Subsurface structure of the Canterbury region and implications for earthquake activity – interpretations from gravity and magnetic data

B. Davy  V. Stagpoole
D. Barker  J. Yu

GNS Science Report 2012/02
January 2012
BIBLIOGRAPHIC REFERENCE


B. Davy, GNS Science, PO Box 30368, Lower Hutt 5040
V. Stagpoole, GNS Science, PO Box 30368, Lower Hutt 5040
D. Barker, GNS Science, PO Box 30368, Lower Hutt 5040
J. Yu, GNS Science, PO Box 30368, Lower Hutt 5040
FIGURES

Figure 1  September 2010-April 2011 seismicity plotted on Canterbury topography ............2
Figure 2  Land gravity surveying .........................................................................................2
Figure 3  Gravity observation locations and active faults plotted over the Bouguer gravity anomaly map .............................................................................................................3
Figure 4  Bouguer gravity anomaly and gravity gradient overlying a buried fault offset in basement rocks ..........................................................................................................................4
Figure 5  Map of Bouguer gravity anomaly slope a) uninterpreted and b) with interpretation highlighting E-ESE lineaments ........................................................................................................5
Figure 6  Seismic profile location for IP_98_01, over a map of Bouguer gravity anomaly slope with E-ESE and NNE lineaments highlighted ...........................................................................6
Figure 7  Seismic line IP-98_01 ............................................................................................8
Figure 8  Reduced-to-pole aeromagnetic anomaly data ......................................................10
Figure 9  Reduced-to-pole aeromagnetic anomaly data with 50 nT contours ....................10
Figure 10 Reduced-to-pole aeromagnetic anomaly data with an alternate colour palette ......11
Figure 11 AGC’d reduced-to-pole aeromagnetic anomaly data........................................12
Figure 12 Power spectrum of RTP magnetic data ...............................................................13
Figure 13 The 5100 m depth-matched filtered magnetic signal ........................................15
Figure 14 The 1255 m depth-matched filtered magnetic signal ........................................16
Figure 15 The 240 m depth-matched filtered magnetic signal ........................................16
Figure 16 A sun-illuminated image of Bouguer gravity slope ............................................17
Figure 17 Linear features in the RTP magnetic anomaly map .............................................18
Figure 18 Gravity anomaly lineaments and magnetic anomaly lineaments plotted over 1,255 m depth-matched filtered magnetic signal .............................................................19
Figure 19 Earthquake locations from 4 September 2010 to after the 22 February 2011 earthquake plotted over the 1255 m depth-matched filtered magnetic signal ....................21
Figure 20 Bouguer gravity anomaly slope overlain by earthquake epicentres from 4 September 2010 to 7 September 2010 .....................................................................................22
Figure 21 Bouguer gravity anomaly slope overlain by earthquake epicentres from 4 September 2010 – 24 September 2010 ...................................................................................23
Figure 22 Bouguer gravity anomaly slope overlain by earthquake epicentres from 4 September 2010 – 21 February 2011 .......................................................................................24
Figure 23 Bouguer gravity anomaly slope overlain by earthquake epicentres from 4 September 2010 – 22 February 2011 .......................................................................................25
Figure 24 Earthquake sequence over 4 hours from the 22 February 2011 earthquake overlaid on RTP magnetic anomaly data .................................................................26
Figure 25 Onshore Bouguer gravity anomaly slope and offshore fault interpretation from Barnes et al. 2011 ....................................................................................................................27
ABSTRACT

Gravity and aeromagnetic data were acquired over the Christchurch and adjacent area to map the subsurface structure and identify possible faults. This report describes the data acquisition and interpretation. The results presented here may be further refined in the future when they are compared with seismic reflection data collected in 2011.

Interpretation of both gravity and magnetic data indicate that there are several distinct sets of lineaments that are postulated to be associated with basement structure and subsurface faults. Although the largest magnetic anomalies are related to Lyttelton Volcano, E-W and ENE oriented magnetic lineaments may correlate with faults in the northern Banks Peninsula region. A magnetic anomaly extends east from the Greendale Fault but it is not a dipolar anomaly, as might be expected for a fault. It may be caused by a subsurface volcanic feature, possibly an intrusion or a Miocene lava flow buried by younger sediments.

Interpretation of gravity gradient data identified two principal sets of lineaments that have ESE to E and NNE orientations. The NNE set of lineaments may relate to NNE faults that formed in Cretaceous time which have been recently reactivated. The E-W to ESE-WNW lineaments are possibly associated with faults on the edges of Cretaceous grabens or half-grabens. Three E-W lineaments are interpreted to extend 20 km east of Rolleston, and there is a good correlation between the middle lineament and the 2010-2011 seismicity. Under Christchurch, seismicity jumps between E-W lineaments during the 2010-2011 earthquake activity.

Interpretation of the datasets suggests that there is a boundary between separate crustal deformation domains in the Rolleston area. The domain between Rolleston and Lyttelton Volcano has E-W structural features segmented on 2-4 km length scale. West of Rolleston, lineaments are typically segmented at 5 km or more. Interpretation of the data suggests plate margin deformation is possibly being preferentially focussed in the Rolleston–Lyttelton Volcano domain by motion of higher rigidity crust associated with the adjacent Lyttelton Volcano.

Keywords

Darfield earthquake, Christchurch earthquake, geophysical survey, gravity survey, aeromagnetic survey.
1.0 INTRODUCTION

Seismicity between September 2010 and April 2011 has a complex pattern that is not reflected in the regional topography (Figure 1). The spatial distribution of bands of seismicity suggests that the Canterbury region is underlain by faults of multiple orientations. In order to provide more information about the sub-surface structure and may help identify possible faults, GNS Science collected gravity and magnetic data in Christchurch region following the 22 February 2011 Canterbury earthquake. These data and other information (active faults and seismic reflection data) are compared with earthquake size and locations (provided by Dr. Stephen Bannister, GNS Science) and are incorporated in the interpretation of the gravity and magnetic data. The interpretation presented in this report is yet to be compared with onshore seismic reflection data acquired in 2011 and as a consequence, the results presented here may be further refined in the future.

This report describes the data collection, reduction and analysis techniques. The analysis includes a description of how straight line segments (lineaments) in both the magnetic and gravity data are interpreted as faults. The interpretation is compared with mapped faults, open file seismic reflection data collected over the Canterbury region and seismicity between September 2010 and April 2011. A short discussion on the association of seismicity and gravity and magnetic anomalies and the implications for crustal structure is also included.

2.0 GRAVITY DATA ACQUISITION AND ANALYSIS

As of February 2011 the GNS land gravity database (http://www.gns.cri.nz/Home/Products/Databases/New-Zealand-Gravity-Station-Network) contained a relatively uniform coverage of gravity stations across the Canterbury Plains, with much of the data obtained in the 1950s and 1960s. While the gravity data set was quite uniform at a regional scale, there were gaps of up to c. 7 km between observations. In April 2011 a team of three GNS Science scientists undertook a land gravity survey to fill in those gaps (Figure 2).

Gravity observations were made between 12 April and 21 April 2011 using the G-106 LaCoste and Romberg gravity meter. Data were processed using the in-house GNS gravity programmes (Woodward 1982, Woodward and Carman 1984). The survey consisted of a total of 165 new observations tied to gravity benchmarks in the Christchurch and Canterbury region. New gravity base stations were established around Burnham (LINZ benchmarks B3A2, AFUQ, 1127). In addition, the Godley Head absolute gravity base station was reoccupied during the survey. The elevation of each gravity observation site was determined using differential GPS, and most stations have an estimated height uncertainty of less than 0.1 m. The standard error determined during reduction of the gravity observations is between 0.03 and 0.06 mGal (0.3 and 0.6 uN/kg). The total estimated error, including height and tie uncertainties, is +/- 0.05 mGal (0.5 uN/kg), although sites with poor height control have greater uncertainty (about 1 mGal (10 uN/kg) for every 3 metres in elevation). Observations in the 2011 survey at the same locations occupied in the earlier 1960s surveys had very similar observed gravity and therefore recently obtained gravity data seamlessly fit with earlier data (Figure 3).
Figure 1  September 2010-April 2011 seismicity plotted on Canterbury topography. Red earthquakes are largest magnitude. Topography contour interval is 50 m. The Greendale Fault System formed during the 4 September 2010 Darfield (Canterbury) Earthquake is highlighted by a thick dark red line. Mapped faults (generally surface rupture faults) from the GNS Science active fault database (http://www.gns.cri.nz/Home/Products/Databases/Active-Faults-Database-of-New-Zealand) are plotted in light red. Rivers and streams are plotted as blue. The urban area of Christchurch City is shaded.

Figure 2  Land gravity surveying (left) was undertaken by GNS staff in April 2011. Aeromagnetic surveying using a MD-520 NOTAR helicopter was performed by Thompson Aviation in May 2011.
Figure 3  Gravity observation locations and active faults (red lines) plotted over the Bouguer gravity anomaly map. Red squares mark gravity observations prior to the September 2010 and February 2011 earthquakes. Yellow squares are the location of observations collected during April 2011. The cross-section (yellow line and inset) shows the 140 uN/kg Bouguer gravity anomaly arch which extends NW from Banks Peninsula. Also highlighted are steep gravity lineations A, B and C.

Subsequent to the 2011 survey, gravity observations throughout the mid-Canterbury region are now typically spaced about 1-1.5 km apart. Such spacing is good for detecting large fault offsets in the greywacke basement which is interpreted to be c. 1 km beneath the Canterbury Plains. Hicks (1989) used gravity data to model the basement structure across the Canterbury Plains. The basement density of about 2.67 Mg/km$^3$ contrasts with overlying sediment that has densities that range from c. 2.1 Mg/km$^3$ for surface sediments to more than 2.5 Mg/km$^3$ for deeply buried stratigraphic intervals (Whiteford and Lumb 1975, Hicks 1989). The average density of sediments is about 2.3 Mg/km$^3$ (Hicks 1989).

The density contrast between basement and sedimentary rocks means that significant vertical offsets (> 100 m) in the basement surface should be well imaged by gravity anomaly data. Figure 4 shows, by way of example, that a 500 m offset in basement surrounded by sediment with an average density of 2.4 Mg/km$^3$ produces a 5 mgal offset in the Bouguer gravity anomaly, with a maximum gravity gradient of about 2 mgal/km.
2.1 Gravity Anomalies

A prominent feature of the Bouguer gravity anomaly in the Canterbury region (Figure 3) is the c. 10 mgal (100 uN/kg) Bouguer gravity anomaly high that extends northwest from Banks Peninsula (Hicks 1989). This gravity high is bounded by sub-parallel gravity ridges about 10 km wide on their outer margins (Figure 3). The wavelength and orientation of this anomaly suggests it probably reflects basement structure and composition, although volcanic flows may contribute in the vicinity of Lyttelton and Akaroa volcanoes.

More detailed interpretation of the gravity anomalies can be undertaken by analysing the Bouguer anomaly slope (Figure 5) that corresponds at each grid point to the maximum horizontal rate of change in gravity anomalies, arising from horizontal contrasts in density. Maxima in gravity anomaly slope correspond to the locally steepest gravity anomaly gradient and hence the greatest horizontal contrasts in underlying density. Although the density contrast between basement and sedimentary rocks enables detection of large basement offsets, volcanic rocks with an average density of about 2.7 Mg/m³ will complicate interpretation of the gravity anomaly data close to Lyttelton Volcano.

A feature of the Bouguer gravity anomaly slope map (Figure 5) is the complex mix of lineaments of multiple orientations. Prominent sets of E–W and ESE trending high-amplitude gravity slope lineaments (labelled A to F in Figure 6) are highlighted with orange lines, and NNE trending high-amplitude gravity slope lineaments are highlighted with pink lines. Some high-amplitude gravity anomaly slope lineaments correspond to mapped faults. For example, an inactive and un-named fault, intersecting the Ashley Fault in northern Canterbury (Forsyth et al. 2008) is associated with an ESE-trending gravity anomaly gradient lineament. Gravity gradient lineament E (Figure 6) correlates with an active fault rupture on the surface (Forsyth et al. 2008).

![Figure 4](image-url)

**Figure 4** Bouguer gravity anomaly and gravity gradient overlying a buried fault offset in basement rocks. The cartoon at left illustrates how horizontal gravity gradient peak correlates directly with density contrasts from a step in basement. The model at right shows the gravity anomaly and gravity anomaly gradient for a 500 m fault offset in basement surrounded by sediment with a density of 2.4 Mg/km³.
Figure 5. Map of Bouguer gravity anomaly slope a) uninterpreted and b) with interpretation. High gravity gradients (green-red) may correspond to steps in basement (see Figure 4). Red lines are mapped surface ruptures of active faults. Orange lines mark gravity gradient lineaments that form continuous segments of high gravity gradient. There is a moderate correlation of high gravity anomaly gradients with mapped surface rupture features. Prominent high gravity gradient lineaments (labelled A, B and C), which extend west from Banks Peninsula, are segmented into offset sections c. 2.5 to 3 km long. Most of these segments comprise right-stepping adjacent segments.
Figure 6  Seismic profile location for IP_98_01 (TAG 2007)(yellow line) over a map of Bouguer gravity anomaly slope a) uninterrupted and b) with interpretation. The seismic profile is shown in Figure 7. Also plotted are lineaments (orange and pink lines with those mentioned in the text labelled with white letters A-F), coastline (black), major rivers and lakes (blue), petroleum wells (red squares) and mapped faults red lines. GF = Greendale Fault.
2.2 COMPARISON OF GRAVITY AND SEISMIC REFLECTION DATA

Publically available seismic reflection profiles in onshore Canterbury include petroleum exploration and scientific survey data (Figure 6). Southwest of Christchurch a seismic reflection line IP-98_01 (Figure 7) ties to petroleum wells Leeston-1, Chertsey-1 and J.D.George-1 (TAG 2007) so it is possible to interpret the base of gravels (Kowai conglomerate), Lyttelton volcanics (80m thick at Leeston-1), View Hill Volcanics (38 m thick at Leeston-1) and laterally short segments of Torlesse greywacke basement. Gravity gradient lineaments C, D, E and F broadly correspond with faults interpreted on the seismic data. The seismic interpretation (Figure 7) suggests that the faults have a flower-structure nature characteristic of strike-slip faulting.

Northwest of Christchurch the Springbank Fault (Dorn et al. 2010) correlates with the northern-most NNE gravity gradient lineament (Figure 6). This NNE lineament is interpreted from offset of a southern segment of the Ashley River Fault (Forsyth et al 2008), from faulting observed on seismic reflection data (Dorn et al. 2010) and from the right-lateral offset of the prominent WNW gravity gradient lineament (Figure 6).

3.0 MAGNETIC DATA AND ANALYSIS

Prior to 2011, no aeromagnetic data had been collected over the Canterbury Plains and Banks Peninsula region. The 2011 survey data were acquired by Thompson Aviation Ltd over Christchurch city and the surrounding region from 16 to 24 May 2011 (Figure 2). Flight lines were flown in a N-S orientation at 400 m spacing with E-W tie lines spaced 4000 m apart. Flight height was 60 to 100 m, except when flying over Christchurch and other concentrated population centres, where the helicopter flew at 300 m above ground-level. At higher flight elevations the fine signal resolution available at a 60-100 m land clearance is compromised, however the magnetic noise caused by steel in cultural features such as buildings, pipe-lines, power-lines and railway-lines falls away as the cube root of the flight height and thus higher flight elevations reduce the effect of these cultural features. Nevertheless, it was essential in interpreting the data to overlay a detailed topographic map in order to recognise any residual cultural magnetic signal.

The data were processed by Thompson Aviation Ltd contractor, Rada Engineering and delivered to GNS Science on 6 June 2011. Rapid flight height variations during the survey, mainly occurring at the margins of populated areas, were problematic for the processing. Data processing techniques reduced the height effects, but did not remove them completely.

In addition, the effects of the Benmore-Haywards DC power line were corrected in the final data and applied prior to levelling. The mean value of the DC power line correction was of the order of 4nT, and is negligible when compared to the high dynamic range in the observed total magnetic intensity (TMI). This combined with the standard polynomial tie line levelling and microlevelling of the data resulted in the correction having a very minor effect on the low frequency responses and no effect on the high frequency responses in the final TMI dataset.
Figure 7  Seismic line IP-98_01. Well intersections from TAG (2007) with major interpreted faults labelled. Location of line IP-98_01 is plotted in Figure 6 (yellow line). The Eocene-Paleocene labelled horizon correlates with View Hill Volcanics in Leeston-1 well. The faults “C” to “F” are interpreted to have a flower-structure nature characteristic of strike-slip faulting.
The mean field values for the survey were:

**Diurnal:** 57,661 nT  
**IGRF:** 57,665 nT  
**Benmore-Haywards DC power line correction:** -4 nT

Magnetic surveys map the variation in magnetisation of rocks within the Earth. Geological structures, particularly faults that offset rocks with different magnetic properties or volcanic flows deposited adjacent to fault-offset topography, often produce characteristic magnetic lineaments observed on maps of comprehensive magnetic surveys. However, man-made structures that contain a lot of iron (railway lines, steel-framed buildings but not the average Christchurch house) may also produce similar features and careful interpretation of the data is always required when surveys are conducted over built-up areas.

The magnetisation of rocks is partly due to a long lived permanent, or natural remanent magnetisation (NRM), and partly due to an induced magnetisation caused by the Earth’s magnetic field. The NRM is the in situ remanent magnetisation present in a rock, while the induced component depends on the magnetic susceptibility $\kappa$ of the rock. Magnetic susceptibility is a measure of the ease with which a rock can be magnetised and is principally governed by the concentration of ferrimagnetic minerals in the rock. The total magnetisation of rocks comprises the vector sum of induced and NRM components and the maximum possible intensity of magnetisation occurs where the induced and NRM components are parallel.

Volcanic rocks, such as those of the Lyttelton Volcano, and igneous basement rocks, contain a higher proportion of magnetic minerals than sedimentary rocks such as Torlesse greywacke basement. Typical magnetisation values for rocks from the Lyttelton Volcano range between 0.5 and 7 A/m (Whiteford and Lumb 1975), which are generally several orders of magnitude greater than sediments of the Canterbury Plains, which are derived from the greywacke rocks of the Southern Alps. Volcanic rocks usually have a significant remanent magnetisation that is “locked in” as the lava cools. The remanent magnetisation may be normal (in the direction of the present day magnetic field) or reversed (in the opposite direction of the present day magnetic field) depending on the earth’s magnetic polarity at the time of eruption. Normally magnetised rocks will cause large positive magnetic anomalies on aeromagnetic survey data, whereas reversely magnetised rocks can cause negative magnetic anomalies.

Figure 8, Figure 9 and Figure 10 show the reduced-to-pole (rtp) magnetic anomaly data resulting from the survey depicted with various colour schemes and contours. The rtp magnetic anomalies are derived by removal of the regional magnetic field (International Geomagnetic Reference Field – IGRF) and correcting for the declination (dip) of the earth’s magnetic field.
Figure 8  Reduced-to-pole (rtp) aeromagnetic anomaly data (in nT). North-South survey lines were flown 400 m apart and E-W tie lines 4000 m apart. Flight height was 300 m over built up areas and 60-100 m elsewhere. Also plotted are the Greendale Fault (red lines), coastline (black lines) and rivers/streams (dark blue lines).

Figure 9  Reduced-to-pole (rtp) aeromagnetic anomaly data, contour interval 50 nT with the zero contour in bold. The University of Canterbury (UC), Christchurch central business district (CBD) and the Bottle Lake Forest landfill are labelled. Also plotted are the Greendale Fault (red lines), coastline (white lines) and major rivers (dark blue lines).
Additional data processing techniques used to enhance interpretation include automatic-gain-control (AGC) and wavelength filtering. Application of AGC spatially equalises the strength of anomalies so that weak magnetic signals have similar amplitude to strong anomalies. The technique reduces the effects of near surface magnetic sources and equalises the amplitude of the signals across the survey area. Figure 11 shows a NW-illuminated hill-shaded image of the 700 m wavelength data with AGC applied. The map, on balance of illumination angles, shows a broadly E-W texture with several prominent ENE and ESE oriented anomalies.

Wavelength filtering of the power spectrum was undertaken using FUGRO-LCT’s GRDFFT software. The magnetic anomaly power spectrum of the survey data can be approximated by straight-line segments (Figure 12) indicative of surface interfaces for magnetic sources (Spector and Grant 1970). The depth to magnetic sources (likely upper surfaces) of 5100, 1255, 243 and 142 m below the survey altitude were derived using this method.

### 3.1 MAGNETIC ANOMALIES

The highest amplitude anomalies are associated with the Lyttelton Volcano at the south eastern edge of the survey area (Figure 8, Figure 9 and Figure 10). The semi-circular Lyttelton Volcano caldera rim hills (i.e. the ‘Port Hills’) and volcanic ridges that radiate to the north are prominent in the data. There is an increase in anomaly wavelength to the north and offshore to the NE, suggesting that magnetic sources are deeper and hence the basin
deepens in this direction. There are ENE alignments of positive and negative anomalies that extend across the survey area that may also be related to deeper (c. 5 km) crustal structure (discussed under depth-matched filtered magnetic anomalies below).

Several c. 3-km-wide positive magnetic anomalies extend mostly north and west of Banks Peninsula. One prominent anomaly, extending c. 20 km NNE offshore from the estuary of Heathcote and Avon rivers, is probably related to lava flows from Lyttelton Volcano (Figure 8). High amplitude (< -350 nT) reversed polarity magnetic anomalies occur in the Port Hills area (prominent blue-purple colour in Figure 10). The pattern and dominance of the negative anomalies suggest they are related to reversely magnetised lava erupted at a time when the earth’s magnetic polarity was reversed. This is not unexpected given that there were several long periods of polarity reversal during the 11-5.8 Ma history of basaltic eruption at Banks Peninsula (Forsyth et al. 2008). The outside edge of the strongly reversed anomalies broadly follows the limit of the modern topography associated with Banks Peninsula.

One exception to the dominantly reversed signal is the >100 nT positive magnetic anomaly over Lyttelton Harbour, Diamond Harbour and bays to the west. This anomaly appears to be related to basalt lava flow deposits in the area (Sewell et al. 1988), and closely matches the northern harbour topography, implying the lava flows were erupted after the formation of the harbour morphology.

Figure 11 Filtered and automatic-gain-controlled (AGC) reduced-to-pole (rtp) aeromagnetic anomaly data. The rtp data is AGC levelled over a 700 m wavelength and then filtered with a > 500 m wavelength band-pass filter to remove short wavelength anomalies (dominated by cultural features). The surface is sun-illuminated from the NW. Also plotted are the Greendale Fault (red lines), coastline (black lines) and drainage (dark blue lines).
Magnetic anomalies from man-made features are generally short wavelength (< 500 m), however, c. 1.5 km wide positive anomalies of 100 to 200 nT occur over both the Christchurch central business district and University of Canterbury. A strong 500 nT anomaly and associated broad negative anomaly occurs over the Burwood landfill in the Bottle Lake plantation (Figure 9).

3.2 DEPTH-MATCH FILTERED MAGNETIC ANOMALIES

The 5100 m depth-match filtered magnetic signal (Figure 13) shows sets of c. 7x10 km magnetic lows with ENE alignment extending across the image. It is likely that much of the ENE magnetic alignment at longer wavelength (> 5 km) derives from deeper magnetic sources within the crust. The magnetic signature is strongest at the southern margin of the image, and may be related to the upper surface of oceanic crust interpreted beneath Christchurch and the offshore Bounty Trough (Davy 1993, Scherwath et al. 2003).

The 1255 m depth-match filtered magnetic signal (Figure 14) broadly corresponds to the depth of the upper surface of basement within the survey area and hence is interpreted to originate from magnetic source interfaces at the top of basement. These sources could be volcanic intrusions at the sediment-basement interface or Cretaceous age volcanic flow deposits. The dashed line in Figure 14 marks a break in the continuity of magnetic anomalies where their pattern and orientation appears to change. This break may reflect the boundary between magnetic anomalies related to volcanic flows that radiate from the Lyttelton Volcano and the regional magnetic anomalies related to basement. However, it is not clear, without
further seismic reflection data, whether this boundary is related to a faulting or to subsurface volcanic morphology.

The 240 m depth-match filtered magnetic signal (Figure 15) shows little high amplitude coherent pattern over the Canterbury Plains, although residual alignments of broader and deeper anomalies are recognisable. Positive anomalies caused by man-made magnetic sources are particularly prominent over Christchurch airport, the central business district, the Burwood Landfill and various gravel pits across the region. Reversed magnetic anomalies are, on the other hand, observed over oxidation ponds. Over the Port Hills area, where basaltic rocks are near, or at the land surface, the high amplitude magnetic signals of volcanic ridges dominate.

4.0 INTERPRETATION OF POTENTIAL FAULTS FROM GRAVITY AND MAGNETIC LINEAMENTS

Three broadly E-W oriented gravity lineaments, labelled A, B and C in Figure 16, extend c. 20 km west of Lyttelton volcano and Christchurch. They are segmented into sections c. 2 to 4 km long by NNE oriented lineaments with most segments, right-stepping relative to adjacent segments. The NNE lineaments, which persist regardless of direction of gravity-slope surface illumination (Figure 16), appear to be discontinuous between E-W lineaments A, B and C, possibly as a consequence of right-lateral E-W oriented offset motion along each set of segments. West of the zone between Rolleston and Lyttelton Volcano the NNE gravity lineaments appear more continuous and they are spaced c. 5 km or more apart.

Closer to Lyttelton Volcano and beneath Christchurch City the gravity anomalies are primarily attributed to the volcano's surface and subsurface structure. Lineaments B and C cannot be traced under the volcano and the eastern extent of lineament A is likely to be influenced by northward dipping and thinning volcanic rocks (i.e. the volcanic apron of Lyttelton Volcano).

Whereas gravity anomalies mostly reflect large vertical offsets of basement that may relate to older faulting, the aeromagnetic data can be processed to highlight shallow changes in geology and may reveal features not evident in the gravity data, e.g., shallower and potentially younger faults (tens of meters displacement), and volcanic units within the sediments. Interpretation of the rtp magnetic data in this report focuses on short-wavelength anomalies (Figure 17) likely to correlate with shallow faults and volcanic features. The yellow lines in Figure 17 highlight offsets and boundaries of magnetic anomalies. Their linearity suggests they are related to faults. A series of three closely spaced NNE lineaments in the magnetic data, parallel to interpreted NNE gravity gradient lineaments, are mapped near gravity gradient lineament B, and three closely spaces E-W trending lineaments in the magnetic data are interpreted at the eastern edge of the survey (Figure 17 inset maps).

Magnetic anomalies that radiate from Lyttelton Volcano are interpreted as lava that has flowed down valleys and constrained by topography, however, it is possible some of these features may be fault-controlled. Breaks in these anomalies on the 1255 m depth-match filtered magnetic signal (Figure 18) are interpreted to be close to the outer limits of the volcanic rocks associated with Lyttelton Volcano.

A magnetic anomaly extends east from the Greendale Fault (yellow dashed line in Figure 17) but it is not a dipolar anomaly, as might be expected for a fault. The ridge-like nature of the lineation suggests that there may be a volcanic feature possibly related to Miocene lava
flows with their spatial extent controlled by topography or faulting. There are several other
ridge-like magnetic anomalies nearby that have a similar origin.

The magnetic anomalies show some correlation with the interpreted gravity anomaly
lineaments (orange and pink lines, Figure 18), particularly the E–W gravity lineament B.
There also appears to be a correspondence between the segmented nature of the magnetic
anomaly signal and the segmentation of the gravity anomaly lineaments.

The 1255 m depth-match filtered magnetic signal shows a degree of correlation with gravity
anomaly lineaments (Figure 18). This is particularly evident for gravity lineament B, and
suggests that the gravity anomaly lineaments originate from faulting and/or structure at
basement level. There also appears to be a correspondence between the segmented nature
of the magnetic anomaly signal and the segmentation of gravity anomaly lineaments inferred
to be related to basement structure.

Figure 13  The 5100 m depth-matched filtered magnetic signal. Contour interval is 20 nT with the zero contour
in bold. Also plotted are the Greendale Fault (red lines), coastline (black lines) and major rivers (dark blue lines).

GNS Science Report 2012/02
Figure 14  The 1255 m depth-matched filtered magnetic signal. Contour interval is 20 nT with the zero contour in bold. Dashed thick green line indicates a natural break in the alignment of magnetic anomalies. Also plotted are the Greendale Fault (red lines), coastline (white lines) and major rivers (dark blue lines).

Figure 15  The 240 m depth-matched filtered magnetic signal. Contour interval is 20 nT with the zero contour in bold. Also plotted are the Greendale Fault (red lines), coastline (white lines) and major rivers (dark blue lines). The central business district (CBD), airport (A), Burwood Landfill (B), gravel-pits (G) and oxidation ponds (O) are labelled.
Figure 16  A sun-illuminated (from southeast) image of Bouguer gravity slope highlighting the NNE oriented trends that segment the E-W gravity gradient lineaments A, B and C. Gravity survey locations are plotted (red and yellow squares). Figure location is shown in the inset.
Figure 17  Linear features in the RTP magnetic anomaly map that may relate to faults (yellow lines). With the exception of the structures (dashed yellow) extending NE from the Greendale Fault, most of the segments are drawn at the contrasting boundaries of magnetic anomalies. Also plotted are gravity gradient lineaments (pink and orange lines), other NNE interpreted lineaments (green lines), coastline (black lines) and drainage (dark blue lines).
Figure 18  Gravity anomaly lineaments (orange and pink lines), other NNE interpreted lineaments (green lines) and magnetic anomaly lineaments (yellow lines) plotted over 1,255 m depth-matched filtered magnetic signal. Also plotted are the Greendale Fault (red lines), coastline (black lines) and drainage (dark blue lines). Gravity lineaments A and B are labelled.
5.0 SEISMICITY AND GRAVITY / MAGNETIC LINEAMENTS

Relocated earthquake epicentres are plotted over gravity and magnetic data to show any correlation between the geophysical data and seismicity. Earthquake epicentres from 4 September 2010 to immediately after the 22 February 2011 earthquake plotted over the 1255 m depth-match filtered signal (Figure 19) broadly follow the pattern of the ‘B’ gravity gradient lineation (Figure 18) and matching positive series of magnetic anomaly highs although the match is far from exact. The 1255 m solution is interpreted as being sourced near the top of basement and it is at this level that the gravity anomalies are likely to also be sourced (Figure 4).

Analysis of the gravity data is helped by plotting the Bouguer gravity anomaly contours over the colour ramp and shading used for the slope of the gravity anomaly. This slope shaded Bouguer gravity anomaly is used as a background for plotting relocated earthquake epicentres between 4 September 2010 and 7 September 2010, in Figure 20 to Figure 23. From 4 to 7 September 2010 seismicity spread along the Greendale Fault and concentrated near Rolleston and along gravity gradient lineament B (Figure 20). Several of the earliest earthquakes shown on the figure, including the magnitude 7.1 Darfield earthquake, lie along a NNW orientation that has little gravity expression, except in the northern 10 km. There is only a slight correspondence between the gravity gradient and the Greendale Fault.

The addition of the next 17 days of relocated earthquake epicentres on the gravity map (Figure 21) shows that both the original NNW trend of seismicity, related to the Darfield Earthquake, and the E-W trend of seismicity related to the Greendale Fault became established. The cluster of earthquakes at Rolleston intensified and further earthquakes occurred southeast of Rolleston. During this period of time the seismicity close to gravity gradient lineament B extended to the NNE gravity gradient lineament immediately west of the Westmorland ridge (Figure 21) and further east along the same trend.

By 21 February 2011 (Figure 22) low magnitude seismicity (<4.2) occupied the region of earlier higher magnitude earthquakes, with little change in the pattern of seismicity. The exception to this pattern was a sequence of earthquakes that occurred directly beneath the centre of Christchurch CBD around Boxing Day 2010. Most of these earthquakes appear to cluster on the trend of gravity gradient lineament A.

Relocated earthquake epicentres from 4 September 2010 to 22 February 2011 (Figure 23) show further seismicity, including the 22 February 2011 magnitude 6.3 earthquake, occurred along the ENE trend south of Christchurch city. The seismicity is on the trend of gravity gradient lineation B (Figure 22). The magnitude 5.8 earthquake that occurred 12 minutes later and the magnitude 5.9 earthquake 2 hours later are also located on the same ENE linear segment of seismicity.

The correlation of earthquake epicentres and interpreted lineaments is shown more clearly in Figure 24, where the sequence of earthquakes over the 3.5 hour period from immediately prior to the 22 February 2011 magnitude 6.3 earthquake is overlaid on rtp magnetic anomaly data. Figure 23 shows the pattern of seismicity between the gravity gradient lineament A and B. A series of magnitude 5 earthquakes (white line Figure 24d) appear to link the between the lineaments, and over the same period several lower magnitude (<4.2) earthquakes highlight the path between lineament B and the main ENE oriented 22 February 2011 sequence.
Figure 19  Earthquake locations from 4 September 2010 to immediately after the 22 February 2011 earthquake plotted over the 1255 m depth-matched filtered magnetic signal. Earthquakes greater than magnitude 4.2 are colour highlighted and plotted over smaller events. Also plotted are gravity anomaly lineaments (orange and pink lines), magnetic anomaly lineaments (yellow lines), other NNE interpreted lineaments (green lines), the Greendale Fault (red lines), coastline (black lines), and drainage (dark blue lines).
Figure 20  Map of the Bouguer gravity anomaly slope and Bouguer gravity anomaly contours overlain by interpreted lineaments and relocated earthquake epicentres recorded from 4 September 2010 to 7 September 2010. Earthquakes greater than magnitude 4.2 are plotted over smaller events (magnitude is indicated by the key). Also plotted are the active faults (red lines), coastline (black lines) major rivers (dark blue lines). Rolleston (R) and the central business district (CBD) are labelled.
Figure 21  Map of the Bouguer gravity anomaly slope and Bouguer gravity anomaly contours overlain by interpreted lineaments and relocated earthquake epicentres recorded from 4 September 2010 – 24 September 2010. Earthquakes greater than magnitude 4.2 are plotted over smaller events (magnitude is indicated by the key). Epicentres from 4 to 7 September (Figure 20) have been shaded grey. Also plotted are the active faults (red lines), coastline (black lines) major rivers (dark blue lines), Rolleston (R), Westmorland (W), the Avon River, gravity lineaments A and B, and the central business district (CBD) are labelled.
Figure 22  Map of the Bouguer gravity anomaly slope and Bouguer gravity anomaly contours overlain by interpreted lineaments and relocated earthquake epicentres recorded from 4 September 2010 – 21 February 2011. Earthquakes greater than magnitude 4.2 are plotted over smaller events (magnitude is indicated by the key). Epicentres from 4 September to 24 September (Figure 21) have been shaded grey. Also plotted are the active faults (red lines), coastline (black lines) major rivers (dark blue lines), gravity lineaments A and B, and Westmorland (W).
Figure 23  Map of the Bouguer gravity anomaly slope and Bouguer gravity anomaly contours overlain by interpreted lineaments and relocated earthquake epicentres recorded from 4 September 2010 – 22 February 2011. Earthquakes greater than magnitude 4.2 are plotted over smaller events (magnitude is indicated by the key). Epicentres 4 September to 21 February (Figure 22) have been shaded grey. The location and magnitude of largest earthquakes of 22 February are marked. Also plotted are the active faults (red lines), coastline (black lines) major rivers (dark blue lines) and the central business district (CBD).
Figure 24  Earthquake sequence over 4 hours from immediately prior to the 22 February 2011 magnitude 6.3 earthquake overlaid on rtp magnetic anomaly data. Seismicity in (b) to (d) are incremental from (a) and earlier seismicity has been grey shaded. The central business district (CBD) and University of Canterbury (UC) are labelled in (a). Interpreted lineaments are also plotted (pink, green, orange and yellow lines). The link to the Boxing Day earthquake sequence beneath the city centre is shown by a line of magnitude 5 earthquakes (white curve in d). Highlighted by arrows in (d) are earthquakes on the trend of lineament 'B' (labelled).
Figure 25 Onshore Bouguer gravity anomaly slope and offshore fault interpretation from Barnes et al. 2011. Also plotted onshore are lineaments (orange and pink lines), coastline (black), major rivers and lakes (blue) and mapped faults red lines. GF = Greendale Fault. NNE Faults bounding Gebbies Pass (Forsyth et al. 2008) are plotted by green lines.
6.0 DISCUSSION

The gravity anomaly principally maps structure on the top of basement, consequently the Bouguer gravity broadly shows basement topography, although other density contrasts, such as crustal density variations, will also influence the anomaly. There are two major sets of gravity gradient lineaments interpreted from the data: E-W to ESE-WNW oriented lineaments and NNE lineaments. The most continuous and prominent lineaments strike E-W to ESE-WNW. Some of these lineaments can be correlated with mapped faults (Forsyth et al. 2008) and faults seen on seismic reflection data (Figure 7), although there is only a small gravity anomaly associated with the Greendale Fault.

Gravity gradient lineaments A, B and C are consistent with north-facing basement faults with offsets of 200–500 m. However, the seismic data show that the faults are not simple offsets in basement, but have complex structures. Interpretation of the seismic data indicates that some of the faults may have formed as Cretaceous normal faults and reactivated as strike-slip faults in the Neogene. The Cretaceous faults don’t appear to be consistent with those bounding south-facing half grabens along the crest of the Chatham Rise (Herzer and Wood 1992), but this may reflect differing patterns of late Cretaceous or later deformation.

NNE striking lineaments interpreted on gravity anomaly gradient data are aligned with major structural trends postulated along the Gondwana subduction margin c. 110–105 Ma (Davy et al. 2008), and with the direction of modern relative plate motion (Wallace et al. 2007). Some of the NNE-striking lineaments are interpreted to offset E-W to ESE-WNW trending lineaments. The continuity of the NNE lineaments varies and the distance between adjacent lineaments decreases from c. 5 km on the Canterbury Plains to 2-4 km close to Lyttelton Volcano. The highly segmented nature of the gravity gradient lineaments is also consistent with the segmented nature of magnetic anomaly data. Gravity gradient lineaments with a NNE orientation cannot be confidently interpreted beneath Christchurch City possibly due to the overlapping presence of volcanic structures. NNE Faults are however interpreted (Forsyth et al. 2008) bounding Gebbies Pass on the southern side of Lyttleton volcano (Figure 25) and a number of the inlets on Banks Peninsula have a NNE orientation.

Immediately offshore from Christchurch, graben structures are dominantly E–ENE oriented (Barnes et al. 2011). The three interpreted lineaments north of Christchurch project offshore (Figure 25) to approximately match the positions of the ENE trending Late Pleistocene faults (Kaipoi Fault Zone, Pegasus Bay Fault and Waikuku Fault) identified by Barnes et al. (2011). Lineaments in magnetic anomaly data are also dominantly ENE oriented with the exception of a group of more E-W oriented lineaments southeast of Lyttelton Harbour.

Following the September 2010 Darfield Earthquake, seismicity generally moved eastwards with time. Seismicity east of Rolleston was concentrated along gravity gradient lineament B. Seismicity appears to have moved NNE from gravity lineament B to lineament A on which a sequence of earthquakes occurred directly beneath the centre of Christchurch CBD around Boxing Day 2010. The 22 February 2011 earthquake and a series of subsequent magnitude 5 earthquakes occurred along the projected trend of the gravity lineament B, immediately north of Lyttelton Volcano.

Gravity lineaments A, B and C do not extend further west than the Rolleston area, suggesting that in this region there is a boundary between separate domains of basement deformation. The domain between Rolleston and Lyttelton Volcano is at the centre of the Canterbury Bouguer gravity anomaly high (Hicks 1989). The orientation of the gravity high broadly parallels the grain of the paleo-Gondwana subduction margin (Mortimer and Tulloch...
and is possibly a region of higher rigidity crust associated with Lyttelton Volcano. The separate domains of basement deformation are also reflected in the pattern of 2010–2011 seismicity and the Rolleston boundary zone between these two domains is a region of intense seismicity.

The lack of a direct correlation between recent seismicity epicentres and interpreted lineaments in gravity and magnetic anomaly data may be due to not all faults having an associated gravity or magnetic anomaly or to the dip on the associated fault planes. Interpreted gravity and magnetic lineaments are sourced at basement or shallower levels (< 1 km below ground surface) whereas most epicentres in the Banks Peninsula occur at c. 6 km depths (Bannister et al. 2011) and seismicity to the west is generally < 15 km deep (Gledhill et al. 2011). Dip on the February 22 2011 rupture has been interpreted as 66° (Beavan et al. 2011) and interpreted faults in Figure 7 dip at up to 45°. The resulting offsets between epicentres and their rupture plane intersection with basement could be 2-5 km near Banks Peninsula and greater further west. The small amplitude of gravity anomalies associated with the Greendale Fault illustrates how strike-slip faulting or deep basement can minimise the observable gravity signal due to fault offsets in basement.

The alignment of epicentres with gravity gradient lineament B suggests that subsequent seismicity can focus on pre-existing faults interpreted from gravity and magnetic anomaly data. However, earthquakes may not be constrained to existing fault planes, and the occurrence of epicentres between lineaments A and B may illustrate rupture away from pre-existing faults.

**7.0 CONCLUSIONS**

Gravity observations were made in the Christchurch region between 12 April and 21 April 2011 to provide a uniform data coverage. The new data have a total estimated error of +/- 0.05 mGal (0.5 uN/kg) and seamlessly fit with earlier data from the region. From 16 to 24 May 2011 aeromagnetic data were acquired by Thompson Aviation Ltd over Christchurch city and the surrounding region. These data provide additional information on the subsurface structure of the region.

The gravity anomalies in the Christchurch region are associated with large topographic and geologic features such as the Lyttelton and Akaroa volcanoes and probably with subsurface basement structure. The interpreted magnetic anomalies are primarily associated with relatively shallow volcanic features. ENE oriented lineaments identified in the magnetic anomaly data may correlate with faulting that offsets, or forms the edge of underlying volcanic units. A magnetic lineation that has a ridge-like nature extends eastward from the Greendale Fault is difficult to explain in terms of simple juxtaposition by faulting of rocks with different magnetisations and may be related to Miocene lava flows or a volcanic intrusion.

Interpretation of gravity data identifies lineaments that have E-W to ESE-WNW and NNE orientations. The NNE gravity gradient lineaments may relate to NNE faults that formed in Cretaceous time and were reactivated during Late Miocene tectonic events. The E-W to ESE-WNW oriented lineaments are possibly associated with faults of grabens, or half-grabens that formed in the Cretaceous. Some of the lineaments align with faults interpreted on seismic reflection data. Three sub-parallel lineaments are interpreted to extend up to 20 km east of the Rolleston area. They appear to be segmented into sections c. 2 to 4 km long with a right lateral sense of offset between adjacent segments.
Interpretation of the gravity and magnetic data in conjunction with seismicity suggests that there is a boundary between separate structural domains in the Rolleston area. The domain between Rolleston and Lyttelton Volcano is interpreted as a region of basement deformation where E-W basement ridges are associated with strike-slip faults. West of Rolleston the basement has a different character and appears to be less segmented and deformed.

8.0 ACKNOWLEDGEMENTS

The authors thank Pilar Villamor, Andy Nicol and Ray Wood for helpful reviews of preliminary drafts and greatly improving the manuscript. We thank CERA, Civil Aviation Authority of NZ and Thomson Aviation Ltd for making the aeromagnetic survey possible. We also appreciate the help given by Dave Collett from LINZ with GPS and gravity surveying. Finally we wish to thank Dr. Stephen Bannister for regular provision of relocated epicentres during a very busy period of seismicity.

9.0 REFERENCES


Tag Oil Ltd.; 2007; Geological Proposal Salmon-1; Ministry of Economic Development New Zealand Unpublished Petroleum Report 3638


