detection And Ranging (LiDAR) is used to image features of Peninsula Point and pingos in the PCL and as a baseline for future change detection.

Surveys were initiated in August 2004 when GSC and PC employees conducted Real-Time Kinematic Global Positioning System (RTK-GPS) surveys of Ibyuk Pingo to measure the elevations of its 5 summits and lakebed to determine its height. Profiles were also collected using RTK-GPS and will be used to monitor changes in slopes. Singlebeam echosounding was conducted in the vicinity of the proposed Parks Canada boat route to the PCL. LiDAR elevation data was also acquired by a private company and was purchased by PC with groundtruthing and analyses conducted by the GSC. In 2005, GSC and PC employees resurveyed Ibyuk Pingo using RTK-GPS, measured the summit and base elevations and collected profiles of Split Pingo, acquired additional echosoundings on the proposed boat route, and collected new echosounding data in the outer part of the PCL, including the depths of the moats of Ibyuk and Split Pingos.

2.1 Vertical Datums and Issues at Tuktoyaktuk

Vertical datums are a complex topic requiring some background information to understand the issues. Elevations may be reported with respect to different datums, or worse, datums of the same name but calculated differently, giving apparent elevation differences. GPS measures elevation relative to the ellipsoid, a mathematical representation of the perfect shape of the earth (Fig. 2). This is the most native form of elevation but coastal areas are often some distance below the ellipsoid, giving negative elevations that appear "odd" to non-experts. Consequently, ellipsoidal elevations are often converted to another datum by adding a constant to appear more "normal". The constant generally is intended to convert the ellipsoidal elevation to mean sea level (aka mean water level), often now represented by a geoid model which is essentially the elevation of mean sea level as it is influenced by gravity. A geoid model (there are many different variations) does not necessarily well-represent mean sea level everywhere. A correction, determined by primary leveling, is applied locally to relate geoid model results to mean water level. In Canada, this corrected datum is termed CGVD28 (Canadian Geodetic Vertical Datum 1928). At Tuktoyaktuk, CGVD28 has not been accurately constrained and is not representative of mean water level, possibly due to an error in the primary levelling (Marc Véronneau, pers. comm.). In this document, we report elevations relative to $CGVD28_{orth}$ (where the subscript orth flags this datum as orthometric) as it is defined by the combined geoid and corrector surface model HTv2.0 freely available online from the Geodetic Survey Division of Geomatics Canada. This provides an ellipsoid-$CGVD28_{orth}$ separation of -7.164 m at Geodetic Survey Division Benchmark M039008 (our primary survey control). All GPS elevations and all LiDAR elevations in this document are reported relative to $CGVD28_{orth}$.

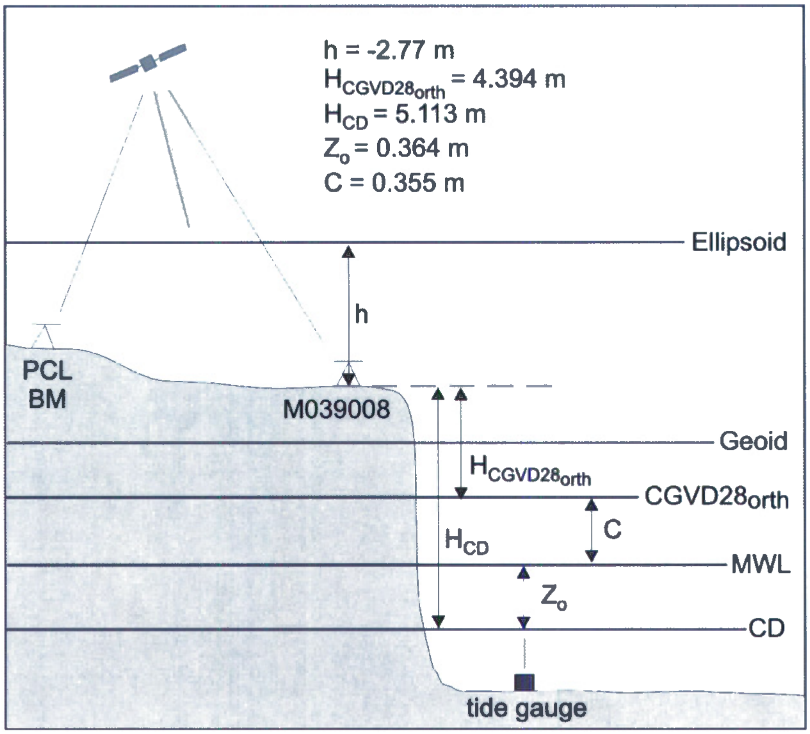


Figure 2. Summary of vertical datums at Tuktoyaktuk.

That $CGVD28_{orth}$ is not representative of mean water level becomes important in relating bathymetric soundings in chart datum to a terrestrial datum. In Canada, chart datum (CD) is the lowest normal tide in a given locality excluding meteorological effects and usually represents lower low water at large tides. Tide gauge data reveal the separation between CD and mean water level. At Tuktoyaktuk, the elevation of mean water level relative to CD (Z_o in Fig. 2) is 0.364 m (Marc Véronneau, pers. comm.). The Canadian Hydrographic Service (CHS), based on primary levelling, reports an elevation for the holding benchmark for the Tuktoyaktuk tide gauge (ID M039008) of 5.113 m CD (CHS, 2005). The separations between chart datum, $CGVD28_{orth}$ and mean water level can therefore be determined and elevations converted using Z_o and a constant C (where C represents the separation between MWL and $CGVD28_{orth}$) (Fig. 2). However, given the uncertainty surrounding the original primary levelling at Tuktoyaktuk and how the recent CHS levelling was conducted, the initial levelling problems may be propagated with this approach. For the purposes of this report, unless otherwise noted, all bathymetric soundings are given relative to CD. Note that by convention, depths are positive downwards whereas elevations are positive upwards.

2.2 RTK-GPS Surveys

RTK-GPS surveys were conducted using an Ashtech Z-Extreme differential RTK-GPS. This system consists of a stationary base receiver transmitting differential corrections via radio modem to a roving receiver. The vertical and horizontal accuracy of the system is approximately 1 cm. Points surveyed in 2004 and 2005 are shown in Figure 3.

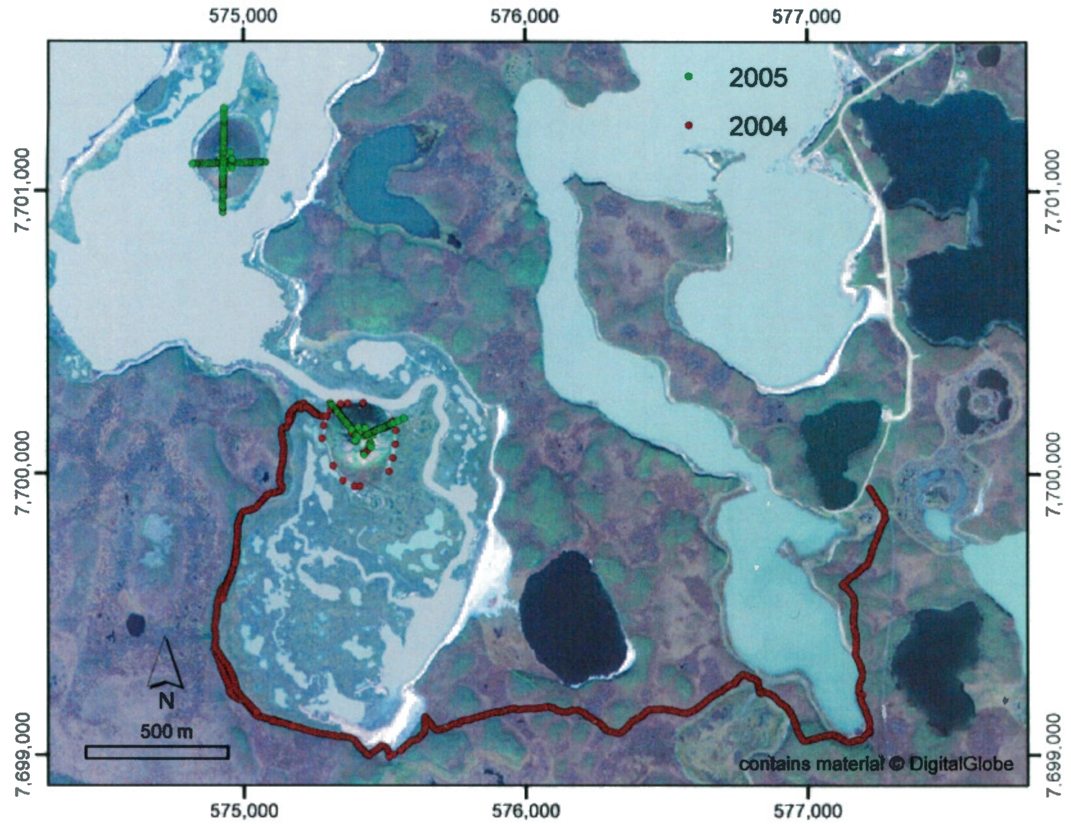


Figure 3. Locations of RTK GPS points collected in 2004 and 2005.

As no GPS survey control previously existed in the PCL, new control was established in 2004. The base receiver was set up on a dedicated RTK-GPS benchmark (Geodetic Survey Division ID M039008, UTM Zone 8 WGS84, 578601.020E 7704515.650N, 4.394 m elevation $CGVD28_{orth}$) (Fig. 1) located near the tide gauge in Tuktoyaktuk. A 1 m length of rebar (labelled PCL BM in Fig. 1) was hammered into the active layer on a low rise west of the Tuktoyaktuk sewage lagoon access road, about 800 m south of the turnoff to the proposed boat launch. Using the RTK rover, the rebar position was determined to be: UTM Zone 8 WGS84, 577211.099E 7700714.751N, 6.958 m elevation $CGVD28_{orth}$. RTK-GPS surveys in 2004 and 2005 were conducted with the base station set up over this control. Because it is anchored in the active layer rather than permafrost, the rebar is likely not stable; therefore, with each successive survey, it is resurveyed relative to M039008 to obtain a correct position. Between 2004 and 2005 no significant movement was measured in the rebar position and the coordinates given above were used for both years.

2.3 LiDAR

LiDAR uses an airborne laser to measure the distance between an aircraft and the ground or vegetation cover. Positioning of the aircraft is provided by differential RTK-GPS and an inertial momentum unit records the aircraft's attitude. Together these give spot elevations with horizontal and vertical accuracy of ~0.25 m (90% confidence limit), and a laser pulse return approximately every square metre.

Depending on where a laser pulse hits, returns can be from the ground, top of the vegetation, or somewhere in the middle of the vegetation. An algorithm filters the data looking for jumps in elevations and codes laser returns as "ground" or "non-ground". Usually non-ground returns are returned from vegetation or structures; however, the data provided were not fully cleaned of errors before delivery and spurious elevations are apparent in the non-ground data. Obvious errors include mismatch between flightlines where errors in outer beam angles are exaggerated, and a wood-grain pattern of unknown origin but common in LiDAR systems of this type. Though only visible on flat ground or water, the wood-grain effect may be found through the entire dataset. Fortunately, for the purposes of morphologic mapping in the PCL, the ground returns are most appropriate and the non-ground data can be excluded. A final issue is that it is unclear to what datum the elevations are reported; GSC has been told orthometric but no information has been given on the geoid model. The authors assume equivalence to $CGVD28_{orth}$. Discussions with the data provider are ongoing regarding how to resolve these data quality issues.

A final product from LiDAR data includes the intensity of the returned laser signal. Because the laser operates in the near infrared range, this imagery is analogous to a grayscale digital infrared photograph. This dataset is still being analysed and the results are not included in this report.

LiDAR ground returns were gridded at 1 m resolution and passed through a routine developed at GSC-Atlantic that fills holes in elevation grids. Some holes still remain, and further work is required on the LiDAR data. The extent of LiDAR acquired is shown in Figure 4.

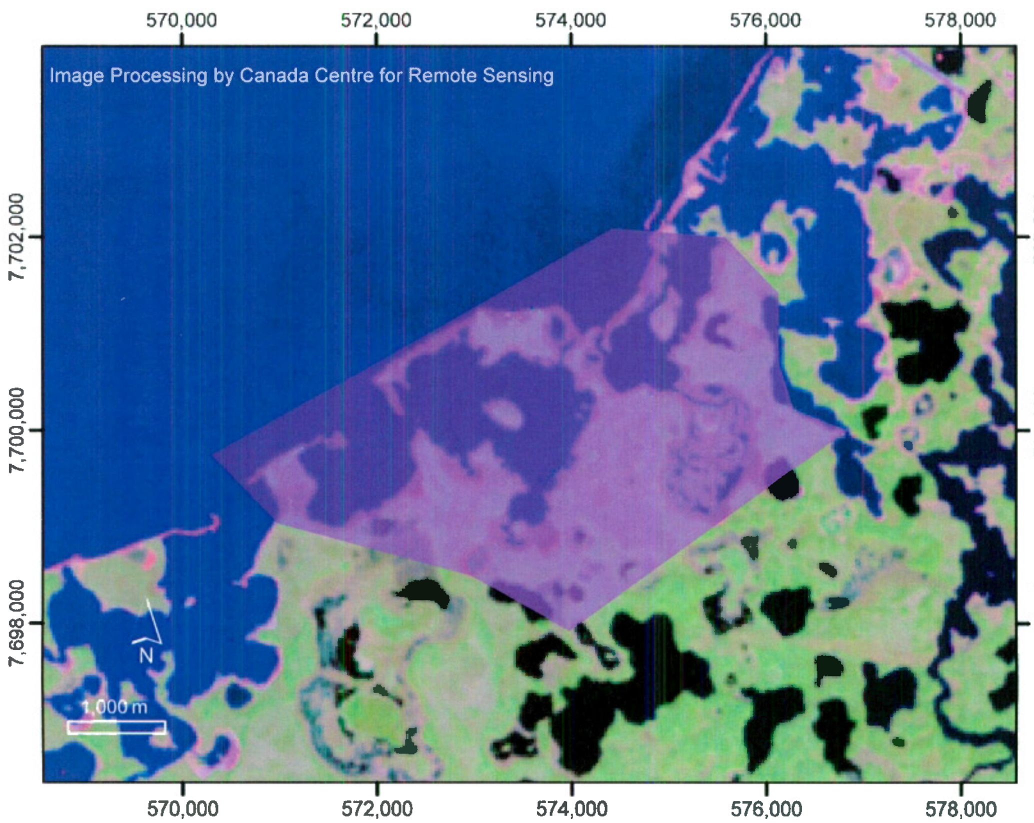


Figure 4. Extent of LiDAR in the PCL.

2.4 Echosounding

Bathymetric soundings were collected from a canoe using a Simrad EQ30 singlebeam echosounder operating at 200 kHz with horizontal positioning from a Garmin 76 handheld GPS connected to a Canadian Differential Global Positioning System (CDGPS) receiver. CDGPS uses differential signals broadcast by the MSat telecommunications satellite network to improve positioning to approximately 3 m horizontally. Vertical positioning was provided by correction of depths to chart datum using tides measured at the Tuktoyaktuk tide gauge. Depths, positions, and tides were merged using software developed at GSC-Atlantic. The extent of soundings collected in 2004 and 2005 are shown in Figure 5.

In the area of the proposed boat route, a total of 16,190 tide corrected soundings from 2004 and 2005 were gridded at 2 m spatial resolution using natural neighbour gridding. Gridding was constrained at waterline with a value corresponding to the shallowest sounding recorded (-0.4 m CD). Some artifacts were generated in the gridding of the echosounding data, usually in the form of anomalously shallow areas where no soundings were collected. This is a persistent and unavoidable problem in gridding irregularly spaced point data.

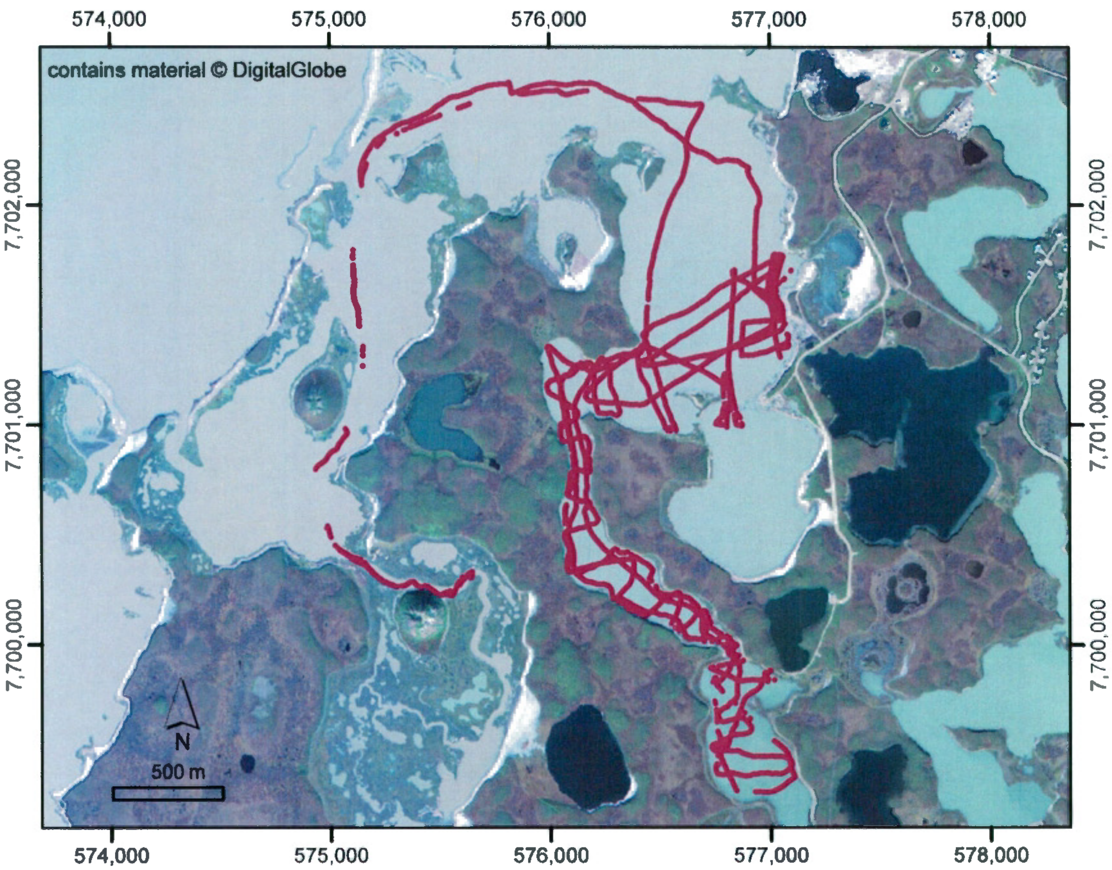


Fig. 5. Extent of echosoundings in the PCL, 2004 and2005.

3.0 Results

3.1 LiDAR Groundtruthing

In 2004, while accessing the PCL on foot, the RTK-GPS rover was mounted on a backpack and set to record a position every 5 m. A total of 504 points overlapping the LiDAR coverage were collected and compared to both LiDAR ground returns and the 1 m gridded elevations.

When comparing the GPS points distribution with LiDAR, 210 GPS measurements were found to have one or more LiDAR ground returns lying within 0.5 m of their location. In the rare cases where more than one LiDAR return was found to lie within the 0.5 m radius, the LiDAR elevations were averaged. The mean difference in elevation was 0.10 m with LiDAR elevations being lower than the GPS. The largest difference where LiDAR elevation was higher than the GPS was 0.10 m, and 0.35 m where LiDAR elevation was lower than the GPS, suggesting a slight underprediction of elevation by LiDAR, although within anticipated accuracies.

When comparing the LiDAR 1 m gridded data with the GPS elevations, the mean difference in elevation was 0.11 m with LiDAR elevations being lower than the GPS. The largest difference where LiDAR elevation were higher than the GPS was 0.25 m and 0.43 m where LiDAR elevations were lower than the GPS, indicating that gridding is overall reasonably accurate. Colour shaded relief images of Ibyuk Pingo, Split Pingo and Peninsula Point from 1 m gridded LiDAR data are shown in Figures 6, 7 and 8.

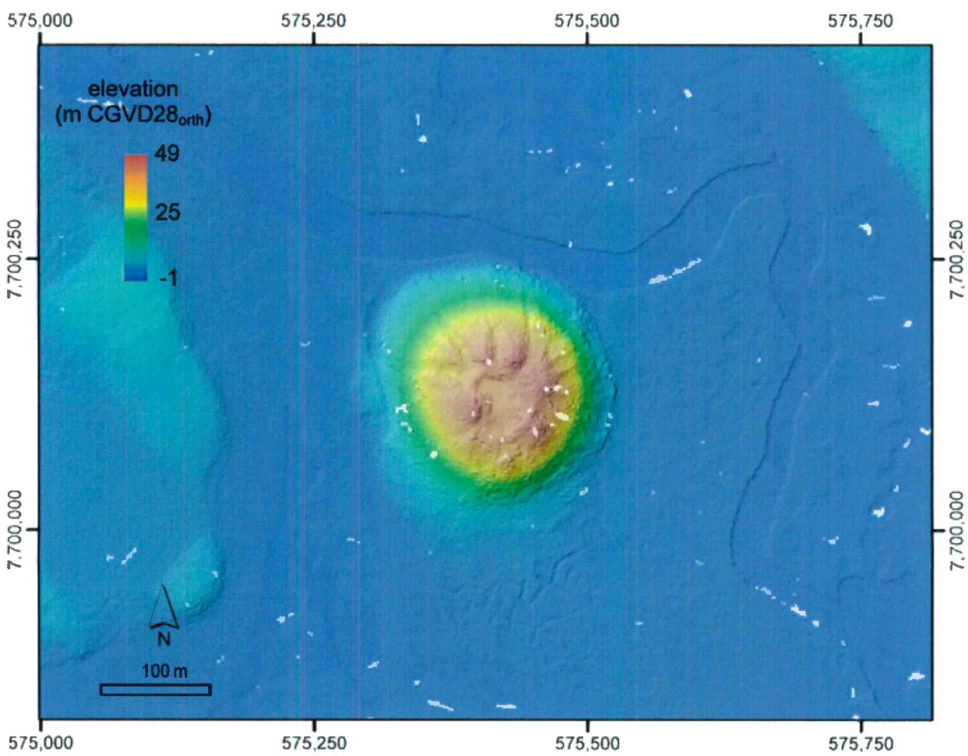


Figure 6. Colour shaded relief image of Ibyuk Pingo.

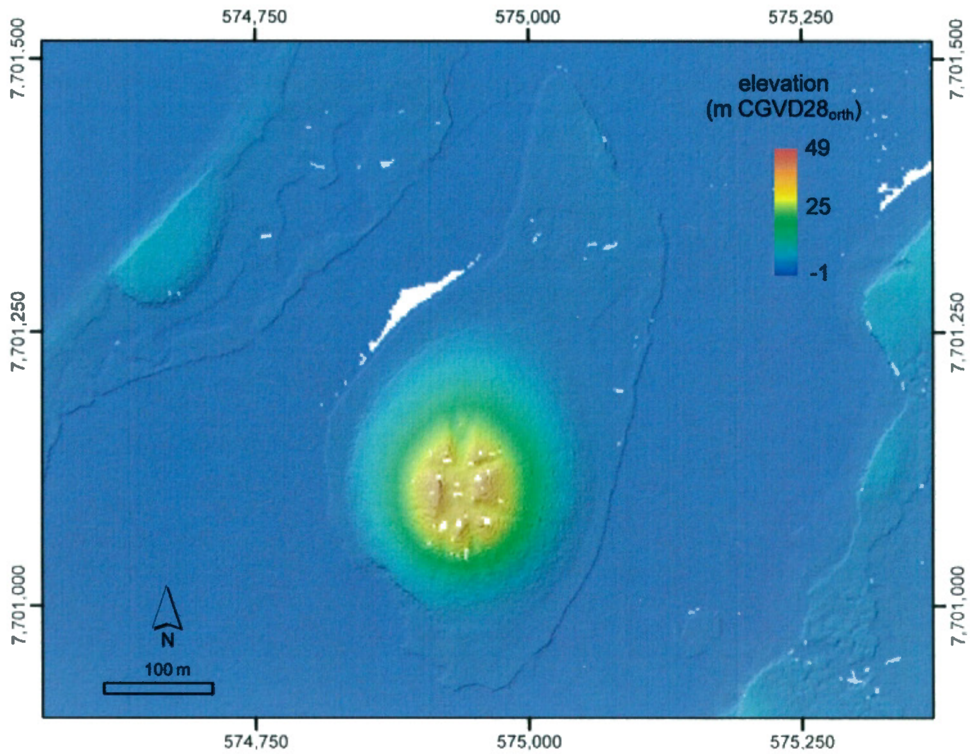


Figure 7. Colour shaded relief image of Split Pingo.

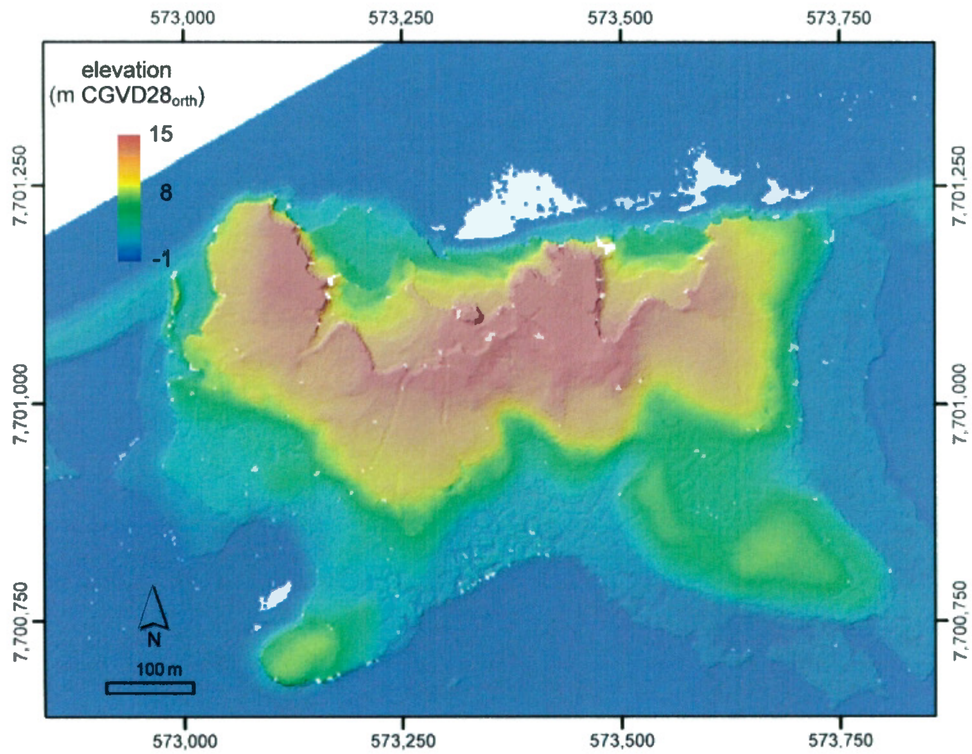


Figure 8. Colour shaded relief image of Peninsula Point.

3.2 Summit Elevations

Pingo summit elevations can be obtained, in decreasing order of accuracy, either from direct RTK-GPS measurements, non-gridded LiDAR ground point data, or gridded LiDAR ground data.

3.1.1 Ibyuk Pingo

The elevation of the highest summit of Ibyuk Pingo measured using RTK-GPS in 2004 was 49.41 m. In 2005 this point was measured again at 49.41 m, showing no significant change in elevation between the two years. The 1 m gridded LiDAR value of this point is 49.22 m, the same value as the ground return closest to the highest summit. Survey control established by the CHS in 1956 on the same summit was measured in 2004 at 49.14 m and 49.13 m in 2005, showing no significant change between the two years. The other lower summits of Ibyuk Pingo range in RTK-GPS elevation from between 46.5 m to 47.8 m with measurements being consistant between 2004 and 2005. These lower summits are not well defined by LiDAR ground points, therefore the 1 m gridded LiDAR underestimates their elevations by up to 1 m. The elevation of Ibyuk's summit pond water level was measured at 39.61 m in 2004 and 39.86 m in 2005.

3.1.2 Split Pingo

In 2005, the elevation of the highest summit of Split Pingo was measured at 37.61 m using RTK-GPS. The elevation of the ground LiDAR return nearest to this summit is 37.35 m, the same as the 1 m gridded LiDAR. Other lower summits of Split Pingo range in elevation from 32.80 m to 37.30 m. Similar to Ibyuk Pingo, these summits were not well captured by LiDAR ground hits and are understimated in the 1 m gridded data. On one summit where an RTK-GPS point and a LiDAR return are almost overlying, the 1 m gridded LiDAR elevation is within 10 cm of the RTK-GPS elevation. A CHS benchmark on Split Pingo was measured with the RTK-GPS to have an elevation of 33.16 m and two t-bars of unknown origin were measured at 37.29 and 37.26 m.

3.3 Base Elevations

While the highest point on a pingo is easily defined, the base of a pingo is less so. The authors consider lakebed elevations from GPS and LiDAR point data.

3.1.1 Ibyuk Pingo

The elevation of Ibyuk's base was surveyed in 2004 using RTK-GPS mounted on a backpack while walking over the its lakebed. The 56 lakebed points captured were found to have an average elevation of 0.43 m. In 2005, seven points interpreted as lakebed were collected as part of the pingo profiles using the RTK-GPS mounted on a staff. The average elevation of these points was 0.52 m. A total of 306,310 LiDAR ground returns lying between the elevations of 0.10 m and 0.65 m, corresponding to the lowest and highest lakebed elevations measured in 2004 and 2005, and matching the lakebed interpreted from QuickBird satellite imagery, were considered returns from Ibyuk's lakebed. These points give a mean lakebed elevation of 0.32 m. From the perspective of the large sample size and capture of the variability in the lakebed elevation, averaging LiDAR ground returns is the preferred method of determining pingo base elevation.

3.1.2 Split Pingo

In 2005, 10 staff-mounted GPS points were collected as part of the lakebed portions of the pingo profiles. The average elevation of these points was 0.20 m. As with Ibyuk Pingo, the mean of the LiDAR ground returns between the minimum and maximum lake bed elevations was used to obtain an estimate of the entire mean lakebed elevation. For Split Pingo, 10,773 points between 0.07 m and 0.47 m gave a mean lakebed elevation of 0.30 m, predictably very similar to that of Ibyuk Pingo.

3.4 Moat Depths

Moats at the base of Spit and Ibyuk Pingos are tidal, anomalously deep, and may be subject to scour, thermokarst subsidence, and cyclic pingo processes (Mackay, 1998). Because they are dynamic, they may play a role in overall pingo stability and monitoring their depth variability may be of value towards understanding pingo dynamics.

3.1.1 Ibyuk

The deepest point in the moat on the north side of Ibyuk was echosounded at 1.9 m CD.

3.1.2 Split

The deepest point in the moat on the southeast side of Split was echosounded at 1.6 m CD.

3.5 Slope Profiles

Repeat GPS profiling of slopes of the two pingos may represent an efficient and effective means of monitoring changes of the side slopes. For profile locations see Figure 3 showing GPS points collected in 2004 and 2005.

3.1.1 Ibyuk Pingo

Two profiles were surveyed on Ibyuk in 2004 and the same profiles were resurveyed in 2005 (Fig. 9). Steep slopes and thick vegetation restricted the number of profiles possible. In 2004, the east profile was inadequately surveyed and the line is not straight enough to compare to 2005. In Figure 9, the 2004 Ibyuk northeast profile is therefore derived from the LiDAR ground returns. The northwest profile follows the prominent snowmobile/walking trail up the slope and is near the profile of Mackay (1986; 1998). Both the northwest profiles and northeast profiles show no significant changes over the two year period.

3.1.2 Split Pingo

In 2005, four profiles were surveyed up the east, west, south and north slopes of Split Pingo (Fig. 9).

3.6 Bathymetry of Proposed Boat Route

No significant submerged hazards to small boat navigation were found between the proposed boat launch and landing sites. Boaters should be cautioned that shallows are ubiquitous in the PCL and obstruct some waterways where even experienced operators may run aground. Generally, obstructions are obvious accumulations of sand or gravel and present little danger. Sharp rocks may be present but these are usually visible above the water surface and confined to channel constrictions. Shallows tend to be more prevalent in the outer areas of the PCL where tidal channels and overwash during storms deliver mobile beach sediments into the outer lagoons, and at the landward terminii of channels. In their central parts, channels tend to contain deep holes (up to 8 m CD). Much of the route between the proposed launch site and the proposed landing follows a channel connecting a string of these holes. Soundings gridded at 2 m are shown in Figure 10. It should be noted that mid-channel shallows shown at A are likely artifacts of gridding. No points were collected in these areas to verify their existence. Also note the nonlinear colour scale chosen to better show shallows.

4.0 Discussion

4.1 Pingo Height

Ibyuk Pingo has been termed the highest known pingo in Canada and the second highest known in the world (Mackay, 1998), a statistic that is making its way into the popular media (e.g. GNWT, 2005). However, the terminology is ambiguous. The height of a landform (e.g. a mountain) is usually measured from a datum to its summit. Thus, Mt. Everest is the highest mountain in the world because its summit is higher above sea level than other mountains. For pingos, as with people, height is measured from a base to a top. Since we refer to the tallest person, Ibyuk Pingo should be referred to as the second tallest. To promote consistent terminology, discontinued use of the phrase “second highest in the world” in favour of “second tallest known in the world” is encouraged. In addition, the precise height of the tallest known pingo in the world remains uncertain. This is believed to be Kadleroshilik Pingo, located approximately 40 km SW of Prudhoe Bay. Mackay (1998) reports it to be 54 m tall from lakebed to summit, but the summit and base elevations are derived from 1975 1:63,360 topographic maps. There may be error up to several metres in the height of Kadleroshilik Pingo.

Pingo height is taken here as the difference in elevations between the pingo summit and its lakebed. The elevation of the Ibyuk Pingo lakebed was calculated to 0.32 m $CGVD28_{orth}$ by averaging LiDAR ground returns, and the summit elevation was measured at 49.41 m $CGVD28_{orth}$

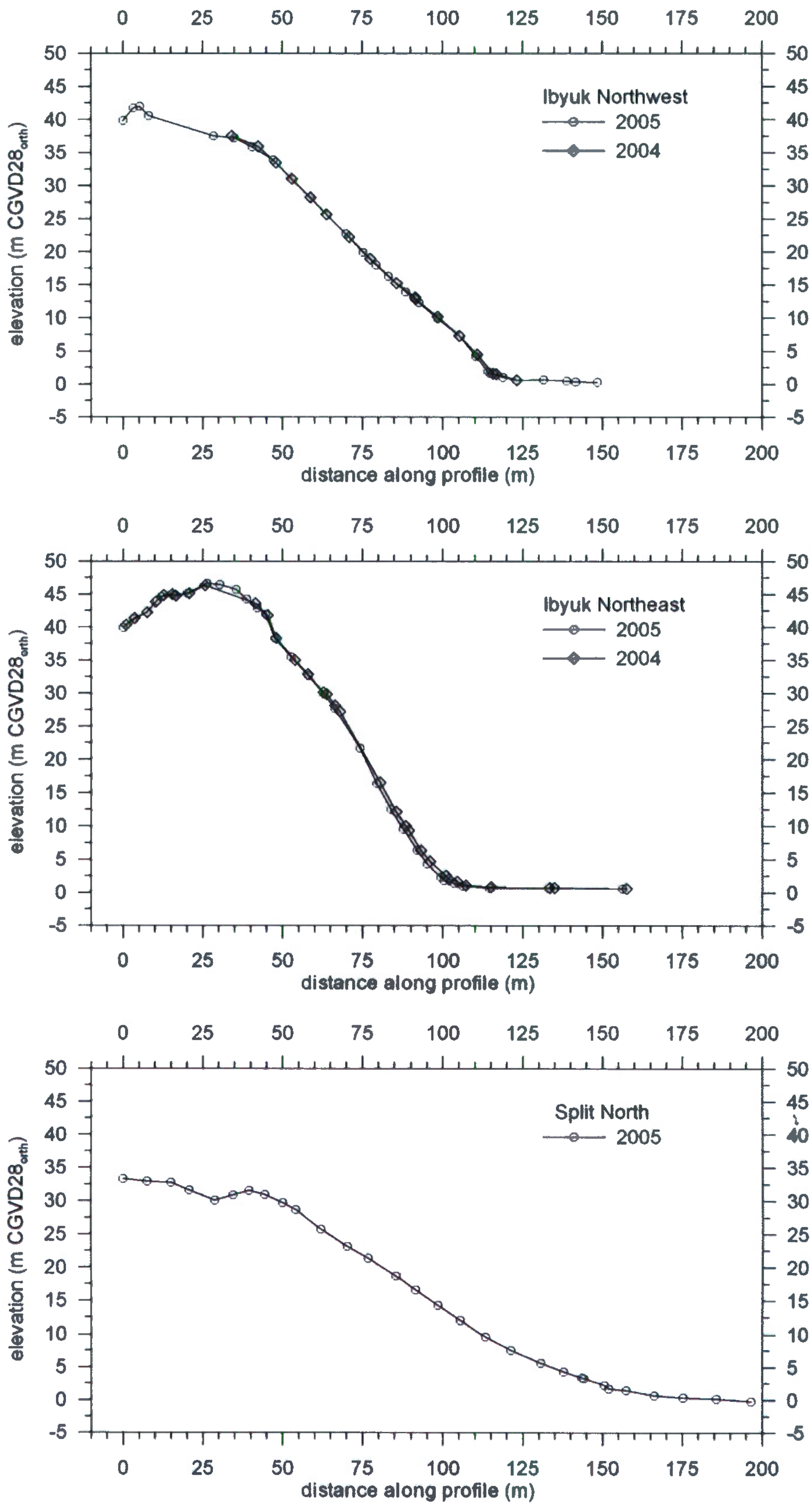
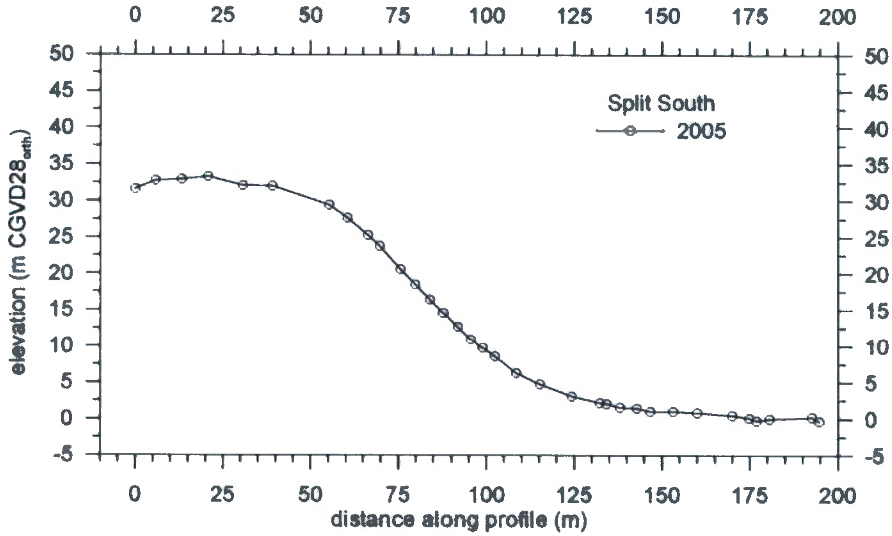
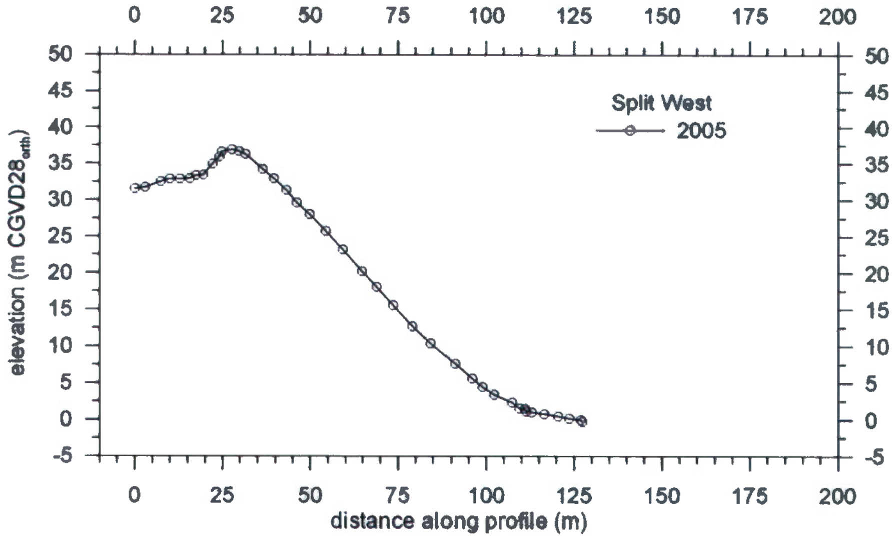


Figure 9. Profiles of Ibyuk and Split Pingos.





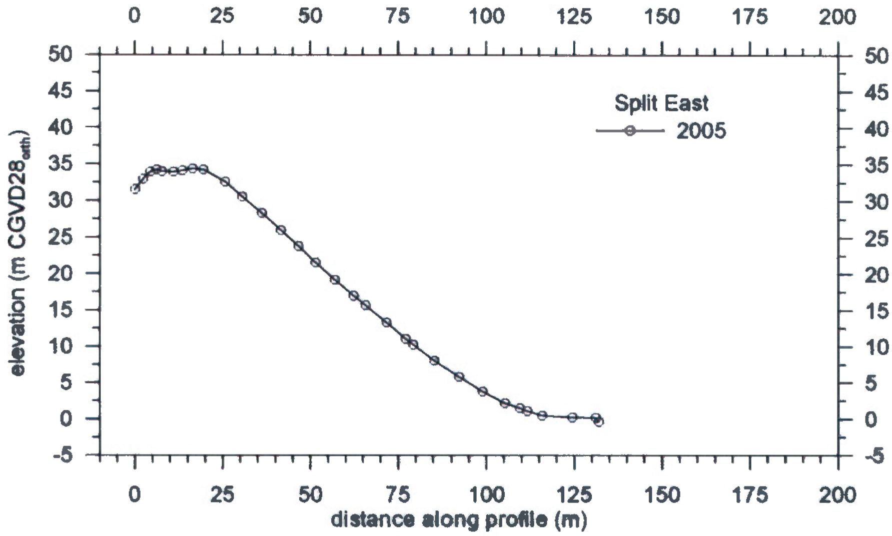


Figure 9. (cont.)

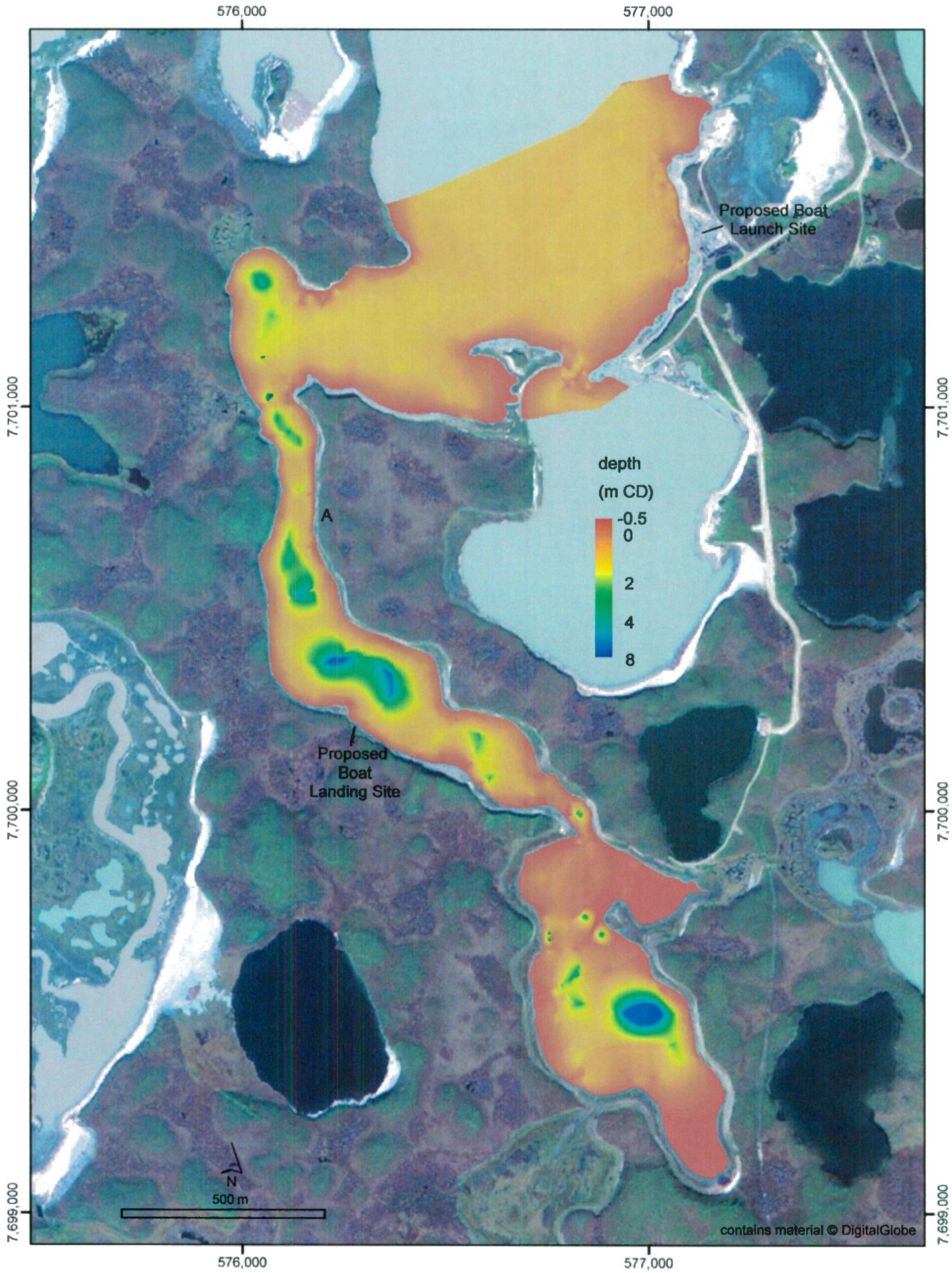


Figure 10. Gridded bathymetry of the proposed boat route.

by RTK-GPS, thus Ibyuk is 49.09 m tall. This value is in good agreement with the lakebed to summit height of Ibyuk measured by Mackay (1998) of approximately 49 m. Following the same method, Split Pingo is 37.31 m tall from lakebed to summit.

4.2 Observations of Mass Wasting

Mackay (1998) noted the initiation of slumping on the south and west slopes of Ibyuk Pingo with the development of small slump terraces. Sometime prior to 2004, a failure occurred on the southeast slope of Ibyuk Pingo. Visitors to the PCL reported this as a new failure occurring between 2004 and 2005, but ground photographs from 2004 show a smaller failure already existing in the same location, although smaller (Fig. 11). In 2004, the failure scarp was visible from the pingo base and vegetated at its top. In 2005, the failure scarp is located about 8 m below the southern summit, at a slope break in an area of bare sand with no vegetation. Failure depth appears to have extended below rooting depth (~ 0.5 m) of the grasses that dominate this slope. The failure is multi-phase, with an initial rapid slide prior to 2004 of mixed turf and unconsolidated sand, followed by slow and prolonged flow of unconsolidated sand (Fig. 12). The original toe of consolidated material partway upslope was incised between 2004 and 2005, and the fan at the toe of the failure has grown considerably to reach the pingo base and engulf willows. On Aug. 4, 2005, sand was observed flowing from the scarp to the fan. The scarp is retreating upslope in unconsolidated sand, toward an older failure scarp and the south summit (Fig. 13).

It is uncertain what initiated this particular failure. Seepage seen in Figure 11 may have been a factor. It also occurred in an area that has previously failed as evidenced by the upslope scarp. The new failure scarp, slope and fan are active and unstable. Mackay (1998) noted people sliding on exposed sandy slopes of Ibyuk. Any human disturbance of this failure will delay the onset of stabilising vegetative cover. The failure sidewalls are prone to slumping; disturbance to sidewalls may result in widening of the active slump slope and increasing instability. With loss of toe support, the upslope area of bare sand is likely to become further destabilised; disturbance here could increase the length of the active slope. To encourage stabilisation and decrease the risk of further failure, motorised and non-motorised traffic should be kept well away from this slope, if not all pingo slopes.

Human impacts continue to be of concern for the stability of valued landforms in the PCL. From casual observation, the level of impact, particularly on wetlands in the area, increased between 2004 and 2005 (Fig. 14). If there are concerns about the sustainability of tourism and ecological integrity of the PCL, there should be concern about the influence of humans and their vehicles on landforms within it. The direct and cumulative impacts of humans may well be the greatest threat to landform stability in the PCL.

4.3 Evaluation of Monitoring Strategies

RTK-GPS measurements are an accurate and efficient way to monitor pingo changes. They are effective in looking both at movements of single points (e.g. summit high points, benchmarks on summits) and changes in slope profiles (if suitable care is taken). The accuracy of RTK-GPS (~±1 cm) should be high enough to detect changes greater than 2 cm/a, but, with slower rates a longer time interval is required for detectable change to occur. If knowledge of long-term average rates of change are desired, a survey every few years is likely adequate, but if knowledge of pingo dynamics is required, surveys should be conducted at least annually. In either case, a long record (i.e. decades), may be required for statistical confidence in trends in rates of change.

LiDAR has been shown to be comparable to RTK-GPS measurements. Accurate profiles can be constructed from LiDAR ground returns, but filtered ground returns may not be suitable for precise determination of pingo summit elevations. In this LiDAR data set, the problem of missing pingo summit elevations is compounded by the use of ground returns alone. The geometry of many pingo summits (i.e. steep sided and relatively small) means automated ground/non-ground point separation algorithms may misclassify summit returns as non-ground. Data quality issues resulted in the non-ground points being excluded from this analysis, but considerably more

Figure 11. Failure on the south slope of Ibyuk. Aug 15, 2004. Photo by JB.

Figure 12. Failure on the south slope of Ibyuk. Aug 4, 2005. Photo by GKM.

Figure 13. Active failure scarp, area of bare sand and previous scarp upslope. Aug 4, 2005. Photo by GKM.

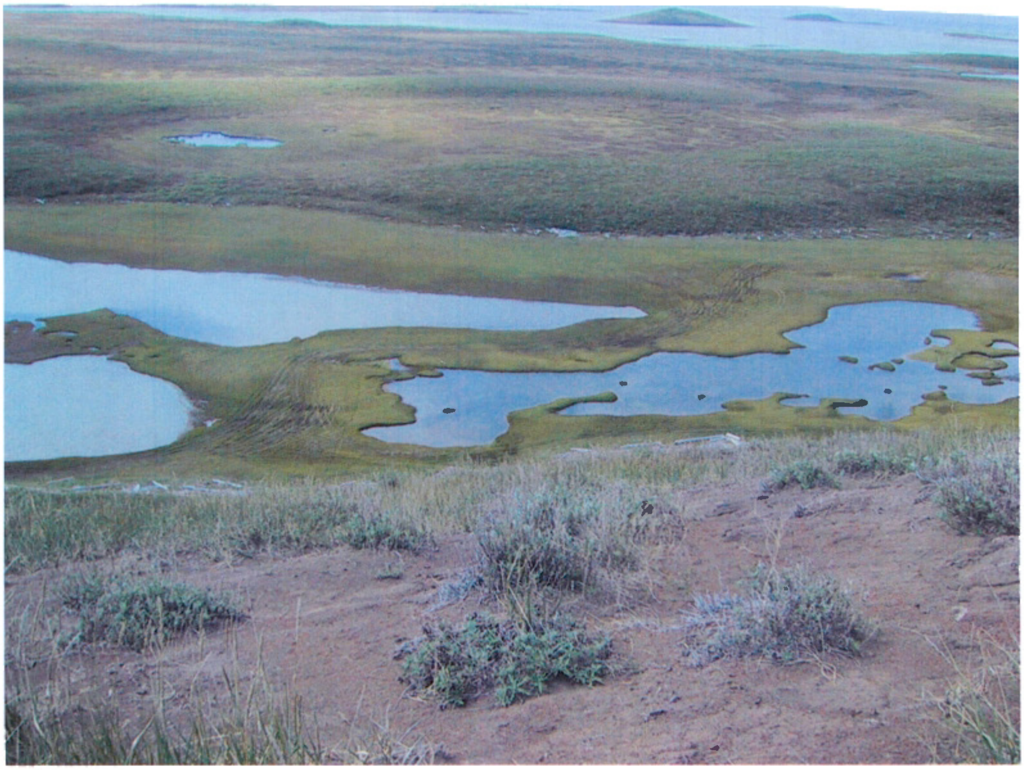


Figure 14. Vehicle tracks in the wetland at the base of Ibyuk. Aug 4, 2005. Photo by GKM.

success may have been possible in measuring pingo summit elevations using LiDAR had they been included. Once the non-ground point quality issues are resolved, LiDAR can be re-investigated for summit elevation monitoring as well as vegetation monitoring and other applications. The possibility of repeat LiDAR can then be considered. This would be most appropriate if RTK-GPS or other monitoring shows significant change in pingo stability and morphology (i.e. changes expected to be larger than 0.5 m over the repeat LiDAR time interval). LiDAR would then have the advantage of areal extent to investigate spatial variability of change. In addition, volumetric measurements would also be possible; for example, the amount of material involved in the active failure could be assessed, as could the volumetric changes of the pingos.

In 2005, repeat ground photography was initiated. The south, north, east and west sides of Split and Ibyuk Pingos were photographed from photo points established using a handheld GPS. This will turn out to be a useful dataset for qualitative monitoring of selected landforms, in particular the human influence. RTK-GPS and LiDAR are less suitable for this application.

Echosounding has been used in more dynamic environments (e.g. Tuktoyaktuk) for monitoring coastal change. Depths inside the PCL are not expected to change appreciably so echosounding is most useful as a morphologic mapping tool. Areas of the PCL where repeat data acquisition could be considered include the outermost parts of the PCL where sedimentation and shallowing may be occurring in lagoons and in flood-tidal deltas in the vicinity of tidal channels. Equipment performance issues in very shallow water in 2005 prevented collection in these areas and the data are not suitable as a baseline for change detection. Periodic resurveying of the deeper pingo moats may reveal morphologic changes there.

5.0 Conclusions

The combination of RTK-GPS, LiDAR and echosounding provides useful information for morphologic mapping and the detection of change in pingos and other coastal features in the Pingo Canadian Landmark.

Some specific findings include:

1) Summit elevations and profiles of Ibyuk did not change significantly between 2004 and 2005. Because of the accuracy of the RTK-GPS (±1 cm) it is possible that the growth of Ibyuk between 2004 and 2005 lies within the margin of error. Longer time intervals are required to further evaluate this change rate.
2) GPS measurements of pingo height are consistent with previous estimates. Ibyuk Pingo is 49.09 m tall from lakebed to summit and Split Pingo is 37.31 m tall from lakebed to summit.
3) No submerged hazards to navigation, other than obvious soft-bottom shallows and rocks above water level were found in the proposed boat route.
4) A failure in unconsolidated sands on the south slope of Ibyuk that occurred before 2004 grew and remained active in 2005.

Areas for further research include:

1) Continued quality-related work on the LiDAR, specifically in differentiating ground, non-ground and errors in the returns
2) Resolution of vertical datum issues at Tuktoyaktuk
3) Improved bathymetric mapping in outer areas of the PCL
4) Monitoring of failures in the PCL, both pingo failures and coastal retrogressive thaw failures
5) Improved monitoring of human influences on landforms in the PCL through repeat ground photography
6) Measurement of the height of Kadleroshilik Pingo using the RTK GPS and LiDAR methods

6.0 Recommendations

1) Parks Canada and the Geological Survey of Canada collaboratively evaluate the morphologic mapping, baseline monitoring and change detection data, monitoring approaches and their contributions to ecological integrity and landform stability in the PCL
2) GPS monitoring continue every 2 to 5 years for change detection purposes
3) New monitoring data be integrated as best as possible with existing monitoring information
4) Photo point monitoring continue annually to assess human influences and monitor the active failures
5) Motorised access to pingo slopes and adjacent wetlands be discouraged, and all access be eliminated entirely on the south and east slopes of Ibyuk.

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