Economic Geology, v. 106, pp. 1031–1041

Geophysical Characteristics of Adularia-Sericite Epithermal Gold-Silver Deposits in the Waihi-Waitekauri Region, New Zealand

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Abstract

Aeromagnetic, airborne radiometric, and surface gravity data from the adularia-sericite epithermal province of the Hauraki goldfield have delineated distinct anomalies associated with pervasive hydrothermal alteration and gold-silver mineralization. Aeromagnetic derivative images, particularly the analytic signal, define the boundaries of several magnetic quiet zones that result from magnetite destruction in the volcanic host rocks. Six discrete zones, each of ≤10-km² areal extent are evident and are comparable in size to modern-day geothermal systems in the Taupo volcanic zone. An extensive (>20-km²) zone in the Waitekauri Valley is likely to be the result of multiple overlapping systems, for which there are also analogues in the Taupo volcanic zone that form single large-scale alteration zones up to 100 km². Low-pass filtering of the analytic signal data reveals still wider zones of relatively low magnetic intensity interpreted as areas of hydrothermally altered rock extending below younger, unaltered cover. Many of these magnetic quiet zones are aligned along a north-northeast–south-southwest structural corridor, indicating that regional-scale structures may have controlled the location of these geophysical features. Radiometric data delineate local high potassium anomalies that reflect up to 12/100 g potassium enrichment in the core of alteration zones in the form of adularia and illite. A broad K/Th anomaly correlates with the extent of the magnetic quiet zones and indicates widespread potassium enrichment in the Waitekauri-Maratoto area. Gravity data in the Waihi district define a unique, double-peaked, 50-gravity unit positive residual anomaly that correlates closely with the extent of the magnetic quiet zone and the locations of the Waihi and Favona deposits. Preliminary modeling indicates that the anomaly source body, beneath the near-surface, low-density altered andesite, has a volume of up to ~11 km³ and a minimum density of 2,900 kg m⁻³. The nature of this source body is enigmatic; possible causes include a dense intrusion, uplifted anomalously dense basement, dense sulfide mineralization, or some combination of these. In addition, the correlation of each of the two gravity peaks with a north-northeast–trending fault may indicate some structural focusing process active at the deposit scale. This integration of geophysical data provides an outstanding case study of the district- to regional-scale geophysical characteristics of a classic epithermal province and demonstrates the strengths of geophysical surveys in the exploration for epithermal mineral deposits.

Introduction

MAGNETIC, radiometric, and gravity methods can provide critical information about the nature of epithermal gold-silver deposits and their location. On a regional scale, high-resolution aeromagnetic data and gravity data can be used to map regional structure and identify structural controls on hydrothermal alteration and mineralization (Webster and Henley, 1989; Allis, 1990; Irvine and Smith, 1990; Izawa et al., 1990; Okada, 1995; Hoschke and Sexton, 2005). At the district scale, detailed aeromagnetic data can delineate zones of magnetite destruction that reflect the location and areal extent of hydrothermal alteration and thus fossil geothermal systems. Detailed gravity surveys over fossil and active geothermal systems also have delineated district-scale anomalies associated with both densification (Hochstein and Hunt, 1970; Criss et al., 1985) and mass loss (Locke and de Ronde, 1987; Locke et al., 1999) attributed to hydrothermal alteration in different lithologic units. More locally, outcropping zones of elevated potassium, associated with high-rank alteration and gold-silver mineralization, can be detected by airborne radiometric methods (Webster and Henley, 1989; Feebrey et al., 1998).

The Waihi-Waitekauri region is located on the southern Coromandel peninsula of New Zealand and lies within the classic adularia-sericite epithermal gold-silver province of the Hauraki goldfield (Christie et al., 2007). Hydrothermal activity in the Waihi-Waitekauri region occurred over a period of 0.8 m.y. (Mauk et al., 2011) pervasively altering an area of approximately 65 km², i.e., ~35 percent of the currently exposed host Coromandel Group rocks (Fig. 1a), based on the geology map of Torckler (1998). Some 15 gold-silver deposits occur in the region including the world-class Waihi deposit, Golden Cross, and the recently discovered Favona deposit. These gold-silver deposits consist predominantly of andesite-hosted quartz veins and are characterized by alteration haloes of pervasive clay alteration, potassium metasomatism, magnetite destruction, and sulfide mineralization, up to 15 km² in areal extent (e.g., Simpson et al., 2001; Simpson and Mauk, 2007, 2011).

This paper describes the magnetic, radiometric, and gravity expressions of adularia-sericite epithermal deposits in the Waihi-Waitekauri-Wharekirauponga region, including a detailed study of the Waihi district. These geophysical data reveal the extent and geometry of at least ten hydrothermal systems that formed at different times over a period of less than 1 m.y. and deposited over 10 million ounces (Moz) Au in less than 200 km³ of the shallow crust.

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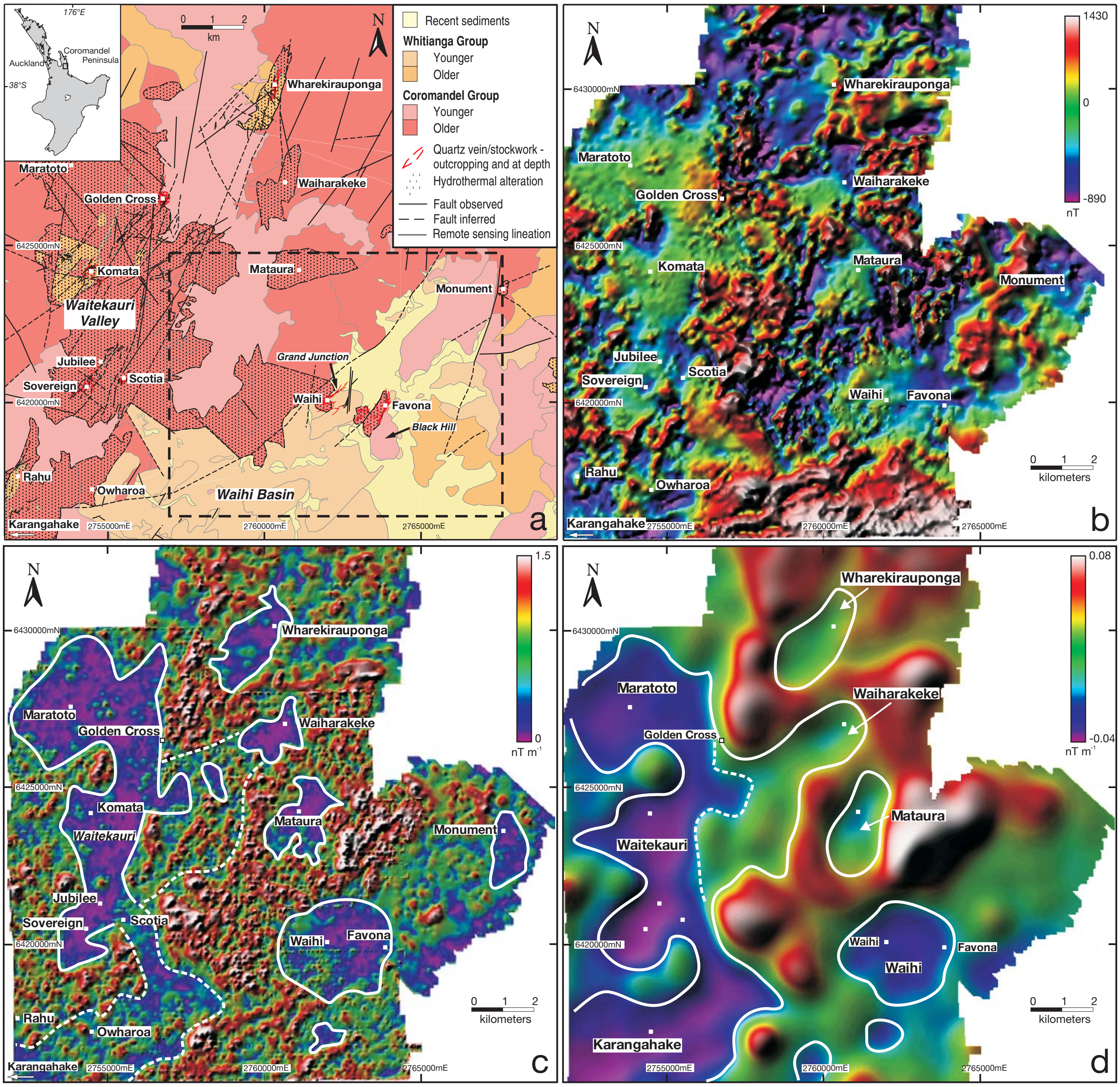

FIG. 1. Maps of the Waihi-Waitekauri region. a. Simplified geologic map after Torckler (1998), showing areas of hydrothermal alteration and known quartz vein systems. Dashed box indicates area of Figure 2a, b. b. TMI pseudocolor image illuminated from the northwest. Deposit locations are shown by white squares. C. Analytic signal pseudocolor image of the RTP TMI data illuminated from the northwest. The boundaries of zones of very low magnetic gradient are marked by the solid white lines. Dotted white lines indicate the boundaries of areas of subdued magnetic gradients. Deposit locations are shown by white squares. d. Low-pass filtered (>5 km retained) analytic signal pseudocolor image. Solid white lines delineate extent of subdued magnetic signature, broken white line delineates very low values. Deposit locations are shown by white squares. e. Potassium distribution comprising three surveys delineated by white lines A = Wharekirauponga, B = Waitekauri, and C = Waihi. High count = white-red-orange, intermediate count = yellow-green, low count = blue-purple. Negative count values result from data reduction. Areas of anomalous potassium are circled by black dashed lines. Deposit locations are shown by black squares. f. K/Th ratio distribution. Surveys, as in (e), delineated by black lines. Boundaries of the magnetic quiet zones (c) are shown by the white lines. High values = orange-yellow, intermediate values = green-blue and low count = pink-white. Deposit locations are shown by white squares.

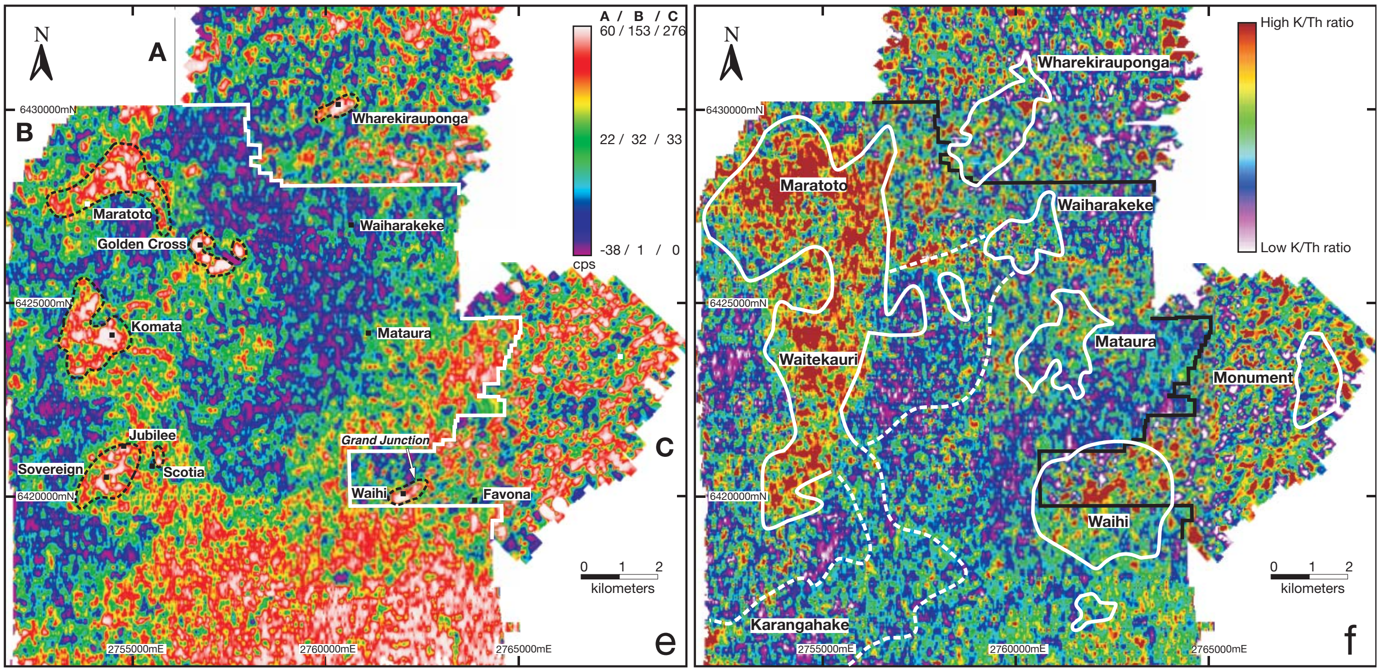

Fig. 1. *(Cont.)*

Geologic Setting

The 40-km-wide Coromandel peninsula lies within the Coromandel volcanic zone, a continental margin volcanic zone, and extends approximately 200 km north to south (Christie et al., 2007). The peninsula is comprised of Late Jurassic basement graywacke that crops out in the north, overlain by extensive Miocene to Pliocene basaltic to rhyolitic volcanic and intrusive units that thicken and young to the south (Skinner, 1972, 1986; Edbrooke, 2001).

In the Waihi-Waitekauri region, Pleistocene to Holocene sediments, ignimbrite, and tephra deposits locally cover the extensive volcanic deposits of the late Miocene to Pliocene Coromandel Group and late Miocene to Pleistocene Whitianga Group (Brathwaite and Christie, 1996). The Coromandel Group, which includes the Waipupu Formation, Waitekauri Dacite, Waiharakeke Dacite, Whiritoa Andesite, Whakamoehau Andesite, and Uretara Formation, comprises a thick sequence of medium K andesite to dacite flow deposits and minor intrusions with intercalated crystal and lithic tuffs, tuff breccia, and epiclastic sedimentary rocks. The Coromandel Group is prevalent in the Waihi-Waitekauri region, and rocks of the Waipupu Formation, Waitekauri Dacite, Maratoto Rhyolite, and Edmonds Formation are extensively hydrothermally altered (Brathwaite and Christie, 1996; Simpson et al., 2001; Haworth and Briggs, 2006; Simpson and Mauk, 2007, 2011). The Whitianga Group, which includes the Maratoto Rhyolite and Edmonds Formation, consists of a sequence of rhyolite lavas, domes, dikes, and extensive, variably welded ignimbrites (Brathwaite and Christie, 1996).

The Hauraki goldfield contains predominantly north-northwest– and northeast– to east-northeast–striking normal faults associated with block faulting in the graywacke basement terrane (Spörli, 1987). Most veins in the southern goldfield strike north-northeast and are parallel to regional faults in the area (Spörli et al., 2006; Grodzicki et al., unpub. data).

Regional magnetic data (Stagpoole et al., 2001) have delineated a number of major features, such as calderas and buried intrusions, and a number of distinct structural trends (Bromley and Brathwaite, 1991; Rabone, 1991; Malengreau et al., 2000). Regional gravity studies (Woodward, 1971) show high values in the west of the peninsula reflecting outcropping or near-surface basement and a series of negative anomalies in the east which are interpreted as resulting from buried calderas (Malengreau et al., 2000; Smith et al., 2006).

Airborne Data Acquisition

High-resolution airborne magnetic and radiometric data were collected across the region during three surveys. In 1989, the Waihi and Wharekirauponga-Pukehuru areas were each surveyed by ACM NZ Ltd. at a nominal ground clearance of 120 m with flight lines spaced at 150 m and oriented northwest-southeast and east-west, respectively (McKay, 1989; Merchant and Associates, 1989; Rabone, 1990). In 1994, Coeur Gold NZ Ltd. carried out a survey of the greater Waitekauri Valley area with a nominal ground clearance of 60 m and flight line spacing of 100 to 150 m, oriented east-west (GeoInstruments Airborne Division, 1995). The data were originally gridded, using a minimum curvature algorithm at one-quarter or one-fifth of the line spacing, following standard procedures to avoid aliasing. These data were subsequently regridded at a smaller cell size of 25 m to facilitate merging of the three surveys and preserve the detail of the highest resolution data. The combined total magnetic intensity (TMI) dataset and radiometric dataset are discussed in the following sections.

Aeromagnetic Investigations

The pseudocolor TMI image (Fig. 1b) shows that the region has a highly variable magnetic character dominated by the extensive volcanic units of late Miocene and late Pliocene age. The central Waihi-Waitekauri area is characterized by short-wavelength, high-amplitude (1,000–1,200 nT) anomalies. These occur over unaltered Whakamoehau Andesite that forms a high-standing topographic ridge between the eastern Waihi and western Waitekauri areas. This short-wavelength, high-amplitude signature also occurs over other high-standing unaltered andesite in the western and north-northeastern areas to the north of Waihi. Northeast of the Waihi district, the magnetic signature is broader in wavelength with an amplitude of approximately 600 nT, which characterizes postmineralization andesite and dacite of the Uretara Formation that forms a north-northeast–south-southwest–trending topographic ridge.

Negative magnetic anomalies in the north and far southeast of the region indicate the possible occurrence of reversely magnetized rocks. The southern part of the region is dominated by the northern section of a large (+800 nT, –200 nT), 12-km-diameter bipolar anomaly associated with the Waihi basin area; the anomaly is attributed to a buried intrusion (Couper and O'Leary, 1980; Smith et al., 2006).

A key feature of the Waihi-Waitekauri region is the occurrence of a number of areas of uniform, low magnetic intensity. Four ovoid zones approximately 3 to 10 km^2 in area occur along a north-northwest trend from the southeastern Waihi district north to Wharekirauponga. In addition, a small (~2 km^2) ovoid area of low magnetic intensity occurs in the Monument area 5 km to the northeast of the Waihi district, and an extensive, ~20-km^2 zone encompasses the Waitekauri-Maratoto area in the west. These magnetic quiet zones occur in areas of known hydrothermal alteration predominantly within the Waipupu Formation but also in late Miocene Maratoto Rhyolite at Komata, Edmonds Formation at Wharekirauponga, Waiharakeke Dacite at Waiharakeke, and Waitekauri Dacite in the southern and eastern Waitekauri Valley.

In the Waitekauri-Maratoto region, the mapped extent of hydrothermal alteration corresponds closely with the regions of low magnetic intensity in the area (Brathwaite and Christie, 1996). To the south and southwest of the Waitekauri area, an area of subdued magnetic intensity coincides with outcropping, hydrothermally altered andesite and dacite; however, there are variable occurrences of postmineralization andesite and ignimbrite deposits north of the Karangahake area with unaltered magnetic signatures in the TMI. Smaller areas of hydrothermal alteration are mapped at the Mataura, Waiharakeke, Wharekirauponga, and Monument areas, but the observed magnetic quiet zones appear to be more extensive than the areas of mapped hydrothermal alteration (Brathwaite and Christie, 1996).

The Waihi area is characterized by an approximately 10-km^2 circular zone of low magnetic intensity that encompasses several small areas of hydrothermally altered andesite (Martha, Union, Gladstone, Favona, and Winner Hills). The western boundary of this magnetic quiet zone is well defined as it occurs across continuously outcropping hydrothermally altered andesite. In contrast, the central and eastern areas of the district are covered by unaltered, postmineralization volcanic deposits of variable thickness. The magnetic quiet zone persists over the relatively thin cover rocks in the central parts of the district but terminates just east of Favona where recent cover, Whitianga Group sediments, and Uretara Formation dacite thicken to the east (Brathwaite and Christie, 1996).

Aeromagnetic data processing

Transformations of magnetic data can highlight particular features (Nabighian et al., 2005). The reduction-to-pole (RTP) transformation is commonly used to simplify and align anomalies over their sources and is applicable here because the area has not been significantly rotated or tilted for at least the last 4.5 m.y. (Ballance, 1999; i.e., any remanent magnetization present will not distort the transformation). Vertical and horizontal gradient transformations highlight both the contrast between higher intensity, short-wavelength signatures, and the magnetic quiet zones. However, the most effective approach for delineating magnetic quiet zones was found to be the analytic signal (i.e., the total gradient) transform (Roest et al., 1992). The analytic signal sharply defines the boundaries of six main magnetic quiet zones that are distinctive areas of low-amplitude response that contrast sharply with the more variable, high-amplitude response in the surrounding areas (Fig. 1c, Table 1). The eastern Waitekauri and southern Karangahake areas also have subdued analytic signal signatures, however these areas are not as well defined as the six magnetic quiet zones described in Table 1.

Low-pass filtering of the analytic signal data removes short wavelength effects, including those from shallow magnetic cover, and resolves larger zones of low magnetic intensity particularly in the eastern Waitekauri and southern, Karangahake, areas (Fig. 1d). These zones may reflect areas of hydrothermally altered rock extending below younger, unaltered cover, although a more detailed survey at Karangahake suggests that this might not be the case (Harris et al., 2005). The Wharekirauponga, Waihareke, Mataura, and eastern Waitekauri-Maratoto areas are characterized by zero filtered

TABLE 1. Geometrical Parameters of the Magnetic Quiet Zones

Magnetic quiet zone	Geometry	Dimensions (km)	Area (km^2)	Dominant orientation
Waitekauri-Maratoto	Extensive and irregular	N/A	22.0	N-S
Waihi	Subcircular	2.8 × 3.6	9.9	N/A
Mataura	Irregular ovoid	1.6 × 3.0	3.7	NNE-SSW
Waiharakeke	Irregular ovoid	1.1 × 1.9	2.1	NE-SW
Wharekirauponga	Ovoid	1.6 × 3.0	4.7	NNE-SSW
Monument	Ovoid	1.0 × 2.2	2.1	N-S

N/A = not applicable

analytic signal values, whereas the Waitekauri-Maratoto, Karangahake, and Waihi zones are characterized by the lowest filtered analytic signal values.

The boundaries of the magnetic quiet zones generally correlate well with the mapped extent of hydrothermal alteration, although the observed magnetic quiet zones at Mataura, Wharekirauponga, and Monument are more extensive than the areas of mapped alteration. Strong to intense hydrothermal alteration is characterized by zones of zero analytic signal values. Subdued but nonzero magnetic gradient values occur toward the boundaries of magnetic quiet zones within the same lithologic unit and also over other areas that are only weakly altered. This indicates that only partial demagnetization has occurred in these locations, which is consistent with detailed studies of alteration mineralogy in these areas (Simpson et al., 2001; Simpson and Mauk, 2007, 2011).

Radiometric Investigations

The most useful information gained from radiometric surveys of epithermal deposits is obtained from the potassium data because intense hydrothermal alteration is normally associated with potassium enrichment in the low-sulfidation deposits of the Hauraki goldfield and elsewhere (Webster and Henley, 1989; Allis, 1990; Irvine and Smith, 1990; Dickson and Scott, 1997; Shives et al., 2000). Thorium and uranium are not generally affected by epithermal alteration and mineralization (Irvine and Smith, 1990; Chiozzi et al., 2007), although some depletion of thorium and uranium has been observed elsewhere (Dickson and Scott, 1997). In the Waitekauri area, thorium is not significantly affected by hydrothermal alteration, whereas uranium may experience slight depletion during hydrothermal alteration (Booden et al., 2011). The total count data and potassium data from our radiometric surveys are well correlated, which shows that potassium dominates the total count data. The multichannel airborne radiometric data from the three surveys were collected concurrently with the aeromagnetic data but have not been merged and are plotted separately.

The potassium image (Fig. 1e) is dominated in the south by a large area of relatively high count, coincident with the occurrence of southward-thickening silicic ignimbrites, and extending to the east of the region where they are also associated with silicic ignimbrite and fall deposits and Pleistocene alluvial deposits. The central and western areas of the region are characterized by low count values interpreted as unaltered andesite units. A distinct, very high potassium anomaly is located over the Waihi deposit; this anomaly is about 350 m wide and extends along a northeast trend for approximately 900 m to the Grand Junction area, spanning the length of the known vein system. The far north of the survey area shows variable count rates including a broad trend of low to intermediate potassium count across the western Whakamoehau Andesite with high to medium counts over the Whiritoa Andesite to the east. The Wharekirauponga deposit in the center of this northern area is associated with a distinct, very high potassium anomaly in a northeast-oriented zone (Fig. 1e).

The western Waitekauri to Maratoto Valley areas are characterized by a large north-south corridor of intermediate count (Fig. 1e) with isolated very high count anomalies superimposed on it. These anomalies include an area of variably high count over the Sovereign and Jubilee vein systems and a large area of very high count over the Komata deposit (Fig. 1e). The largest potassium anomaly in the region covers an area of 0.5 km^2, coincident with the north-northeast–trending Komata vein swarm hosted in Maratoto Rhyolite; areas of high count extend beyond the known area of mineralization within the mapped extent of rhyolite.

The Golden Cross area contains several distinct, very high potassium anomalies that coincide with known mineralization. The westernmost circular high anomaly covers approximately 0.1 km^2 that coincides with the quartz vein stockwork exposed by the open pit that was active during the 1994 survey; a smaller high anomaly correlates with an additional mined bench at the northeast end of the pit. The large rectangular anomaly low is the response of the water-filled tailings pond; it is surrounded by other areas of high potassium count to the north and south that correlate with the locations of smaller mined areas and mined material. The Maratoto Valley in the far northwest contains a large 2.4-km^2 area of very high potassium count that correlates with numerous quartz veins exposed at the surface.

The potassium to thorium (K/Th) ratio filters the response of primary lithologic variations in the area, and also any signal attenuation due to vegetation cover, as potassium and thorium generally covary with changing silica content in unaltered rocks; for example, the K/Th ratio image of the area shows intermediate values over the ignimbrite in the south of the area compared with hydrothermally altered rocks in the Waitekauri Valley (Fig. 1f). The area west of the Waitekauri Valley, extending from the Sovereign-Jubilee district in the south through to the Maratoto district in the north, is characterized by a large distinct area (~28 km^2) of high K/Th ratio that closely correlates with the location of the magnetic quiet zone. The Waihi survey in the east shows a strong, high K/Th anomaly coincident with the Waihi deposit extending northeast, as observed on the potassium image. A distinct high ratio anomaly coincides with the known quartz vein stockwork at the Wharekirauponga deposit.

Geochemical studies show that the K/Th ratio is nearly constant for all unaltered rock types in this study (Booden et al., 2011). However, epithermal deposits in the region show strong potassium metasomatism that reflects intense and pervasive adularia and illite alteration at the core of their hydrothermal alteration zones (Mauk and Simpson, 2007; Booden et al., 2011). The very high count potassium anomalies that occur over epithermal veins in the area reflect intense potassium metasomatism at the core of the hydrothermal alteration haloes that envelop these veins, and the intensity of potassium metasomatism diminishes with distance from the veins. The broad anomalies of elevated K/Th ratios reflect minor regional potassium enrichment, whereas the more localized potassium anomalies in the radiometric data reflect more intense K metasomatism (Booden et al., 2011).

Gravity Investigations at Waihi

Gravity data

A total of 155 new ground-based gravity measurements were collected at an average station spacing of ~300 m; locations and elevations were determined by differential GPS to an accuracy of ±10 and ±2 cm, respectively. The data have been corrected using the IGF 1967, a standard density of 2,670 kg m^{-3} (Reilly, 1972), and fully terrane corrected using regional and local digital terrane models. The estimated total uncertainty in the gravity data is ±0.6 gravity units (1 gu = 0.1 mgal). These new data were combined with data from 114 existing regional and exploration gravity stations (Woodward, 1971; Couper and O'Leary, 1980) to provide thorough data coverage across the Waihi district.

The resulting Bouguer gravity anomaly map (Fig. 2a) shows a positive anomaly covering approximately 3 × 2 km of the Waihi district that correlates closely with the Waihi magnetic quiet zone described above. Two discrete highs within this anomaly, with maximum Bouguer anomaly values of 620 and 600 gu are centered just west of the Waihi deposit and to the southwest of the Favona deposit, respectively. The two peaks are ovoid in shape with their major axes oriented northeast-southwest and each apparently correlates with a north-northeast–trending fault. The southern part of the Bouguer anomaly map is dominated by the north-south–trending gradient associated with the Waihi basin (Smith et al., 2006), whereas the Bouguer gravity gradients are more subdued in the northern part of the area.

In order to isolate the local anomalies, a regional field dominated by the strong gradient associated with the Waihi basin was subtracted. Gravity stations representative of the regional field (Fig. 2a) were chosen on the basis of changes in the gravity gradients across the Waihi district. This was achieved by analyses of seven gravity profiles across the area; stations delineating areas of local closure were excluded. A comparison of the boundaries of this exclusion zone and the location of the previously defined magnetic quiet zone shows they correlate closely.

As the regional gravity field in the area varies from a strong gradient in the south to flat-lying in the north, we used a local polynomial gridding method (Golden Software, 2002) to approximate the regional field, which accommodates these broad-scale variations. The estimated regional field was subtracted from the Bouguer anomaly data to give the residual gravity anomaly (Fig. 2b). The local peaks are more clearly resolved into two separate positive anomalies with magnitudes of 49 gu in the west and 50 gu in the east, both of which are bounded by steep gradients. Both peaks are ovoid in shape with the western peak oriented north-northeast–south-southwest and the eastern peak approximately north-south.

This residual positive gravity anomaly occurs over several outcropping lithologic units in the district and correlates closely with the magnetic quiet zone. The western peak is centered on Waipupu Formation andesite immediately north-northwest of the location of the Martha Hill open-pit operation and is transected by the inferred location of the north-northeast–trending Waihi fault (Brathwaite and Christie, 1996). The eastern gravity peak is centrally located over Waipupu Formation andesite between the Union and Gladstone-Winner Hills and is also bisected by a mapped north-northeast–trending fault. The central area between the two peaks occurs across a paleovalley filled by late Pliocene to Pleistocene ignimbrite deposits. The steep western boundary of the gravity anomaly occurs over continuously outcropping Waipupu Formation that is hydrothermally altered to the west and southwest and unaltered to the north (Brathwaite and Christie, 1996). The southern and northern boundaries of the anomaly occur across southward-thickening ignimbrite deposits in the south and Pleistocene sediments overlying ignimbrite deposits in the north. The eastern boundary crosses Uretara Formation dacite lavas that form Black Hill.

Gravity data interpretation

Graywacke basement in the Coromandel peninsula has a density of 2,670 kg m^{-3} (e.g., Whiteford and Lumb, 1975;

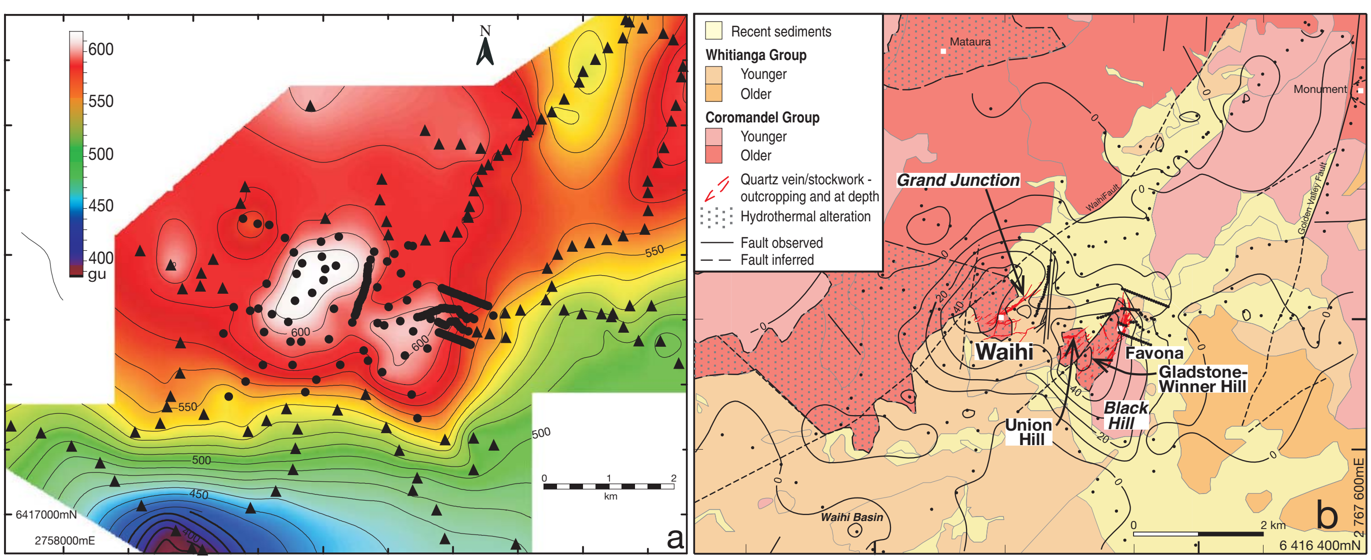

FIG. 2. Gravity maps of the Waihi district (area delineated in Fig. 1a). a. Bouguer gravity anomaly map. Gravity contour interval is 10 gu. Black triangles show gravity stations used to calculate the regional gravity field, black dots show gravity stations excluded from the regional field calculation. b. Residual gravity anomaly map (contour interval is 10 gu) showing correlation of residual anomalies with the mapped geology, particularly the Martha (Waihi) and Favona deposits and the mapped and inferred faults.

Malengreau et al., 2000). This closely approximates the density of unaltered andesite in the area (e.g., Hatherton and Leopard, 1964; Locke and de Ronde, 1987). Extensive density measurements of surface and drill hole samples in the Waihi area (n >300) give an average of 2,500 ± 10 kg m^{-3} for intensely altered andesite (M. Simpson, pers. commun., 2003; Waihi Gold, writ. commun., 2003). This is consistent with other measurements in the region which give values, for example, of 2,440 ± 150 kg m^{-3} for the density of altered andesite (Locke and de Ronde, 1987).

Altered andesite in the Waihi district, therefore, forms a shallow, low-density zone that subdues the magnitude of the observed positive anomaly, and therefore a significantly greater mass anomaly than suggested by the observed gravity data must occur at depth. All known lithologic units in the Waihi area have densities that are less than that of unaltered andesite, and so the source of this positive gravity anomaly is enigmatic as it must have a density of >2,670 kg m^{-3}.

In order to quantify the parameters of the dense source body(s) that must be responsible for this anomaly, we calculated the gravity effects of a range of simple geometrical three-dimensional block models using two and a half-dimensional gravity modeling along three profiles: two southwest-northeast profiles across the centers of the two closed positive residual anomalies and a third orthogonal profile, oriented northwest-southeast (which bisects both closed positive anomalies). The parameters of the block models were adjusted to achieve a reasonable correspondence between the calculated gravity effect and the observed residual anomaly; RMS discrepancies between calculated and observed gravity effects were about 6 and 10 gu on the southwest-northeast and northwest-southeast profiles, respectively. These calculations incorporate the known near-surface, low-density rocks, extending to 250 to 300 m below sea level, and the range of models tested includes both single and two source body(s) configurations.

The results show that the observed gravity anomaly could be generated by either a single, large dense body, elongated northwest-southeast or two smaller dense bodies. The range of possible models (Table 2) shows densities of 2,900 to 3,500 kg m^{-3} and volumes of 3 to 11 km^3, which are equivalent to an anomalous mass of about 2.6×10^{12} kg. The results also confirm that the lateral extents of the source body(s) are tightly constrained by the gravity gradients and that source body(s) with densities less than 2,900 kg m^{-3} cannot account for the observed anomaly.

TABLE 2. Summary of the Parameters of the Modeled Bodies[1]

Source body density (kg m^{-3})	NW-SE extent (m)	SW-NE extent (m)	Depth extent (m)
Single source body			
2,900	3,200	2,100	1,700
3,500	3,300	2,200	370
Two source bodies			
3,000	2,620; 1,800	1,640;1,120	1,460; 1,320
3,500	2,820; 1,800	1,550; 680	1,030; 520

[1] Where a model comprises two source bodies, dimensions for each of the two bodies are given

The source of the gravity anomaly

Although gravity studies over active geothermal systems and adularia-sericite deposits in New Zealand and elsewhere have defined both positive and negative anomalies (Allis, 1990; Irvine and Smith, 1990), a positive gravity anomaly over an adularia-sericite deposit in host rocks with a high primary density, as described here, has not previously been documented. For example, a positive gravity anomaly of 100 gu across the Broadlands-Ohaaki geothermal field in the central North Island reflects densification by mineral deposition in low-density porous rocks (Hochstein and Hunt, 1970). Similarly, a positive gravity anomaly over the Yankee Fork mining district, Idaho, reflects density increases of the porous host rock by the deposition of quartz and calcite (Criss et al., 1985). A positive anomaly at the Hishikari deposit, Japan, was attributed to shallow uplifted dense basement (Izawa et al., 1990). Conversely, within dense host rocks negative anomalies typically occur such as at Golden Cross where the anomaly results from alteration of andesites (Locke and de Ronde, 1987) and at Puhipuhi in northern New Zealand where hydrothermal alteration of basement graywacke has occurred (Locke et al., 1999).

The host rocks at depth below Waihi are relatively dense andesite and hence the positive gravity anomaly cannot result from simple deposition of minerals within existing porous country rock. Possible sources for the observed positive gravity anomalies are (1) uplifted, denser basement rocks, (2) a basic intrusion, (3) the occurrence of dense sulfide minerals, or (4) a combination of (1) through (3).

The graywacke basement that presumably underlies the Waihi area has not been intersected by drilling but it is estimated to occur 1 to 2 km below sea level, although this depth is poorly constrained. Graywacke and unaltered andesite have very similar densities, and therefore, if uplifted graywacke were the cause of the observed anomalies, the graywacke would need to be anomalously dense (i.e., ≥2,900 km^{-3}), but such densities for New Zealand graywacke are unknown. It is possible, however, that a local basement high with a moderately higher density than is typical for graywacke contributes to the observed gravity anomaly.

Given the rock types in the Coromandel region, the most likely composition of any intrusion would be diorite, quartz diorite, or granodiorite, however, only dioritic to gabbroic rocks could have sufficiently high density to account for the observed gravity anomaly. Such an intrusion would be expected to have a detectable magnetic anomaly. However, the positive gravity anomalies coincide with the magnetic quiet zone and therefore any mafic intrusion at depth must be nonmagnetic, which is unlikely, or it must have been altered sufficiently to destroy its magnetite content without significantly reducing its density. This is possible if the intrusion had been emplaced before or during the period of hydrothermal alteration such that magnetization was reduced by partial destruction of magnetite; such an occurrence has been described, for example, in the andesite volcanoes in Taranaki (Locke et al., 1994). Furthermore, adularia-sericite deposits commonly occur above and offset from the implied heat source (Heald et al., 1987; Hedenquist et al., 2000).

Sulfide mineralization is not generally considered prevalent in the adularia-sericite epithermal environments that characterize the Coromandel peninsula, although studies in the Waihi district indicate that it has occurred in increasing amounts at depth (Brathwaite and Faure, 2002). This is corroborated by drilling that has intersected strong sulfide mineralization in veins at depths of >400 m (Rabone and Keall, 1986a, b). High pyrite concentrations also characterize hydrothermal alteration at Monument (Skinner, 1975), and extensive fracture-hosted base metal mineralization occurs at the Tui deposit (Wodzicki and Weissberg, 1970; Bates, 1989). For such sulfide deposition to account for the observed gravity anomaly, a fracture volume of 0.55 km^3 within the host rock has to have been filled with sulfide-bearing vein material of approximately 4,800 to 5,000 kg m^{-3} density. Dense minerals deposited within an extensive fault-fracture network are therefore a feasible explanation for at least part of the positive gravity anomaly.

A combination of a dense intrusion and high sulfide content might occur in porphyry Cu-Au deposits, which are typically associated with a central intrusion with distinct alteration zones and extensive disseminated pyrite (Lowell and Guilbert, 1970; Seedorff et al., 2005). Although 10 percent pyrite would be required to increase the density of andesite sufficiently to account for the observed gravity anomaly, only 7 percent pyrite could densify a diorite or granodiorite intrusion, which is probably more likely. Secondary magnetite is a characteristic of the central alteration zone of porphyry deposits (Sillitoe, 2000; Garwin, 2002), but not all porphyry deposits show a magnetic anomaly (Cooke et al., 1998), and therefore the lack of a magnetic anomaly at Waihi does not preclude a porphyry deposit as the cause of the gravity anomaly.

Finally, the peaks of the gravity anomaly coincide with the locations of two known and/or inferred faults, which might be expected if the basement were uplifted. Equally, these faults could enhance structural focusing of an intrusion or the transport and deposition of hydrothermal minerals.

Discussion and Conclusions

The aeromagnetic, radiometric, and gravity results presented here provide an outstanding case study of a classic epithermal province. The aeromagnetic data reveal seven well-defined magnetic quiet zones; six are localized features less than 10 km^2 in areal extent, whereas the Waitekauri Valley zone is more extensive (>20 km^2) and represents an amalgamation of at least four separate hydrothermal cells that formed over a 0.8-m.y. period (Mauk et al., 2011). The area of hydrothermal alteration defined by magnetic quiet zones is ~48 km^2, constituting 20 percent of the near surface.

Magnetic quiet zones are typical of adularia-sericite deposits worldwide and tend to be of large scale, reflecting the dimensions of former geothermal systems (Allis, 1990). The magnetic quiet zones defined here in the Waihi-Waitekauri region have dimensions comparable with present-day geothermal systems, such as those in the Taupo Volcanic Zone of New Zealand which range from 4 to 36 km^2 (Allis, 1990; Bibby et al., 1993), and with the magnetic quiet zones associated with epithermal deposits in the Hokusatsu region of Japan (Feebrey et al., 1998). Magnetic quiet zones at Pajingo, Australia, however, extend only 50 m from the veins (Hoschke and Sexton, 2005).

The epithermal deposits in the Waihi-Waitekauri region are all associated with magnetic quiet zones. In contrast, the Hishikari epithermal deposit in Japan is not associated with a well-defined magnetic anomaly due to the occurrence of relatively unaltered volcanic cover rocks (Izawa et al., 1990). Most of the epithermal deposits in the Waihi-Waitekauri region occur in the central parts of their respective magnetic quiet zone, with the exception of the Golden Cross and Favona deposits which appear to be located toward the edge of their zones. Both these latter deposits are adjacent to a lithologic boundary where younger magnetic cover rocks may partially mask the full extent of the magnetic quiet zone; however, mineralogical evidence indicate that these deposits occur near the margins of their parent hydrothermal systems (Simpson et al., 2001; Simpson and Mauk, 2007).

Aeromagnetic data can delineate regional structures that may have influenced hydrothermal activity, for example, the Vera-Nancy trend at Pajingo (Hoschke and Sexton, 2005) and the occurrence of the Bimurra-Conway deposits at the intersection of a series of magnetically quiet corridors (Irvine and Smith, 1990). Similarly, many of the magnetic quiet zones identified in this study lie within a north-northeast–south-southwest structural corridor (Fig. 3), which suggests that regional-scale structures may control the location of these features (Hay, 1989; Rabone, 1991; Grodzicki et al., unpub. data). Structural control appears also to be important for localization of deposits outside this corridor zone, but on a district, rather than regional, scale.

The local high K anomalies in the Waihi-Waitekauri region reflect intense and pervasive hydrothermal alteration and potassium metasomatism that has deposited adularia and illite at the core of the alteration zones (de Ronde and Blattner, 1988; Simpson et al., 2001; Mauk and Simpson, 2007; Simpson and Mauk, 2007; Booden et al., 2011). Adularia is prevalent in the Waihi-Waitekauri region, coinciding with K_2O additions of up to 12/100 g (Booden et al., 2011; Simpson and Mauk, 2011) and indicates zones of high permeability and subsurface boiling of geothermal fluids (Browne, 1978); hence the high K anomalies indicate favorable conditions for gold deposition (Hedenquist et al., 2000). Coincident anomalies of high potassium count and K/Th ratio characterize adularia-sericite deposits in the Hokusatsu region, Japan (Feebrey et al., 1998) and Queensland, Australia (Webster and Henley, 1989). In the Waitekauri Valley, a significantly broader K/Th anomaly is mapped, reflecting more widespread potassium enrichment (Booden et al., 2011). A similar zone is evident in the K/Th ratio over the Bimurra-Conway region, Australia (Irvine and Smith, 1990).

The radiometric method has thus proved effective for defining areas of potassium enrichment and metasomatism in this region of the Coromandel despite variable vegetation cover that has been shown to attenuate radiometric signals in other epithermal provinces (Irvine and Smith, 1990). The most intense potassium anomalies occur at deposits exposed at the surface by mining where there is no vegetation cover (e.g., Waihi and Golden Cross); in contrast, the subsurface deposit at Favona has no associated expression in the potassium data.

Unexpectedly for an epithermal deposit hosted in low-porosity dense rocks, the Waihi and Favona deposits are asso-

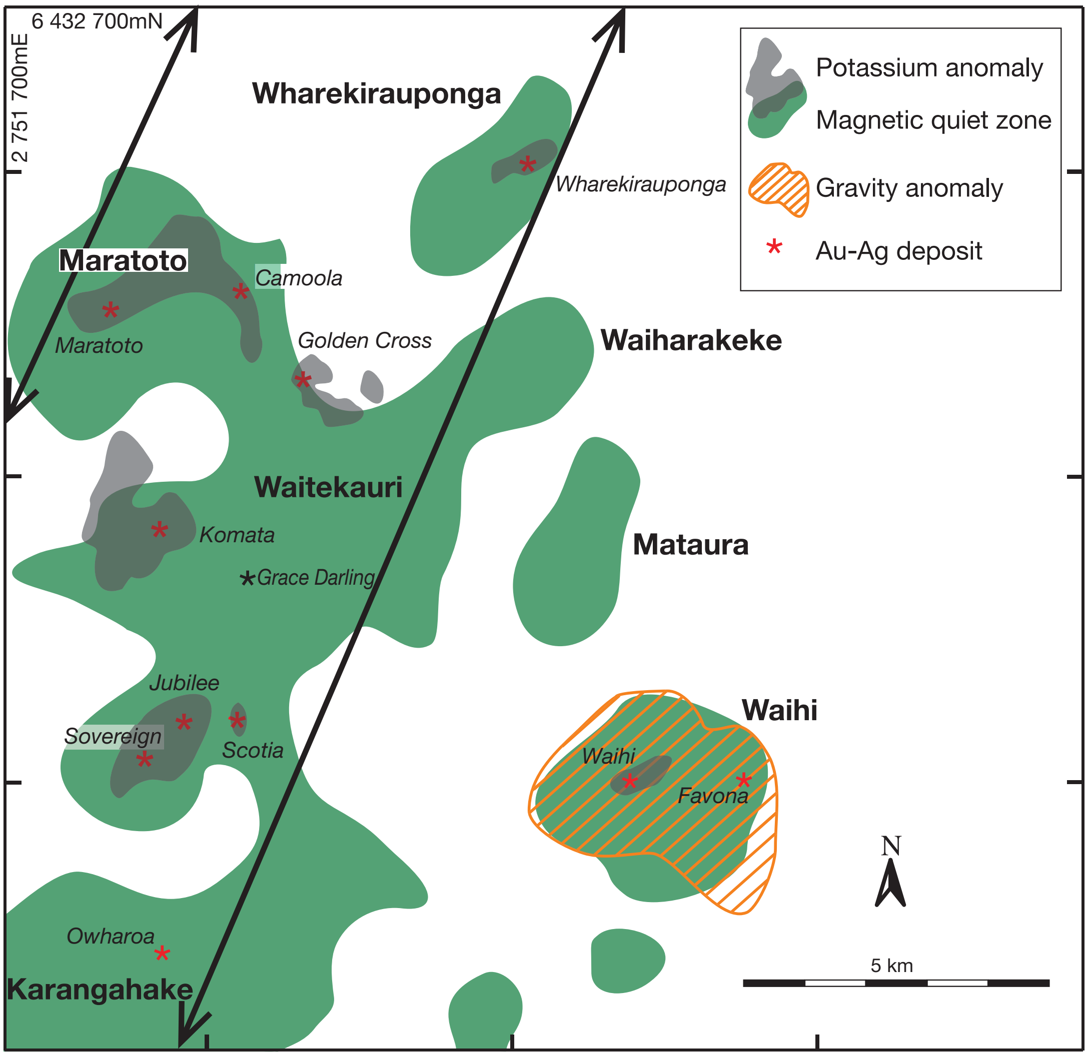

FIG. 3. Spatial relationships between the geophysical anomalies in the Waihi-Waitekauri region. The magnetic quiet zones are defined from the wavelength-filtered analytic signal image (Fig. 1d), the potassium anomalies from the potassium image (Fig. 1e), and the gravity anomaly from the residual Bouguer gravity (Fig. 2b). Black lines delineate the Tui-Ohui structural corridor.

ciated with a striking positive residual gravity anomaly. Similar positive anomalies have subsequently been identified at other deposits in the southern Coromandel (Harris et al., 2005; Kirkby, 2008), which suggests that these enigmatic dense structures are not unique to Waihi, though, as noted previously, similar gravity anomalies have not been identified outside New Zealand. It may be significant that all these deposits are located adjacent to the major regional faults delineating the Waihi basin structure (Locke et al., 2007). To date, no positive anomalies have been resolved in the Waitekauri Valley, and the Golden Cross and Scotia deposits are associated with local negative anomalies (Locke and de Ronde, 1987). There is some indication, however, of a positive anomaly toward the north of the Waitekauri Valley (Maratoto; de Ronde, 1985; Locke et al., 2007), but this is poorly defined due to a paucity of data.

There is a close spatial correlation between all the observed geophysical anomalies (Fig. 3). Aeromagnetic anomalies are the most extensive geophysical signature of the epithermal systems, covering areas of several to tens of square kilometers. They represent district- to regional-scale hydrothermal alteration and all other geophysical anomalies occur within these magnetic quiet zones. The extent of the positive residual gravity anomaly in the Waihi district very closely correlates with the extent of the corresponding magnetic quiet zone. As the source of the gravity anomaly lies below the upper, low-density altered andesite, this source body must have a much more confined lateral extent and the coincidence of separate gravity peaks over the two main areas of mineralization may indicate some focusing process at the deposit scale. The distinct K anomalies in the radiometric data are the most localized (and intense) geophysical anomalies and result from deposit-scale zones of intense hydrothermal alteration and potassium metasomatism that accompanies gold-silver mineralization across the region. The Waitekauri-Maratoto area contains several potassium anomalies that probably represent individual upflow zones within the area defined by the magnetic quiet zone.

The integration of geophysical methods as described here provides an outstanding example of how key structural, lithologic, and alteration features at different scales associated with major orebodies can be elucidated. The nested geophysical anomalies delineate district- to regional-scale hydrothermal alteration, well-defined magnetic quiet zones, and broad K/Th highs delineate the extent of the former geothermal systems, and K anomalies highlight localized zones of intense hydrothermal alteration. The distribution of alteration in the region defined by the magnetic data indicates that geothermal systems were active both in isolation, forming discrete zones (e.g., Wharekirauponga), and clustered producing extensive alteration zones (e.g., Waitekauri Valley) as multiple systems overlapped during the 800,000 years of hydrothermal activity.

Acknowledgments

We thank Newmont Waihi operations for providing aeromagnetic data, airborne radiometric data, and unpublished geologic maps. We thank Newmont staff, particularly Lorrance Torckler, Mike Sexton, and Terry Hoschke, for many helpful discussions about the geology and geophysics of the Waihi-Waitekauri region. The New Zealand Foundation for Research, Science and Technology, Newmont Waihi Operations, and the New Zealand Branch of the Australasian Institute of Mining and Metallurgy provided funding for this research. We thank reviewers Mike Dentith and Greg Arehart for valuable comments and David John for his editorial assistance.

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