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Open File

GRAVITY SURVEY OF THE COCAGNE-BUCTOUCHE-RICHIBUCTO AREA, (PARTS OF NTS 21 I/02, 03, 06, 07, 10 & 11) EASTERN NEW BRUNSWICK

J. Evangelatos and K.E. Butler

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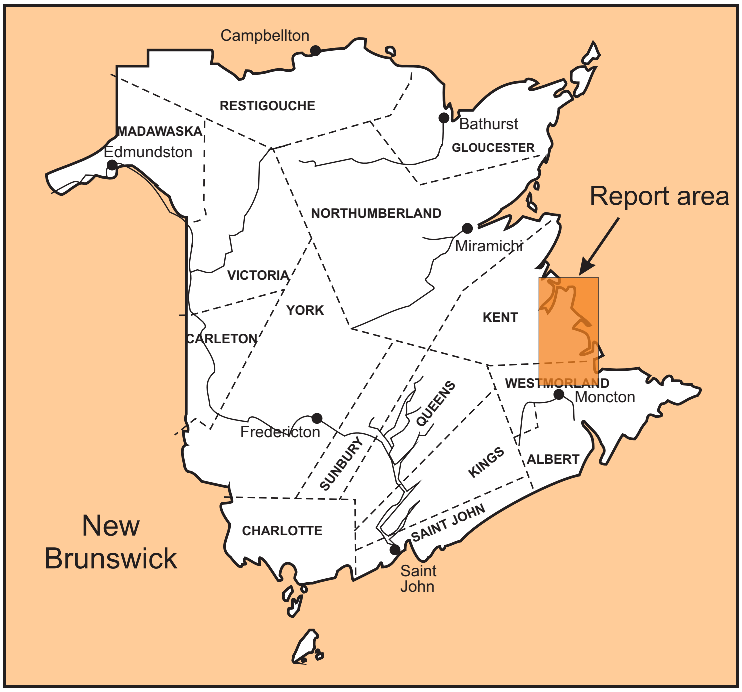

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Gravity Survey of the Cocagne-Buctouche-Richibucto Area, (parts of NTS 21 I/02, 03, 06, 07, 10 & 11) eastern New Brunswick

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DIGITAL DATA ON DVD-ROM

- Folder “Cocagne2009_GPS” containing raw GPS data (RINEX ASCII text files, filenames ending with “09o”).
- Folder “Cocagne2009_Gravity” with daily traverse files containing raw gravity readings and post-processed GPS data in format suitable for input to *PCGrav* (ASCII text files, filenames ending with “0XX”, where “XX” represents a number that corresponding to the traverse day).
- ASCII text file “2009203ALL.OUT” containing reduced gravity observations as output by *PCGrav* and referenced to NAD27 geographic coordinates.
- ASCII text file “2009203ALL.LIS” containing additional information output by *PCGrav*, including the Earth tide correction applied to each measurement and the closure error for each gravity traverse (i.e., each survey day). Information is segregated by traverse day.
- MS Excel (2003) spreadsheet “GravityTraverseClosureErrors.xls” summarizing and analyzing the daily gravity traverse closure errors given in file “2009203ALL.LIS” described above.
- MS Excel (2003) spreadsheet “GPS-GravityFiles_notes.xls” containing the names of all the GPS filenames. Filenames created by the GPS rover, listed in the worksheet named “GPS Rover” have corresponding gravity stations, antenna heights, instrument heights, traverse day numbers, date of acquisition, and other pertinent survey information. Filenames created by the GPS base, listed in the worksheet named “GPS Base”, have corresponding antenna heights, traverse day numbers, date of acquisition, and other pertinent survey information.
- MS Excel (2003) spreadsheet “Previouspoints.xls” containing old gravity data points located within the survey area. Points that were merged with the new data are listed in the worksheet named “Included”, while previous points excluded from the gridding process are found under “Excluded.”
- Folder “Geosoft files” containing a Geosoft database file “Cocagne_2009_GSD_NBDNR.gdb” and Geosoft grid (“.grd”) files of terrain-corrected Bouguer anomaly gravity and its vertical gradient as shown in Figures 9–11.
- Folder “Surfer files” containing Surfer grid (“.GRD”) files of terrain-corrected Bouguer anomaly gravity and its vertical gradient as shown in Figures 9–11.
- MS Word (2003) document “CGSN_site_descriptions.doc” containing control station descriptions and photographs as per the GSD standards.

ABSTRACT

A regional, land-based gravity survey was undertaken in the Cocagne-Buctouche-Richibucto region of eastern New Brunswick to better define multiple northeast trending gravity anomalies within the Maritimes Basin that intersect the Northumberland Strait subperpendicular to the coastline. The Cocagne Subbasin, thought to be a graben-like structure hosting Late Carboniferous formations at depth, is evident as a well-defined gravity low in the southern part of the survey area. The purpose of the survey was to improve resolution of the northeast-trending gravity anomalies by adding new gravity stations, and, concurrently, to assess the quality of old datasets.

A total of 708 gravity stations were established between October 3rd and December 17th, 2009 using a Scintrex CG-5 gravimeter and a pair of high-precision dual frequency GPS receivers for positioning. The targeted station spacing was approximately 1 km, but coverage was coarser in areas with restricted road access and denser along profiles of particular interest. The survey extended over an area measuring approximately 54 km along the Northumberland Strait coast reaching between 11 km and 23 km inland, covering ~ 1000 km^2. Repeated gravity and GPS observations attest to a high degree of precision (± 0.01 mGal standard deviation) in the reduced Bouguer anomaly values. Data reduction entailed standard corrections including scaling, instrumental drift, Earth tide, free air, Bouguer slab, and terrain. The acquisition and processing of the gravity survey followed the standards of the Geodetic Survey Division of Natural Resources Canada and the data are to be integrated in the Canadian Gravity Standardization Network (CGSN) database.

Comparison of Bouguer anomaly and vertical gradient maps based on old data, new data, and their combination reveals the substantial improvement in resolution and noise reduction afforded by the latest GPS and gravimetric technology. This study shows that, overall, the old data can be successfully integrated with the new, more precise data, provided that efforts are made to identify and remove old points that deviate strikingly from the Bouguer anomaly field yielded by the new data.

Results of this survey suggest that the Belleisle Fault should be repositioned about 5 km north of its current location to coincide with an abrupt change in the vertical gravity gradient. The trajectory of the Belleisle Fault was previously extrapolated through this area along a prominent magnetic anomaly that is now recognized to run along the axis of the Cocagne Subbasin gravity low. The presence of a fault near this trajectory is supported by gravity data. However, it is suggested that this fault be referred to as the Cormierville Fault, allowing the Belleisle Fault to retain its originally defined significance as the southern margin of the New Brunswick Platform in this area and elsewhere to the southwest.

RÉSUMÉ

Un levé gravimétrique régional au sol a été réalisé dans la région de Cocagne-Bouctouche-Richibucto, dans l'est du Nouveau-Brunswick. Ce travail avait pour objectif de mieux définir les multiples anomalies gravimétriques orientées vers le nord-est dans le bassin des Maritimes et qui entrecoupent le détroit de Northumberland de manière sous-perpendiculaire par rapport au littoral. On avait cru initialement que le sous-bassin de Cocagne était une structure apparentée au graben qui abritait en profondeur des formations de la fin du Carbonifère. Il apparaît de manière manifeste sous forme de creux gravimétrique bien défini dans la partie sud du secteur étudié. Le levé visait à mieux définir les anomalies gravimétriques orientées vers le nord-est par l'ajout d'autres stations gravimétriques, et à évaluer par la même occasion la qualité des ensembles de données existantes.

En tout, 708 stations gravimétriques ont été établies entre le 3 octobre et le 17 décembre 2009 à l'aide d'un gravimètre Scintrex CG 5 et de deux récepteurs GPS de grande précision bifréquence, pour le positionnement. L'espacement recherché entre les stations était d'environ 1 km, mais dans certains secteurs où l'accès par la route était difficile, la couverture était plus éparse, tandis qu'elle était plus resserrée dans l'axe des points qui revêtaient un intérêt particulier. Le levé a été réalisé dans une bande d'une longueur d'environ 54 km, le long de la côte du détroit de Northumberland et d'une largeur comprise entre 11 et 23 km à l'intérieur des terres, soit une superficie de plus ou moins 1 000 km2. Les observations gravimétriques et par GPS répétées ont permis d'obtenir un grand degré de précision (± 0,01 mGal d'écart type) dans les valeurs d'anomalie corrigées de Bouguer. La correction de données a comporté des corrections standard comme la mise à l'échelle, la dérive instrumentale, la marée terrestre, l'atmosphère libre, la plaque de Bouguer, et le terrain. L'acquisition et le traitement des données du levé gravimétrique ont respecté les normes de la Division des levés géodésiques de Ressources naturelles Canada. Ces données doivent être intégrées dans la base de données du Réseau de normalisation canadien de la gravimétrie (RNCG).

La comparaison des anomalies de Bouguer et des cartes de gradients verticaux à la lumière des données existantes, des nouvelles données et de leur regroupement, rend compte des importantes améliorations rendues possibles dans la définition et la réduction du bruit grâce à la technologie la plus récente des GPS et de la gravimétrie. Cette étude révèle que dans l'ensemble, il est possible d'intégrer avec succès les anciennes données aux nouvelles données, plus précises, dans la mesure où des efforts sont consentis pour repérer et éliminer les vieux points dont les coordonnées sont aberrantes par rapport au champ d'anomalies de Bouguer établi par les nouvelles données.

Les résultats de ce levé portent à croire qu'il faudrait déplacer la faille Belleisle à environ 5 km au nord de son emplacement actuel, de manière à la faire correspondre au brusque changement observé dans le gradient gravimétrique vertical. Auparavant, le tracé de la faille Belleisle dans cette région avait été extrapolé dans l'axe d'une anomalie magnétique importante qui, selon une récente découverte, est parallèle à l'axe du creux gravimétrique du sous-bassin de Cocagne. La présence d'une faille à proximité de ce tracé est corroborée par les données gravimétriques. Toutefois, il est suggéré de nommer plutôt cette faille la faille Cormierville, ce qui permettrait ainsi à la faille Belleisle de conserver son importance initiale en tant que marge méridionale de la plate-forme du Nouveau-Brunswick dans cette région et ailleurs dans le sud-ouest.

INTRODUCTION

Background and Previous Work

In eastern New Brunswick, bedrock geology largely consists of clastic sedimentary rocks of the Early Carboniferous Pictou Group and offers few clues about the underlying structures defining the geometry and thickness of the Martimes Basin adjacent the Northumberland Strait (Fig. 1). Regional aeromagnetic and ground gravity data, however, indicate the presence of major northeast-trending structures in the crystalline basement that can be linked to faults and structures evident in older sediments and basement rocks exposed at surface southwest of the report area (e.g., Belleisle Fault). The gravity survey discussed in this report was designed to improve definition of these buried structures over the eastern end of the Cocagne Subbasin where the Martimes Basin is locally thickened and over adjoining areas of the New Brunswick Platform to the north where the sedimentary cover is thought to be much thinner.

The Cocagne Subbasin, extending from central to eastern New Brunswick, is one of several subbasins separated by basement uplifts underlying the Martimes Basin (Fig. 1). It hosts the Early Devonian–Late Carboniferous Horton Group, and the Late Carboniferous Sussex, Windsor and Mabou groups, which are unconformably overlain by the Early Carboniferous Cumberland and Pictou groups (St. Peter 2006). The Cocagne Subbasin is divided in two by the Smith Creek Fault. The northwestern panel is buried beneath Early Carboniferous cover and coincides with a gravity low. The southeastern panel, which is bounded to the south by the North River Fault contains exhumed Horton Group rocks and is also considered to be part of the Indian Mountain Deformed Zone (St. Peter and Johnson 2009). The New Brunswick Platform lies to the north of the Cocagne Subbasin. It is reported to have thin sedimentary cover composed of the Early Carboniferous Mabou and Pictou groups (St. Peter and Johnson 2009).

Old gravity data in the report area, which encompasses the entire area shown in Figure 2, can be categorized into two general populations:

- In the 1960s and 1970s, the Earth Physics Branch of the Dominion Observatory, Ottawa, conducted surveys along a grid pattern with an approximate station spacing of 5 km by 5 km, with elevations were measured predominantly by barometric altimetry (±3 m precision). Elevations along roads were generally derived from optical levelling relative to benchmarks (±0.03 m precision). These datasets are assigned the names 1964025, 1968108, and 1974106 by the Geodetic Survey Division (GSD) of Natural Resources Canada (NRCAN).

- In the 1970s and 1980s, dense sampling along highways was sponsored by the New Brunswick Department of Natural Resources (NBDNR) in collaboration with the Canadian Department of Regional Economic Expansion (DREE), and by private industry. Summaries of those surveys (GSD datasets 780005, 79005, 80005, 82005, 83005, and 84005) can be found in reviews by (Hassan 1996, 2000).

Prior to this survey, the available regional Bouguer anomaly gravity maps, based on the digital compilation of Hassan (2000), showed alternating gravity highs and lows striking subperpendicular to the Northumberland Strait (Hassan 1999; Allard and Rennick 2009). The

Figure 1. Distribution of Late Devonian–Carboniferous uplifts and subbasins in the Maritimes Basin of eastern New Brunswick (modified after St. Peter 2006; St. Peter and Johnson 2009), as well as the location of present-day oil, natural gas, and potash/salt producers. Inset map shows the area of the Maritimes Basin in eastern Canada.

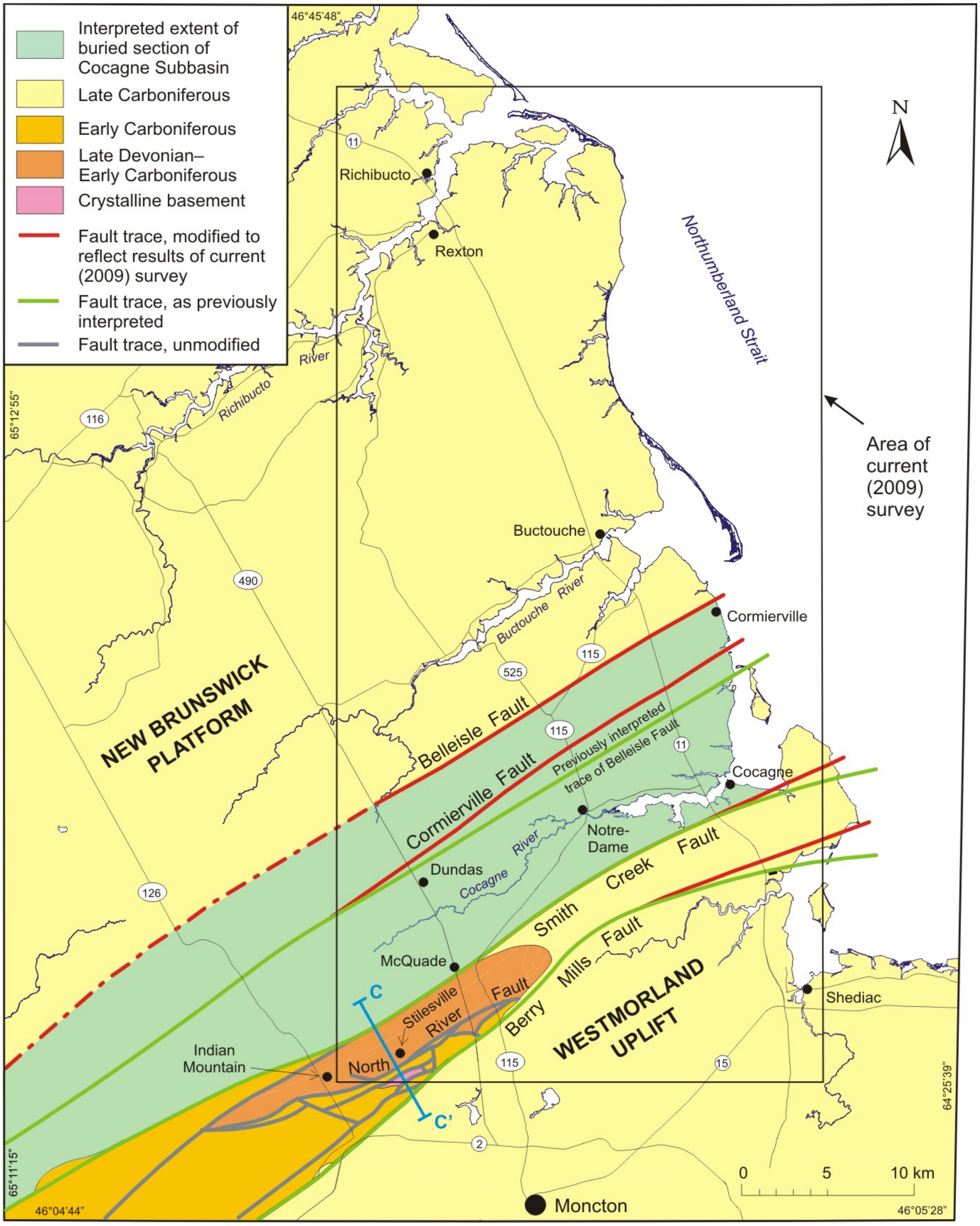

Figure 2. Simplified geology map of the report area (modified after Smith 2008), showing limits of the survey area. C–C' marks the line of section across the Indian Mountain Deformed Zone, illustrated in St. Peter and Johnson (2009, their Fig. 85). Figure 1 indicates the location of the report area in eastern New Brunswick.

lack of interpretation for these anomalies is likely due to scarce bedrock exposure and limited drilling in the region.

Objectives

Similarities between its stratigraphy and that of the Moncton Subbasin, which is known for its historical and present-day reserves of oil, natural gas, and potash, make the Cocagne Subbasin a prospective region for hydrocarbon and evaporite deposits. One objective of this survey was to contribute a high quality gravity dataset to the sparse background geoscience data available for the Cocagne Subbasin. A second objective was to provide improved definition of prominent northeast-trending gravity anomalies present in the old gravity data to gain a better understanding of the underlying basement structures and sedimentary cover thickness in the survey area. This Open File report encompasses a detailed description of the gravity data acquisition and processing methods, a comparison of the quality of the new data relative to existing data in the area, and a brief discussion on the geological implications of this work. Evangelatos and Butler (2010) elaborate on the latter.

DATA ACQUISITION

Survey Design and Location

The Cocagne Subbasin and adjoining areas to the north were selected as the focus for this project in consultation with geologists at the Geological Surveys Branch of the New Brunswick Department of Natural Resources (NBDNR-GSB). Survey planning took place at the Fredericton office of the DNR in late September, 2009. It was decided that acquisition would begin in the Cap-de-Cocagne area (46°18’42” N, 64°34’19” W) and progress approximately 50 km northward along the coast to Richibucto covering a band extending approximately 20 km inland. A nominal spacing of 1 km was agreed upon. Efforts were made to ensure that the newly acquired data met Geodetic Survey Division (GSD) standards for quality so that it would be integrable with the national database.

Personnel

The project was directed by Karl Butler of the Department of Geology at the University of New Brunswick (UNB). John Evangelatos, former M.Sc. student of Butler, was hired to lead the field operations, process the data, and carry out preliminary interpretation and modelling. Evangelatos received instructions on operating the gravimeter from Carey Gagnon at the GSD’s office in Ottawa. GSD personnel Jacques Liard, Diane Jobin and Philip Salib provided additional technical advice and training in the use of their *PCGrav* software for reduction of the gravity observations.

Heather Campbell, also a former M.Sc. student at UNB, was hired as a second field operator. During Evangelatos’ scheduled leave of absence between October 19th and December 3rd 2009, Campbell assumed the leading role, and was aided by Holly Stewart from NBDNR-GSB. Matthew McAdam, an undergraduate from UNB’s Department of Geodesy and Geomatics Engineering, provided training in GPS data acquisition and in the standard differential GPS data processing used by Evangelatos to locate each gravity station relative to one of four GPS base stations distributed across the survey area. McAdam determined locations for these GPS base stations using a network adjustment procedure based on simultaneous GPS observations from three permanent GPS stations in the New Brunswick Active Control Network (discussed in more detail below).

Serge Allard, Paul Rennick, Steven Hinds, and Tim Webb from NBDNR-GSB assisted technically and logistically through the provision of geological advice, maps, and other information about the survey area.

Instrumentation

Surveying was carried out using a state-of-the-art relative gravimeter, along with a pair of dual-frequency GPS receivers for the measurement of station locations and heights. The main items of equipment used during the field survey were as follows:

– One Scintrex CG-5 gravimeter, #X0490 (on loan from the GSD, NRCAN).
– Two Trimble 5700 dual frequency GPS receivers (on loan from the Department of Geodesy and Geomatics Engineering at UNB).
– One Trimble Zephyr GPS antenna (used with the roving GPS receiver).
– One Trimble Micro-centered L1/L2 GPS antenna (used with the base GPS receiver).
– One Tripod for the GPS base.
– One Bipod for the GPS rover.
– One hand-held Garmin GPS (model GPS76CSx), with digital topographic maps (used to help navigate and locate points at desired station spacing).
– One notebook computer running *Trimble Geomatics Office* software.

Survey Procedures and Distribution of Gravity Data

Position Measurement (GPS Surveying)

To achieve high precision (≤0.01 mGal) in our Bouger anomaly values, we aimed for a precision of ellipsoidal heights of ±5 cm, thereby remaining within the 10 cm error margin expected of GSD standard gravity measurements. To this end, we employed the “rapid-static” method of GPS surveying, which required two sets of GPS equipment (Santos et al. 2000). While the GPS base station recorded continuously from a fixed location, a second set (the rover) operated alongside the gravimeter and travelled with it from one station to the next. On advice from professor Marcelo Santos, at UNB’s Department of Geodesy and Geomatics Engineering, the GPS rover did not stray more than approximately 10 km of the GPS base and recorded at least 10 minutes of data at each gravity station. When stations were occupied beyond the desired 10 km radius from the GPS base (e.g., at a maximum of about 16 km north of Richibucto) the GPS rover collected data over a longer period to help compensate. Four different GPS base stations (not to be confused with the gravity base stations) were established to cover the desired survey area. The GPS base stations were located in open fields or lawns with unobstructed views of the sky and (for security purposes) within view of the homes of property owners who had agreed to their temporary emplacement. Both receivers were configured to sample at 1 Hz with an elevation mask angle of 10 degrees above the horizon.

The GPS base station was assembled each morning using a tripod and tribrach to position the antenna precisely above a wooden stake set in to the ground at one of the four base locations. The centre of a screw inserted into the top of the stake was used as the reference point. Heights between the screw and the antenna were measured twice a day: once during setup, and again just prior to disassembly. The height of the stake above ground surface was also verified daily. GPS observations were stored in the GPS receiver, which was powered by a 12 V marine battery (Fig. 3).

The antenna of the GPS rover was mounted on a range pole supported by a bipod that was easy to set up adjacent to the gravimeter during the occupation of a gravity station (Fig. 4). The height of the antenna was read using a tape measure and recorded in a GPS field book (distinct from the gravimeter field book provided by the GSD). Ideally, the ground between the rover and gravimeter would be perfectly horizontal to avoid bias in the vertical measurement. In practice, this was not always possible in the field and small adjustments (usually ±1 cm) were added to compensate.

GPS data from the base and rover receivers were downloaded and post-processed together, using *Trimble Geomatics Office* software, every evening to assure quality. Final processing of the GPS data to establish precise station coordinates took place after the field work was completed, as described below.

Figure 3. GPS base station #1. Note wooden stake beneath the antenna. The blue bin contains the yellow GPS receiver and a DC-AC inverter eventually replaced by a direct DC connection.

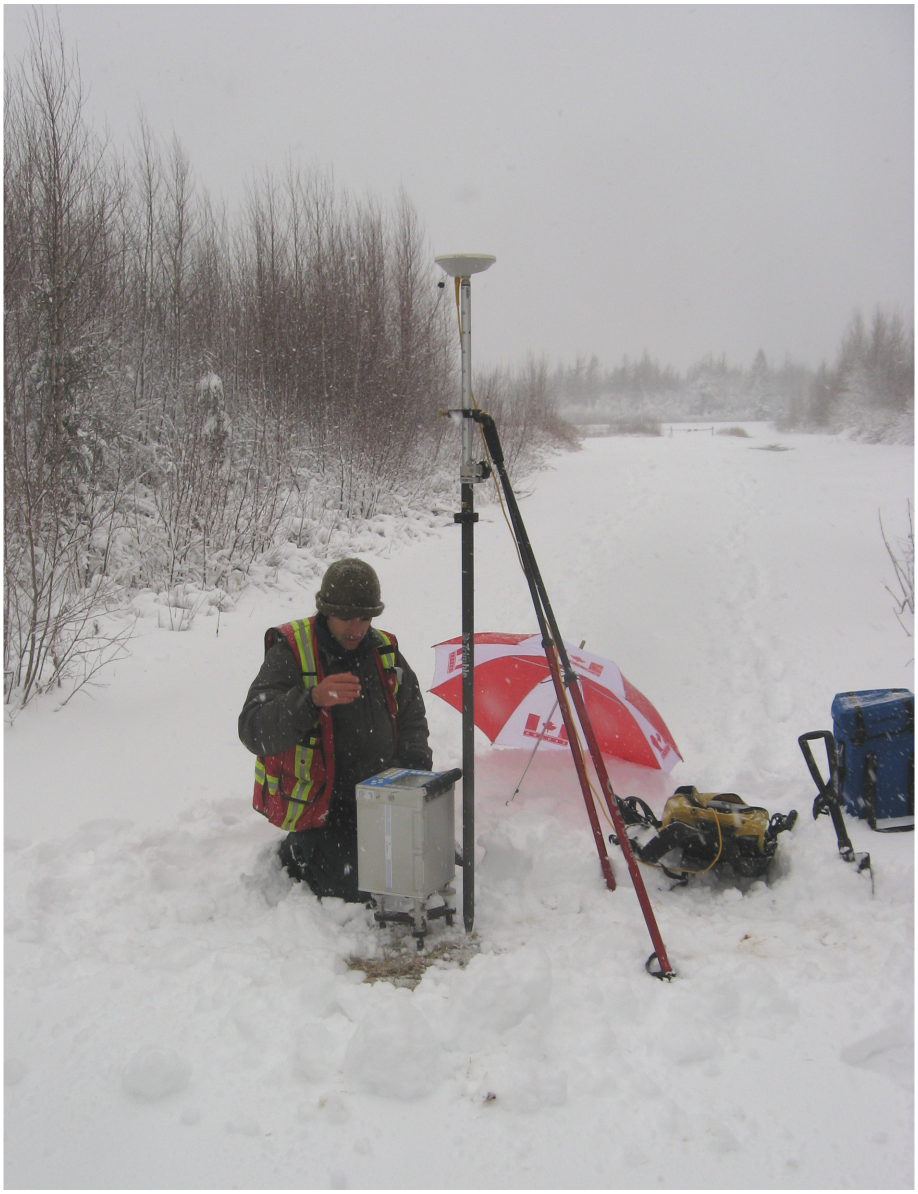

Figure 4. GPS rover antenna and CG-5 gravimeter shown during acquisition.

Gravity Measurement

A single Scintrex CG-5 gravimeter (GSD# X0490) was used for the duration of the survey. It was a relative gravity meter with a reading resolution of 0.001 mGal and, according to the manufacturer, a field repeatability of better than 0.01 mGal standard deviation (Scintrex Limited 2006). It was deployed on a specially designed tripod, about 18 cm tall, with legs that were easily adjusted for levelling. Most gravity measurements were acquired on the shoulders of paved roads; whether primary or secondary highways or residential streets. The surface where the gravimeter was set in these situations was either asphalt or a hardened mix of silty mud and pebbles/gravel. When surveying in backroad environments, the gravity station was set up on the road itself as this generally provided a more compact surface and better exposure of the sky (and hence GPS satellites). When soft ground was encountered (e.g., grass field, moss), the tripod was pushed as far into the earth as possible, before setting the gravimeter. The same procedure was repeated with snow, with the added work of shoveling down to surface to estimate the thickness of snow. Tilting of the gravimeter's base with respect to a horizontal plane was measured and stored internally as TiltX and TiltY in arcseconds. During surveying, if the ground did not readjust under the weight of the meter, it was usually possible to level the meter to within 10 arcseconds. A tilt correction was calculated automatically by the gravimeter and applied to the stored average gravity reading.

At each station, the height of the gravimeter was measured and recorded in a gravity field book issued by the GSD. This height corresponded to the distance between the ground and the gravimeter's levelling plate, which is located at the base of the gravimeter's enclosure. The rover GPS antenna was erected on a range pole and bipod adjacent to the gravimeter. Oftentimes, several gravity readings (i.e., 120 s averages as described below) would be taken at a given station, but only those with the lowest number of rejected points, standard deviation and off-tilt values would be preserved. In general, one reading was stored per station. Topography near the station was noted in the field book but not quantified.

The Scintrex CG-5 gravimeter was programmed to collect a time series of relative gravity over a time period of 120 s at a sampling frequency of 1 Hz. The seismic filter, a built-in function that reduces low frequency background noise during acquisition, was enabled throughout the survey. This function smoothed the 120 raw points using a tapered averaging window. The mean of these measurements was stored. Outliers[1], such as might occur when a heavy vehicle drove by or during intense gusts of wind, were automatically rejected and thereby excluded from the mean calculations. The mean gravity readings were time-stamped according to the mid-point of the recording time. Standard deviations, and temperature deviations (in mK) were saved along with the gravity recording. The automatic tide correction and terrain correction options were disabled.

All gravity readings, times of reading, standard deviations, gravimeter heights and commentaries were recorded in GSD field books 20 to 22, project#2009203. The gravity station numbers range from 2001 to 2731 and were collected between October 3rd and December 17th, 2009.

Gravity Station Distribution

The gravity data distribution for this project is shown in Figure 5. A spacing of 1 km was sought for this survey, but, due to limited road accessibility, this was not achieved. Snowfall in early December also impeded travel on arterial roads. The field vehicle used for most of the survey, an all-wheel-drive crossover type SUV (Ford Edge), allowed access to many backroads, but was lacking in ground clearance and tire tread. In December, that vehicle was replaced with a pickup truck with 4WD, which proved more suitable for both backroad travel and winter conditions. The most effective way to increase gravity station density in the survey area in the future would likely be to use an all terrain vehicle.

In addition to the regular grid spacing, gravity was measured every 250 m on Highway 11 over a length of 11.5 km, every 500 m on Highway 115 over 25.3 km, and again every 500 m on

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[1] Outliers are defined as measurements > 6 standard deviations from the mean when the seismic filter is activated, or 4 standard deviations when it is not (Scintrex Limited 2006).

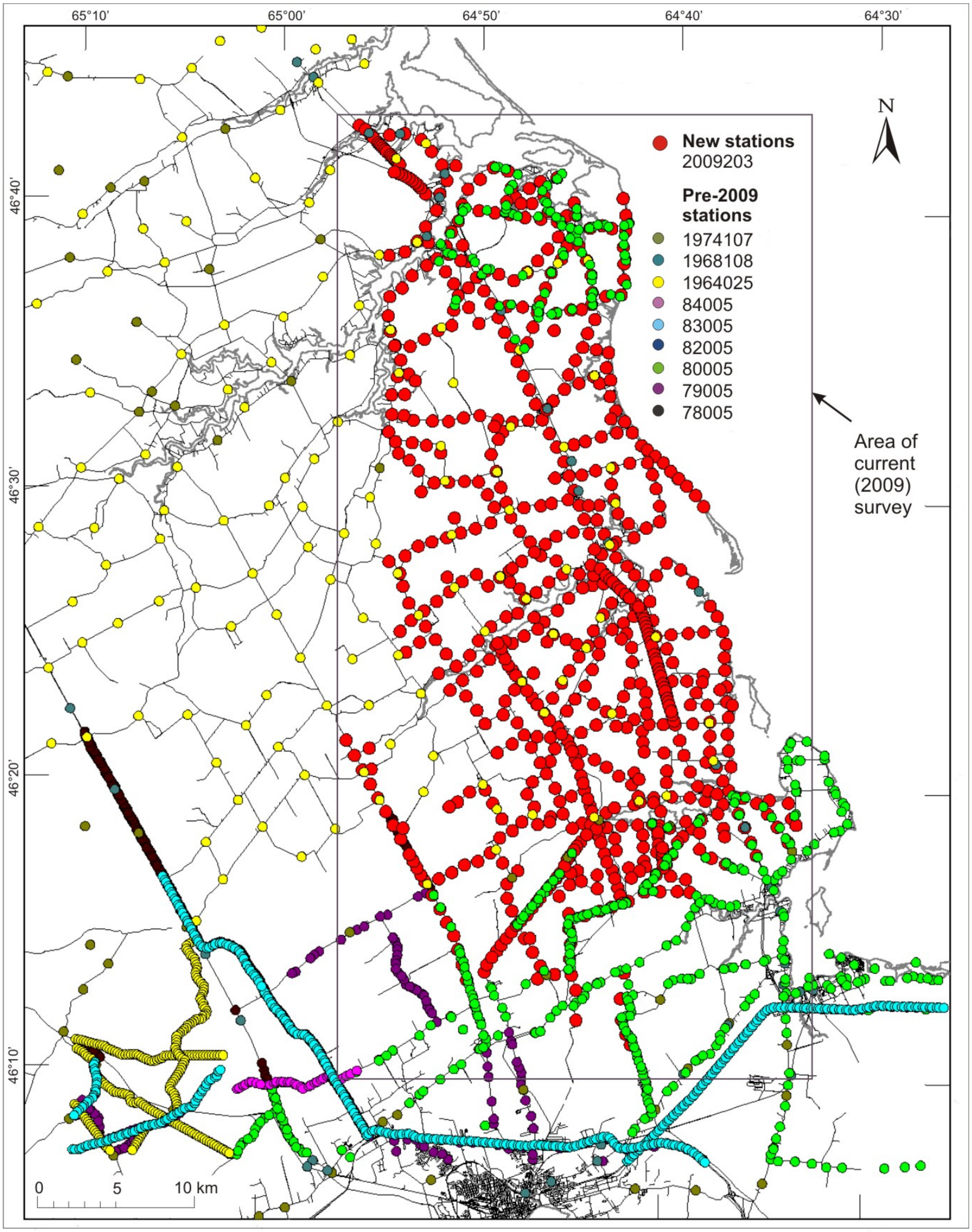

Figure 5. Map of the report area, showing distribution of the new and old gravity stations, numbered according to their Geodetic Survey Division database names. Large red dots indicate stations of the new (2009) survey. Figure 1 shows the location of the report area in eastern New Brunswick. NAD27 geographic coordinates are used in this map and in those that follow.

Falconer Road located just south of the Cocagne River. All of these high-density transects cross the Cocagne gravity low at or very near 90°. High-density sampling at ~ 250 m increments was also carried out west-northwest of Richibucto along de la Petite Rivière Road and Highway 11. The purpose of this high-resolution profile was to aid in identifying possible bedrock valleys or channels relevant to the groundwater flow regime in the area. In total, the team covered an area of approximately 1000 km^2.

Gravity Control

Gravity base stations were occupied at the beginning and end of each traverse day. This was done to correct for instrumental drift during later processing. Shorter loops were not closed during the day as the CG-5 gravimeter is designed to reliably exhibit constant, and therefore efficaciously corrected, drift (Scintrex Limited 2006). Existing stations from the Canadian Gravity Standardization Network (CGSN) could not be used as bases, because they were located too far from the survey area. As a result, four new gravity base stations were established for the project and added to the CGSN by tying them to the absolute gravity station in Shediac. Data for the gravity ties and absolute gravity values for these four stations are given in Appendix A. Detailed descriptions of the new stations are provided in the Word document “CGSN site descriptions.doc” found on the enclosed DVD-ROM.

DATA REDUCTION

GPS Data Reduction

The locations of the four GPS bases were calculated by post-processing their static GPS observations to determine baselines to three active control stations operated by Service New Brunswick (SNB) in Miramichi, Escuminac, and Moncton. A network adjustment process was then used to solve for a best-fit solution in each case. Details of this procedure are provided in Appendix B.

After fixing the locations of each GPS base, the baselines to the rover (gravity) stations were then calculated using the rapid-static post-processing method as implemented in the *Trimble Total Control* (*TTC*) software package. Precise satellite ephemerides, downloaded from the International GNSS Service (Dow et al. 2009), were incorporated into the final solutions. *TTC* exported coordinates in the International Terrestrial Reference Frame, ITRF 2005. Using an online program from NRCan’s website called *TRNOBS* the coordinates were re-projected to NAD83 (CSRS). Subsequently, elevations were transformed from ellipsoidal heights (heights above the reference ellipsoid) to orthometric heights (heights above mean sea level) using the HTv2.0 geoid model as implemented in program *GPS-Hv2*. Finally, positions were re-projected to NAD27 to comply with the GSD’s convention for gravity stations. This operation was done using a different NRCan online program named *NTv2*. Conversions from geographic to Universal Transverse Mercator (UTM) NAD27 coordinates were performed using NRCan’s *GSRUG* online program. All the aforementioned NRCan programs are available for on-line use or for download at www.geod.nrcan.gc.ca.

A total of 719 rover baselines, including 11 GPS repetitions, were successfully processed. Baselines for an additional 15 stations exhibited anomalously large uncertainties in *TTC*; gravity measurements taken at those stations were therefore excluded from the final dataset to avoid introducing unreliable Bouguer anomaly values. Some of these rejected stations were in areas with poor sky exposure.

While the rapid-static processing method provided estimates of positioning uncertainty, such estimates are known to be overly optimistic as they are based on sequential GPS observations relative to a single base that are subject to correlated errors (M. Santos, pers. comm., 2009). Better estimates of uncertainty were obtained by reoccupying 11 rover stations at later times as discussed in the second section following (Quality Control Analysis).

Gravity Data Reduction

PCGrav (VB512), a software program developed by the GSD, was used to reduce the gravity data. This process involved instrumental scaling, tide and drift corrections needed to compute absolute gravity at each station, and, finally, the calculation of free air and Bouguer anomalies. Subsequently, terrain corrections for distant topography (though not for inner Hammer Zones B and C) were computed for both the new data and old data in the survey area, using the Geosoft *Oasis montaj* software package with a digital elevation model (DEM) available from the GeoBase online database (www.geobase.ca). Details of these gravity data reduction steps are presented in Appendix C. Unless otherwise mentioned, the terrain-corrected Bouguer anomaly values (or CBA) are hereafter used for further data processing and map production.

QUALITY CONTROL

Repeatability of Gravity and GPS Measurements

Gravity stations were occasionally reoccupied, usually on a later day, to statistically evaluate the precision of our methodology. Gravity measurements were repeated in each case, while GPS observations were repeated less frequently owing to the longer time required to record them.

GPS repetition measurements are presented in Appendix D. The average discrepancy in repeat measurements of ellipsoidal height at 11 stations was very small with a mean of only 1.4 cm and a median of 1.1 cm. Even the maximum observed vertical discrepancy of 4.3 cm fell within our target range of ±5 cm. The average vertical uncertainty of 1.4 cm given here does not take into account potential errors in the heights of the four temporary GPS bases established for this survey. However, estimated uncertainties in those heights, as discussed in Appendix B were similarly small, ranging from 1.2 to 1.4 cm at the 95% confidence level.

One must further consider long wavelength uncertainties in the geoid model used to convert from ellipsoidal heights measured by GPS to the orthometric heights derived from traditional optical levelling used in older surveys when comparing the new Bouguer anomaly values to old data in the area. Huang et al. (2006), presenting a GSD-led study of regional geoid errors across Canada, has estimated this uncertainty at less than 3-4 cm in the region of our survey. This is encouraging as it would translate to a regional bias of less than 0.01 mGal in the combined Free Air and Bouguer slab corrections that would be calculated based on GPS-derived elevations versus the elevations derived from optical levelling.

Of the 708 new gravity stations that were established and found to be credible, 41 were reoccupied at least once at a different time, and usually at a later date. Two of them were reoccupied twice and one was reoccupied three times. Consequently, there were 45 repetitions for 754 observations or 6%. The histogram in Figure 6 shows that the overwhelming majority of repeat measurements (38 of 45) were within 0.01 mGal of the original measurement, in agreement with Scintrex's claim that the precision of the CG-5 model is ≤0.01 mGal standard deviation (Scintrex Limited 2006). Additional details on the gravity repetition process and a list of the repeated stations are provided in Appendix E.

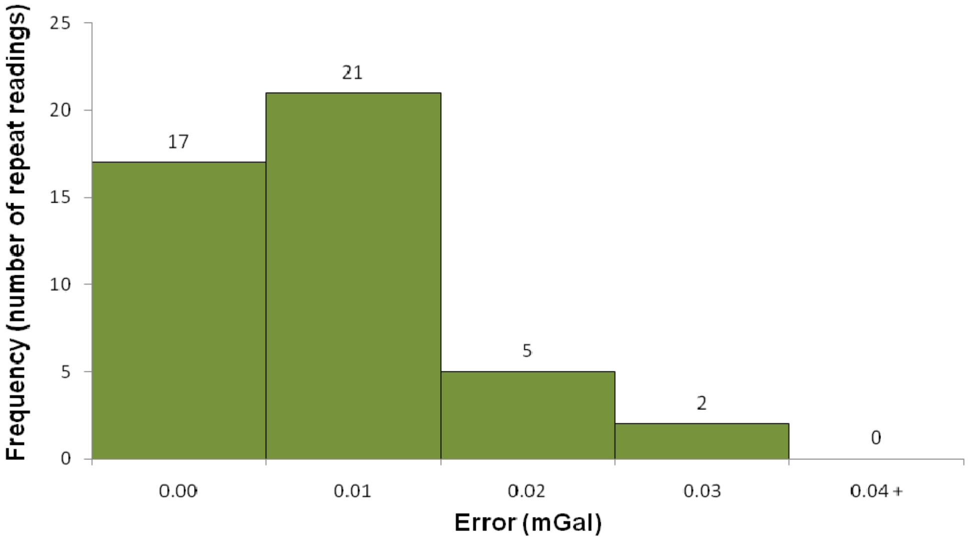

Figure 6. A histogram showing the frequency of the discrepancy in Bouguer anomaly values for 45 repeated stations. The mean error is 0.01 mGal.

Figure 7 graphically attests to the high quality of the data by showing clear definition of subtle residual Bouguer anomalies on a traverse crossing the Richibucto peninsula. The traverse was surveyed with relatively tight station spacing (~250 m) in a search for evidence of buried bedrock valleys that would be of interest for groundwater resources. This residual profile was calculated by removing a linear trend from the Bouguer anomaly values. The gravity low centered at ~5 km may be a consequence of the fact that measurements in that area were made along a portion of Hwy 11 that is built-up above surrounding boggy, low-lying land (an idea that could be tested by returning to the stations and using an inclinometer to make the measurements required for calculating terrain corrections for inner Hammer Zones B and C). However, the smaller gravity low (at ~2 km) cannot obviously be attributed to surface topography and could be indicative of a buried bedrock valley.

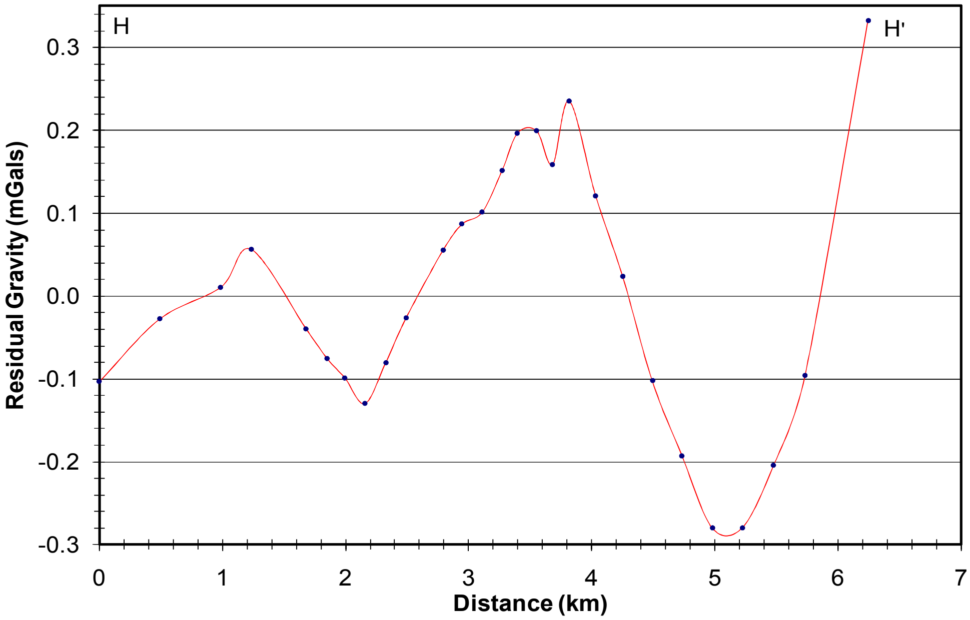

Figure 7. Subtle anomalies on the order of 0.1 mGal are well-defined by multiple stations in this detailed residual gravity profile crossing the Richibucto peninsula (line H-H' in Fig. 11).

Gravity Traverse Closure Errors

Closure errors as calculated by *PCGrav* refer to the difference between gravity readings taken at a base station at the start and end of each traverse day, after accounting for any changes in Earth tides, and instrument height (and taking the gravimeter's scale factor into account). The "drift correction" applied during gravity data reduction was calculated under the assumption that closure errors accumulated linearly with time over the course of each survey day. It is therefore relevant to plot the closure errors on a day by day basis and look for any anomalous values which might lead one to question the accuracy of the drift corrections applied on particular days.

Closure errors for each traverse (day) of the survey are given in the ASCII format file "2009203ALL.LIS" included with the digital data accompanying this report. These values were transcribed to an MS Excel spreadsheet called "GravityTraverseClosureErrors.xls" for further analysis. Figure 8a shows that closure errors for most days ranged from -0.05 to -0.2 mGal and that the typical closure error increased over the course of the survey from about -0.09 mGal in early October to -0.16 mGal by mid-December. Given that closure errors typically accumulate over the course of a day, some of the observed scatter in daily closure errors can be attributed to differences in survey day durations (typically 8 ± 1.5 hrs). Indeed, a plot of closure errors normalized by survey day durations shows significantly less scatter (Fig. 8b). It is interesting to note that the most anomalous closure error (-0.32 mGal on traverse day 38) occurred on the day of a magnitude 6.3 earthquake off the Queen Charlotte Islands, British-Colombia. The field operators also reported markedly higher standard deviations in the gravity readings on that day.

In the case of the CG-5 gravimeter, closure errors are expected to be dominated by two terms: (i) inaccuracies in the linear drift compensation that is applied internally within the gravimeter to

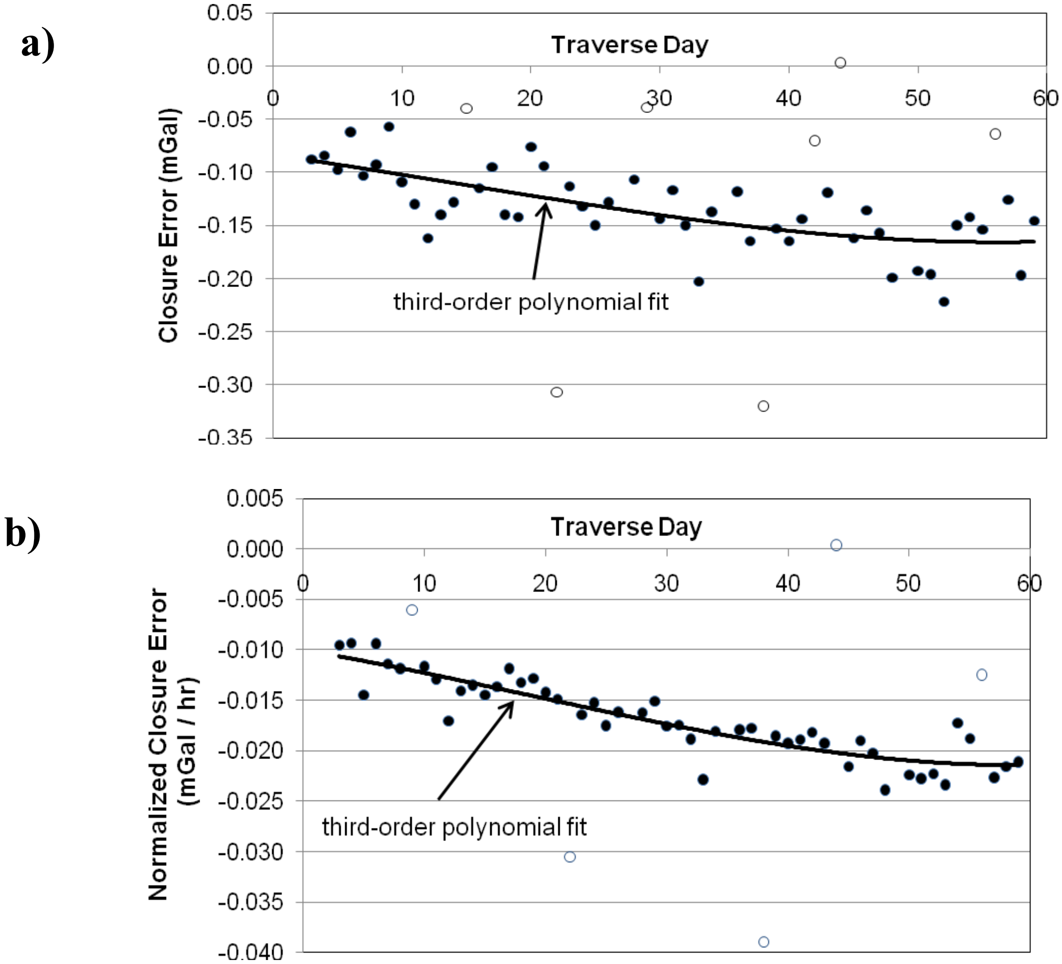

Figure 8. a) Observed gravity closure errors for the 57 active traverse days of the survey (days 3–59). The black line shows the third-order polynomial that best fits the trend of the data ignoring seven outliers (plotted as open circles). b) Closure errors show much less scatter when normalized by survey day durations, illustrating that they were dominated by linear drift of the gravimeter on all but a handful of days.

account for stress relaxation in the quartz spring, and (ii) so-called residual drift or tares associated with transportation or rough treatment of the gravimeter (Scintrex Limited 2006). The CG-5's internal drift compensation scheme is based on a "drift constant" (mGal per unit time) specified by the user. This constant should occasionally be checked and updated as stress relaxation effects in the spring diminish over time (Scintrex Limited 2006). While this constant would have been updated by GSD personnel prior to loaning us the gravimeter, we did not check or update it during our survey which ended three months later. With this in mind, we propose that the closure errors shown in Figure 8a can be interpreted as outlined below.

First, we infer that the average daily closure errors of 0.09 mGal to 0.16 mGal were the result of inaccuracy in the drift constant that was specified for the gravimeter's internal drift compensation algorithm. The results in Figure 8b suggest that the specified drift constant was initially in error by approximately 0.011 mGal/hr. This error increased to approximately 0.022 mGal/hr by the end of the survey, as the rate of stress relaxation in the quartz spring diminished over time. Fortunately, drift related to stress relaxation is known to be essentially linear on the time scale of a day (Scintrex Limited 2006). We can therefore expect that this component of the closure error was effectively removed by the linear drift correction applied during data reduction.

Secondly, day to day fluctuations in closure error about its long term trend are attributed partly to differences in the durations of the survey days (as demonstrated by the reduced level of fluctuation in Fig. 8b), and partly to the above-mentioned residual drift effects associated with physical stress on the meter during transportation. The transportation effects may not accumulate linearly during the course of a survey day. As a result, it is the difference between the observed closure errors and their long term trendline that is of most concern. An inspection of Figure 8a shows that this difference never exceeded 0.17 mGal and was less than 0.05 mGal for 50 of the 57 survey days.

Ultimately the precision of the Bouguer anomaly values derived from this survey is best represented in a statistical sense by 45 repeat measurements summarized in Figure 7. The closure error analysis presented here simply shows that there is potential for individual stations acquired on certain days to be in error by more than the discrepancies of 0.01 mGal to 0.03 mGal determined from those repetitions.

INTEGRATING PREVIOUS GRAVITY DATA

To improve spatial resolution and extend the report area westward of the 2009 survey area, data from the previous gravity surveys were combined with the new dataset. However, as nearly half of the old data was assigned an elevation uncertainty of ± 3 m (especially off-road measurements acquired using altimeters), it was necessary to filter this dataset prior to integration. This involved manually removing points that strikingly deviated from the smooth interpolated contour map produced using the new dataset alone. Survey project 81005, comprising 285 stations acquired in 1981, proved particularly incongruous with respect to data from other surveys, and was thus entirely excluded. Within the confines of the extended survey area, project 81005 is concentrated south of des Breau Road along Highway 11, on Shediac River/Cape Breton Road between Highways 11 and 115, and on Highway 490 south of Dundas. Despite having to exclude 327 previous points due to incompatibility, the integration of the old data proved successful. A complete list of the excluded points is provided in the spreadsheet file “Previous points.xls” on the accompanying DVD-ROM.

GRIDDING, 2D FFT PROCESSING AND MAP PRODUCTION

The terrain-corrected Bouguer anomaly (CBA) data were interpolated onto a grid using the kriging algorithm of *Oasis montaj*. The grid cell size was 400 m when using the new dataset or a combined set of new and old data. Due to a sparser station distribution (made sparser by the deletions discussed above) grids created from the old data alone were interpolated using a coarser node spacing of 800 m. Subsequently, the vertical gradient (i.e., the first vertical derivative) of the CBA was calculated using a 2D Fast Fourier Transform (FFT)-based algorithm within *Oasis montaj*. The CBA grid was low-pass-filtered using a cut-off wavelength of 1200 m prior to calculation of the vertical gradient in order to reduce short-wavelength noise and combat gridding artifacts in areas with wider station spacing. Nonetheless, caution is recommended when interpreting very short wavelength features, particularly in the vertical gradient maps. To this end, station locations are plotted on most maps so that the density of measurements supporting anomalies may be readily assessed.

RESULTS

As depicted in Figure 9, the improvements in defining Bouguer anomalies afforded by denser sampling, greater precision resulting from better elevation control, and the high resolution of the Scintrex CG-5 gravimeter, are substantial. These improvements are accentuated in maps of the vertical gradient of Bouguer anomaly gravity shown in Figure 10. In addition to validating past gravity observations, the enhanced signal-to-noise ratio in the new data reveals interesting features briefly discussed in the following section.

The Cocagne Subbasin is evident in the southern part of the Bouguer anomaly map as a 13 mGal northeasterly-trending gravity low (Fig. 11). The Belleisle Fault is defined as the southern boundary of the New Brunswick Platform and northern boundary of the Cocagne Subbasin in this area and elsewhere to the southwest (St. Peter and Johnson 2009). The trajectory of the Belleisle Fault previously extrapolated from surface exposure northeasterly along a pronounced magnetic anomaly (M. McLeod, pers. comm., 2010) is now recognized to bisect the better resolved Cocagne Subbasin gravity low (Evangelatos and Butler 2010). Both gravity and regional aeromagnetic data support the presence of a significant fault near this trajectory, which Evangelatos and Butler (2010) renamed the Cormierville Fault. This allowed the interpreted trace of the Belleisle Fault to be moved (4–5 km north of its previous location) to align with the abrupt change in the vertical gravity gradient demarcating the northwestern boundary of the Cocagne gravity low. Figure 12 shows the fault traces overlain on a colour-shaded grid of the CBA for the report area.

The Smith Creek Fault, which represents the southern margin of the buried part of the Cocagne Subbasin, roughly correlates with the southern limit of the Cocagne gravity low. As shown in Figure 2, the trace of this fault, like that of the Berry Mills Fault to the south, has been straightened near the coast to better agree with gravity trend. This is acceptable as there are no clear geological constraints on the positions of these faults. The nearest outcrops are Late Carboniferous in age and lie to the southwest in the exhumed part of the Cocagne Subbasin approximately 15 km inland (S. Johnson, pers. comm., 2010). Indeed, the straightened fault trends are more similar to those shown on recent geological maps of the Indian Mountain Deformed Zone (St. Peter and Park 2009; St. Peter and Johnson 2009). A summary of the modified fault trace interpretations resulting from analysis of the new gravity data is provided on the geological map given in Figure 2.

As presented and discussed in Evangelatos and Butler (2010), the depth and overall geometry of the Cocagne Subbasin was estimated using simple 2D forward modelling. The results suggest that, within the survey area, the subbasin is 3 km to 4 km deep north of the Cormierville Fault, and 2 to 3 km deep south of the Cormierville Fault. The reader is referred to Evangelatos and Butler (2010) for a more detailed discussion of the modelling methodology and results.

A prominent (12–24 mGal) gravity low appears in the northern part of the survey area near Rexton. The oval-shaped anomaly measures approximately 11 km by 5 km with a long axis paralleling the regional geological trend of 50° NE. While the shape of the anomaly is suggestive of an intrusive igneous body, there are no deep boreholes or seismic reflection data over the area to rule out the possibility of a sedimentary subbasin. An attempt to distinguish between these two possible sources following the method of Bott (1962) proved inconclusive, probably because the body was not sufficiently two-dimensional and the transect of gravity stations across the width of the anomaly was not optimally aligned.

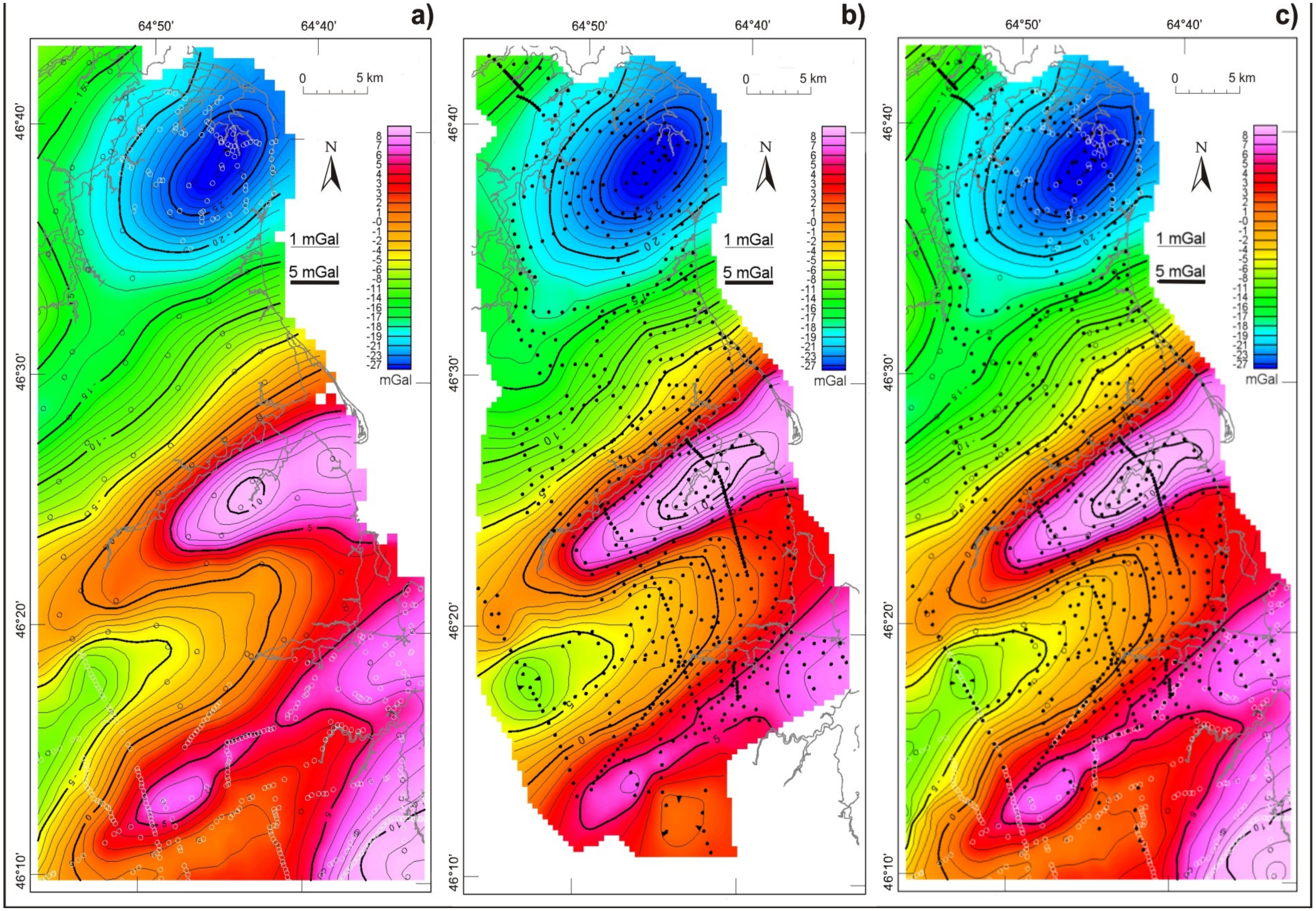

Figure 9. Comparison of terrain-corrected Bouguer anomaly gravity maps for the survey area, based on a) old data, b) new data, and c) combined old and new data. Gravity station locations are identified here as open black circles (old GSD data), open white circles (old NBDNR data), and filled black circles (newly acquired, 2009 data). See Figures 1 and 2 for the location of this survey area in eastern New Brunswick.

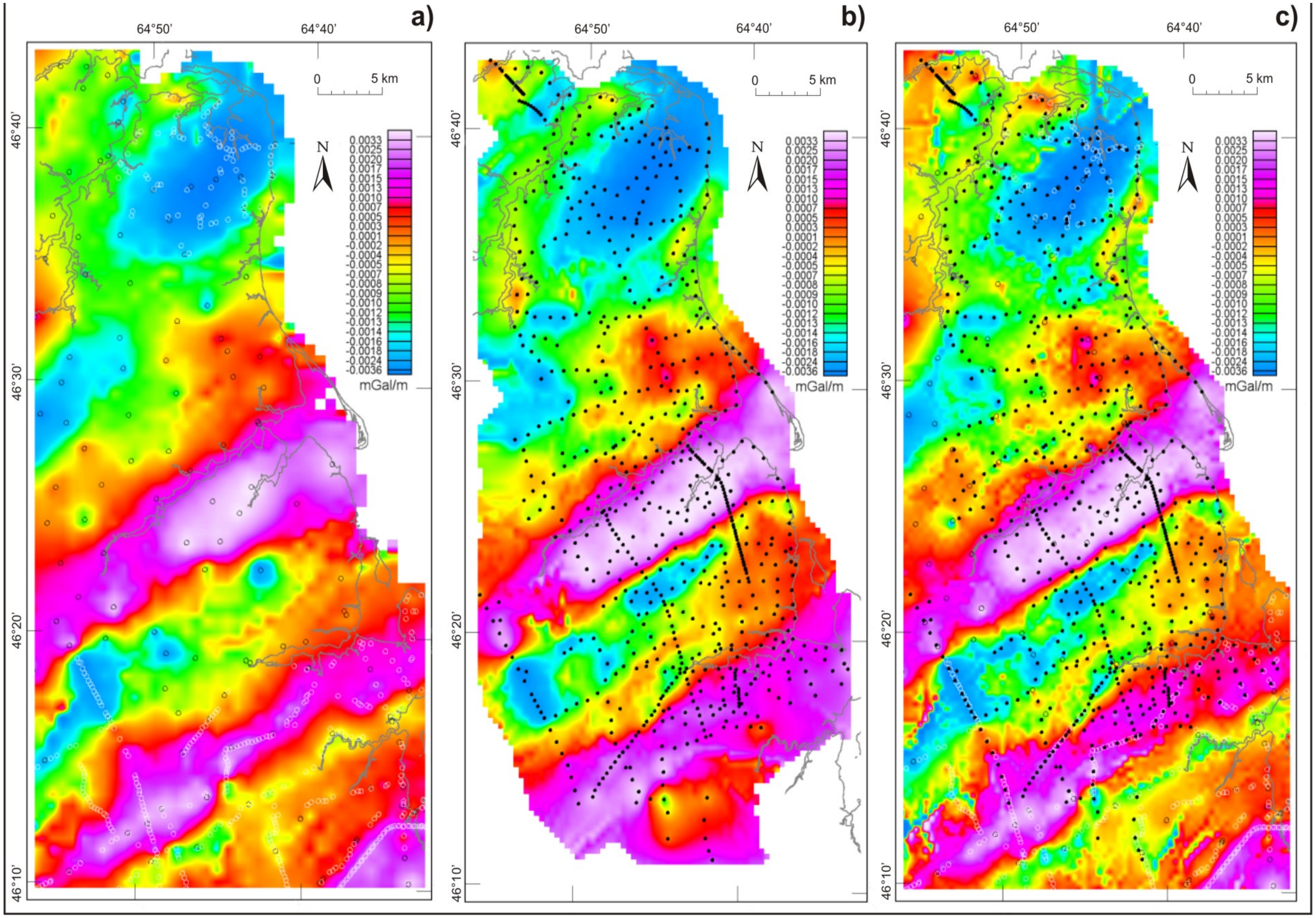

Figure 10. Comparison of maps of the vertical gradient of terrain-corrected Bouguer anomaly gravity, based on a) old data, b) new data, and c) combined old and new data. Gravity station locations are as identified in Figure 9. See Figures 1and 2 for the location of this survey area in eastern New Brunswick.

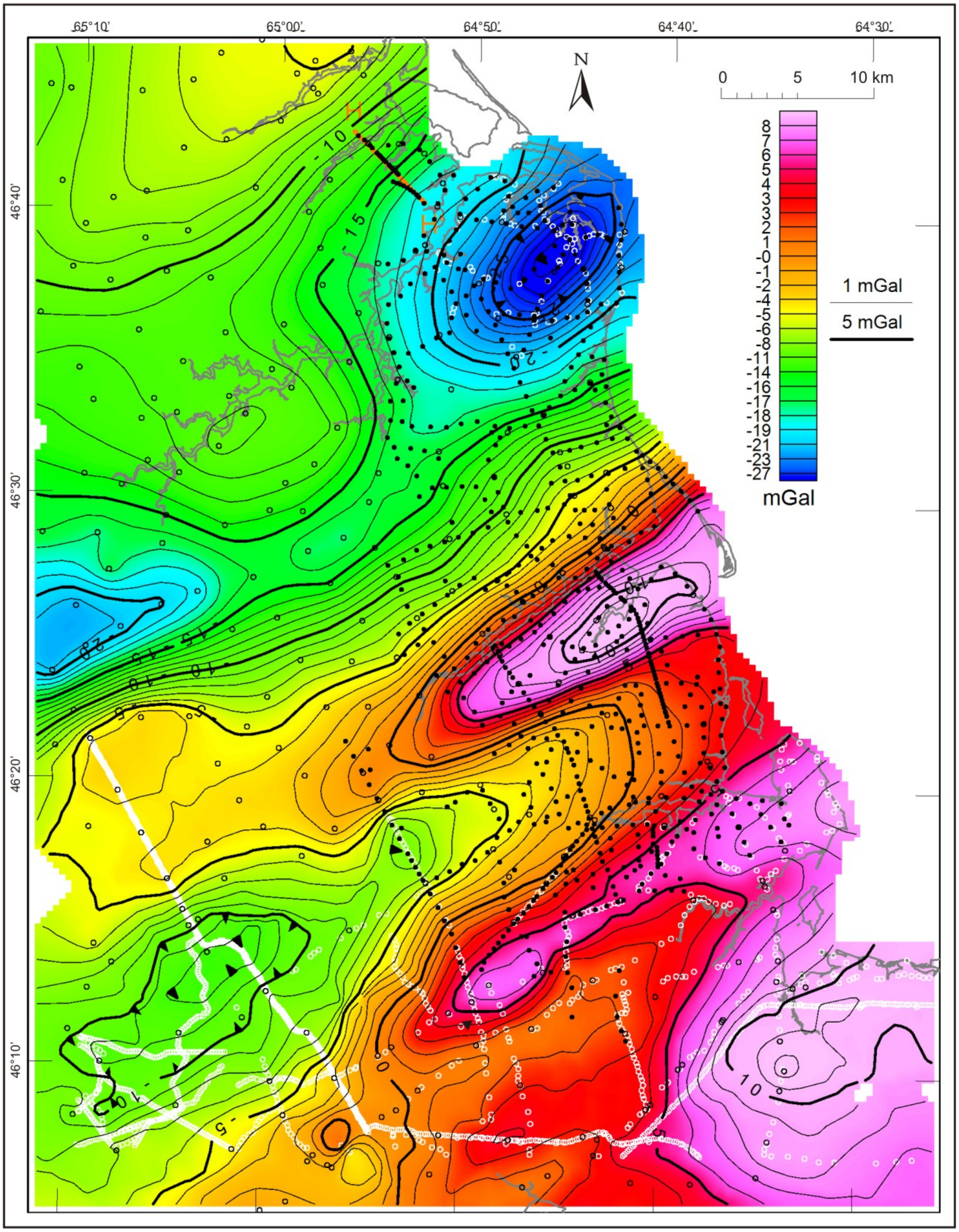

Figure 11. Terrain-corrected Bouguer anomaly map of the survey area and adjoining region. Gravity stations are identified as in Figures 8 and 9. Profile H–H' from Figure 7 is displayed as an orange line.

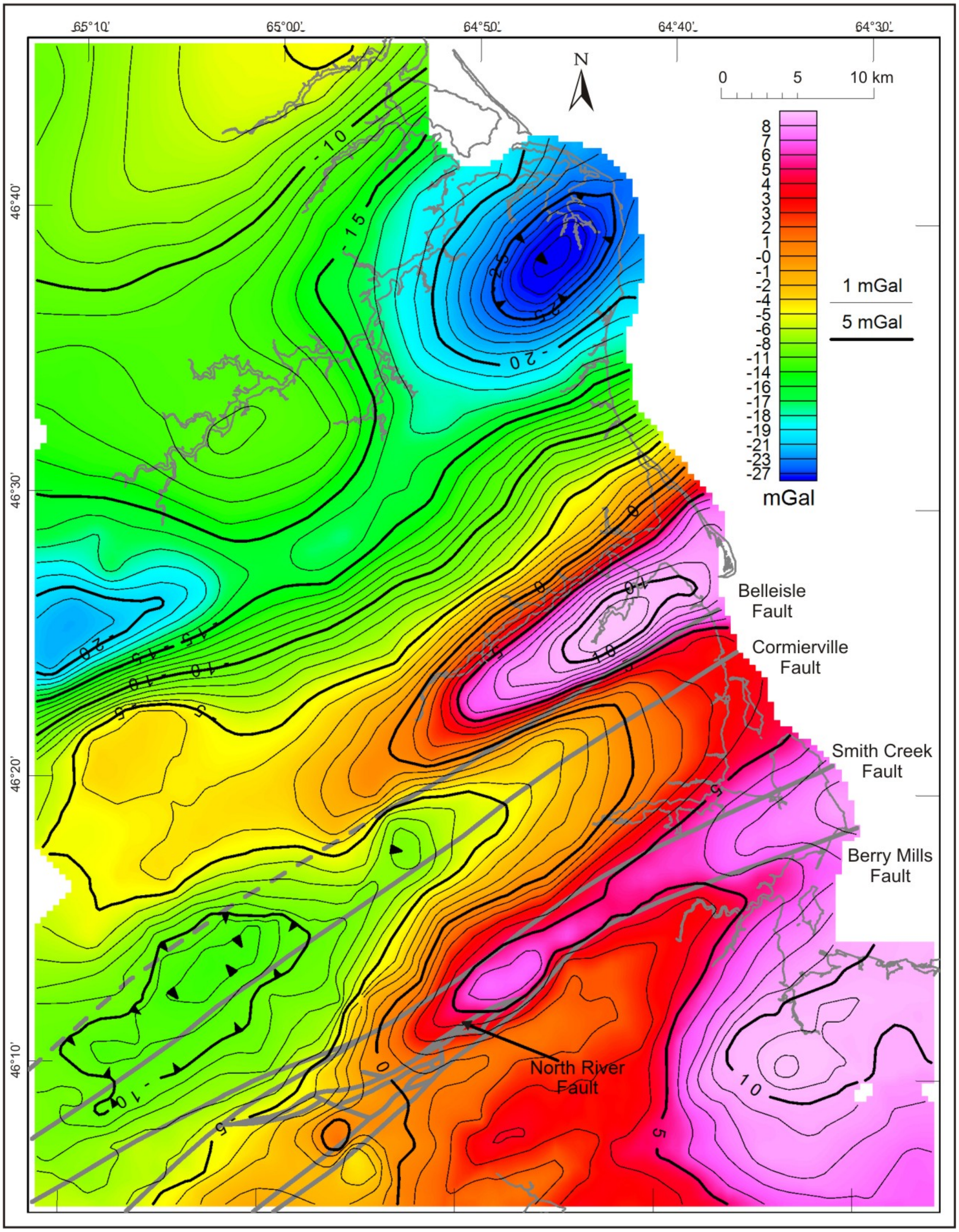

Figure 12. Terrain-corrected Bouguer anomaly map of the report area. Fault boundaries are depicted as thick grey lines (modified from Plate NR-10 (Smith 2008)).

CONCLUSION

The resolution and precision of Bouguer anomaly gravity maps for the Cocagne–Buctouche–Richibucto area of eastern New Brunswick have been significantly improved by the acquisition of 708 new gravity stations covering nearly 1000 km2 with a nominal spacing of approximately 1 km. The quality of GPS and gravity data was excellent, with repeat measurements attesting to mean discrepancies of 1.4 cm in elevation values and 0.01 mGal in the Bouguer anomaly values.

Bouguer anomaly and vertical gravity gradient maps produced from the new data confirm the presence of major northeast-trending anomalies. The anomalies were evident in the old regional data but had been considered uncertain, due to the variety of survey vintages and precisions on which they had been based. A comparison of the new and old Bouguer anomaly data identified 327 questionable old gravity stations (many of which had poor elevation control) that were suspect. Removal of data acquired from these old stations allowed for the smooth merging of data from the remainder.

In the southern part, the Cocagne gravity low has been much better resolved, leading to new insights concerning the subbasin structure. The new gravity data suggest that the Belleisle Fault is situated well north of its previously indicated position and that the Cocagne Subbasin is significantly wider than once thought. The recently introduced Cormierville Fault, which bisects the Cocagne Subbasin, is inferred based on coinciding anomalies in the vertical gradients of both the total aeromagnetic field and the Bouguer anomaly gravity field.

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APPENDIX A: GRAVITY CONTROL STATION TIE-IN DATA

The following gravity tie-ins were anchored on the Shediac absolute gravity station (9813-2007) and the newly established Shediac gravity station (9271-2009). The presented format is compatible with *PCGrav*'s "Network-Ties" program.

Bouctouche (9272-2007):

```
98132007 20091102 1613 X0490 01 5137534 20 47 084 203 2 000000
92712009 20091102 1633 X0490 01 5137390 20 47 084 203 2 000000
92722009 20091102 1718 X0490 01 5156998 20 47 084 203 2 000000
98132007 20091102 1826 X0490 01 5137598 20 48 084 203 2 000000
92712009 20091102 1847 X0490 01 5137462 20 48 084 203 2 000000
92722009 20091102 1946 X0490 01 5157084 20 48 084 203 2 000000
98132007 20091102 2047 X0490 01 5137669 20 49 084 203 2 000000
92722009 20091102 2139 X0490 01 5157112 20 49 084 203 2 000000
92712009 20091102 2226 X0490 01 5137520 20 49 084 203 2 000000
98132007 20091102 2250 X0490 01 5137670 20 50 084 203 2 000000
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Richibucto (9273-2009):

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98132007 20091113 1515 X0490 01 5142582 21 12 084 203 2 000000
92712009 20091113 1542 X0490 01 5142445 21 13 084 203 2 000000
92732009 20091113 1657 X0490 01 5158277 21 13 084 203 2 000000
98132007 20091113 1822 X0490 01 5142692 21 13 084 203 2 000000
92712009 20091113 1835 X0490 01 5142546 21 14 084 203 2 000000
92732009 20091113 1943 X0490 01 5158356 21 14 084 203 2 000000
98132007 20091113 2102 X0490 01 5142723 21 15 084 203 2 000000
92732009 20091113 2204 X0490 01 5158343 21 15 084 203 2 000000
92712009 20091113 2319 X0490 01 5142533 21 16 084 203 2 000000
98132007 20091113 2333 X0490 01 5142683 21 16 084 203 2 000000
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Moncton (9274-2009):

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98132007 20091214 2246 X0490 01 5158602 22 02 084 203 2 000000
92712009 20091214 2309 X0490 01 5158449 22 03 084 203 2 000000
92742009 20091214 2359 X0490 01 5117269 22 03 084 203 2 000000
98132007 20091215 0045 X0490 01 5158566 22 03 084 203 2 000000
92712009 20091215 0109 X0490 01 5158411 22 04 084 203 2 000000
92742009 20091215 0204 X0490 01 5117238 22 04 084 203 2 000000
98132007 20091215 0252 X0490 01 5158549 22 04 084 203 2 000000
92742009 20091215 0345 X0490 01 5117257 22 04 084 203 2 000000
92712009 20091215 0433 X0490 01 5158442 22 05 084 203 2 000000
98132007 20091215 0449 X0490 01 5158605 22 05 084 203 2 000000
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Table A1: Gravity values for CGSN stations. See Word document "CGSN site descriptions.doc" on DVD-ROM for additional information.

Name	***Station No.***	***Gravity value (mGal)***	***Records***
Shediac abs-g	9813-2007	980736.0920	photos
Shediac	9271-2009	980735.9740	photos, description
Bouctouche	9272-2009	980755.5635	photos, description
Richibucto	9273-2009	980751.7565	photos, description
Moncton	9274-2009	980694.8072	photos, description

APPENDIX B: GPS BASE STATION COORDINATE DETERMINATIONS

A total of four temporary base stations were used for the GPS survey, each requiring an independent determination of its associated coordinates. This appendix summarizes that procedure and gives the coordinates along with their associated standard deviations.

Procedure for Coordinate Determination

The general procedure for coordinate determination was the same for all base stations. However, there were specific exceptions that created some differences in processing of the final coordinates (related to the final adjustment). The following section discusses the general procedure employed along with the specific changes that were needed for each of the four base stations.

Processing Software

Two commercial products were used for the analysis, *Trimble Total Control* (*TTC*) and *Geolab*. *TTC* is a GPS processing package and *Geolab* is a least squares adjustment software package. *TTC* was used for processing the GPS baselines, and *Geolab* was used for the final least squares adjustment of the network.

Network

To determine the coordinates of the base stations, a small independent network was created for each of the base stations that consisted of the base station in question and the three New Brunswick Active Control (NBAC) stations listed in Table B1. Figure B1 is an example of the network for base station 3, but it is typical in all situations. The baselines processed for all instances extend from the base in question to NBAC stations at Escuminac (ESCU), Miramichi (MIRA), and Moncton (MCTN).

Table B1: Coordinates (NAD83(CSRS) – GRS80 ellipsoid) of the three NBAC stations used in the determination of the four temporary GPS base stations.

NBAC Station	***Latitude (φ)***	***Longitude (λ)***	***Ellipsoidal Height (h)***
MIRA	N 46 59 29.8197	W 65 34 02.8739	-11.509 m
MCTN	N 46 05 46.9639	W 64 50 03.0388	27.820 m
ESCU	N 47 04 24.2174	W 64 47 55.3553	-14.930 m

GPS observation files for each NBAC station, in RINEX format, are provided by Service New Brunswick (SNB) at no charge from their website. Observations at 10 second intervals are provided in hourly files for MCTN and MIRA, and in daily (24 hr) files for the ESCU. Processing was completed based on daily occupations, so the hourly MCTN and MIRA files had to be merged into daily files. The RINEX file handling and merging capabilities of *TTC* were used for this process.

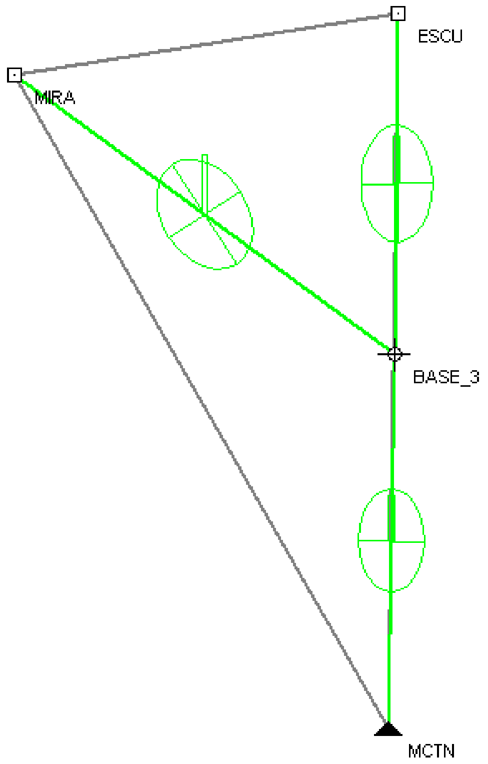

Figure B1. Typical network configuration for GPS base station coordination. This example shows the location of GPS Base 3 relative to the three NBAC stations at Moncton, Miramichi, and Escuminac.

Baseline Processing

As stated, baseline processing was completed using *TTC*. Table B2 summarizes the processing parameters that were used for the analysis. The parameters outlined in Table B2 were common for all baselines and all base station determinations. Since each base station was occupied over several days, the determination is made up of multiple sessions. Table B3 summarizes the total number of processed baselines for each connection in the network. Each baseline's session length is considered to be equivalent to approximately 8 hours of occupation time, and one baseline is processed per session.

Table B3 shows that in the cases for Base 1 and Base 2, more baselines (i.e. more days of useable data) were available for the stations at Moncton and Miramichi than for Escuminac. This was due to a combination of data availability from SNB and *TTC*'s inability to resolve integer ambiguities.

Table B2: *TTC* baseline processing parameters.

Parameter	***Description***	***Notes***
Ephemeris	Precise	Obtained from IGS in ITRF05
Processing Type	Static	
Processing Method	Ionosphere Free Linear Combination	
Cut-off Angle	10 degrees	
Tropospheric Model	Niell	MSIS meteorological model (default for TTC)
Antenna Calibration	IGS Absolute	IGS Antenna Working Group

Table B3: Number of baselines processed for each base station.

Location	***Number of Baselines***		
	MCTN	***ESCU***	***MIRA***
Base 1	17	16	17
Base 2	16	14	16
Base 3	12	12	12
Base 4	6	6	6

Final Adjustment

The final adjustment was performed in *Geolab* using the imported baselines and their resulting covariance. A weighted constraint adjustment was performed for each of the base station networks with the standard deviation for the NBAC monuments set at 1 cm. The NBAC coordinates were initialized to the published values, but the coordinates required a transformation to ITRF05 to ensure compatibility with the GPS processing completed in *TTC*. SNB publishes the geodetic coordinates for their active control stations in NAD83(CSRS), but the precise ephemeris files are provided in ITRF05, which results in coordinates from *TTC* in ITRF05. The coordinate transformations were completed using the free service, *TRNSOBS*, from Natural Resources Canada's website (http://www.geod.nrcan.gc.ca/apps/trnobs/trnobs_e.php).

Difficulties were encountered while completing the processing for Base 1. Namely, integer ambiguities for the baseline between Base 1 and MIRA could not be resolved. Therefore, the float solutions were used for the adjustment. The length of this baseline is approximately 100 km, which makes it difficult to resolve the ambiguities. Table B4 summarizes the baseline lengths for
all of the baselines used in the adjustment. There were some isolated instances where *TTC* could not resolve the ambiguities for baselines involving other base stations, but these baselines were excluded from the final adjustment.

Table B4: Baseline length (m) to NBAC monuments for each base station.

Base Station	***MIRA***	***ESCU***	***MCTN***
Base 1	101833.775 m	84952.094 m	27296.062 m
Base 2	85495.861 m	68984.374 m	39979.856 m
Base 3	71562.743 m	57056.534 m	51586.904 m
Base 4	95778.905 m	88513.015 m	20386.354 m

In the case of Base 1 to MIRA, all the baselines solutions were float. To deal with the float solutions a statistical analysis was completed to remove suspected outliers from the mean. The framework of the outlier analysis was established by determining the mean and standard deviation from the sample of baselines. An upper and lower limit was then established by taking two standard deviations (plus and minus) from the calculated mean. Each of the x,y,z components of the baseline were then compared to the boundary and excluded if any x,y,z value fell outside. Once the initial set of outliers was removed, the process was repeated until no more outliers could be identified. A total of four outliers were identified, so only 13 Base1-MIRA baselines were used for the final adjustment. This procedure was only used in the Base 1 adjustment. The remaining base stations did not experience the excessive float solutions.

The baselines from Base 1-MIRA were also weighted accordingly. The final standard deviation from the outlier analysis was used as a basis to scale the baseline covariance such that Base1-MIRA would carry less weight in the adjustment. The scale factor was determined by making a comparison to the standard deviations of the other two baselines in the network. The magnitude of the Base1-MIRA standard deviation was an average of 3.6 times larger than the standard deviations of the other baselines in the network. Therefore, the addition of a variance factor to the *Geolab* input file scaled the baseline covariance. The variance factor acts as a scale factor, thus reducing the weight in final adjustment. Again, this was only done for the Base 1 adjustment. The remaining base station adjustments used equally weighted baselines.

Final Coordinates

Table B5 lists the resulting base station coordinates. Corresponding standard deviations at 95% confidence are provided in Table B6. The standard deviations are the combination of processing by *TTC* and a network adjustment by *Geolab*. The baseline standard deviations were imported into *Geolab* (from *TTC*) and then scaled in an attempt to better represent the true uncertainty in the GPS measurements. The standard deviations listed in Table B6 are a result of this network least squares adjustment.

Table B5: Adjusted coordinates for each base station (ITRF05 with GRS80 ellipsoid).

Base Station	***Latitude (deg)***	***Longitude (deg)***	***Ellipsoidal Height (m)***
Base 1	N 46 18 51.402912	W 64 40 18.308955	-5.1221
Base 2	N 46 27 11.514730	W 64 46 7.975776	13.1736
Base 3	N 46 36 34.064864	W 64 48 47.052730	16.2177
Base 4	N 46 16 42.608222	W 64 51 55.626777	50.0229

Table B6: Standard deviation of the GPS base station coordinates at 95% (2σ) confidence.

Base Station	σ_φ	σ_λ	σ_h
Base 1	0.0136 m	0.0138 m	0.0142 m
Base 2	0.0116 m	0.0116 m	0.0118 m
Base 3	0.0116 m	0.0116 m	0.0120 m
Base 4	0.0119 m	0.0115 m	0.0135 m

APPENDIX C: GRAVITY DATA REDUCTION

Pre-Reduction Gravity Data Processing

The Scintrex ASCII file exported by the gravimeter was demerged and re-formatted into 54 distinct traverse files (one for every day of surveying) compatible with GSD's in-house gravity program *PCGrav*. After appending the sensor height[2] and final position to each station in each traverse file, the whole was then processed in *PCGrav*, which is referenced to the International Gravity Standardization Net 1971 with theoretical gravity values used for computing anomalies based on the 1967 Geodetic Reference System.

Processing applied by *PCGrav* involved first multiplying the raw gravity readings by the most recent scale factor for the Scintrex CG-5 serial number X0490, which is 1.000004. The scale factor is explicitly instrument-dependent but, unlike with old Lacoste & Romberg gravimeters that require calibration tables, is constant irrespective of the magnitude of the raw reading. Next, an improved Nakai formula, which incorporates the latitude-dependent "DC tide" correction, was used to subtract the gravitational effects of the Sun and Moon (Nakai, 1979; *PCGrav* manual, 2002). The formulae for the tide correction are lengthy and complex and, therefore, excluded from this report. They may be requested from the Geodetic Survey Division, Natural Resources Canada. The readings were then adjusted to correct for the height of the sensor above the ground. Finally, readings were corrected for instrument drift calculated by linearly interpolating the difference between scaled and instrument height-corrected gravity readings taken at the gravity base at the start and end of the day. The aggregate of these four corrections, for each gravity station was as follows:

$$R_c = s * R + c_t + c_h + c_d$$

where

R : the raw gravity readings (mGal)
s=1.000004, and is a dimensionless instrument-dependent scale factor
c_t : tide correction (mGal)
c_h : height correction (mGal), and is equal to $\frac{dg}{dz} h_i$, where
$\frac{dg}{dz} =$ 0.3086 mGal/m is the average gravity gradient per metre of elevation, and
h_i : sensor height above the ground surface (m)

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[2] The instrument heights recorded in the field books correspond to the distance between the ground and the levelling plate. However, the heights inputted into the traverse files are the sum of the instrument heights, the thickness of snow and the (constant) sensor-to-plate distance.

The drift correction, c_d, is given by

$$c_d = D\left(T - T_{b1}\right),$$

where the T represents the time of recording taken in the middle of a 120 s acquisition period, and D is the rate of instrumental drift given by,

$$D = -\frac{(R_{b2} - R_{b1}) - (g_{b2} - g_{b1})}{(T_{b2} - T_{b1})}$$

Here

R_{b1}, R_{b2} : are the scaled, tide and instrumental height corrected readings from the opening base and closing base, respectively (mGal).

g_{b1}, g_{b2} : are the absolute gravity values from the opening base and closing base, respectively (mGal).

T_{b1}, T_{b2} : are the times of recording taken in the middle of a 120 s acquisition period for the opening base and closing base, respectively (s).

Note that for all traverses, with one exception on October 17th, the opening and closing gravity bases were identical so that $g_{b1} = g_{b2}$.

An absolute gravity value, g_o, for each station was calculated from its corrected relative gravity reading R_c at time T as follows:

$$g_o = g_{b1} + \left(R_c - R_{b1}\right) - (T - T_{b1}) * D$$

Gravity Data Reduction

To use gravity data in a geologically meaningful way requires further processing to produce Bouguer anomaly gravity values that highlight lateral changes in subsurface density (i.e., contrasts relative to a homogenous Earth). To this end, absolute gravity values must be adjusted or 'reduced' to remove the effects of latitude, elevation and topography.

Expected variations of gravity with latitude are well represented in an equation for theoretical absolute gravity g_t on the surface of a rotating reference ellipsoid that is based on the 1967 Geodetic Reference System. *PCGrav* calculates g_t for every station according to the GRS67 formula:

$$g_t(\varphi) = 978031.85\left(1.0 + 0.005278895 \sin^2\varphi + 0.000023462 \sin^2\varphi\right)$$

where φ is the latitude of the observation

The Free Air Anomaly (FAA), representing the amount by which absolute gravity differs from its theoretical (GRS67) value after compensating for a station's height above mean sea level was calculated as follows:

$$FAA = g_o - g_t + \frac{dg}{dz}h$$

where

$\frac{dg}{dz} =$ 0.3086 mGal/m, and is the average vertical gravity gradient
h : orthometric height of the gravity station (m).

The Bouguer anomaly (BA) further accounts for the gravitational attraction of mass lying between the station and mean sea level. It was calculated within *PCGrav* by subtracting the so-called Bouguer slab correction from the Free Air Anomaly:

$$TBA = FAA - 2\pi G\rho_c h$$

where

$G =$ 6.672 x 10^{-6} m^2 kg^{-1}mGal, and is the gravitational constant and $\rho_c =$2670 kg/m^3 is the standard slab density used for stations in the CGSN.

LaFehr (1991) recommends further correcting the Bouguer anomaly by accounting for the effect of a spherical cap up to a radius of 166.7 km from an observation point. This correction, known as the Curvature (Bullard B) correction, is not insignificant for surveys conducted in areas of rugged topography with ranges in elevation greater than 500 m. However, as the station elevations for this survey are entirely below 115 m, the curvature effect is estimated at <0.1 mGal, and, thus, not implemented.

Terrain Correction

Terrain corrections were calculated using Geosoft's *Oasis montaj* v.7.2 software. This process involved using 1:50,000 Digital Elevation Models (DEMs), which are regional topographic data interpolated onto a 2D grid with fixed node spacing of approximately 20 m in the N-S and E-W directions. The DEMs for this survey were derived from the federally managed GeoBase website (www.geobase.ca).

Because deriving the terrain correction for each station is computationally expensive, *Oasis montaj* expedites the calculation by creating a special grid that contains regional terrain corrections beyond a fixed distance. Combined with the local terrain effects, this "regional correction grid" is used to produce the total terrain correction value for each observed gravity location. For this research, regional effects are defined as lying 15 km to 125 km beyond the border of the local DEM (which is about 15 km from the edge of the survey area).

The algorithm for calculating the local correction divides the area centred on the station into three discrete zone: near, intermediate and far. As detailed in *Geosoft*'s help menu:

"… in the near zone (1 cell radius ring from the station), the algorithm sums the effects of four sloping triangular sections, which describe a surface between the gravity station and the elevation at each diagonal corner. In the intermediate zone (2 to 16 cells radius ring), the terrain effect is calculated for each point using the flat topped square prism approach of Nagy (1966). In the far zone, (greater than 16 cells), the terrain effect is derived based on the annular ring segment approximation to a square prism as described by Kane (1962)."

The maximum observed terrain correction is 0.21 mGal, and (predictably) correlates with a zone of steep elevation gradients. The reader should note that sea level was assigned an elevation of zero and efforts were not made to correct for bathymetric effects (i.e., to account for the low density of seawater compared to the slab density). Consequently, Bouguer values, and in particular those within 10 km of the coast, are underestimated. The discrepancy is not anticipated to be greater than the maximum observed terrain correction above sea level (0.21 mGal).

APPENDIX D: GPS REPETITION ANALYSIS

The points below represent gravity stations that were reoccupied and for which GPS was recorded anew. Note that the difference in horizontal position in the table below is likely caused by not having erected the GPS antenna over the exact spot as previously, but still fairly close (~29 cm on average). This is acceptable as horizontal position is not as critical as height when reducing gravity data.

Table D1: GPS repetition analysis.

Station	***Δ Elevation (cm)***	***Δ Horizontal (cm)***	***Δ Bouguer (mGal)***
2030	0.2	57.7	0.03
2045	1.2	7.7	0.02
2047	4.3	47.0	0.03
2071	1.2	11.1	0.00
2157	0.2	38.1	0.01
2253	0.3	7.6	0.01
2495	1.1	23.6	0.00
2618	0.5	15.3	0.02
2651	2.0	47.1	0.00
2675	0.7	44.4	0.00
2701	3.3	22.2	0.00
Mean	1.4	29.3	0.01
Median	1.1	23.6	0.01
Standard dev.	1.3	18.1	0.01
RMS	1.9	34.0	0.00

APPENDIX E: GRAVITY REPETITION ANALYSIS

The points below represent stations that were reoccupied at a later time and typically at a later date. Sequential readings are not included. Δ Bouguer is the difference in the Total Bouguer anomaly (mGal) as derived by *PCGrav*. Stations that were occupied more than twice (namely, stations 2030, 2071, and 2495) the difference is calculated relative to the first reading. Note also that GPS was not generally re-acquired during repeat observations. In this case, the position of the first reading was used to reduce the gravity data of repeat measurements that lacked corresponding GPS information.

Table E1: Gravity repetition analysis.

Station	***Δ Bouguer (mGals)***
2018	0.00
2019	0.00
2030^1- 2030^2	0.03
2030^1- 2030^3	0.01
2030^1- 2030^4	0.01
2045	0.02
2047	0.03
2071^1- 2071^2	0.00
2071^1- 2071^3	0.01
2139	0.01
2150	0.01
2157	0.01
2174	0.01
2184	0.00
2252	0.00
2253	0.01
2290	0.00
2293	0.01
2305	0.00
2350	0.00
2359	0.00
2421	0.02
2445	0.02
2446	0.00
2447	0.01
2448	0.01
2449	0.00
2451	0.00
2452	0.01
2453	0.01
2454	0.02
2456	0.01
2457	0.01
2484	0.01
2486	0.01
2488	0.01
2493	0.01
2495^1- 2495^2	0.00
2495^1- 2495^3	0.01
2618	0.02
2647	0.01
2651	0.00
2654	0.00
2675	0.00
2701	0.00
Mean	0.01
Median	0.01
Standard dev.	0.01