GEOPHYSICS, VOL. 71, NO. 3 (MAY-JUNE 2006); P. J23–J29, 7 FIGS., 2 TABLES.
10.1190/1.2189387

Measuring gravity on ice: An example from Wanapitei Lake, Ontario, Canada

Hernan A. Ugalde[1], Elizabeth L'Heureux[1], Richard Lachapelle[2], and Bernd Milkereit[1]

ABSTRACT

Large lakes have always represented a problem for regional gravity databases; the difficulty of access means gaps or coarse spacing in the sampling. Satellite, airborne, and shipborne gravity techniques are options, but the resolution and/or cost of these systems make them impractical or inaccurate for exploration or environmental studies, where the required resolution is <0.1 mGal/km. In this study, the feasibility of a ground gravity survey over a frozen lake where ice moves because of windy conditions is assessed. Lake Wanapitei, widely accepted as resulting from the impact of a meteorite 37 million years ago, is one of these cases in which the necessity of expanding coverage over poorly sampled regions arose from a significant gap between surface and airborne geophysical maps. Two gravity surveys were completed on the ice of Lake Wanapitei in the winters of 2003 and 2004. To study the structure, long-time series of gravity field measurements were recorded for 98 stations, allowing for improved control over the noise sources in the data. Final processing and integration with an existing regional data set in the area and the application of terrain corrections reduced the amplitude of the circular anomaly from 15 to 9 mGal and its diameter from 11 to 6 km. The feasibility of gravity surveys on ice was assessed, and we determined that for large-scale studies such as this one, the quality of the data, even under noisy conditions, was acceptable. However, for more detailed mapping, calm wind conditions and long time series are required.

INTRODUCTION

Gravity prospecting has been used widely in oil and gas exploration since the 1920s (Telford et al., 1990); however, its higher cost compared to magnetic and electromagnetic (EM) methods and the necessity of a centimeter-accuracy digital elevation model of the area for the reduction of topographic effects have relegated it to secondary status when more expensive follow-up ground techniques are required. Recently, however, geoenvironmental applications such as the location and monitoring of abandoned mine workings (Hoover et al., 1995; Styles, 2003) and reservoir monitoring (Hare et al., 1999; Fujimitsu et al., 2000) have increased interest in microgravity and 4D microgravity.

Gravity databases, such as the one maintained in Canada by the Geological Survey of Canada (GSC), still exhibit gaps or coarse spacing in areas of difficult access such as lakes. To overcome this problem, satellite, airborne, or shipborne gravity could be options, but their resolution and/or cost makes them impractical or inaccurate for exploration or environmental studies, where the required resolution is <0.1 mGal/km. Satellite gravity has improved dramatically with the launch of new systems such as CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) and GRACE (Gravity Recovery and Climate Experiment), improving resolution from about 20 mGal in 25 km in the mid-1980s to approximately 3 mGal in 5 km today (Fairhead and Odegard, 2002). Airborne gravity systems have developed considerably over the past 10–15 years, but because the resolution of current systems is still 0.2–1 mGal over 2 km for fixed-wing systems traveling at 100 knots or 0.3 mGal over 1 km for helicopter-mounted systems traveling at 50 knots (Fairhead and Odegard, 2002), airborne surveying is still not feasible for detailed mapping at the prospect scale. Shipborne gravity can lead to a resolution of about 0.2 mGal over 0.25 km (Fairhead and Odegard, 2002), but its cost is still much higher than an airborne survey.

Therefore, filling gaps in gravity data over lakes with traditional methods is unavoidably expensive if good resolution is required. Conducting a ground gravity survey over the frozen lake is a natural alternative, but because ice moves under windy conditions, the feasibility of such a study must be assessed.

Presented at the 74th Annual International Meeting, SEG. Manuscript received by the Editor February 8, 2005; revised manuscript received September 1, 2005; published online May 17, 2006.
[1]University of Toronto, Department of Physics, Toronto, Ontario M5S 1A7, Canada. E-mail: ugalde@physics.utoronto.ca; lheureux@physics.utoronto.ca; bm@physics.utoronto.ca.
[2]Scintrex Ltd., Concord, Ontario, Canada. E-mail: rlachapelle@scintrexltd.com.

PREVIOUS STUDIES

Wanapitei Lake is located about 40 km northeast of Sudbury in northern Ontario, Canada (Figure 1). The area is the site of a meteorite impact that occurred 37 million years ago, leaving behind a crater in the central portion of the lake. As of a few years ago, the only geophysical evidence for the impact was the original gravity survey published by Dence and Popelar (1972). The Bouguer anomaly map revealed a −15-mGal circular anomaly, 11 km in diameter and covering nearly the entire lake. The survey was carried out in 1969 and consisted of 38 stations regularly spaced at 500-m intervals on two northeast profiles plus 38 stations on the shores and islands (Figure 2). No terrain corrections were applied to the data.

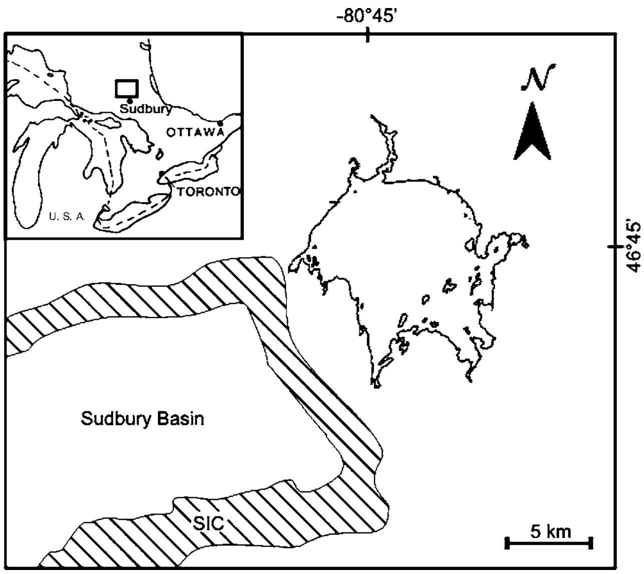

Figure 1. Lake Wanapitei location map. The square in the inset shows the location of the area of study in the detailed map. The eastern portion of the Sudbury Basin is shown for scale and location purposes. SIC is the Sudbury Igneous Complex.

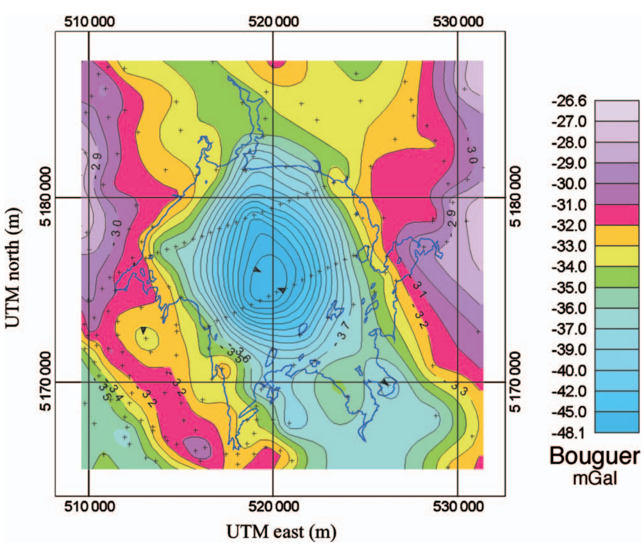

Figure 2. Bouguer gravity anomaly over Wanapitei Lake, as published by Dence and Popelar (1972). Gravity stations are shown as black crosses; lake outline is in blue (extracted from Dressler, 1982). Contour interval is 1 mGal; amplitude of the anomaly is 15 mGal. Data are from the Geological Survey of Canada (GSC).

Studies done since 1972 have revealed samples of impact-related minerals and rocks around the shores of Lake Wanapitei, such as coesite (a high-pressure form of silica) and suevite (a rock consisting of clastic breccia and melt particles) (Dence and Popelar, 1972; Dence et al., 1974; Grieve and Ber, 1994; Dressler et al., 1997). Shatter cones, conical systems of fractures formed at pressures of 1–4 GPa by a shock wave interacting with small heterogeneities in the target material, have also been found (Dressler, 1982; Dressler et al., 1997). According to Dence and Popelar (1972), further evidence that the structure is impact induced is the apparently concentric pattern of lakes and rivers around Lake Wanapitei, as seen in topographical maps and aerial photographs (Dressler, 1982). Geophysical evidence for the impact includes a circular total magnetic field anomaly and a circular cavity under postimpact sediments, as seen on high-frequency, single-channel seismic data (L'Heureux, 2003). These data indicate the crater is approximately 7 km in diameter and is located within the central portion of the lake. The main cause for the observed negative gravity anomaly over impact structures is the reduction in density as a result of impact-induced fracturing (Pilkington and Grieve et al., 1992). The expected gravity anomaly over a 7-km crater is smaller than what is observed at Lake Wanapitei.

To constrain the large gravity anomaly and to correlate it with the newer geophysical data, we collected additional gravity data over the frozen lake between 2003 and 2004.

DATA ACQUISITION AND REDUCTION

To provide accurate sampling of the anomaly, 98 new stations were collected during two surveys in the winters of 2003 and 2004. To ensure the best data quality, at least three 60-s readings were recorded at each station. Gravity was measured with a Scintrex CG-5 digital gravimeter, and positioning was recorded by a differential global positioning system (DGPS) (Figure 3). The 2003 survey was positioned with real-time kinematic (RTK) DGPS. In 2004, postprocessed, carrier-phase ambiguity resolution DGPS was used,

Figure 3. Picture taken during the 2004 survey. The gravimeter and the differential GPS system are shown as well as the snowmobile used for travel between stations.

with occupation times of 10–15 minutes. Both systems provided centimeter-resolution elevations. Because a snowmobile was used for displacement between stations, all equipment had to be secured between measurements; therefore, it was impractical to navigate with the DGPS system. A handheld GPS was used for navigation and to get close enough to the desired location; then the DGPS system was used for accurate positioning. A base station was set up on the shore of the lake, which was reoccupied every few hours to correct for residual instrumental and dynamic drift.

The CG-5 processes the raw gravity signal to remove the effects of sensor tilt. It samples the raw gravity signal six times per second and records it along with the analog signals from the temperature and tilt sensors. This improvement is beneficial and instrumental in collecting gravity data because it allows on-site quality control of the data and a better evaluation of equipment performance. As we show later, it is a great advantage to record a longtime series of the gravity signal instead of a single point in situations such as those encountered on ice.

An essential part of CG-5 operation is the correction for nonverticality applied to all recordings. The inclination of the gravity sensor is measured by electronic tilt sensors, and its effect is removed from the data; the processed signal is then analogous to one obtained with a sensor in a purely vertical position. The uncompensated gravity reading GC changes in response to tilts according to the following expression (as noted in Scintrex Ltd., 2003, CG-5 instrument design notes):

$$GC(\theta_x, \theta_y) = GC(0,0) - g(1 - \cos\theta_x \cos\theta_y), \tag{1}$$

where g is the value of gravity at the reading site and θ_x and θ_y are the tilts of the gravity sensor about two perpendicular horizontal axes (x and y), with $\theta_x = \theta_y = 0$ defined as the orientation in which the uncompensated gravimeter reading is maximized.

The tilt correction TiC operates over a range of ±200 arc-sec and is defined by (Scintrex Ltd., 2003, CG-5 instrument design notes)

$$TiC = g_t(1 - \cos X \cos Y), \tag{2}$$

where g_t is an average sea-level gravity value of 980.6 gal and X and Y are the indicated gravimeter tilts.

Assuming $g_t = g$, which in the worst case leads to an error of 0.002 mGal, the corrected reading will be

$$GC(\theta_x, \theta_y) = GC(0,0) + g_t(\cos\theta_x\, cos\ \theta_y - \cos X \cos Y). \tag{3}$$

If $X = \theta_x$ and $Y = \theta_y$, then

$$GC(\theta_x, \theta_y) = GC(X, Y) = GC(0,0), \tag{4}$$

and errors from instrument tilt are eliminated. The x- and y-values are adjusted during calibration so that equation 4 is satisfied (Scintrex Ltd., 2003, CG-5 instrument design notes).

During the tilt calibration, each gravimeter is adjusted to true vertical position for the tilt sensors by measuring any offset on the tilt sensors and compensating for this; the same applies for tilt sensor sensitivities, or the amount of μgal/arc-sec. Each gravimeter is unique, i.e., it has its own values of tilt sensitivities and offsets. Once the tilt sensors are calibrated properly, they give the exact tilts in the x- and y-axes (respectively, θ_x and θ_y), and these values are used in the tilt correction. Therefore, when the CG-5 measures gravity, the tilt correction (equation 2) is always being applied, and the gravity value is being corrected to what it should be if the measurement were taken with a perfectly vertical gravimeter (Scintrex Ltd., 2003, CG-5 instrument design notes).

The automatic tilt correction proved to be essential during data collection. The constant winds or the snow melting under the weight of the gravimeter made the ice an unstable platform; therefore, the gravimeter was not always levelled throughout the 60 s that each reading took. However, the tilt correction compensated for up to ±200 arc-sec of tilt on both x- and y-planes within a measurement, which made readings feasible.

Figure 4 shows three examples of 60-s readings recorded continuously at 6 Hz. The base station (purple curve) shows a noise envelope of ±0.1 mGal, whereas both tilts vary by ±0.3 arc-sec. The blue curve corresponds to a station recorded in the middle of the lake under windy conditions. The gravimeter recorded ice-wave effects of ±7 mGal, and the tilts oscillated accordingly at ±5 arc-sec. The same station was read the next day under calmer wind conditions (red curve). Measured gravity varied ±0.6 mGal, and the tilts were ±2 arc-sec. The noise on the windy station can be separated as ice oscillations from wind, with periods of approximately 10 s, and small vibrations on the gravimeter because of direct wind, with periods of about 1 s. This separation is evident on the tilts, which show both frequency components. The quiet day station (red curve) exhibits a monotonous variation on the tilts, probably related to the gravimeter settling on the ice. A board was used between the ice and the gravimeter tripod to prevent the latter from sinking. However, depending on the temperature conditions of the day, the board still sank because of the weight of the gravimeter and the melting snow/ice underneath.

Finally, to process the recorded gravity data, standard drift, theoretical gravity, and free air (FA) corrections were applied. The Bouguer anomaly (BA) was then obtained by subtracting the effect of a slab of homogeneous density ΔB_R; to avoid overcorrection, the effect of the body of water ΔB_W was considered. It is computed with the following equations:

$$\Delta B_R = 2\pi G \rho_c h, \tag{5}$$

$$\Delta B_W = 2\pi G(\rho_c - \rho_w) d_w, \tag{6}$$

$$BA = g_0 - g_t + \frac{dg}{dz} h - (\Delta B_R - \Delta B_W), \tag{7}$$

and

$$= FA - (\Delta B_R - \Delta B_W), \tag{8}$$

where g_o is observed gravity; g_t is theoretical gravity at the surface of the reference ellipsoid; dg/dz is 0.3086 mGal/m, the average vertical gravity gradient per meter of elevation above sea level; G is $6.672 \times 10^{-6}\ m^3\ kg^{-1}\ s^{-2}$; h is station elevation in meters above mean sea level; d_w is depth in meters below surface observation, or bathymetry; ρ_c is 2670 kg m^{-3}, the density of crustal rock; and ρ_w is 1000 kg m^{-3}, the density of freshwater.

Because the bathymetry is not flat, the Bouguer correction does not account properly for the effect of the body of water; therefore, a terrain correction was calculated using the lake bathymetry compiled with the surrounding topography. We measured bathymetry in August 2002 (Figure 5; L'Heureux, 2003). Data were collected with a 200-kHz echo sounder on north-south lines spaced at 500-m increments. Lake depth reaches 120 m in the deepest section, along a north-south valley in the southern bay. The thickness of the ice cover (no more than 0.6 m, according to many local fishermen) was not considered for the terrain corrections because it was not precisely known over the entire lake. Considering the large depths encountered in the lake and the low density contrast between ice and freshwater ($100\ \mathrm{kg\ m^{-3}}$), the effect of this approximation is negligible, as shown later in the discussion of the results.

The Geological Survey of Canada (GSC) holds the original data from the 1969 survey by Dence and Popelar (1972) (Figure 2). This data set, which consists of 38 stations on ice and 38 stations on the shores or islands within the lake, was merged with the 2003 and 2004 surveys (Figure 6). The new map has the same amplitude

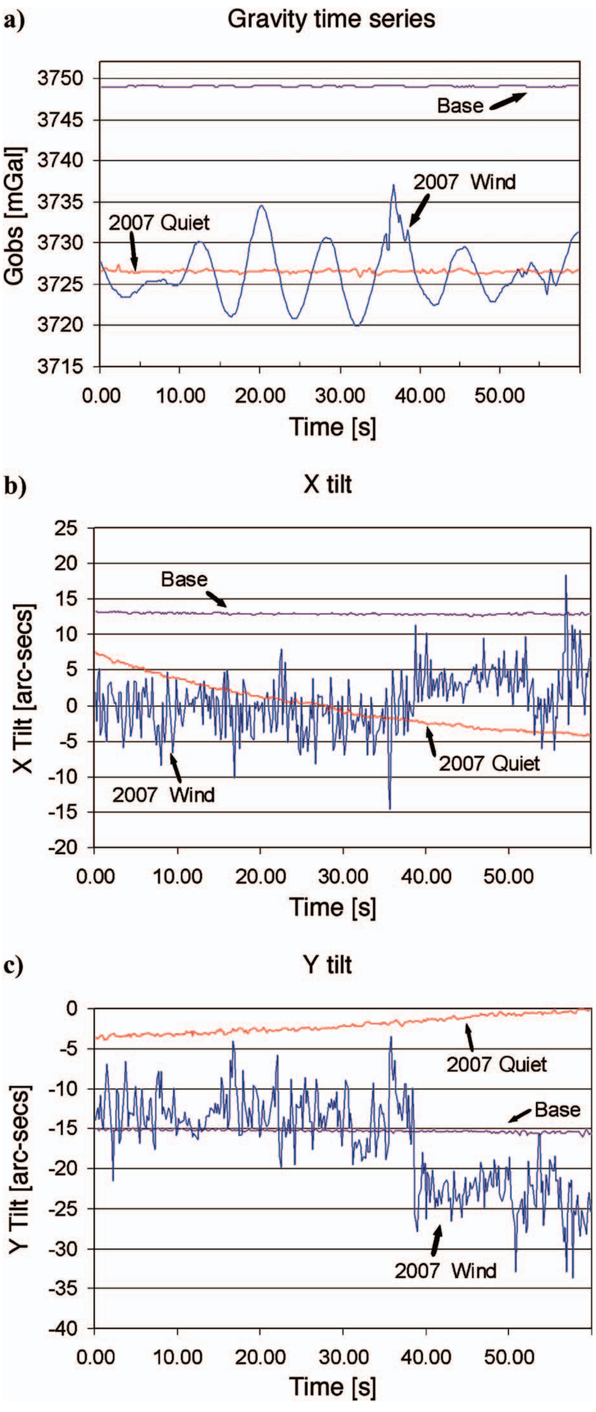

Figure 4. (a) Gravity, (b) X-tilt, and (c) Y-tilt recordings for three stations: the base station (purple line), a station under windy conditions (blue line), and a station under calm conditions (red line).

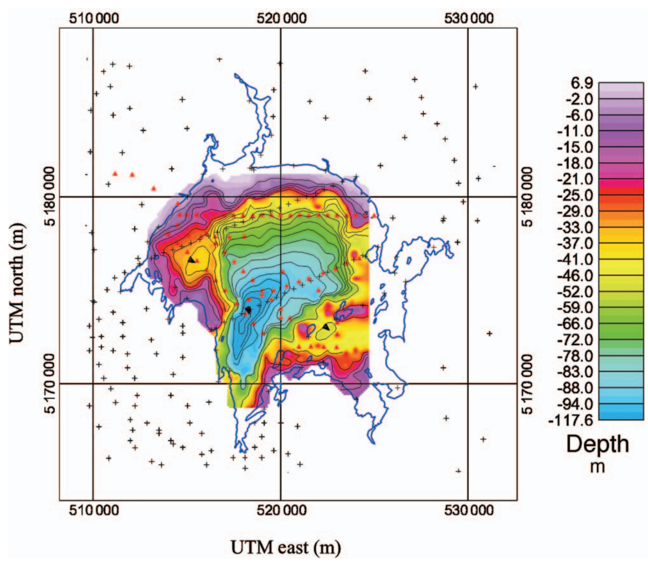

Figure 5. Bathymetry of Lake Wanapitei. The greatest depths of approximately 120 m are found in the southern bay (L'Heureux et al., 2005). Old gravity stations are shown as black crosses; new stations are shown as red triangles; lake outline is in blue. Contour interval is 10 m.

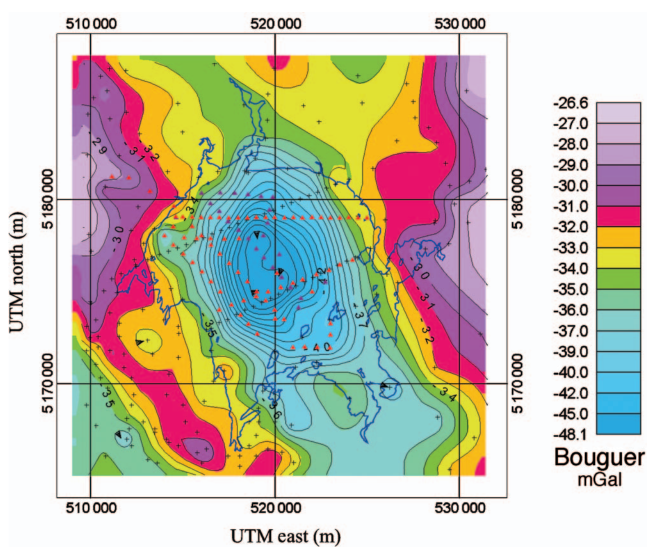

Figure 6. Bouguer gravity anomaly over Wanapitei Lake after compiling new and old data. Old gravity stations are shown as black crosses; new stations are red (2003) and blue (2004) triangles; lake outline is in blue. Contour interval is 1 mGal. Data are not terrain corrected.

as the old one (15 mGal); however, because of the improved sampling, the anomaly exhibits more texture at its center. Table 1 shows the difference between the final gravity and the distance between 1969 stations and the nearest 2003–2004 measurements. Navigation on the open ice proved to be difficult; therefore, it was not always possible to reach the exact coordinates of the old stations. Because the distances between stations are irregular, the gradient (difference in measured gravity divided by station distance) was calculated instead of the mean value for the error between readings. This was multiplied by average distance to find an estimate of the average misfit between the old and new surveys. Thus, the global weighted error for the three surveys is 0.024 mGal.

Table 1. Difference in gravity measurements at nearby stations. Difference in the measured terrain-corrected Bouguer anomaly in nearby stations during different surveys. Year–year of the survey (1969, GSC; 2003 and 2004, University of Toronto); *g* — terrain-corrected Bouguer anomaly at that station; Distance — distance between stations; *dg* — difference in *g* between stations; *dg*/m — *g* difference over the stations' distance. See text for discussion.

Station ID	Year	*g* (mGal)	Distance (m)	*dg* (mGal)	*dg*/m (mGal/m)
51	1969	−40.714	111.000	−0.264	−0.002
108	2003	−40.450			
50	1969	−41.231	55.000	−0.216	−0.004
109	2003	−41.015			
57	1969	−33.800	140.000	0.074	0.001
752	2003	−33.874			
56	1969	−34.737	180.000	−0.163	−0.001
202	2003	−34.574			
13	1969	−32.603	97.000	0.471	0.005
120	2003	−33.074			
41	1969	−34.841	250.000	0.191	0.001
712	2003	−35.032			
39	1969	−34.987	107.000	0.031	0.000
711	2003	−35.018			
38	1969	−35.809	73.000	−0.020	0.000
710	2003	−35.789			
35	1969	−39.548	141.000	−0.127	−0.001
708	2003	−39.421			
27	1969	−35.177	202.000	−0.154	−0.001
808	2003	−35.023			
59	1969	−33.901	260.000	−0.686	−0.003
802	2003	−33.215			
100	2003	−33.498	50.000	−0.480	−0.010
1002	2004	−33.018			
106	2003	−36.142	180.000	0.680	0.004
2004	2004	−36.822			
48	1969	−38.323	200.000	1.777	0.009
4003	2004	−40.100			
Minimum			50.000	−0.686	−0.010
Maximum			260.000	1.777	0.009
Mean			146.143	0.080	0.000
Sandard deviation			65.580	0.578	0.004
Weighted error*				0.024	
Weighted standard				0.271	

*Product of average distance and average *dg*/m

Because precise bathymetry is now available, we applied the terrain correction on the new and old data using a digital terrain model of the lake subsurface and in-house software from the GSC (Rupert, 1991). The software uses sloping-top triangular prisms generated from a data set of irregularly spaced depth values that model the actual topography close to the observed gravity station to estimate the gravitational terrain correction. The calculated terrain effects on gravity range from 0.5 mGal in the shallow areas to 7.2 mGal in the main depression. With that, the terrain-corrected Bouguer anomaly (Figure 7) was reduced to 9 mGal — still circular but with a long axis of about 6 km, which is much closer to what one would expect for a 7-km-wide impact crater.

RESULTS AND DISCUSSION

Analysis of the time-series data shows large variations in the noise envelope, depending on wind conditions. A first source of noise is the movement of the gravimeter during the time it takes to complete a reading, either because of wind or melting snow. The automatic tilt correction compensates for movement within ±200 arc-sec from the true vertical position of the meter. Out of that range, the graphic display of both tilts and gravity allows the user to reject the data, or it can be done afterward during data processing.

A second and more important source of noise is the ice oscillation caused by the wind, which generates a considerable variation in the gravity field. As a result of their periodic nature, those waves in the observed signal tend to cancel out when a longtime series or several of them are averaged. However, care must be taken when

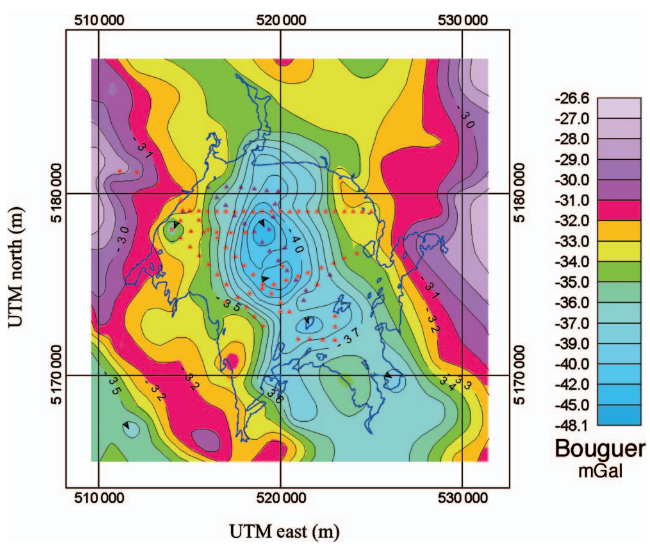

Figure 7. Compiled (1969, 2003, and 2004 data) and terrain-corrected Bouguer gravity anomaly over Wanapitei Lake. Old gravity stations are shown as black crosses, new gravity stations are shown as red triangles, and lake outline is in blue. Contour interval is 1 mGal. The amplitude of the anomaly is reduced to 7 mGal.

analyzing the time series and computing the most representative gravity value for that station. If complete cycles are not considered when averaging the data, the average will be biased and will not be representative. The power spectrum can be used to get the longest period signal, but for that, time series longer than 60 s are required. The good repeatability of the data proves that averaging the time series gave good results in this case, making the data usable for regional or semidetailed studies. For prospect-scale studies, calm wind conditions and longer time series are recommended. The measured difference between nearby stations is acceptable and quite good, considering the windy conditions and large oscillations seen when the data were collected.

The 1969 survey was positioned by means of manually measuring the distance and azimuth between stations and then positioning the inferred location on a topographic map. According to the GSC database, the positioning error is estimated at ±20 m, the elevation error at ±1 m, and the measured gravity at ±0.1 mGal. By using the free-air reduction gravity formula of $dg/dz = 0.3086$ mGal/m, we can estimate the gravity error induced by ±1 m of elevation to ±0.3086 mGal. This can be considered the maximum possible accuracy when merging all data sets and can explain the 0.024-mGal mean discrepancy between the 1969 and newer data in Table 1.

Because this lake is used to generate hydroelectric power, its water level is very likely to change in 35 years. The effect of this is assessed using a simple model. The body of water that changes from survey to survey is modeled as a vertical cylinder of thickness L and radius R, whose gravity effect is given by Telford et al. (1990) as

$$g = 2\pi G\rho\left[L + R - \sqrt{(L^2 + R^2)}\right]. \tag{9}$$

Considering a 5000-m-radius cylinder to account for the effect of water in the entire lake and a density of 1000 kg m^{-3} (density of freshwater), a thickness L of 0.5–1 m is enough to produce an anomaly of 0.02–0.04 mGal, i.e., large enough to be observable with the equipment used on the new surveys but undetectable if we consider the ±0.3086-mGal upper-bound accuracy limit.

The same argument can be used to justify the approximation of not using a layer of ice on top of freshwater for both Bouguer and terrain corrections. Considering a 5000-m-radius cylinder to account for the entire lake, a density contrast of 100 kg m^{-3} (ice-freshwater density contrast), and the observed ice thickness L of 0.6 m, the associated gravity anomaly is just 0.002 mGal.

Finally, the topography of the ice is not flat. The strong winds observed in the area can easily shift the ice to produce elevation variations of approximately 1 m, which can account for a gravity anomaly of 0.0419 mGal if we consider a simple slab with gravity effect $2\pi G\rho h$ and a density of 1000 kg m^{-3} (density of freshwater). Some of these ridges were observed during the new surveys. Therefore, it is not rare that different surveys measured nearby stations over different elevation water levels or over different ice topography.

After reducing the gravity, the repeatability of the readings was within 0.002 mGal. Table 2 shows the values obtained for the final terrain-corrected Bouguer anomaly at the stations that were measured more than once during each survey. Only readings collected on different days at the same station were considered because the purpose was to assess the repeatability of the measurements under different ice and wind conditions. The difference in readings is within ±0.077 mGal, with a mean value of 0.002 mGal — acceptable, considering the large oscillations of Figure 4. These oscillations are mainly the result of wind on the open lake causing vibrations on the ice, with periods on the order of 3–10 s. Leveling problems from tilt movement can be ruled out, because these are eliminated by the automatic tilt correction during measurement (equation 2).

After we applied the terrain correction to both data sets (old and new), they merged smoothly. The negative amplitude of the original 15-mGal anomaly was reduced to 9 mGal, and its dimensions were better constrained by the improved sampling (Figure 7). The anomaly no longer appears perfectly circular but rather takes a more elongated (north-south) shape that coincides more closely with the elongated anomaly associated with the east side of the Sudbury structure. The central depression in gravity also coincides more closely with the location of the proposed meteorite impact crater within the central part of the lake (L'Heureux et al., 2005). Meteorite impact craters typically have circular anomalies of about 5–8 mGal when of the same diameter as this crater (Pilkington and Grieve et al., 1992). This is a result of the low-density contrast induced by the fractured basement underneath the crater and the usually low-density postimpact sedimentary infill.

To use this technique for applications that require better accuracy, such as reservoir monitoring or 4D gravity measurements, longer measurements are desirable, as confirmed by Brady et al. (2002). Recordings should also be repeated often to increase the S/N ratio.

Table 2. Measurement repeatability. Repeatability of the gravity measurements from day to day; *g* is the final terrain-corrected Bouguer anomaly, and *dg* is the difference between repeats.

Station	*g* (mGal)	*dg* (mGal)
101	−32.515	
	−32.519	−0.004
	−32.518	0.001
111	−39.009	
	−39.050	−0.041
205	−39.476	
	−39.418	0.058
11	−33.922	
	−33.940	−0.018
801	−32.546	
	−32.529	0.017
810	−34.444	
	−34.521	−0.077
2007	−43.409	
	−43.332	0.077
Minimum		−0.077
Maximum		0.077
Mean		0.002
Standard		0.050

According to Hare et al. (1999), water injection in a reservoir will produce a 0.1-mGal gravity anomaly after five years and a maximum of 0.18–0.25 mGal after 15 years. Fujimitsu et al. (2000) have detected a residual gravity decrease of 0.04 mGal at the production zone of the Takigami geothermal field (Japan), attributable to the flow of underground geothermal fluids. Therefore, 4D gravity on ice for reservoir monitoring is feasible, but calm winds, long time-series recordings, and repeated measurements are mandatory.

As in the case of land gravity, proper terrain correction is critical to eliminate the topographic component from the measured anomaly. In this case, bathymetry mapping with a resolution comparable to the gravity stations' spacing is imperative.

The improved capabilities of systems like the CG-5 have proved to be highly valuable in acquiring gravity data on ice. However, if such a system is not available, the same required conditions as demonstrated by Brady et al. (2002) apply, in which four gravity surveys over ice were accomplished in the same area that tested an EDCON Super-G meter, a Scintrex CG-3M, and a Micro-g Solutions A-10 absolute gravimeter. To improve the data repeatability to ±0.008 mGal, at least three readings were obtained at each location in calm weather conditions, where each reading consisted of one-minute intervals and subsequently were averaged over a 10-minute period for most stations (Brady et al., 2002).

CONCLUSIONS

Our study has shown that gravity surveys on ice provide data as accurate as surveys on solid ground. Modern gravimeters such as the CG-5 offer the opportunity to evaluate noise on site, enabling the user to assess the resolution and quality of data as the survey is being carried out. This in turn provides the ability to collect more accurate and quality-controlled data. Despite small variations caused by moving ice and wind, the data collected on Lake Wanapitei was smoothly integrated with past measurements on ice as well as data from stations on the lakeshore and islands. The ideal conditions for collecting gravity data on ice are similar to those of surveying on ground: Calm winds are needed to reduce noise in tilt and from shifting ice. Under those circumstances, a production rate of 20–30 stations/day was easily accomplished, depending on temperature conditions: Warmer temperatures make ice too soft for snowmobile travel between stations, and extreme cold makes the ice crack and therefore increases signal noise.

The new gravity map has constrained the anomaly over Lake Wanapitei to one whose size and amplitude better fit the nature of the 7-km-diameter meteorite impact crater. Further modeling of the newly acquired data set, integrated with other geophysical data, will allow for better constraint on the size of the impact structure and its effect on local densities.

ACKNOWLEDGMENTS

The Whanapithae First Nation provided valuable logistic support in the different stages of this study. We thank Erick Adam, who participated in data collection during the first survey in 2003, and Diane Jobin, who computed the terrain correction for the entire data set at the Geological Survey of Canada. Associate editor John Peirce and three anonymous reviewers provided helpful comments on a previous version of the manuscript. H. U. and E. L'H. are supported by the National Sciences and Engineering Research Council of Canada.

REFERENCES

Brady, J. L., J. F. Ferguson, J. E. Siebert, T. Chen, J. L. Hare, C. L. Aiken, F. J. Klopping, and J. M. Brown, 2002, Surface gravity monitoring of the Gas Cap Water Injection Project — Prudhoe Bay, Alaska: 78th Annual Conference, SPE, paper 77513 .

Dence, M. R., and J. Popelar, 1972, Evidence for an impact origin for Lake Wanapitei, Ontario, *in* J. V. Guy-Bray, ed., New developments in Sudbury geology: Geological Association of Canada Special Paper 10, 117–124.

Dence, M. R., P. B. Robertson, and R. L. Wirthlin, 1974, Coesite from the Lake Wanapitei crater, Ontario: Earth Planetary Scientific Letters, **22**, 118–122.

Dressler, B. O., 1982, Geology of the Wanapitei Lake area, district of Sudbury: Ontario Geological Survey Report 213, Ministry of Natural Resources.

Dressler, B. O., D. Crabtree, and B. C. Schuraytz, 1997, Incipient melt formation and devitrification at the Wanapitei impact structure, Ontario, Canada: Meteorite Planetary Science **32**, 249–258.

Fairhead, D., and M. Odegard, 2002, Advances in gravity survey resolution: The Leading Edge **21**, 36–37.

Fujimitsu, Y., J. Nishijima, N. Simosako, S. Ehara, and K. Ikera, 2000, Reservoir monitoring by repeat gravity measurements at the Takigami geothermal field, central Kyushu, Japan: World Geothermal Congress, Proceedings, 573–577.

Grieve, R. A. F., and T. J. Ber, 1994, Shocked lithologies at the Wanapitei impact structure, Ontario, Canada: Meteoritics **29**, 621–631.

Hare, J. L., J. F. Ferguson, C. L. Aiken, and J. L. Brady, 1999, The 4-D microgravity method for waterflood surveillance: A model study for the Prudhoe Bay reservoir, Alaska: Geophysics **64**, 78–87.

Hoover, D. B., D. P. Klein, and D. C. Campbell, 1995, Geophysical methods in exploration and mineral environmental investigations, *in* E. du Bray, ed., Preliminary compilation of descriptive geoenvironmental mineral deposit models: USGS Open-File Report 95-831, 19–27.

L'Heureux, E., 2003, Experimental studies of an impact structure: Processing and interpretation of magnetic and seismic data over Lake Wanapitei: M.S. thesis, University of Toronto.

L'Heureux, E., H. Ugalde, B. Milkereit, J. Boyce, W. A. Morris, N. Eyles, and N. Artemieva, 2005, Using vertical dikes as a new approach to constraining the size of buried craters: An example from Lake Wanapitei, Canada, *in* T. Kenkmann, F. Hörz, and A. Deutsch, eds., Large meteorite impacts III: Geological Society of America Special Paper 384, 43–50.

Pilkington, M., and R. A. F. Grieve, 1992, The geophysical signature of terrestrial impact craters: Review of Geophysics, **30**, 161–181.

Rupert, J., 1991, Triter: A gravitational terrain correction program for IBM compatible personal computers: Geological Survey of Canada Open File 1834.

Styles, P., 2003, Environmental geophysics: A site characterization tool for urban regeneration in the post-mining era: Geology Today **19**, no. 5, 173–178.

Telford, W. M., L. P. Geldart, and R. E. Sheriff, 1990, Applied geophysics: Cambridge University Press.