Massive Ice and Ice-Rich Soil Detection by Gravimetric Surveying at Dry Creek, Southwestern Yukon Territory, Canada

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Abstract**:** Gravity measurements were made using a Scintrex CG-5 Autograv gravimeter in permafrost terrain conditions where bodies of buried ice were expected. The main objective was to assess the feasibility of using gravimetric technology to detect massive ice bodies at Dry Creek, Yukon Territory, Canada. Tests at 11 gravimetric survey lines and 10 boreholes were performed during the summers of 2013 and 2014. Residual anomaly profiles provide a quick first estimate of the amount of ice in underlying soil strata. A mean anomaly of -0.10 mGal was found near a thermokarst, south of the Dry Creek rest area along the Alaska Highway. The cryostratigraphy comprises at depth an ice-rich diamicton covered by massive ice with suspended silty inclusions and an overlying layer of glacio-fluvial gravel. At the base of a small glacio-fluvial hill deposit, on the southeast side of the road, a mean anomaly of -0.260 mGal was found. A massive ice body of 9.3 m of maximum thickness was drilled through. Since drilling is planned after gravimetric surveys, it is possible to assess whether or not this technique is effective for detecting sub-surface ice features. This paper presents an overview of the site, the gravimetric detection technique employed, and gravimetric and borehole test results and analysis.

Keywords: Geophysics; Gravimetry; Permafrost; Massive ice.

1 INTRODUCTION

Construction of linear structures, such as roads and railways, in permafrost zones presents many engineering challenges. Below road embankments, thawing of ice-rich permafrost containing massive ground ice such as ice wedges, ice beds, and buried ice reduces almost completely the bearing capacity of soil, creates sinkholes, causes severe subsidence, and requires intensive maintenance with associated costs. Melting of massive ground ice body in a short time can create large thermokarst features that threaten the integrity of linear transport structures and the safety of users (Doré 2009).

The common practice to overcome these problems is to simply avoid thaw-sensitive areas or to apply appropriate design and building techniques in areas where it is impossible to avoid such features. There are few, if any, reliable and affordable methods for determining the volume and extent of ice-rich permafrost and massive ground ice bodies. Geomorphological indications of ice-bearing permafrost features can be inferred from satellite imagery and aerial photography. However, these remote-sensing techniques are limited to evaluate the volume of ground ice or to detect massive ground ice without surface expression such as glacier ice covered by sediment.

The occurrence of massive ground ice at the Dry Creek rest area (31 km south of Beaver Creek, YT) was confirmed by permafrost drilling and coring in 2014. Gravimetric surveys were conducted to evaluate the extent of massive ice in the permafrost. This geophysical method has been successfully used in the past to detect ground ice features (Mackay 1962, Rampton and Walcott 1974, Kawasaki et al. 1982, Allard et al. 1991, Vonder Mühll and Klingelé 1994, Sylwester and Dugan 2002, Doré 2009).

2 OBJECTIVES

The main objective of this paper is to evaluate the feasibility of detecting ice-rich soils and massive ground ice using micro-gravimetric geophysical techniques. The area of Dry Creek was studied to investigate the presence of ground ice leading to the development of thermokarst features (e.g. lake, sinkhole, depression) at the study site. The second objective is to obtain a better understanding of the distribution of massive ground ice of this area for road design, construction and maintenance applications.

3 TEST SITE

The Dry Creek study site (62^{o} 09' 49" N; 140^{o} 40' 55" W;~735 m a.s.l) is located along the Alaska Highway approximately 31 km south of the village of Beaver Creek (Figure 1), Yukon Territory, Canada. Under an organic cover a few decimeters thick, the surficial deposit at the study site comprises glacio-fluvial gravel layer of varying thickness. A portion of the gravel layer has been removed by earthwork to provide fill material during reconstruction of the Alaska Highway in the mid-1990s. The bottom of the excavation was then levelled and a rest area was constructed at the site. Major settlement problems occurred after the rehabilitation of the highway in 1994-95; however, previous settlement problems have already been reported for the area prior to rehabilitation work (B. Stanley, personal communication). This highway section requires intensive maintenance due to recurrent thaw settlement problems. Surface disturbances due to organics and gravel removal, ground levelling and compaction resulted in the development of thermokarst lakes, large depressions, linear settlement crossing the road in several places and sinkholes (Figure 1). A > 8.5 m deep and 30 m large depression was observed along the road embankment during the summer 2008 on the east side of the road (location 2 in Figure 1 and Figure 2). This led us to support the assumption that very ice-rich soils and most likely massive ground ice occurred at depth. Drilling and coring operations conducted during the summer 2014 revealed a very complex cryostratigraphy with layers of both ice-rich and ice-poor silt, pure ice layers and the striking occurrence of massive beds of sediment-poor ice several meters thick.

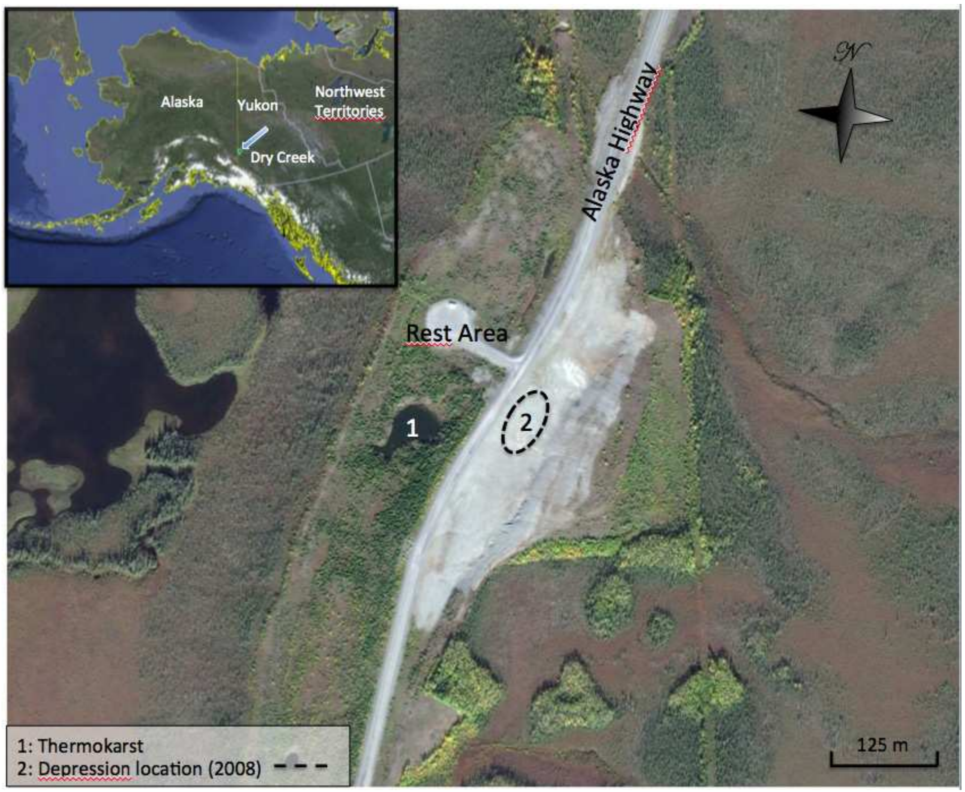

Figure 1. Study site location: Dry Creek rest area, south-western Yukon. 1) Thermokarst lake; 2) former gravel borrow pit where large depressions and sinkholes were observed over the years (1994-2014). The zone left of the highway has also been stripped of its vegetation and surface gravel cover in the past but is now colonized by vegetation (source: Google Earth, 2015).

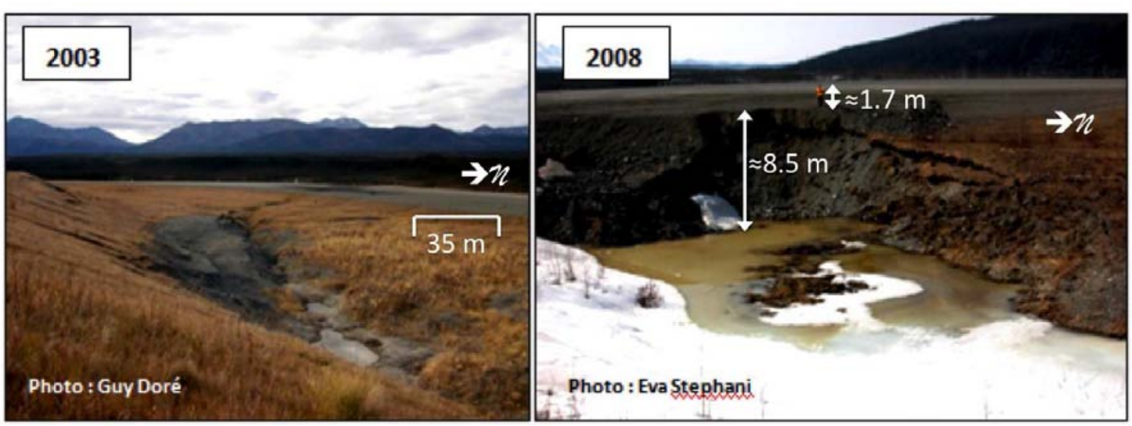

Figure 2. Evolution (2003-2008) of settlement on the east side of the road, Dry Creek rest area (location 2 in Figure 1). Left: linear depression incised in gravel at the foot of the revegetated borrow pit. The highway embankment is in the background. Right: large depression at the base of the road embankment (person for scale).

4 METHODS

4.1 Field Work

A high-precision gravimeter Scintrex CG-5 AutoGrav was used to measure micro-gravimetric anomalies at the Dry Creek study site. This unit has a detection limit of 0.001 mGal (1 μGal). A total of 11 survey lines were done in July and September 2013. The total length of the survey was 645 linear meters for a total of 384 measurements. Most surveys were performed at an interval of 2 meters, except 3 survey lines where measurements were collected each meter. The instrument's time to make each measurement was manually set between one and two minutes for accurate results (Seigel 1995). The positions of the survey lines were selected through a detailed study of the terrain geomorphology. Unstable areas, showing signs of thaw-settlement as well as stable areas were surveyed. A drilling and coring campaign took place in May 2014. Sonic and air-jet drilling were used to verify and determine permafrost subsurface conditions for comparison with micro-gravimetric measurements. Drilling locations were mostly based on negatives anomalies in the gravimetric data at 10 target locations. More than 55 meters of drilling were completed with the boreholes ranging from 0.8 to 13 m deep. The site gravimetric survey lines and the drill holes locations are presented in Figure 3.

Figure 3. Survey lines (numbered) and borehole (DC) locations, Dry Creek study site.

4.2 Gravimetric Data Processing

The earth is made up of materials with different densities, causing variations in the earth's gravitational field. This gravitational field varies depending on the surficial geologic layers. These variations, also known as anomalies, are detectable using a gravity meter. A gravity meter is a device that detects differences in gravitational acceleration caused by bodies of different masses as stipulated by Newton's second law. Ice has a density of about half of the surrounding soil; thus it is possible to detect the presence of significant subsurface ice volumes expressed as a negative anomaly (lower gravitational acceleration) on a gravity survey. It is common to name the anomaly the Bouguer anomaly, which refers to corrected gravimetric anomaly result (Reynolds 1997). Gravimetric results are commonly expressed in Gal (1 Gal = 0.01 m/s^2).

Empirical calculations were first made to assess detection level and expected results on site. Spheres of ice were used in the model (Reynolds 1997). It is by varying the input parameters such as the radius of the sphere, the difference in density between the surrounding soil and ice and burial depth of the sphere that one gets an idea of the expected results. For example, maximum gravity anomalies are in the order of 0.128 mGal for three 4 m-radius horizontally juxtaposed ice sphere at 1 m depths, with a delta density of 1,100 kg/m^3.

Gravimetric field results require several corrections to find the residual anomaly (also called Bouguer anomaly). Data processing was carried out as proposed in the literature (Reynolds 1997):

$$\Delta g_b = g_{obs} + \Sigma(\text{corrections}) - g_{base} \quad [1]$$

where Δg_b is the Bouguer, g_{obs} is the gravitational acceleration observed and g_{base} is the measure of the gravitational acceleration at a selected base station. The total gravimetric corrections, Σ(corrections), is defined as:

$$\Sigma(\text{corrections}) = \Delta g_l + (\Delta g_f - \Delta g_b) + \Delta g_{tc} - \Delta g_d \quad [2]$$

where Δg corrections deltas are specifically related to:
l: latitude, f: free air, b: Bouguer slab correction, tc: correction field and d: instrumental drift and correction for earth tide effect.

The 0 elevation datum is chosen arbitrarily and the highest elevation measurement of the survey line is designated as the reference point. The Scintrex CG-5 gravimeter is equipped with a GPS that automatically compensates for the earth tidal and latitude effects. In order to measure and correct for instrumental drift, the first point of each survey line was used as a reference station and occasionally re-measured to determine variations and a correction factor calculated based on a time weighted average was applied (Reynolds 1997). The correction for the free air effect was made according to:

$$\Delta g_f \cdot \Delta h = 0.3086 \text{ mGal / m} \quad [3]$$

where Δh is the difference in height (m) relative to the reference station. As the reference station is at a greater height than all other stations, this value is finally subtracted (because Δh is negative) to g_{obs}. The Bouguer slab effect, which refers to underlying terrain, is given by:

$$\Delta g_b \rho_b = 0.0419 \text{ mGal} \cdot \Delta h / \text{m} \quad [4]$$

where ρ_b is the density based on semi-infinite slab theory of the underlying terrain. This value will eventually be added (for negative Δh) to g_{obs}. A ρ_b of 2 Mg/m^3 was chosen as a representative density of the area. The terrain correction was estimated by Hammer's rings correction (Hammer 1937), which is an additional correction that reflects the undulations of the terrain, corrects the Bouguer effect, which is based only on the semi-infinite slab theory. This correction is essential for gravity surveys over rough terrain when the required accuracy is high as in micro-gravimetric surveys.

5 RESULTS AND DISCUSSION

Gravimetric results show negatives anomalies on survey lines 3, 6, 7 and 11. The other surveys have shown no anomalies and no massive ice or ice-rich soils were detected during drilling. Therefore only survey 3, 6 and 7, where ice-rich soil (survey 3) and massive ice (survey 6 and 7) were encountered by drilling will be discussed. An arbitrary zero for topography is set for each survey lines presented.

5.1 Survey Line 3

The survey line 3 is located perpendicular to linear depressions, which is likely associated with the linear degradation of ice wedges (Figure 3). These linear depressions reach the northeast part of a thermokarst that appeared in the late 1990s. The corrected results of the survey are presented in Figure 4. The survey was 53 m long and the measurements were made approximately each meter. This survey includes variables Bouguer anomalies, ranging from -0.283 to 1.028 mGal. The positive anomaly, from 29 to 34 m was interpreted as the result of melting of subsurface massive ice wedges, thus substantially increasing the density at that location. Beyond this positive anomaly, the entire area has various negative anomalies, with an average of -0.095 mGal for the 35.5 to 49 m zone. For this reason, a borehole (DC-1) was drilled at the 35.5 m point (Figure 4). The cryostratigraphy comprised ice-rich silty soils from 1 to 1.5 m depth, massive ice, which origin is yet unknown, down to 2.5 m depth, and ice-rich silt with pluri-centimeter thick ice lenses from 2.5 to 3.8 m. The borehole terminated in an ice-rich diamicton at 4.8 m, at which depth, drilling could not continue because of blocks tumbling down into the drill hole. The negative anomaly at 35.5 m (borehole location) is -0.129 mGal. A second borehole (DC-2), about 10 m northeast from the survey line 3, exhibited a similar surficial stratigraphy with an average anomaly around -0.10 mGal (Figure 3 and 4). Ice thickness equivalent is presented in Figure 4 since a complex mix of massive ice and ice-

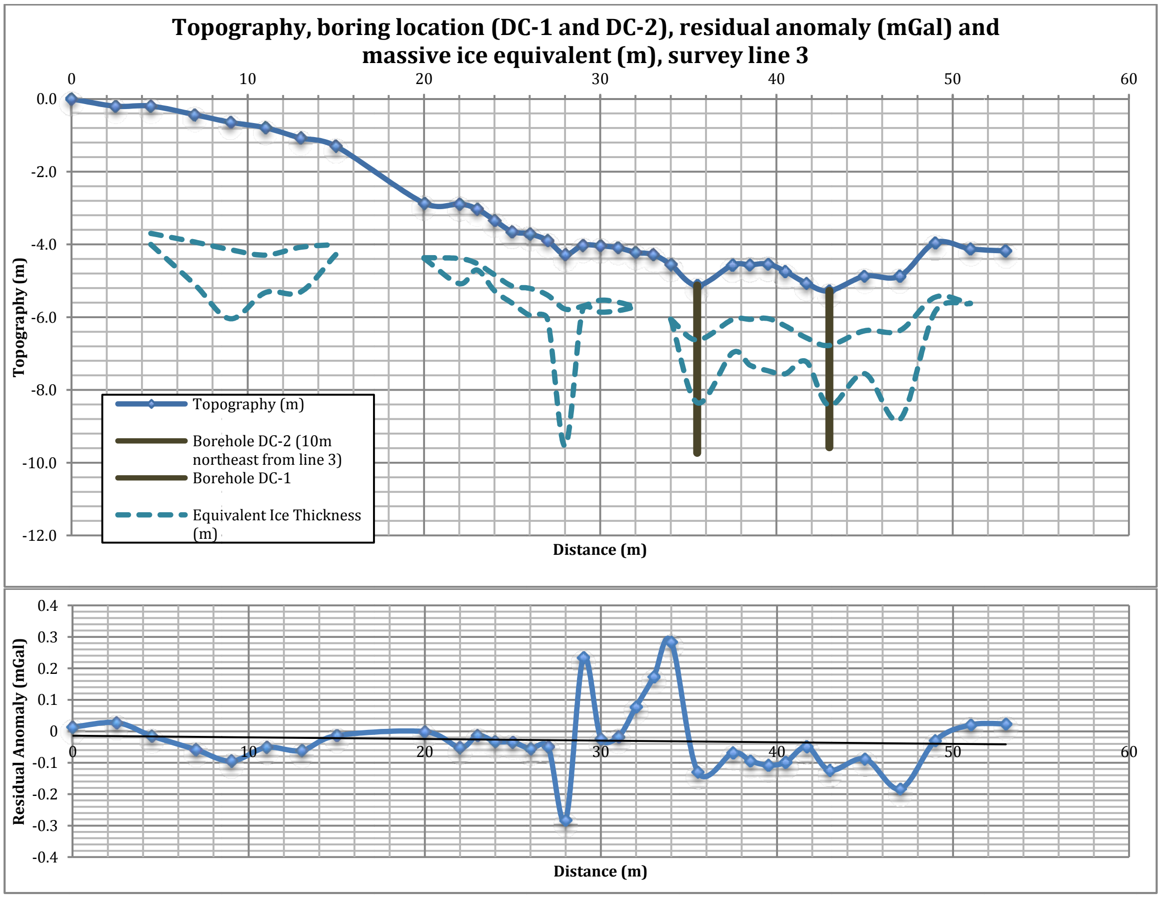

Figure 4. Microgravimetric survey line 3 with boreholes localisation (DC-1 and DC-2) and residual anomaly.

rich silt and diamicton was encountered. Ice thickness equivalent propose an equivalent thickness of massive ice for the entire underlying soil according to gravimetric data.

5.2 Survey Line 6 and 7

Survey lines 6 and 7 are located in the southeast portion of the site and follow an east-west orientation, from the bottom of the borrow pit where the glacio-fluvial material was excavated to the top of a small hill (not excavated) (Figure 3). The survey lines follow a parallel course, which is why they will be analysed simultaneously. A major thaw-settlement related depression was observed at the foot of the escarpment, which is likely associated with degradation of the permafrost due to the excavation of the granular material. The adjusted results of survey 6 and 7 are presented in Figure 5 and 6, respectively. Survey line 6 is 74 m long and measurements were made at 2 m intervals, except at the end of the survey because of the irregularity of the terrain. Negative anomalies begin at 20 m and end on the slope at 50 m, reaching a maximum of about -0.520 mGal at 40 m. The survey line 7 has a length of 49 m and measurements were also made at 2 m intervals, except at the end of the survey line. The negative anomalies begin at 8.5 m and decline almost linearly to 17.5 m, where a negative value of -0.698 mGal is observed. The anomaly decreases linearly to reach 0 mGal at 34 m, a point also located under the glacio-fluvial deposit forming the hills. Three boreholes were drilled along the lines; 2 on survey line 6 (DC-5 and DC-10), and one on the survey line 7 (DC-4) (Figures 3, 5). Borehole DC-5 was 9.5 m deep. The first meter was typical of soils found at the bottom of the excavated area (sandy gravel with silt and boulders). The massive ground ice begins at 2 m and continued until the end of the borehole at 9.5 m. DC-4 borehole was 12.8 m deep. Similar to DC-5, the cryostratigraphy comprised 1 m of sandy gravel over 1 m of ice-rich silt. Massive ground ice was encountered between 2 and 11.3 m, where ice-rich silt extending down to 12.5 m. From 12.5 to 12.8 m, the soil sampled was unfrozen, probably due to permafrost thawing during drilling operations. Boreholes DC-3, 3AJ, 6, 7, 9 and 10 where conducted to verify the absence of ice-rich soils/massive ice suggested by the absence of residual anomaly at those locations (Figure 3). No massive ice and/ or ice-rich soils were indeed detected.

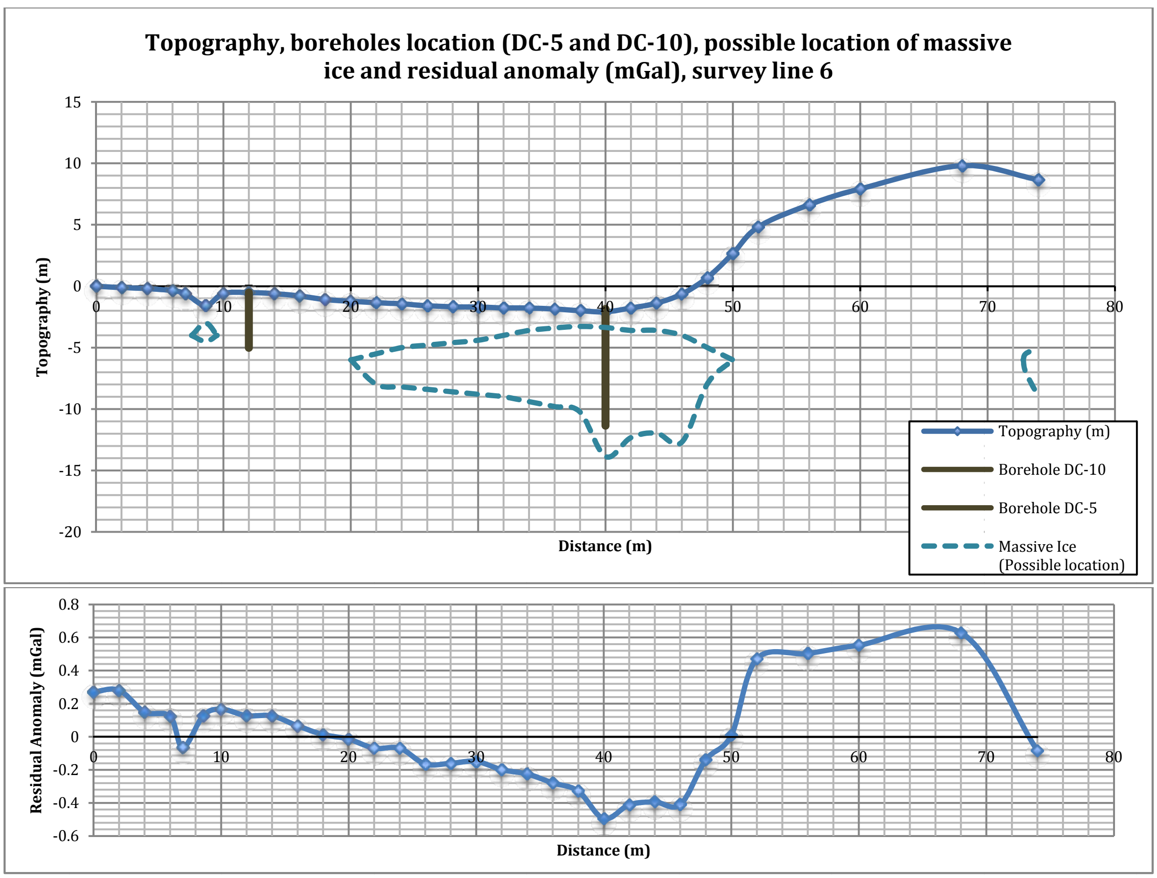

Figure 5. Microgravimetric survey line 6 with boreholes localisation (DC-5 and DC-10) and residual anomaly.

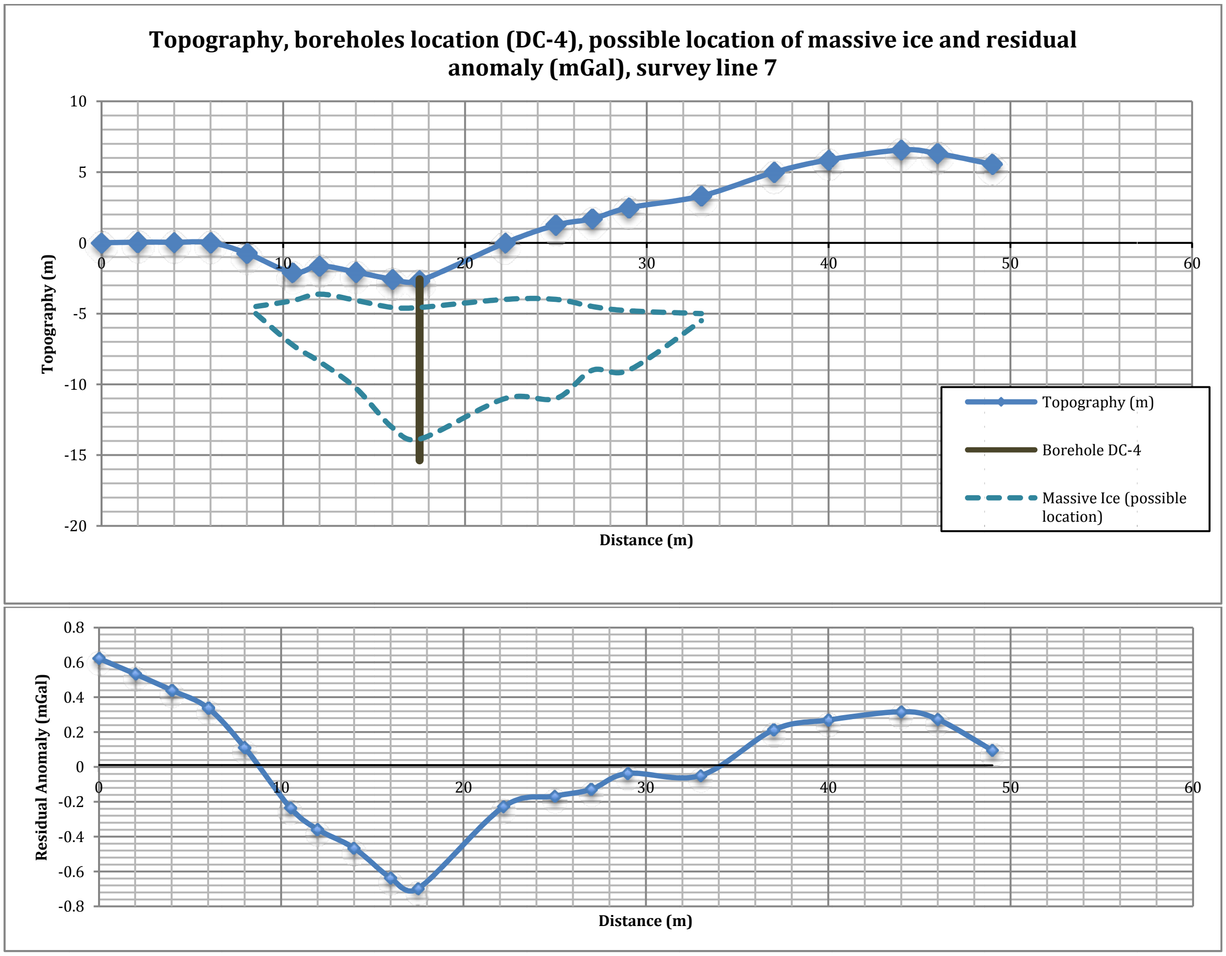

Figure 6. Microgravimetric survey line 7 with borehole localisation (DC-4) and residual anomaly.

5.3 Analysis and Interpretations

It was possible to demonstrate through boreholes that large amounts of massive ice and ice-rich permafrost are present in some areas of the Dry Creek study site. For survey line 3 (borehole DC-1 and DC-2), ice-rich silt and an ice-rich diamicton have been detected (Figure 3, 4). Figures 5 and 6 show the target area and depth where massive ground ice is likely to be present based on gravimetric results. For survey line 7, the massive ice was completely cored through which constrains the depth under this borehole. Other boreholes drilled in areas show no significant residual anomalies and neither massive ground ice nor ice-rich soils were encountered. Based on the gravimetric surveys, no significant amount of massive ice was detected near east side of the road. Some ice could still be present beneath the embankment near the thermokarst area (survey line 3). However, it is important to keep in mind that equivalent ice thickness do not shows necessarily exact representation and depth of bodies of Ice. Every represented bodies could be deeper and larger and would present the same negatives anomaly responses. The large subsidence and depressions observed over the years strongly suggest that large volume of massive ground ice already melted. The linear and differential settlements observed along the road could be caused by the degradation of ice wedges and/or of the ice-rich diamicton. Results of negative residual anomalies measured in the field were significantly higher than the results obtained from theoretical calculation for the same volume of ice. It was expected to find anomalies around 0.130 mGal for three 4 m horizontally juxtaposed ice sphere and the anomalies measured on-site were rather around 0.4 to 0.6 mGal. The complexity of the zone and the different thickness of underlying possible ice-rich diamicton could in part explain those differences. Since variability of terrain's densities is important, ice bodies at shallow depth seem to give more precise results. Larger densities could interfere with the gravimetric signal as it is supposed beneath the hill on east end of survey lines 6 and 7 were ice could possibly be expected. Work is in progress to quantify precisely relations between depth, volumes and gravimetric signals obtained on field.

6 CONCLUSION

Gravimetric detection of massive ground ice and ice-rich soil at the Dry-Creek study site has proven to be an efficient method. Gravimetric anomalies and boreholes clearly demonstrated the presence of massive icy beds and ice-rich soils in the area. The technique seems to give better results for ice bodies located at shallow depth. Although micro-gravimetric measurements were successful in identifying the potential presence of ice-rich soils/massive ice in the subsurface, further work remains to derive potential volume and geometry of ice-rich soil/massive ice from micro-gravimetric anomalies.

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