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Integrating airborne geophysical data into new geological maps of New Zealand mineral provinces

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ABSTRACT

Modern, high resolution airborne geophysical surveys have been undertaken over mineral-prospective areas in Northland, central North Island, West Coast and Otago. Further surveys are planned for Nelson-Marlborough and west Otago-Southland. These surveys collectively will cover ~30% of onshore New Zealand. The existing datasets reveal geophysical anomalies that can generally be explained by mapped geology and provide excellent validation of existing geological maps. Anomalies at variance with known surface geology may reflect buried geological sources or deficiencies in the geological mapping that can be rectified through reinterpretation. Some geophysical anomalies can guide exploration, either indirectly through delineating potentially mineralised host rock and structural features, or more rarely by a direct geophysical response from the mineralisation itself. Geological modelling of aeromagnetic data has helped reveal the depth, shape and composition of buried sources of anomalies in Northland and West Coast. Aeromagnetic datasets can assist with the interpretation of subsurface geology beneath covering sediment and have enabled production of new basement-focussed geological maps of parts of Otago and West Coast. The geophysical datasets are continuous, unlike geological maps based on outcrop information, so lend themselves to defining fault geometry, structures that might be mineralised, as well as spatial modelling for prospectivity analysis.

Keywords: geological maps, airborne geophysics, aeromagnetics, radiometrics, interpretation, Northland, West Coast, Otago

INTRODUCTION

Mineral resource exploration companies are attracted to New Zealand prospects in part by the availability of regional geological and geophysical datasets (Fraser Institute, 2014). These datasets help focus exploration activities aiding selection of prospective permit areas and identify parts of permit areas to concentrate exploration activities. They also assist in defining specific targets for detailed follow up work such as geochemical sampling, ground-based geophysics and drilling. Airborne geophysical data are measurements of potential fields and radiation from which rock properties can be deduced. Aircraft-mounted sensors acquire these measurements along many parallel flight lines covering wide areas. These measurements are typically gridded and the resultant images are interpreted by exploration geologists and geophysicists. A feature of airborne geophysical surveys is that they provide a continuous objective dataset across an area, where geological outcrop information may be discontinuous and in places subjective. Magnetic intensity measurements at flying heights 30-100 m above ground are the most commonly acquired geophysical data and arguably one of the more informative in terms of adding to available geological information. Radiometric data recording natural gamma ray flux from radiogenic elements, particularly potassium, thorium and uranium, are commonly acquired along with aeromagnetic data. Radiometric signals are subdued by vegetation and moisture so have limited application for geological mapping in New Zealand, but can have a role in differentiating soil types. Other less commonly acquired aircraft-mounted geophysical measurement methods include airborne electromagnetics and aerogravity/gradiometry. Nearly a quarter of on-land New Zealand is now covered by modern, publically available, high resolution aeromagnetic data in northern North Island, West Coast and Otago (Figure 1). These surveys have been commissioned by exploration companies, and central and regional government agencies. Further surveys in Nelson, Marlborough, Otago and Southland are being acquired for government agencies between 2015 and 2017 which will increase aeromagnetic survey coverage to ~30% of onland New Zealand.

Geophysical imagery can be easily combined and analysed with geological map information using Geographic Information System (GIS) software. The QMAP 1:250 000 Geological Map of New Zealand (Rattenbury and Isaac, 2012) is particularly useful as it is now available in nationally seamless GIS software file formats (Heron, 2014; Rattenbury and Heron, this volume). Existing geological information provides insight into possible rock mineralogy and the causes of many geophysical anomalies. Conversely, magnetic anomalies may be at variance to existing geological map interpretation and can contribute to adjustment of geological map unit boundaries. Some geophysical datasets such as aeromagnetics, electromagnetics and aerogravity are influenced by geological sources both near and distant to the sensor, whereas others such as radiometrics record only shallow surface sources.

Available airborne geophysical data are being used by GNS Science for a series of resource mapping projects that aim to enhance geological mapping and improve understanding of subsurface geology in three New Zealand mineral provinces; Northland, West Coast and Otago. In this contribution we provide an overview of three new airborne geophysical datasets in these regions and some highlights associated with their integration into regional geological mapping and exploration. These datasets are influencing new geological maps in production for these areas.

NORTHLAND

Airborne geophysical data covering over 13,590 km^2 (80,710 line km) were acquired over Northland region in 2011 in a partnership between Ministry of Economic Development, Far North District Council, Enterprise Northland and the Northland Regional Council (NZP&M, 2011). A fixed wing aircraft with a tail stinger magnetometer and floor mounted crystal pack, collected magnetic and radiometric data at 200 m line spacing and 60 m sensor height from Kaipara Harbour northwards. Data processing and initial interpretation were carried out by GNS Science (Stagpoole *et al*, 2012). In this region of complex geology where exposures away from the coast are limited and typically deeply weathered, the geophysical data are a particularly valuable resource for geological mapping. The survey provides a large amount of detailed information that provides new insight into Northland's geology and structure.

The Northland region contains a wide variety of mineral commodities and has produced high quality ceramic clays, limestone for cement and agriculture, and rock and sand aggregates (Christie and Barker, 2007). Antimony, coal, copper, diatomite, kaolinite clay, kauri gum, manganese, mercury, peat, serpentine, silica sand and silver have been mined in the past and there are prospects for aluminium, bentonite, chrome, feldspar sand, gold, lead, nickel, phosphate, zeolite and zinc.

The most up to date geological maps of Northland are the 1:250 000 QMAP sheets (Isaac, 1996; Edbrooke and Brook, 2009) and most magnetic anomalies can be related to mapped geological features. The geophysical data provide an opportunity, however, to refine the mapping of many geological units and give insights into their subsurface character. There are several prominent magnetic anomalies that have no explanation from what is currently known of surface and near-surface geology (Stagpoole *et al*, 2012, in press), confirming the potential of aeromagnetic interpretation to refine existing geological maps and subsurface 3D structure.

The survey data provide a basis on which to improve geological mapping in many parts of Northland, but particularly in eastern Northland where Northland Allochthon cover is thin or absent. Magnetic datasets allow new structural interpretation of Caples, Waipapa and Mt Camel Terrane basement rocks and enable a better understanding of their subsurface distribution and likely boundaries. Igneous rocks of the Tangihua Complex are clearly imaged by the magnetic data, as are the younger Neogene volcanics and associated intrusives (Figure 2). Long-wavelength magnetic anomalies highlight the position and segmentation of deeply buried ophiolites of the Dun Mountain-Matai Terrane. The subsurface extent of partly or completely concealed volcanoes, such as Kaipara Volcano beneath North Kaipara Barrier, can also be seen in the data. Some volcanic centres exhibit negative anomalies (Figure 2), indicating that they are reversely magnetised and therefore erupted at times of magnetic reversal. Contrasting radiometric signals also help to differentiate some basement and cover units, but they most clearly show differences within the Pliocene and Quaternary dune complexes of the west coast and far north. The radiometric data, mainly potassium, reveal different periods of dune development and variation in source materials.

New geological mapping priorities are focussed on the east coast of Northland, between Whangarei and Kaitaia. Based on historic and current exploration activity this is the most prospective part of Northland with a record of mineral indications from previous geological mapping and geochemical prospecting. Proposed work will focus on two areas of particular interest in the vicinity of large positive magnetic anomalies of unknown origin. In an area east of Kaitaia there is a circular anomaly with weaker, arcuate anomalies to the north. Surface geology is dominated by allochthonous Eocene and Oligocene calcareous mudstone and muddy limestone of the Motatau Complex that are inferred to be at least 600 m thick. Preliminary 3D modelling of the anomaly suggests that the source is a flat topped circular body, about 4 km across, that reaches to within 100 m of the surface (Stagpoole *et al*, in press). The modelled magnetisation, size and depth suggest that it is an igneous intrusion or volcano of intermediate composition (eg quartz diorite). Further analysis of the magnetic data, together with more detailed mapping of the potential Motatau Complex host or cap rocks is needed to establish if a mineralised epithermal system is associated with the feature.

A similar, but larger, circular anomaly (5 km across, Figure 2) is present west of Whangaruru Harbour and its source is likely to be an igneous intrusion, here hosted in Waipapa Terrane basement rocks. Preliminary modelling predicts that the top of body is mainly about 200 m below the surface, possibly with two localised shallower extensions (Stagpoole *et al*, in press). Currently the area is not well mapped, although previous prospecting has identified extensive fracturing of the basement rocks with numerous quartz veins and a series of mineralised breccia dikes. More detailed mapping in the area is warranted, although exposure is poor and getting the most out of the magnetic data will be important. The area is about 10 km north of the Puhipuhi mining area where mercury and silver have been produced in the past.

The radiometric dataset provides an opportunity to improve mapping of small rhyolite domes that when weathered commonly host high-value china clay deposits. The rhyolite domes have high uranium and thorium signatures and this could be used to determine the full extent of known domes and aid exploration for new rhyolite-hosted clay deposits. The potassium channel radiometric response of coastal sands also suggests that these data can be used to differentiate and map areas of feldspar-rich sand from contrasting areas of silica sand.

WEST COAST

New Zealand Petroleum and Minerals commissioned an airborne survey of the West Coast of the South Island, covering 21,150 km^2 (70,572 line km) that was acquired between 2011 and 2013 (Vidanovich, 2013). Magnetic and radiometric data, collected by a helicopter with a stinger mounted magnetometer and floor-mounted crystal packs, were acquired at 200 m line-spacing at nominal 50 m terrain clearance. Sampling frequencies of between 0.05 and 1 s provided data at intervals of between 2 and 50 m along each line. The mountainous glaciated terrain covered in bush in the region was a particular challenge for maintaining constant flight elevation and quality data acquisition.

The West Coast is transected by a major plate boundary fault, the Alpine Fault, which juxtaposes two distinct geological provinces. Northwest of the Alpine Fault, the Paleozoic-Mesozoic metasedimentary and plutonic basement rocks are fragments of the Gondwana supercontinent. Southeast of the Alpine Fault, there are thick, deformed packages of Permian-Jurassic sedimentary and metasedimentary basement rocks that formed at the Gondwana margin. Sustained uplift along the Alpine Fault has resulted in much of the mountainous topography of the Southern Alps. Erosion of the uplifted rocks has resulted in thick deposits of glacial till and alluvial outwash over large parts of low-lying West Coast and offshore region. The geology of the West Coast is described by the Nelson, Kaikoura, Haast, Greymouth and Aoraki 1:250 000 geological maps of the QMAP series (Rattenbury, Cooper and Johnson, 1998; Rattenbury, Townsend and Johnston 2006; Rattenbury, Jongens and Cox, 2010; Nathan, Rattenbury and Suggate, 2002; Cox and Barrell, 2007).

Metallic mineral occurrences include hard-rock and alluvial gold, and mineral-rich beach sands that contain ilmenite and gold (Christie, Barker and Brathwaite, 2010). The region has a long history of coal extraction including some high value, low ash bituminous coals, and there are sedimentary sequences containing petroleum that attract exploration. Pounamu (New Zealand jade) is a locally important non-metallic mineral that also has economic and spiritual significance to Māori.

The West Coast Region contains abundant, well exposed rock in the hills and mountains but the flatter low-lying areas are dominated by unconsolidated Quaternary sediments of fluvioglacial origin. The 2013 West Coast Airborne Geophysical Survey aeromagnetic data have revealed a lot of new information in the areas with Quaternary covering sediment (Figure 3), as well as highlighting subtleties in the older basement rocks that weren’t apparent or depicted on existing geological maps (Vidanovich, 2013; Rattenbury, 2014, 2015b). The largest magnetic anomalies coincide with igneous rocks; notably some of the Mesozoic plutons (eg the Rahu, Darran and Separation Point suites), mafic volcanic flows (Arnott Basalt) or metavolcanic bands (Aspiring Lithologic Association greenschist) and ultramafic rocks (Pounamu Ultramafics, Dun Mountain Ultramafic Group). Most sedimentary rocks in the West Coast area are weakly magnetic, with the exception of those with substantial amounts of igneous rock-derived material or accumulations of magnetite and/or ilmenite at unconformities, paleoshorelines and in dunes.

Many mapped plutons have spatially coincident magnetic anomalies. Areas where anomalies are at variance to geologically mapped boundaries may be due poor outcrop or interpolation assumption. For example, plutons mapped in the Mokihinui River catchment in north Westland, show some variance with magnetic anomalies and will be a target for new field-based verification and mapping. Alternatively lateral variations in magnetic susceptibility with depth can result in apparent mis-alignment of anomalies with geological sources in map view. This is evident in the Victoria Range where near-surface, shallow-dipping contacts between plutons of contrasting magnetic susceptibility accounts for why magnetic anomalies exist where the exposed plutonic rocks have low magnetic susceptibility.

There are many magnetic anomalies that cannot be correlated with mapped geology nearby. The largest uncorrelated feature is the Kumara Magnetic Anomaly (Rattenbury, 2015b) in an area of otherwise subdued magnetic anomalies that correlate with Neogene sedimentary rocks and Quaternary fluvioglacial and coastal sediments. This Kumara Magnetic Anomaly has been attributed to a high magnetic susceptibility pluton whose upper contact is approximately conical with its apex two kilometres below surface (Rattenbury, 2015b). The many linear ‘ridge’ anomalies in the region are usually interpreted as mafic igneous dikes and linear ‘step’ anomalies as faults that have juxtaposed rocks of differing magnetic susceptibility. More elliptical and confined anomalies are interpreted as buried magnetic plutons. The Greenland Group that hosts auriferous quartz veins and is viewed as the West Coast’s most prospective rock unit, is very weakly magnetic (Rattenbury, 2015b) although relatively magnetic facies within it may be an exploration target that could be resolvable with the aeromagnetic dataset (Rattenbury, 2015a).

In general the radiometric data correlate poorly to mapped geology. This is attributed to the prevalence of high mobility and intermixed surface materials that are the source of the recorded signal over much of the West Coast. Areas of good rock exposure, that is, without significant transported surficial material and light vegetation, are better expressed in the radiometric images. For example, different Rahu Suite plutons in the Mt Turiwhate-Tuhua area in central Westland have varying thorium and potassium signals.

OTAGO

An airborne geophysical survey was acquired over ~13 000 km^2 (52,000 line km) of central Otago in 2007 for the mineral exploration company Glass Earth Limited and partners. Magnetic (including horizontal gradient) and electromagnetic (AEM) data were collected at 300 m line spacing, locally infilled at 150 m and 75 m, using two helicopters towing 9 m RESOLVE^{TM} 'birds' at 30 ± 10 m elevation (Fugro, 2007). Recording at 0.1 second frequency provided magnetic data approximately every 4 m along the lines. The geophysical data are being utilised in a new geological map covering the Middlemarch area in Otago (Figure 4, Martin, Cox and Smith Lyttle, 2016) and are integral in plans for subsequent maps of Bendigo, Serpentine Diggings and the Hyde Macraes Shear Zone (Martin *et al*, 2015).

Gold is the predominant mineral commodity in Otago, either in hard rock occurrences or alluvial placers. The world-class Macraes gold (± tungsten) deposit is currently being mined, and there are other active exploration projects for gold in the region. The region has also produced scheelite (tungsten) and stibnite (antimony), marble, phosphate, diatomite, high-purity quartz sand, and there are local resources of rock, sand and clay aggregate. There are substantial deposits of lignite and subbituminous coal, and groundwater resources are becoming increasingly important.

The Glass Earth geophysical survey covers a large part of the Otago Schist metamorphic belt and overlaps parts of the Dunedin, Wakatipu, Waitaki and Murhiku QMAP 1:250,000 geological maps (Bishop and Turnbull, 1996; Turnbull, 2000; Forsyth, 2001; Turnbull and Allibone, 2003). Clastic sedimentary rocks of the Caples and Rakaia terranes, interlayered with less common mafic rocks and chert, have been metamorphosed to schist and overprinted by extensive deformation. The regional geological map coverage is complemented by detailed prospect datasets (eg Cox, 1999a, 2001). The Glass Earth geophysical dataset shows regional-scale variations in magnetism and conductivity that can be related to major geological domains and the regional Mesozoic metamorphic geology (Doyle and Henderson, 2007; Coote *et al*, 2008). For example, the regional magnetic intensity is higher over the metavolcanic-rich Aspiring Lithologic Association in West Otago. Some variation in magnetic intensity can be linked to geological structures that are host to mineralisation (Cox, 2001; Cox and Gorman, 2009).There is a contrast between low magnetic susceptibility greyschist and medium-high greenschist rocks in the Otago Schist, with the latter's magnetic susceptibility caused by prograde growth of magnetite (Martin, Rattenbury and Cox, 2013). Around Middlemarch in East Otago, individual greenschist units plunge shallowly northwest beneath outcropping greyschist for up to 30 km (Figure 4). These are interpreted to be rods of greenschist in isoclinal fold hinges that reflect regional-scale, poly-deformed macroscopic recumbent folding (Mackenzie, Craw and Martin, 2015). The orientation of the lithological units and the scale and style of folding defined from interpretation of geophysical data can be used to target zones of high-grade mineralisation within deposits (Cox, 1999b).

The Oligocene-Miocene volcanic rocks (Figure 4) are highly magnetic and typically associated with prominent positive anomalies in the aeromagnetic dataset. The mapping of their surface extent and their sub-surface form has been refined from the aeromagnetic data. The AEM dataset is particularly useful for determining conductivity zones in alluvial basins. In the Middlemarch area, the depth of Quaternary sediments forming the Strath-Taieri Basin can be interpreted from the AEM dataset (Martin, Mortimer and Cox, 2014). Furthermore, Quaternary sediments derived from recent river deposits have different conductivity to Quaternary sediments shed from the adjacent topographic high (the Rock and Pillar Range) and hence the electromagnetic data can be used to map the different units. Geophysical modelling of AEM data can be used to predict the presence of groundwater aquifers in these sediments (Westerhoff *et al*, 2014). Conductivity contrasts caused by the presence of water and/or clay mineralogy also highlight the position of faults in the Otago Schist. In the Middlemarch map area this has helped define the location and throw on regional-scale NW-SE trending faults, such as the Barewood Fault where gold mineralisation has been mined historically.

EXPLORATION METHODOLOGY

Airborne geophysical datasets provide continuous coverage over wide areas. The data are commonly expressed in terms of anomalies, that is, departures from regional background values. Anomalies can be correlated with mineralisation potential, either directly (eg conductive sulfide minerals) or indirectly (eg prospective host rock or structures that control ore deposit location). Geophysical anomalies usually have a geological source, and the exploration geologist can use the geophysical data to better determine the shape, distribution and characteristics of prospective geological structures. Some geophysical methods give direct information about location of the anomalous source (radiometrics) whereas other methods are indicative (gravity, magnetics, electromagnetics) and require modelling to predict the shape, depth and physical properties of the anomaly source. Geological maps provide important context for an office-based assessment at a regional scale but field-based observation, assisted by ground-based detailed geophysical surveys and measurements are the established next steps for an explorer.

Gridded geophysical datasets provide continuous uniform coverage that can be used to infer rock properties, in contrast to geological maps that are interpolated or extrapolated interpretations of discontinuous observations at available outcrops. With careful interpretation geophysical datasets can reveal the faults, fractures and contacts that are commonly the 'plumbing system' through which mineralisation fluids pass. Their identification may be aided by ground-based evidence shown in geological maps, but these faults and fluid conduits are typically composed of weak strength material and are rarely seen in outcrop. The geophysical data enable structure and geometric variations, such as bends and dilational jogs, to be defined and appraised for their potential to control and host mineralisation. The continuous coverage of geophysical datasets also lends them to spatial statistical analysis, such as the Weights of Evidence method commonly applied for prospectivity assessment (eg Partington *et al*, 2002; Partington, Christie and Rattenbury, 2006; Rattenbury and Partington, 2003, Peters *et al*, this volume).

CONCLUSIONS

High resolution airborne geophysical surveys are a valuable part of the resource exploration process. The acquisition of high resolution regional aeromagnetic and other geophysical datasets in the last decade has resulted in the identification of new exploration targets and validated much of the available modern geological mapping. GIS-based geological maps are critical for context and understanding the sources of geophysical anomalies and in turn the geophysical data can inform on and improve geological map quality. The geophysical datasets can be used to indirectly indicate mineralisation potential through the delineation of potentially prospective host rock and structural features, and their continuous coverage make them ideal components for spatial mineral prospectivity modelling. Improved geological maps of mineral-prospective areas are being generated using the geophysical data and this will facilitate and stimulate mineral exploration in New Zealand mineral provinces.

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FIGURE CAPTIONS

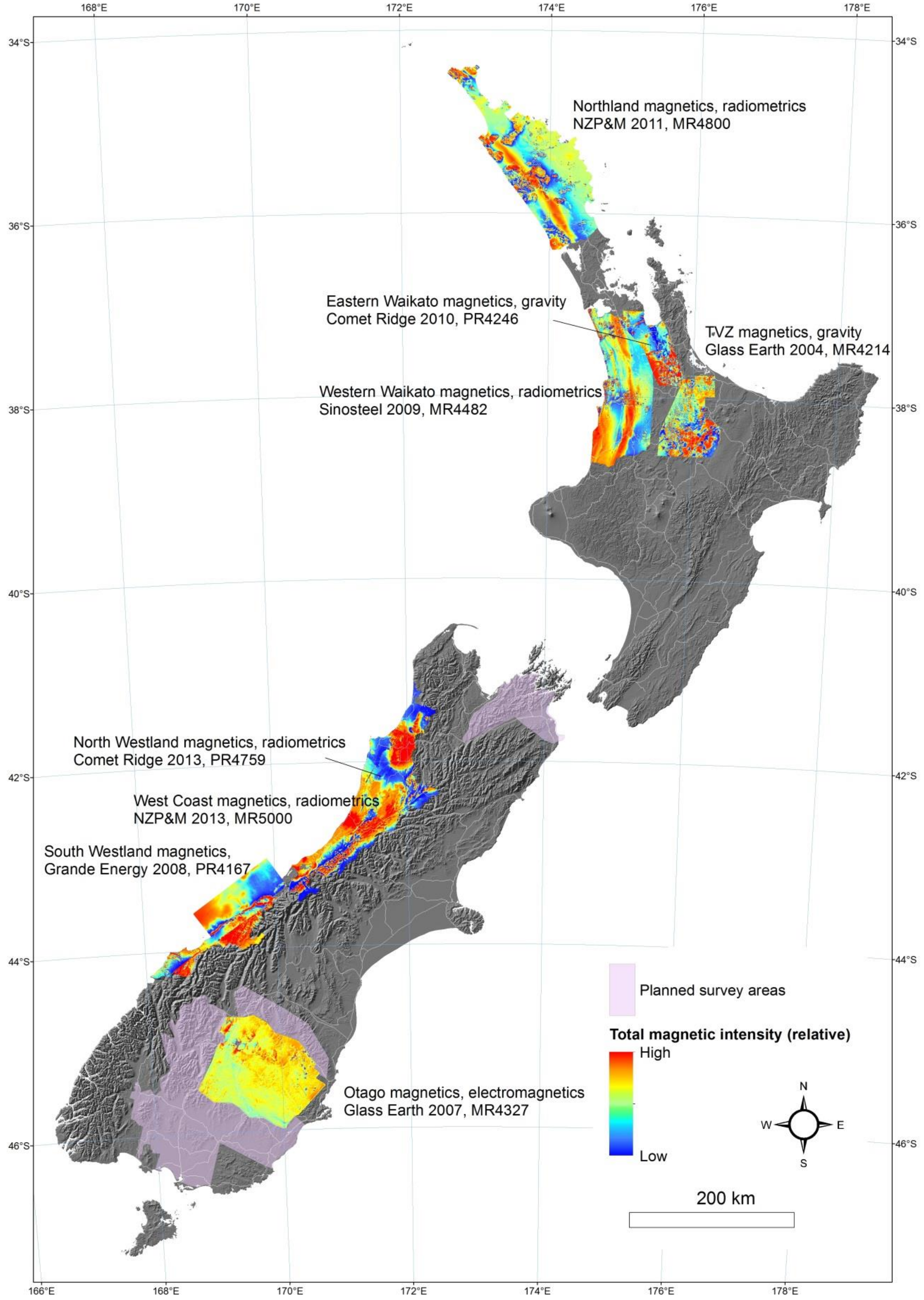
Figure 1 – Recent, high resolution, open-file airborne geophysical surveys, shown as total magnetic intensity, that are available from New Zealand Petroleum & Minerals mineral reports (MR) and petroleum reports (PR). New government-funded surveys will be acquired during 2015-2017 in Nelson, Marlborough, Otago and Southland.

Figure 2 – Simplified geological map units and aeromagnetic anomalies from the Puhipuhi area in Northland. Reversely magnetised anomalies (R) are associated with some Neogene volcanic rocks and a broad lower intensity anomaly (P) is interpreted to be a pluton intruding sedimentary basement rocks to within 200 m of the surface (Stagpoole *et al*, in press). Geological map data after Heron (2014).

Figure 3 – Geological map of Moana area of central Westland emphasising pre-Quaternary map units. The older rocks have been extrapolated and interpolated from mapped surface outcrop, in part based on interpretation of aeromagnetic anomaly data shown as a greyscale shaded total magnetic intensity image. Geological map data after Heron (2014).

Figure 4 - Extract from the new Middlemarch geological map (Martin, Cox and Smith Lyttle, 2016). Greenschist bands (Ytg) are mapped at the surface but are also inferred and extrapolated below surface (hatched areas) based on aeromagnetic anomalies. Outcropping Miocene volcanic rocks (Mdv2) correlate closely with high intensity anomalies.

FIGURES (COPY HERE OR INCLUDE AS SEPARATE ATTACHMENTS)



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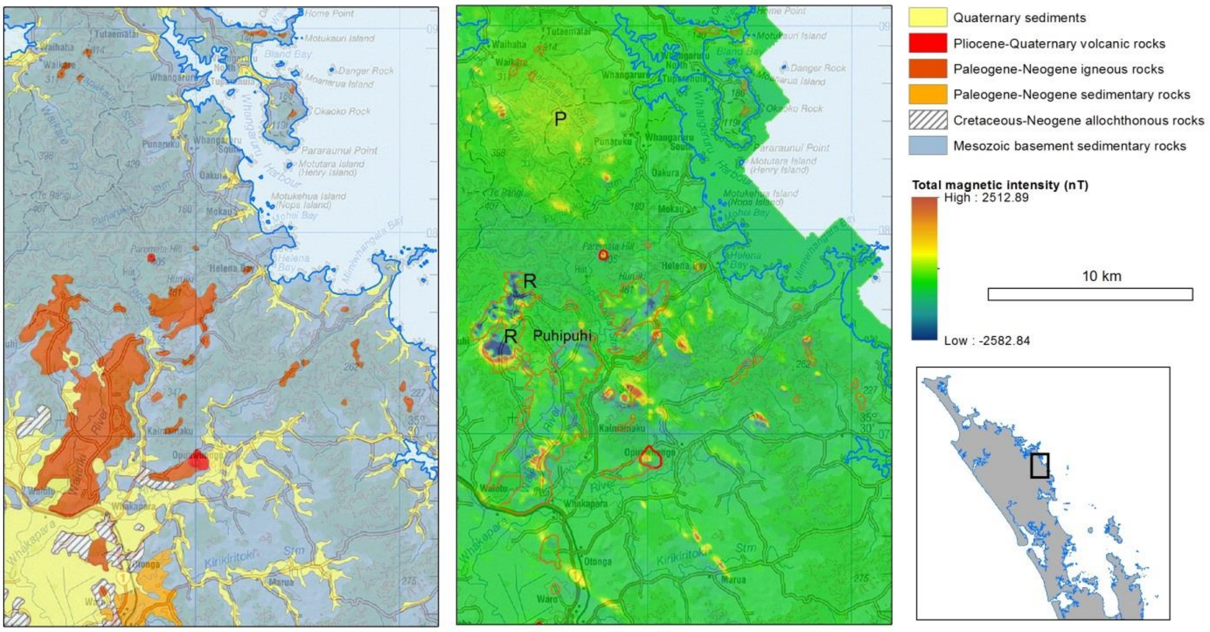

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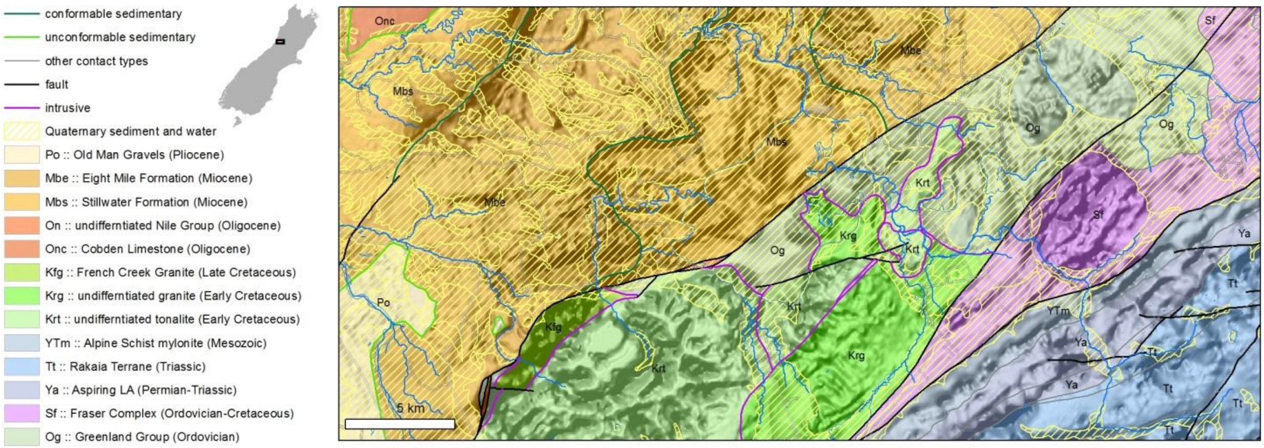

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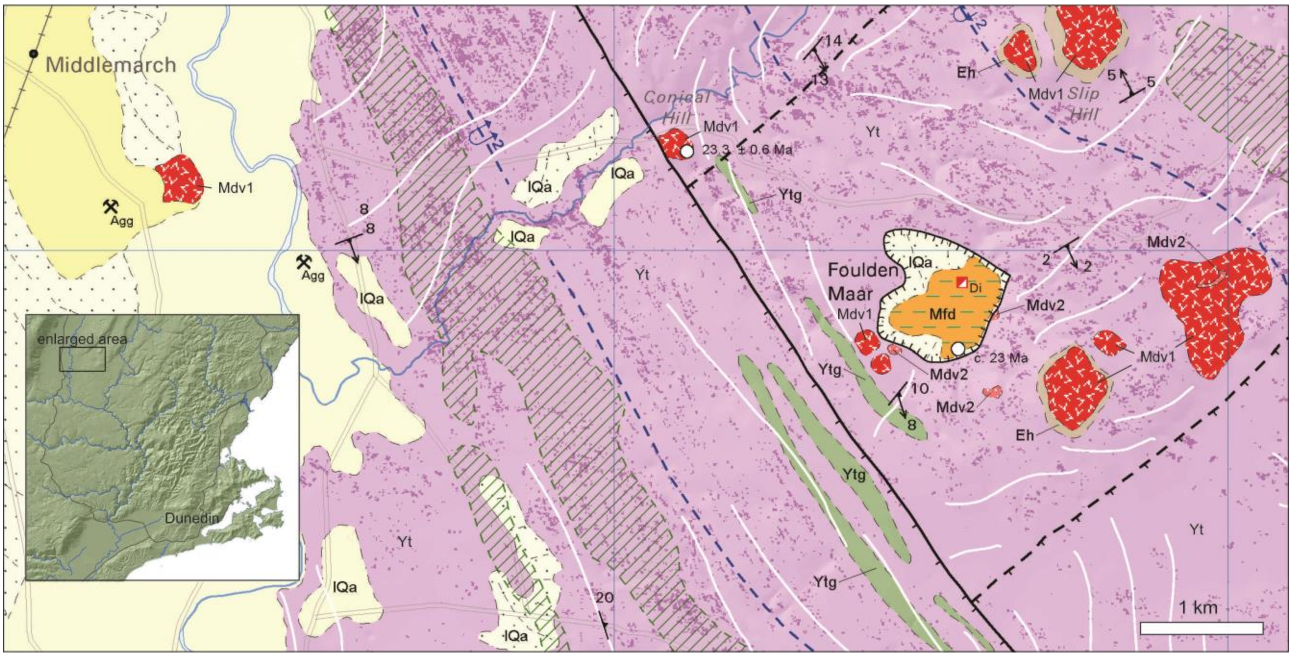

FIG 4 – Extract from the new Middlemarch geological map (Martin, Cox and Smith Lyttle, 2016). Greenschist bands (Ytg) are mapped at the surface but are also inferred and extrapolated below surface (green diagonal areas) based on aeromagnetic anomalies. Outcropping Miocene volcanic rocks (Mdv1, Mdv2) correlate closely with high intensity anomalies.