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Tectonophysics 424 (2006) 119 – 133
TECTONOPHYSICS
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Delineation of a large ultramafic massif embedded within a major SW Pacific suture using gravity methods

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Received 20 November 2005; received in revised form 16 June 2006; accepted 18 July 2006
Available online 17 August 2006

Abstract

Gravity studies have delineated the largest ultramafic massif in New Zealand, embedded within a buried major SW Pacific crustal suture zone. This suture records terrane collision onto the Gondwana margin during the Mesozoic and separates a forearc terrane from an outboard accretionary prism terrane. It can be traced throughout the length of New Zealand as the Junction Magnetic Anomaly and contains the Permian Dun Mountain Ophiolite Belt, which in the South Island of New Zealand is characterized by a string of isolated ultramafic massifs in a sheared matrix of serpentinite and sediment. Our analysis reveals a steep gravity gradient at the suture boundary which is attributed to a newly recognised density contrast (0.1 Mg m^{-3}) between terranes of the forearc and the accretionary prism. The massif itself is marked by the occurrence of a strong, elongate residual gravity anomaly (+120 g.u.) extending 50 km along the suture and coincident with the Junction Magnetic Anomaly. It is modelled, at its southern end, as a dense, 15 km wide source body, extending to at least 6 km in depth. In conjunction with detailed aeromagnetic data, this modeling indicates the presence of a spindle-shaped ultramafic massif, analogous to, but larger than similar bodies found within the Dun Mountain Ophiolite Belt elsewhere. This fabric of sheared serpentinites enclosing ultramafic massifs therefore extends at least the length of New Zealand and probably beyond. In part it may result from accretion of asperities in the subducting plate, but it is also due to disruption of larger ultramafic bodies during subsequent strike-slip motion, which caused the remarkable linearity of the Dun Mountain Belt. Given the common occurrence of the plate tectonic processes involved, it is likely that such structures can be found in other regions around the world using similar geophysical potential field methods.

Keywords: Terrane suture; Waipapa terrane; Murihiku terrane; Maitai terrane; Dun Mountain Ophiolite Belt; Ultramafic massif; Gravity

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1. Introduction

Terrane boundaries typically mark major mechanical discontinuities, and hence important zones of weakness in the upper crust (Gates, 1996; Birt et al., 1997 Holdsworth et al., 2001). During subsequent tectonic events they may continue to be particular loci of deformation, and by reactivation can become the boundaries of major fault blocks, thus influencing the geological history of a region long after their inception. Detailed information on the continuity, internal fabric and structural development of such zones is crucial for understanding crustal processes such as terrane amalgamation, continental break-up, seismicity, location of volcanic activity and mineralization. In some instances, an entire terrane can become so deformed due to crustal collision, combined with strike-slip motion, that it eventually comes to mark a thin, predominantly

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0040-1951/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2006.07.009

linear boundary between its neighbor terranes. This is the case in New Zealand, where the Maitai terrane (Johnston, 1981; Spörli, 1987; Bradshaw, 1989; Rattenbury et al., 1998) comprises the highly deformed remnants of oceanic crust between the forearc Murihiku terrane and the accretionary prism of the Waipapa terrane. The Maitai terrane, and especially its constituent Dun Mountain Ophiolite Belt, presently forms a first-order linear geophysical marker throughout the entire length of the New Zealand micro-plate (Fig. 1). This unit has many global analogues; for example, it has been compared by Coombs et al. (1976) to the Coast Range Ophiolite in the Great Valley Sequence (Franciscan assemblage) of California (e.g. Shervais et al., 2005). Similar linear belts of mafic ocean floor rocks are found in the broad collision zone of the Himalayas (Aitchison et al., 2000) and also occur in older terrane assemblages ranging back to the Precambrian (Gibb et al., 1983; Hutchinson et al., 1983; Ferraccioli et al., 2002; Genna et al., 2002; Bierlein and Betts, 2004).

In contrast to the more mountainous South Island of New Zealand, investigation of the major basement terrane boundaries in the North Island is hampered by the extensive cover of younger sedimentary and volcanic rocks, and a paucity of boreholes that penetrate to basement. Geophysical methods, especially aeromagnetic, can provide important information on such buried crustal boundaries (e.g. Wonik et al., 2001; Genna et al., 2002). Applications of gravity methods for investigating terrane boundaries are less common on account of their intrinsically lower resolution of complex structures, however, the gravity method does have advantages in the modeling of deeper structures.

The effectiveness of gravity methods for detecting and delineating sutures (e.g. Gibb et al., 1983; Ferraccioli et al., 2002; Bierlein and Betts, 2004) can be attributed to a number of factors: 1) sutures commonly bound terranes of different composition or metamorphic grade, which lead to density contrasts across the suture zone (Gibb et al., 1983); and 2) suture zones commonly define the final closure of oceans during collisional tectonics, a process which can lead to the preservation of slivers of oceanic lithosphere along them (Aitchison et al., 2000). In this scenario, these preserved slivers can produce either negative or positive gravity anomalies depending on the degree of serpentinisation, and hence density, of the ultramafic rocks. Geophysical methods also have the important advantage of providing a continuity of information that is often unavailable in regions with thick post-tectonic cover.

In this paper we use gravity and other geophysical data to elucidate the geometry of a buried ultramafic body, which is part of a major ophiolitic terrane suture in an area of subdued topography, and where detailed aeromagnetic data over the ophiolites have been analyzed (Eccles et al., 2005). We distinguish, for the first time, the different gravity effects of basement terranes that have previously been treated as uniform. This provides a better understanding of the complex regional gravity field across the suture, allowing a prominent residual gravity anomaly to be better resolved. Our approach as applied to this suture zone is widely applicable elsewhere in the world.

2. Regional tectonics

The basement rocks of the New Zealand micro-continent (Spörli, 1987) consist of a number of tectonostratigraphic terranes that have been grouped into a Western and an Eastern Province (Bradshaw, 1989). The units described here are entirely within the Eastern Province, which was accreted against the Western Province terranes during the Mesozoic, forming part of the Gondwana margin. By the Late Cretaceous, accretion gave way to lithospheric extension, which heralded the separation of New Zealand from Gondwana and the opening of the Tasman Sea (Bradshaw, 1989). Convergent tectonics resumed in the late Oligocene/Early Miocene with the emplacement of the Northland Allochthon (Ballance and Spörli, 1979), subsequent formation of arc volcanics in northern New Zealand, and initiation of the dextral Alpine Fault, which marks the present oblique-slip plate boundary through New Zealand (Fig. 1). During the Pliocene, subduction beneath the New Zealand micro-continent shifted southwards and eastwards to its present location off the east coast of the North Island, leaving northernmost New Zealand (including the present study area) in an extensional back-arc position.

The Murihiku forearc terrane (Ballance and Campbell, 1993) forms a continuous regional synclinorium (Spörli, 1978) along the edge of the Eastern Province towards Gondwana. The Maitai terrane, consisting of the Dun Mountain Ophiolite Belt and overlying Permian/Triassic sediments of the Maitai Group (Johnston, 1981), is associated with a remarkably linear geophysical feature named the Junction Magnetic Anomaly (Hatherton and Sibson, 1970), part of the regional Stokes Magnetic Anomaly System (Hunt, 1978). In the South Island, the Junction Magnetic Anomaly is attributed to outcropping serpentinised igneous rocks of the Dun Mountain Ophiolite Belt (Hunt and Mumme, 1978).

The terranes adjoining the Maitai terrane on its Pacific (outboard) side are more complexly deformed

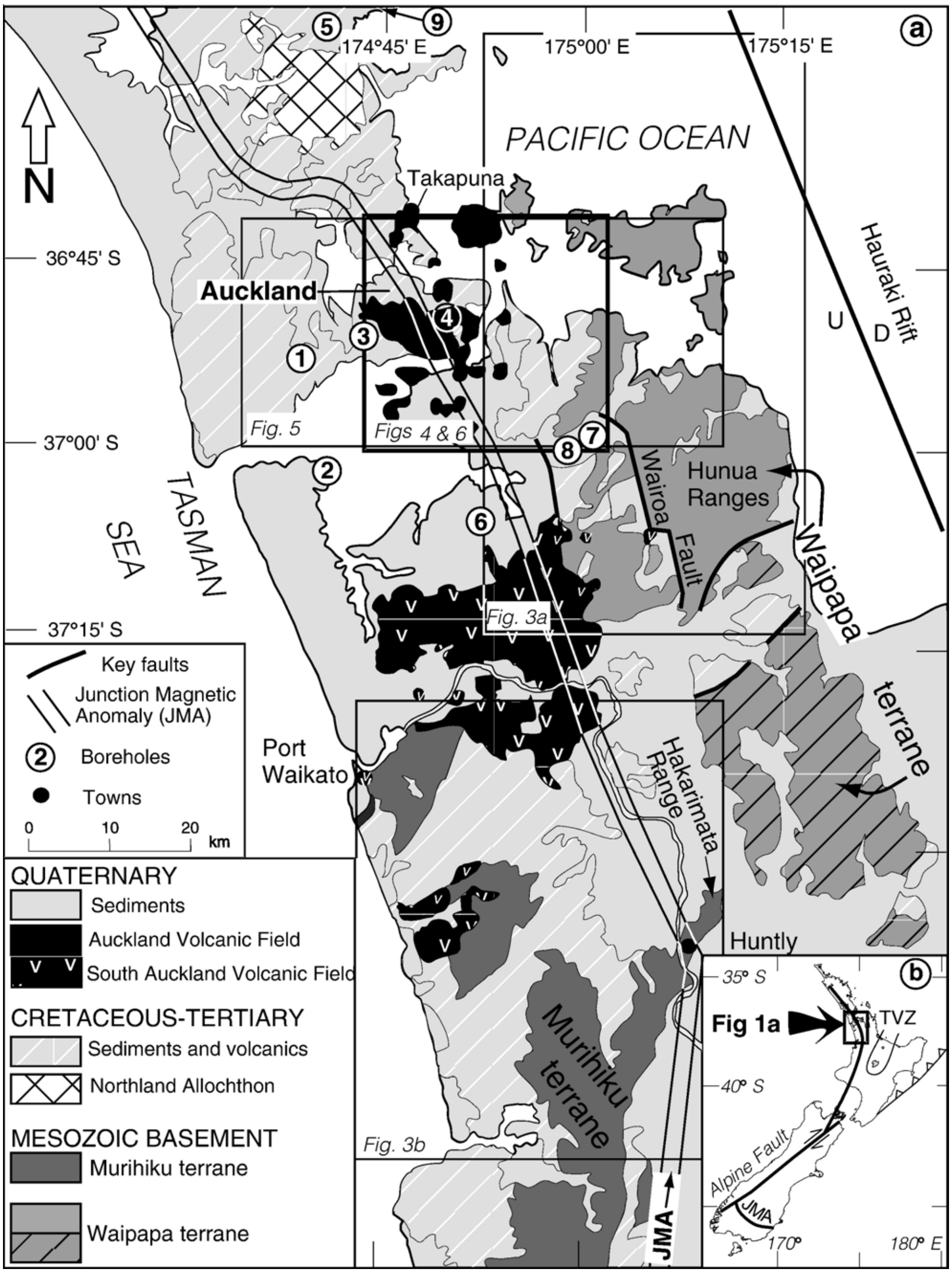

Fig. 1. (a) Geological map of the Auckland–Waikato region, modified after Edbrooke (2001), with trace of the axis of the Junction Magnetic Anomaly marked. Quaternary sediments include Tauranga Group; Cretaceous–Tertiary sediments include Waitemata Group, hatched Waipapa terrane denotes Morrinsville facies, unhatched denotes Hunua facies. Circled numbers are locations of boreholes, which intersect basement (see Table 1). Inset rectangles locate Figs. 3–6. The Hakarimata Range, where Murihiku terrane is thrust eastwards across axis of Junction Magnetic Anomaly, is indicated. Inset (b) shows location of main map (a) and occurrence of Junction Magnetic Anomaly (marking the Dun Mountain Ophiolite Belt of the Maitai terrane) throughout New Zealand, including its displacement by the Alpine Fault. TVZ: Taupo Volcanic Zone. Thrust symbol: present day subduction zone.

than the Murihiku terrane because they were parts of accretionary prisms assembled by terrane amalgamation in the late Mesozoic. Over most of the length of the micro-continent, the Caples–Pelorus terrane lies immediately outboard of the Maitai terrane (Bradshaw, 1989; Black, 1994). However, this unit has not yet been detected in the middle and southern part of the North Island. The Waipapa terrane (Spörli, 1978; Adams and

Maas, 2004) is the next terrane to the east in the North Island. The Torlesse terrane, also a part of the accretionary complex, is consistently east of the Caples–Pelorus–Waipapa terranes as far north as the central North Island. The relationship between the Waipapa terrane and the Torlesse terrane of the northern North Island is still controversial. The accretionary terranes consist of monotonous terrigenous clastics ("greywackes"), of quartzo-feldspathic composition in the case of the Torlesse terrane, and lithic-volcanic in the Caples and Waipapa terranes. Occasional seams of ocean floor volcanics, cherts and green mudstones mark the thrust zones in these accretionary complexes (Spörli et al., 1989; Aita and Spörli, 1992).

3. Geology of the Auckland area

3.1. Basement

In the Auckland region, only the Waipapa terrane is exposed at the surface (Fig. 1) in NNW-trending uplifted fault blocks. This terrane was subdivided by Kear (1971) into the more offshore Hunua facies in the north and the coarser, more nearshore Morrinsville facies in the south (Fig. 1). In the Hunua facies, stacked thrust slices between approximately one hundred to several hundred meters thick have been recognized (Spörli et al., 1989). Each consists of thin ocean floor basalt at the base, overlain by red chert followed by green argillites and finally as the dominant part of the section, terrigenous clastics ('greywackes'). Generally, they dip moderately to steeply to the west, but there are local dip reversals due to later, approximately N–S trending folds (Schofield, 1967; Spörli et al., 1989). These rocks have been metamorphosed to prehnite–pumpellyite grade (Hawke, 1978; Black et al., 1993).

The nearest surface exposure of the Murihiku terrane lies 80 km to the south of Auckland, on the west coast at Port Waikato (Fig. 1), forming a simple N–S-trending, westerly inclined syncline with a steep eastern limb and a more shallowly dipping western limb, part of the Kawhia Synclinorium (Spörli, 1978). The sandstones and mudstones of this terrane are richly fossiliferous and range from Late Triassic to Late Jurassic in age (Ballance and Campbell, 1993). Murihiku terrane rocks are of much lower metamorphic grade than the Waipapa terrane, only reaching upper zeolite facies (Black et al., 1993). Drill holes (see Table 1) confirm that this unit extends into the Auckland area.

The location of the Maitai terrane can only be inferred from the presence of the Junction Magnetic Anomaly which trends NNW–SSE in the Auckland area (Eccles et al., 2005). In addition, schistose rocks brought up by two of the Auckland volcanoes (Searle, 1959) may have been derived from this terrane. Active subsidence is occurring in the NNE-trending Hauraki Rift (Hochstein and Ballance, 1993) to the east of the uplifted Waipapa terrane blocks (Fig. 1). These structures appear to be reactivating faults inherited from an earlier rifting episode associated with opening of the Tasman Sea during the Cretaceous (Spörli, 1987).

3.2. Overlying lithologies

Eocene to Oligocene Te Kuiti Group sediments unconformably overlie basement rocks south of Auckland, and their presence has been confirmed in central Auckland (borehole 2, Fig. 1; after Edbrooke et al., 1998); remnants of the sub-Te Kuiti Group erosion surface are preserved in uplifted basement blocks to the east. Over most of the area however, it is the Upper Oligocene to Lower Miocene Waitemata Group sediments that unconformably overlie the basement, with latest Quaternary Tauranga Group sediments in turn unconformably overlying the Waitemata Group. The basaltic Kerikeri Volcanic Group is represented in the greater Auckland region by two distinct fields, the Early Pleistocene South Auckland Volcanic Field (Fig. 1) and the Late Pleistocene to Holocene Auckland Volcanic Field (Edbrooke, 2001).

3.3. Thicknesses of cover rocks and depth extent of basement greywackes

Several boreholes in the greater Auckland region provide information on depths, or minimum depths, to basement (i.e. thickness of cover sediments) (Table 1). Four of these indicate Waipapa basement at depth in the

Table 1
Summary of basement depths from boreholes within the Auckland region

Borehole No.	Depth to basement (mbsl)	Basement terrane
1	485	Not documented
2	340	Murihiku
3	c. 592–622	Not penetrated
4	>590	Not penetrated
5	860	Waipapa
6	>595	Not penetrated
7	<297	Waipapa
8	<292	Waipapa
9	424	Waipapa

Borehole numbers as in Fig. 1. References: 1. W. Russell, pers. comm. (2002); 2. Waterhouse (1989); 3. Edbrooke et al. (1998); 4. and 6– 8. Isaac (1994); 5. Schofield (1989); 9. Waterhouse (1968).

east of the region and one confirms Murihiku basement terrane to the west. In the region of the Murihiku terrane (boreholes 1, 2, 3 and 6; Fig. 1) depth to basement varies from about 300 m to 600 m. For the region underlain by Waipapa terrane, the values are less than 297 m in the south (boreholes 7 and 8) and 400 to 860 m in the north (boreholes 5 and 9). These variations in depth to basement show no overall systematic pattern across the region and are of the same order of magnitude as topographic variations in the flat-topped, exposed basement ranges to the east and south, which are a relict of Late Cretaceous–Early Tertiary peneplenation followed by faulting (Fig. 1).

Little information is available on the depth extent of these basement rocks, however a seismic refraction transect (Stern et al., 1987) through the North Island shows a distinct seismic velocity change, from 5.4 to 6.4 km s^{-1}, at approximately 6 km depth under Auckland. This change was interpreted as either the structural base of the greywacke basement terranes or an abrupt increase in metamorphic grade (Stern et al., 1987). Magnetic modeling in the Auckland region suggests that basement terrane slices extend to at least mid-crustal depths, i.e. 15 km depth in one model (Eccles et al., 2005). Equivalent basement terranes seen at the surface in the southeast of the South Island are also modelled to extend to 25–30 km in depth (Mortimer et al., 2002).

4. Density of basement rocks

The average density of basement greywackes in the North Island is reported to be 2.65±0.04 Mg m^{-3} (Hatherton and Leopard, 1964; Whiteford and Lumb, 1975) and regional gravity data throughout New Zealand have conventionally been corrected using a standard basement density of 2.67 Mg m^{-3} (e.g. Robertson and Reilly, 1960; Reilly, 1972). Recent modeling studies in the South Island have suggested the occurrence of density contrasts between terranes (e.g. Mortimer et al., 2002), however, no systematic study of such density variations either between, or *within*, New Zealand basement terranes has been made.

Density measurements were carried out on 103 samples of basement rocks from the Murihiku (sourced from outcrops in the southwest of the study area) and the Waipapa (sourced from outcrops in the east of the study area) basement terranes (Fig. 1). The results (Fig. 2) clearly show two populations: Waipapa rocks have an average (saturated) density of 2.69 Mg m^{-3} whilst Murihiku rocks have an average density of 2.59 Mg m^{-3} (with standard deviations of 0.04 and 0.07, respectively) i.e. there is a difference in average bulk density of 0.1 Mg m^{-3} between the two terranes, which is likely to have a significant gravity effect.

Both Murihiku and Waipapa terranes consist of alternating sequences of relatively coarse sandstones and finer-grained mudstones/argillites. No relationship between measured density and grain size is apparent for the Waipapa rocks. However, the results of our measurements show that for Murihiku rocks, density decreases slightly with increasing grain size (as might be expected in these more poorly indurated rocks) and this may account for the greater range of corresponding

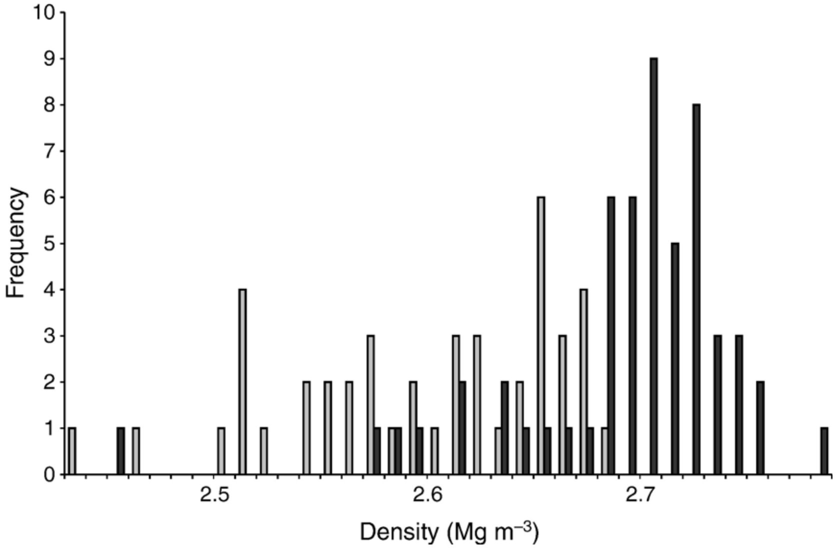

Fig. 2. Histogram showing the frequency distribution of measured density values for Waipapa terrane samples (black bars) and Murihiku terrane samples (grey bars).

density values. There is no systematic variation of density with geographic location in either terrane.

Given the different density–grain size relationships for the two terranes, the rate of density increase due to compaction with depth is also likely to differ. Petrographic studies of surface Waipapa rocks in the Auckland region indicate maximum metamorphic temperatures of 300 °C (Nishimura et al., 2004). Diagenesis, and hence maximum compaction, is known to occur between 100 and 300 °C (Lemée and Gueguen, 1996), therefore it can be inferred that the Waipapa rocks have approached maximum compaction and closure of pores. Hence, any further increase in density with depth is likely to be relatively minor. In contrast, surface exposures of carbonaceous rocks within the Murihiku terrane show a maximum reflectance of 0.7% (Black et al., 1993), indicating that these rocks have attained temperatures up to only about 100 °C. The density of Murihiku rocks therefore is likely to increase with depth.

The geothermal gradient in the Auckland region is unknown, but for the North Island in general has been estimated to be approximately 30 °C km^{-1} (Pandey, 1981). Therefore, at approximately 6–7 km depth, where a major geophysical boundary occurs (Stern et al., 1987), Murihiku rocks could be expected to approach a density comparable to that of surface Waipapa rocks. The density contrast between the Murihiku and Waipapa terranes therefore is likely to decrease to zero at about 6 km, where both rock types would be approaching greenschist metamorphic facies.

5. Gravity data

The existing gravity data in the greater Auckland region were supplemented by 115 new gravity measurements (Fig. 3). Station elevations were determined to ±30 cm by differential GPS and the gravity data were corrected using the IGF (1967) with a standard density of 2.67 Mg m^{-3} (Robertson and Reilly, 1960) and terrain corrections applied to 22 km. The data are tied to the New Zealand Primary Gravity Network (Robertson and Reilly, 1960). The resulting Bouguer gravity

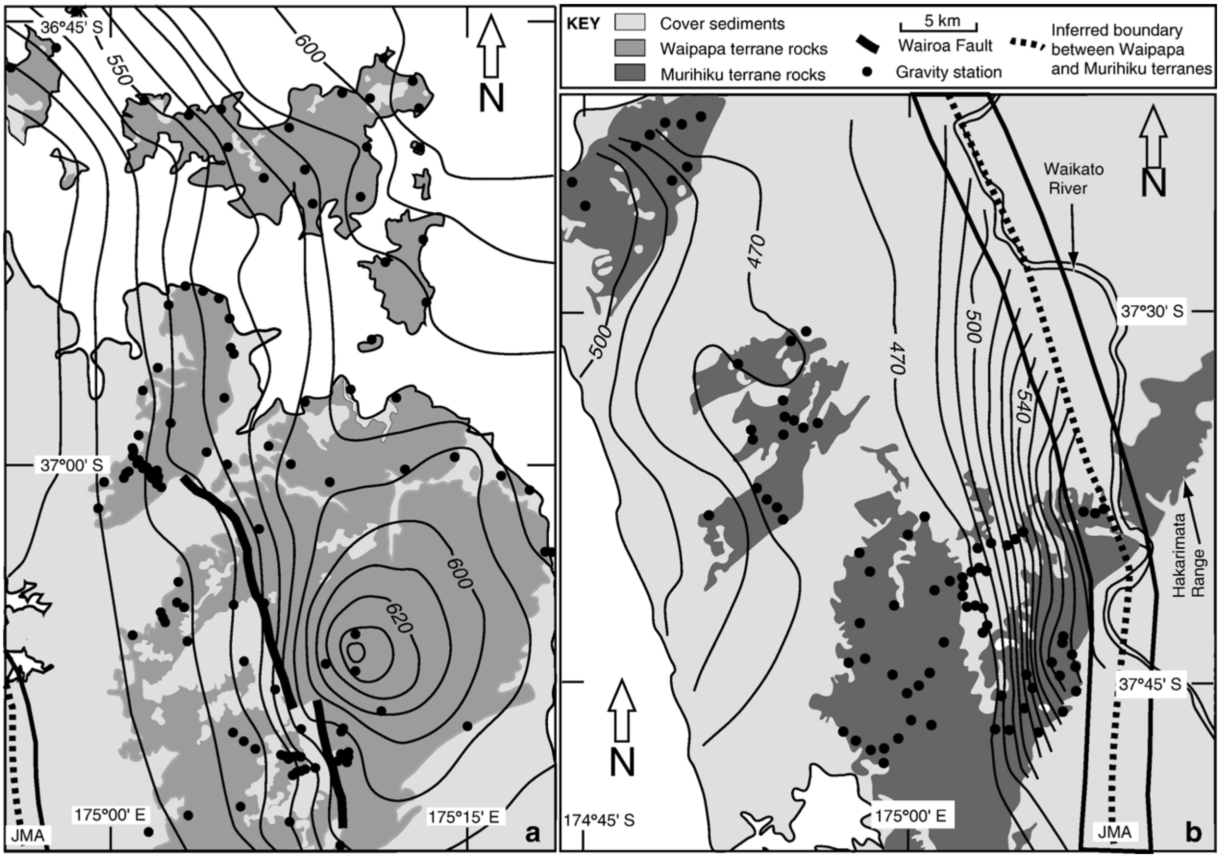

Fig. 3. Regional gravity fields over the outcropping basement terranes of the Auckland–Waikato region: (a) Waipapa terrane, (b) Murihiku terrane (areas of maps shown in Fig. 1); contour interval is 10 g.u. Gravity data from this study, with additional data from Woodward (1971a,b), Wise (1999) and Al-Salim (2000). The inferred terrane boundary is based on the location of the axis of the Junction Magnetic Anomaly.

anomaly across the region is complex and comprises a number of component wavelengths which are discussed below with reference to particular basement terranes and their structural relationships.

5.1. Gravity field over outcropping Waipapa and Murihiku terranes

The Bouguer gravity field over the Waipapa terrane (Fig. 3a) has two components; in the northeast and southwest of the area, the field decreases to the west-southwest with a relatively smooth gradient of 3 g.u. km^{-1}, striking at 165°. This is consistent with a broader regional field for the Waipapa terrane reported by Henrys and Hochstein (1985). In the southeast, immediately east of the Wairoa Fault (Fig. 3a), this broader gravity field is disrupted by a closed, second-order (shorter-wavelength) positive gravity anomaly, peaking at 640 g.u., which is superimposed upon it. The shape and extent of this second-order anomaly appears to mimic that of the fault block-generated outcrop pattern of the Waipapa rocks however data are sparse in this area. The steep gravity gradients are sub-parallel to known bounding fault structures of NNW–SSE (and to a lesser degree ENE–WSW) orientation. At the Wairoa Fault (Fig. 3a), the gravity gradient of this second-order anomaly is steep (10 g.u. km^{-1}) and strongly linear. These steeper gradients are located wholly over outcropping Waipapa terrane greywacke and are interpreted to represent a density contrast within the Waipapa basement, related to faulting. Buried dense ultramafic rocks of the Maitai terrane are unlikely to be the cause of this anomaly, as the Junction Magnetic Anomaly marking the terrane lies almost 20 km to the west of the Wairoa Fault and there are no magnetic anomalies in this area (Hunt, 1978). However, surface exposures of Waipapa rocks either side of the Wairoa Fault offer no explanation for this anomaly. A full interpretation of this gravity anomaly would require more data, especially to the north, but would be problematic due to dense bush cover.

The gravity field over outcropping Murihiku terrane in the southwest of the area (Fig. 3b) is characterized by a gradient of 3 g.u. km^{-1} similar to that on the Waipapa terrane, but with values decreasing to the east. In the area of the present study (Fig. 1), Murihiku, Maitai and Waipapa terranes are not exposed in immediate proximity of each other. A complication exists in the Hakarimata Range near Huntly (Fig. 1) where Murihiku units cut eastwards across the Junction Magnetic Anomaly due to late thrusting associated with dextral strike slip motion along the suture (Kirk, 1991). Due to the anomalous position of this Murihiku block east of the Junction Magnetic Anomaly, and a lack of information on its geometry, we have disregarded gravity stations located on it. However, in the region immediately to the south, intercalation of the Maitai terrane between the Murihiku and the Waipapa terranes has been confirmed in coal mines and in one outcrop (Kirk, 1991). In the northern South Island, contacts between the three terranes are well exposed (e.g. Johnston, 1981, 1996). Despite the one local complication, Fig. 3b shows that the suture between the Murihiku and Waipapa terranes is marked by a transitional gravity gradient, where the regional gradient reverses and steepens to 10 g.u. km^{-1} over a zone about 10 km wide, resulting in a 100 g.u. increase in the Bouguer gravity value across the axis of the Junction Magnetic Anomaly. This gravity increase can be accounted for by the density contrast between the two terranes persisting to a depth of 4–6 km (as discussed earlier).

5.2. Gravity field across central Auckland

The Bouguer gravity anomaly across central Auckland (Fig. 4) is dominated by a 20 km wide, NW–SE elongate gravity anomaly with a maximum of 620 g.u., in the NW of the area. As discussed previously, recent borehole data (Table 1) indicate that the basement surface is relatively flat-lying across central Auckland and hence the source of the gravity gradients is likely to be density variations within and/or between basement terranes. In order to determine the residual gravity anomaly across central Auckland and hence model density structure within the basement in this area, a composite first-order regional gravity field across the entire Auckland region was estimated. This was done by correcting for the gravity effect of rocks overlying basement, where their minimum or absolute thickness is known from borehole data, and by extrapolating the observed gravity fields on outcropping basement terranes over the central Auckland region.

The observed gravity gradient (3 g.u. km^{-1}, dipping east) on outcropping Murihiku terrane to the south (Fig. 3b) was assumed to extend north into the Auckland region, west of the Junction Magnetic Anomaly, and where this terrane is known to occur from borehole 2 (Fig. 1 and Table 1). An important quantitative constraint on this assumption is provided by boreholes 1 and 2 (and to some extent borehole 3). At these boreholes, the gravity effects of the known thicknesses of overlying sedimentary rocks were calculated using previously published densities (Hatherton and Leopard, 1964) and subtracted from the observed gravity values to give

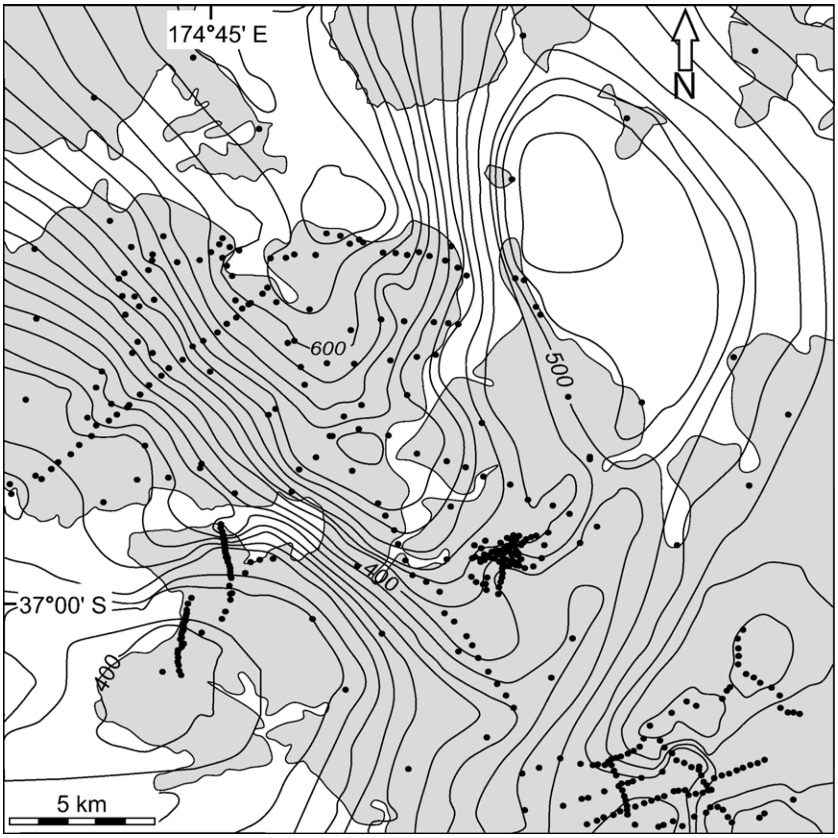

Fig. 4. Bouguer gravity field over the Auckland region (for area shown in Fig. 1); contour interval is 10 g.u. Gravity data from this study, with additional data from Woodward (1971a), Miller (1996), Affleck (1999), Al-Salim (2000) and France (2003). Symbols as for Fig. 3, except that shading denotes land area.

equivalent values on basement of 476 g.u. and 475 g.u., respectively, in this critical area. These values were combined with the assumed gradient, and observed values on outcropping Murihiku, to estimate the level and strike of a planar gravity gradient (3 g.u. km^{-1} striking 169°), representing the first-order regional

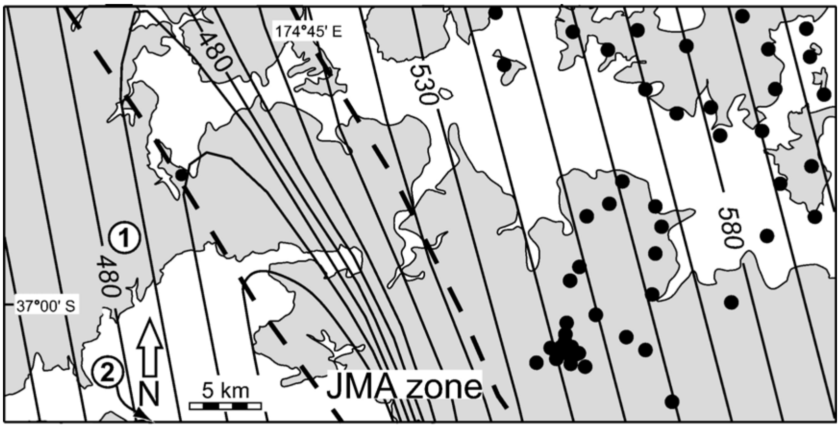

Fig. 5. A combined regional gravity field for the Auckland region (for area shown in Fig. 1), interpolated across the Junction Magnetic Anomaly zone (JMA) whose approximate width is indicated (see text for discussion). Contour interval is 10 g.u.; locations of boreholes 1 and 2, used to constrain the regional field to the west of the JMA are shown. Symbols as for Fig. 4.

gravity field on Murihiku terrane across the Auckland region.

The regional gravity field (3 g.u. km^{-1} dipping west) characteristic of the Waipapa terrane east of the Junction Magnetic Anomaly is better constrained because of the available gravity data on outcropping greywacke in the east of the study area immediately east of the Junction Magnetic Anomaly. However, a transition between these regional gravity gradients must occur across the Junction Magnetic Anomaly because the gradients on the Waipapa and Murihiku terranes are in opposing directions and are slightly oblique. The width of this transition zone can be inferred to be about 15–20 km wide, based on the observed gradient on basement to the east which persists to within about 10 km of the axis of the Junction Magnetic Anomaly, and on the similar width of the steep gravity gradient observed to occur across the terrane suture to the south (Fig. 3b) where it is better defined (although the gradient in Auckland may be more subdued due to thicker sedimentary cover). This width is also consistent with that defined for the Junction Magnetic Anomaly by Eccles et al. (2005). An inferred gravity field on basement across this transition zone was calculated by interpolating between the regional gravity fields on the Murihiku and Waipapa terranes (Fig. 5). The resulting gravity gradient across this zone, 5–10 g.u. km^{-1}, is very comparable to that observed over the boundary between the Waipapa and Murihiku terranes further to the south (Fig. 3b). This interpolation is a first-order approximation and makes no assumptions about the boundary between the Murihiku and Waipapa terranes; any significant structural complexities at this boundary could be expected to be reflected in the residual gravity anomaly data. The composite first-order regional field shown in Fig. 5 was subtracted from the observed Bouguer anomaly data to give the residual gravity anomaly (Fig. 6).

5.3. Residual gravity anomaly in central Auckland

The residual gravity anomaly for the central Auckland region delineates the southern part of a large elongate positive gravity anomaly (total amplitude up to +120 g.u.), which we term the “Takapuna Gravity Anomaly” (Fig. 6). This anomaly is oval in form with a NW–SE orientation and is bounded by steep linear

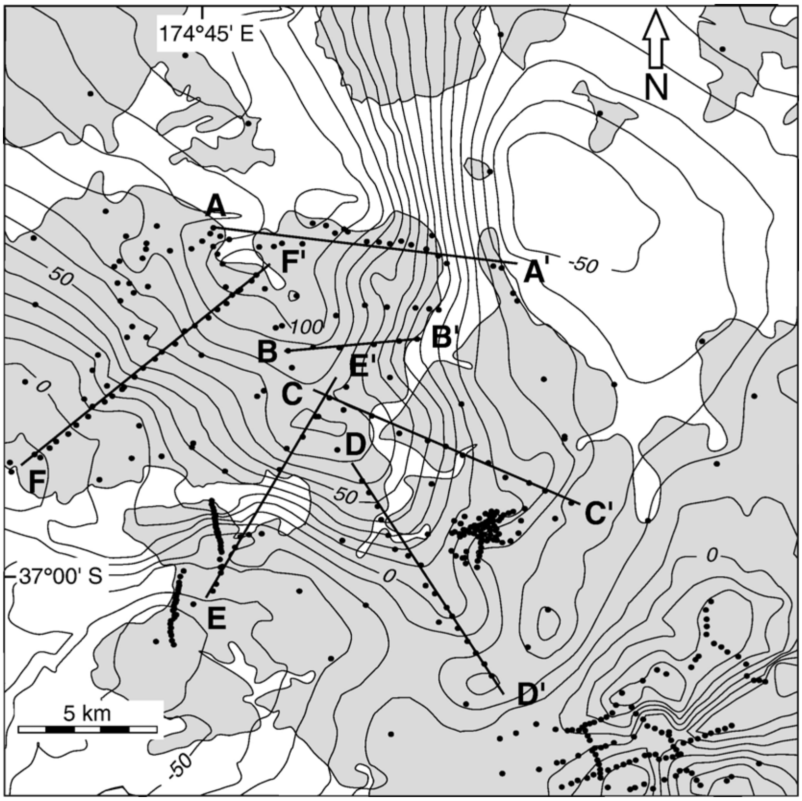

Fig. 6. Residual gravity field over the Auckland region (for area shown in Fig. 1); contour interval is 10 g.u. Symbols as for Fig. 4. A–A′ etc. mark profile lines for the models shown in Fig. 7.

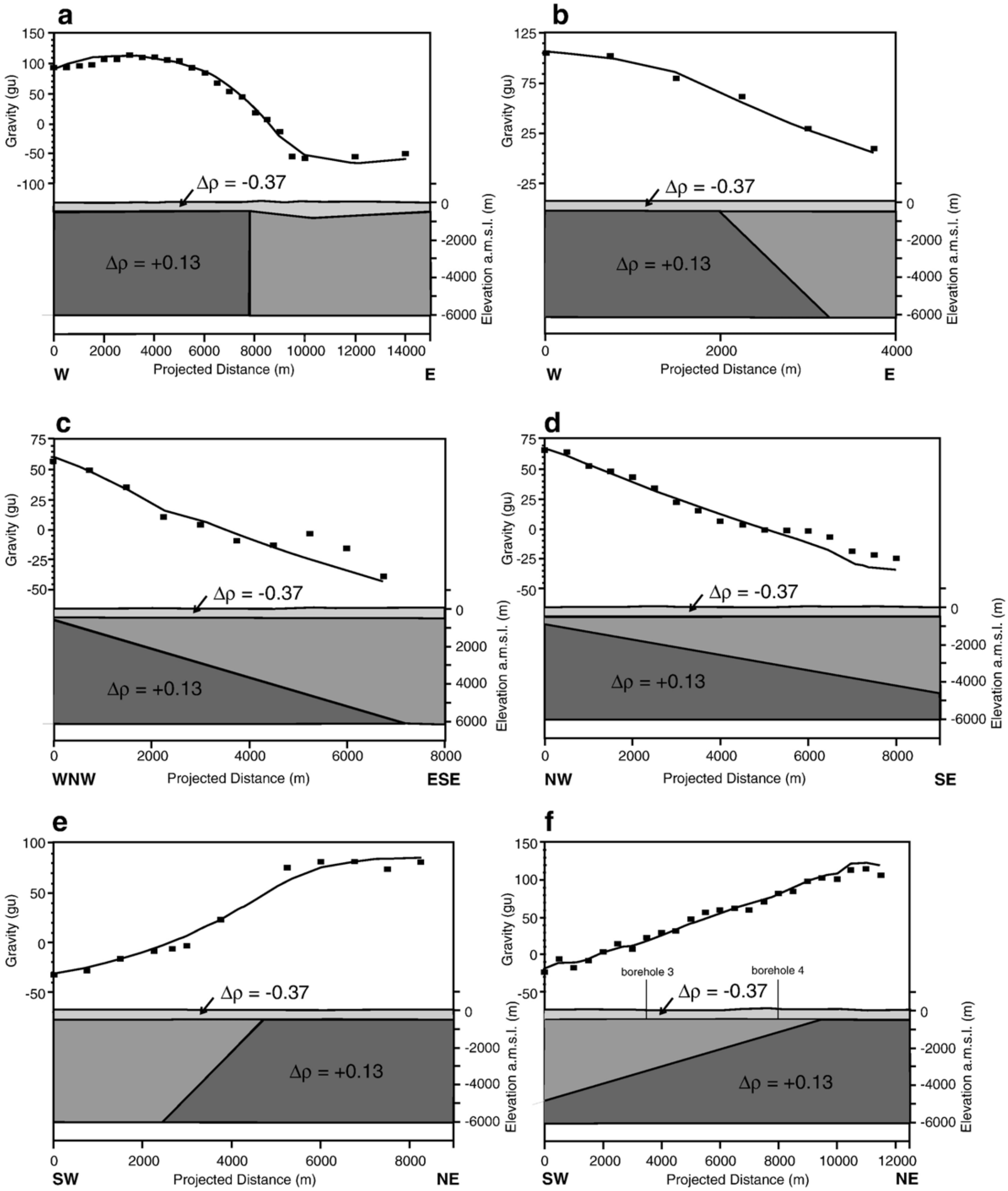

Fig. 7. Results of 2.75D gravity modeling along profiles A–F (Fig. 6) showing fit between observed (squares) and calculated (solid lines) gravity values. Density contrast of dense body is +0.13 Mg m^{-3} with respect to a nominal average value for basement greywacke. The thin layer of Tertiary sediments (density contrast − 0.37 Mg m^{-3}), which is based on thicknesses encountered in boreholes, has a near-constant gravity effect except where modeling requires the sediments to thicken in the east along profile A.

gradients, especially on its eastern margin where a gradient of up to 40 g.u. km^{-1} occurs.

The causative body for this anomaly is modelled (at its southern end) along a series of radiating profile lines (Fig. 7: A–F) using Interpex Magix XL (version 3) software. A 2.75D model was constructed along each profile. For each profile modelled, the extent and orientation of the body either side of the profile was

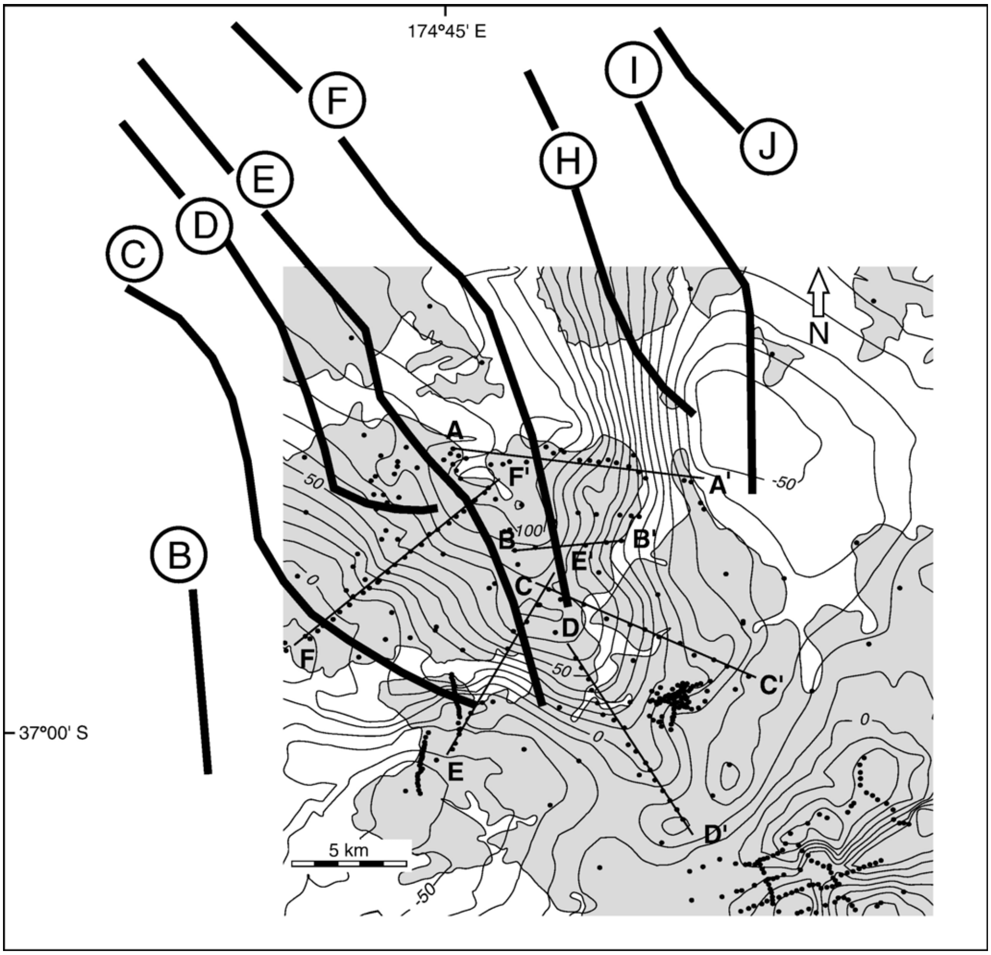

Fig. 8. Residual gravity field over the Auckland region showing locations of gravity profiles modeled for this study, compared with locations of sub-maxima (thick black bands B–J) of the Junction Magnetic Anomaly (after Eccles et al., 2005). Bands C to H are interpreted to be serpentinite shear zones within the ultramafics, whereas B, I and J may be basic volcanics marking accretionary thrusts in the adjacent terrigenous clastics.

estimated using the residual gravity map (Fig. 6) and the 2.75D models were correlated to ensure that together they form a coherent overall 3D model. A number of consistent constraints were applied to all profiles. Firstly, deep drillholes (Table 1) indicate that the Miocene sedimentary rocks overlying basement in the Auckland region are approximately 500 + 100 m thick, hence the cover rocks are given a uniform thickness of 500 m in the models across the isthmus. Secondly, the source body was modeled with a density contrast of 0.13 Mg m^{-3} giving an average density of 2.80 Mg m^{-3} compared to the standard ‘average’ value for greywacke basement (Reilly, 1972). This is considered to be a reasonable first approximation given that any component of the gravity effect across the Murihiku–Waipapa boundary has been accounted for in the regional field. Overlying Miocene sedimentary rocks were assigned a density of 2.30 Mg m^{-3} (Hatherton and Leopard, 1964). It was assumed initially that the body extends to 6 km, i.e. to the major geophysical boundary identified from seismic data (Stern et al., 1987).

The best-fit models comprise a body approximately 15 km wide and of average density 2.80 Mg m^{-3} within the basement greywacke (Fig. 7). The eastern margin of this body is vertical, whereas the western and southern margins dip shallowly (20–25°). To the immediate northeast, there is a significant negative gravity anomaly which is modeled as Waitemata sediments thickening from ~ 500 m to ~ 900 m. The root mean square discrepancies between the calculated and observed gravity values along these profiles range from 4 to 11 g. u., i.e. about 5–10% of the maximum anomaly amplitude. As the regional field is better constrained in the east than in the west, the geometry of the source body, and especially its bounding faults, are correspondingly better constrained on the eastern side. However, the location and overall geometry of the dense body within the basement is not substantially affected by these uncertainties.

6. Source rocks of the Takapuna gravity anomaly

The modeled dense body is coincident with the Junction Magnetic Anomaly zone. Elsewhere, the Junction Magnetic Anomaly coincides with outcrops of the Maitai terrane (e.g. Johnston, 1981); therefore we suggest that dense Maitai terrane rocks are the source of the Takapuna Gravity Anomaly. However the presence of Caples terrane rocks, which would have little density contrast with Waipapa rocks, immediately to the east cannot be excluded. A general association of gravity anomalies with ultramafics of the Dun Mountain Ophiolite Belt was noted by earlier workers (e.g. Hatherton, 1967; Hatherton and Sibson, 1970). The modeled density lies between that of Maitai Group sediments (2.75 Mg m^{-3}) and Dun Mountain Belt Ophiolite ultramafics (3.1 Mg m^{-3}) (Hatherton, 1967). There are two end-member combinations of lithologies that could produce an average 2.80 Mg m^{-3} density: 1) Maitai Group sediments with thin lenses of denser ultramafics or 2) ultramafic rocks with a high proportion of low-density serpentinites. Option 1 is inconsistent with the observed coincident magnetic anomaly, attributed to highly magnetic serpentinite (Eccles et al., 2005). Our interpretation therefore is that a large body of Dun Mountain Belt ultramafics occurs beneath Auckland. This interpretation is also supported by the occurrence of anomalous schistose rocks and gabbroic xenoliths that have been ejected from two basaltic volcanoes that lie directly above the eastern boundary of the Takapuna anomaly (Searle, 1959).

7. Discussion

The Mesozoic tectonic evolution in the North Island, as exemplified in the Auckland region, is characterized by episodic accretionary events along the Gondwanan margin and includes the incorporation of oceanic lithosphere at the suture between an accretionary prism and a younger forearc terrane, in a manner similar to the relationship between the Franciscan Terrane and the Great Valley Sequence in California (Coombs et al., 1976). The contrasting gravity signatures of these terranes have been maintained throughout their evolution. We have used these signatures to identify and model a large ultramafic massif embedded within the terrane suture through Auckland. Several aspects of our results warrant special consideration, as discussed below.

7.1. Complexities of the regional gravity field

The opposing regional gravity gradients of the Waipapa and Murihiku terranes either reflect internal density variations within the individual terranes, or thickness changes in both terranes towards the suture. For the Murihiku terrane, the eastward gravity decrease may be due to the regional eastward dip of the main limb of the asymmetric Kawhia Synclinorium (Spörli, 1978), which causes younger, lower density rocks to thicken to the east. The cause of the westward gravity decrease over the Waipapa terrane is unclear. Analogous studies of terrane sutures have suggested that regional gravity decreases towards suture zones due to a gradual thickening of crust (by up to 20 km towards the suture) as a remnant from terrane amalgamation (e.g. Gibb et al., 1983; Hackney, 2004). However, such a crustal root would require isostatic compensation, with generation of uplifted topography, which is incompatible with the consistent low elevations in the Auckland region. Also, no such crustal root is apparent in the crustal refraction data of Stern et al. (1987) for the northern North Island.

In other studies (e.g. Ferraccioli et al., 2002), regional gravity gradients dipping towards a suture zone are attributed to lower-crustal density contrasts across the suture. As noted, the bulk density contrast at shallow crustal levels (up to 6 km depth) between the Murihiku and Waipapa terranes is characterized by a relatively short wavelength signal. However, deeper-seated density contrasts at the suture cannot account for the opposing regional gravity gradients on either side of the suture, hence the source of the longest-wavelength gradient over the Waipapa terrane is still unknown.

7.2. Geometry of the embedded ultramafic body

The residual gravity anomaly at the terrane suture described earlier cannot be attributed to any configuration of the greywacke basement, but requires the presence of a discrete, anomalously dense body. Since this body coincides with the multiple linear magnetic anomalies described by Eccles et al. (2005), and noting the exposed lithologies of the Dun Mountain Ophiolite Belt in the South Island, we interpret this gravity anomaly as resulting from a dense ultramafic body (Figs. 7 and 8) cut by a number of serpentinite shear zones (Fig. 8). As elsewhere in the belt (Johnston, 1982, 1996), minor volumes of Permo-Triassic sedimentary rocks may also be present.

The southern part of this ultramafic massif has been modeled to extend to depths of 6 km, though it should be noted that this depth is a minimum. Important features of its geometry (Figs. 7 and 8) are: 1) a tapering-off of the body towards the south; 2) an eastern boundary with an abrupt change from gently dipping contacts in the south to a subvertical contact in the north; and 3) a flat top surface caused by Late Cretaceous–Early Tertiary erosion. The full extent of the Takapuna Anomaly, as shown in the regional gravity map of Woodward (1971a), can be used to estimate a possible continuation of these geometrical features to the north; the entire anomaly has a broadly oval shape, implying that there is some north-south symmetry in the shape of the source body. This suggests a spindle shape for the massif, similar to the map patterns at Red Hills (Rattenbury et al., 1998) and on D'Urville Island (Johnston, 1996; Eccles et al., 2005). As the southern end of the source body has a slight asymmetry, as shown in the modeled profiles of Fig. 7, there may be an equivalent shape at the northern end, possibly indicating horizontal shear along the body. The subvertical part of the eastern boundary, presumably a steep fault, also must continue some distance to the north.

Based on the extent of the Bouguer gravity anomaly (Woodward, 1971a), a reasonable estimate for the areal extent of the whole ultramafic body is 50 km × 10 km. Comparable ultramafic bodies outcropping elsewhere in New Zealand have layering with steep dips (e.g. Rattenbury et al., 1998) which suggests that the surface exposures approximate a cross section through each massif, making the areal extent (as read from maps) a useful criterion for comparing the sizes of the massifs. All these massifs occur in the South Island and have the following dimensions: Red Mountain (Bishop, 1994), 13 km × 5 km; Red Hills (Lensen, 1962; Johnston, 1982), 18 km × 9 km); Dun Mountain (Johnston, 1981), 20 km × 2 km. The source body of the Takapuna Gravity Anomaly is therefore by far the largest ultramafic massif within the Dun Mountain Ophiolite Belt, and indeed in New Zealand.

7.3. Conclusions

Our geophysical analysis has confirmed that a structure of ultramafic lenses (massifs) embedded in a matrix of serpentinite and sedimentary rocks of the Dun Mountain Ophiolite Belt extends throughout New Zealand. We have also shown that the lens discovered in the Auckland region is the largest in the entire New Zealand belt. Combined gravity and magnetic studies may reveal similar structural patterns in other regions around the world, because these patterns are due to common plate tectonic processes that occur at convergent margins associated with collision of terranes. Such processes include the arrival of individual asperities (e.g. seamounts or tectonically elevated portions such as inside corners at transform/spreading ridge intersections, or horsts) on the subducting oceanic plate, and the disruption of competent units during subsequent strike-slip movement along the resulting suture zone, as was the case in New Zealand (Spörli and Aita, 1995), so that the isolated ultramafic massifs now form useful shear sense indicators and strain markers. Gravity studies such as reported here are therefore an important, and somewhat under-utilised, tool for delineating and understanding the overall fabric of ophiolite-bearing terrane sutures.

Acknowledgements

We thank Louise Cotterall for the assistance with drafting figures, Colin Yong for technical assistance and Jennifer Eccles for the helpful discussions. Pete Betts is thanked for reviewing the manuscript and contributing valuable suggestions towards its improvement. Two anonymous reviewers are thanked for their very constructive comments.

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