Modelling of mafic Ni–Cu–PGE and porphyry Cu–Au prospectivity throughout Southland, New Zealand.

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Prospectivity modelling of mafic nickel-copper and platinum group mineralisation (PGE) and porphyry copper-gold mineralisation has been completed over Southland in New Zealand using the GIS based Fuzzy Logic modelling technique. The modelling was constrained by the minerals systems concept, which defines those parts of a mineralisation system that are critical to the ore-forming process. These ore-forming processes are mapped spatially using geographic information systems (GIS) analysis and used to predict mineral potential. Spatial modelling techniques, in particular fuzzy logic modelling, can be used effectively in greenfields exploration to indentify potential locations of mineralisation by analysing large databases of existing geological information in a GIS. This technique requires expert knowledge about the mineral systems and uses digital databases of geological information that include geological mapping, geochemistry, and geophysics. The modelling in this study used fuzzy membership functions to weight the mineral system themes that were generated from the geological databases and then combines those themes using fuzzy operators into a single prospectivity map showing areas favourable for mafic Ni–Cu–PGE or porphyry Cu–Au mineralisation. The prospectivity modelling successfully identified known areas for both types of mineralisation in the Longwood Range and Greenhills regions of Southland as well as several new localities now under investigation for mafic or porphyry mineralisation.

Keywords: mafic nickel-copper mineralisation, platinum group elements (PGE), fuzzy logic, spatial modelling, Southland, mineral systems concept, prospectivity.

Introduction

Prospectivity modelling of mafic nickel-copper and platinum group mineralisation and porphyry copper-gold mineralisation has been completed over the Southland region of New Zealand using the fuzzy logic modelling technique (Bonham-Carter, 1994). The modelling has used a geographic information system (GIS) database that was compiled from all relevant historical exploration data over the region, which was then developed into predictive maps for the model using various spatial and statistical techniques. Minerals systems concepts and subsequent predictive models were generated for both the mafic Ni–Cu–PGE and the porphyry Cu–Au deposit types as geological data confirm the mineral potential of the area with respect to the two styles of mineralisation. This modelling has been conducted to optimise exploration and target selection throughout Southland and illustrates the potential for the discovery of economic gold, platinum group elements (PGE), and nickel and copper mineralisation.

Exploration Data Analysis

The modelling in this study has been constrained by the minerals systems concept, which defines those parts of a mineralisation system that are critical to the ore-forming process (Wyborn et al., 1994). The mineral systems approach is essentially the critical parameters of ore deposit formation. These ore-forming processes are identified from existing literature about the mineralisation system (e.g. Barnes and Lightfoot, 2005; Candela and Piccoli, 2005; McOnie, 2006) and spatially using GIS analysis to predict mineral potential in the study region. This modelling has mapped possible sources of metals in the region, structures that could be used for fluid migration, zones ideally suited to host a mineral deposit and outflow zones that indicate a subsurface deposit. Ore deposit formation is precluded where a particular mineral system lacks one or more of these essential components. Being process-based, the application of the mineral systems approach is neither restricted to a particular geological setting nor limited to a specific ore deposit type; indeed, the flexibility of this approach allows for multiple ore deposit styles to be realised within a single mineral system, thereby acknowledging the inherent natural variability among deposits.

Data for the modelling has been acquired from historical exploration reports, geological mapping projects, online databases, and current exploration programmes in the region. Crown Minerals reports have been the main source of historical exploration results and these have been compiled into a digital database and include rock chip, stream, soil, and drill hole geochemistry. GNS Science QMAP geological mapping over Southland (Bishop and Turnbull, 1996; Turnbull, 2000; Forsyth, 2001; Turnbull and Allibone, 2003) has been used in this study with prospect scale mapping integrated where available from exploration reports. The GNS Science PETLAB online database was also used as a source of historical sample results and integrated into the digital database. Results from some current exploration programmes were also made available to this study and have been integrated into the digital database.

Spatial analysis

Spatial data modelling requires a geological database from which predictive evidence for a particular deposit can be developed based on an exploration model and ideally training data sets based on historic mines. The relative weights for each predictive theme in the model then have to be statistically calculated or inferred from either expert knowledge or the training data set. The predictive maps are then combined according to the weights to calculate the probability of the undiscovered mineral resources. The Southland area contains no operating hard rock mines and has a limited number of mineral occurrences for porphyry Cu–Au and mafic Ni–Cu–PGE mineralisation. Therefore techniques that require training data, like weights of evidence, are not appropriate and fuzzy logic modelling is more appropriate for this region.

Fuzzy logic is a popular and easily understood method for combining exploration datasets using subjective judgment. This method relies on expert opinion to derive weights that rank the relative importance of the variable for the map combination. Each exploration dataset to be used is weighted using a fuzzy membership function, which expresses the degree of importance of the model variables as predictors of the deposit type under consideration. Maps may be combined by a variety of fuzzy combination operators (fuzzy AND, fuzzy OR, fuzzy gamma, etc.) according to a scheme that may be represented with an inference network. These functions were all carried out in MapInfo using the MI-SDM extension created by Avantra Geosystems. The output from the fuzzy logic model is a map showing mineral favourability, combining the effects of the input predictive maps.

This modelling study has investigated 98 digital data-sets of geological, geophysical, topographic and cadastral information. Forty-four new predictive maps have been developed using the mineral system models and these were combined by modelling to develop prospectivity maps for porphyry Cu–Au and mafic Ni–Cu–PGE mineralisation styles. The predictive maps for each of the models were chosen as having the best regional coverage, a significant association with the mineralisation model being considered, and where possible not to include layers with similar map patterns.

Porphyry Cu–Au mineralisation model

Porphyry-related metal deposits are large-tonnage, generally low-grade, hydrothermal systems related to igneous intrusions emplaced at high crustal levels (Barnes and Lightfoot, 2005). Geologically, the deposits occur close to, or in, granitic intrusive rocks that are porphyritic in texture. There are usually several episodes of intrusive activity, with contemporaneous swarms of dykes and intrusive breccias. The host rocks can be any kind of lithology, and often there are wide zones of closely fractured and altered rock surrounding the intrusions as a result of widespread hydrothermal activity. Mineralisation in porphyry deposits occurs mostly in fractures or in the adjacent alteration zones.

Evidence for appropriate sources of metal, fluid and energy to drive the mineral system mainly comes from regional scale geology, whole rock geochemistry, magnetic data and historic mineral occurrences. The geology of the region comprises a variety of calc-alkaline plutons of gabbro, diorite and granite, of mostly Triassic-Cretaceous ages. The Triassic-Cretaceous continental margin suites have the most potential for porphyry Cu–Au mineralisation. Potential sources of metals and energy have been confirmed by the presence of contemporaneous intermediate volcanics and intrusives ranging from diorite through to leucogranite in composition.

The source fluids and metals within a mineral system have to be able to migrate effectively to a site of deposition for economic quantities of metals to be present. The evidence for migration of fluids comes entirely from geological mapping at regional and prospect scales. For porphyry mineralisation potential transport pathways for metals have been confirmed in the permit region with the identification of pre– to syn–intrusion second order faults that have numerous fault intersections and jogs that can localise hydrothermal fluid flow. The presence of hydrothermal fluids associated with porphyry intrusion is also confirmed by breccias in the intrusions and their host rocks.

The formation and type of trap is one of the most important variables in any mineral system as the trap will determine the size and continuity of any resulting ore body. The trap may influence depositional processes, therefore grade continuity, and the type of trap present in a mineral system can be assessed using geological and geophysical data to look for lithological or structural controls on mineralisation. The size of trap can be assessed using low level geochemical data to map the probable extent of the mineralising system, either by using the metal of interest or pathfinder elements. The distribution of alteration zones may also provide information on the scale of the mineral system. Potential trap sites for porphyry mineralisation in the permit area have been modelled using lithology (e.g. carbonate host rocks make excellent trap sites for porphyry mineralisation) and where vein type and density are used as evidence for hydrothermal fluid trapping. The possible scale of porphyry mineralisation was assessed using a combination of anomalous rock, stream sediment and soil values for Ag, Au, Cu, and Mo.

The efficiency of the processes controlling the deposition of the metals of interest in a mineral system is critical to the grade and continuity of economic mineralisation in an ore deposit. Due to the lack of fluid chemistry and limited sulphide and alteration distribution mapping in the region, the best evidence for the efficiency of metal distribution comes from economically significant geochemical anomalism for gold, copper and molybdenum in the porphyry mineral system.

Predictive themes were generated for the model using the mineral systems concept for porphyry Cu–Au mineralisation described above. Sixteen from forty–four predictive maps were used in the model (Table 1) as they had the best coverage and were the most suitable for indentifying mineralisation in the region. Each theme was converted into two or three classifications using statistical and spatial analysis. These classes were assigned a Fuzzy Value that weighted the themes when all the evidence was combined to create the final model.

Table 1. Fuzzy membership functions and themes in the Porphyry Cu-Au model.

Spatial Variable	**Measure**	**Theme Code**	**Fuzzy Value**
P1: Extraction from Sources			
Intermediate Intrusives	Source of metals or fluids.	NZMDiorite	Cover 0.1, Diorite 0.7, Host 0.01
Contemporaneous Intermediate volcanics	Level of intrusive activity in the crust. Identifying those areas where igneous activity is near surface.	NZMCoMag	Cover 0.1, CoMag 0.4, Host 0.01
Stream Sed. anomalous Cu	Geochemical pathfinder that has a large geochemical signature due to dispersion down rivers and streams.	NZMCuSS	Cu>70ppm 0.4, Background 0.01
Stream Sed. anomalous Mo	Geochemical pathfinder that has a large geochemical signature due to dispersion down rivers and streams.	NZMMoSS	Mo>3ppm 0.4, Background 0.01
Stream Sed. anomalous Au	Geochemical pathfinder that has a large geochemical signature due to dispersion down rivers and streams.	NZMAuSS	Anomalous Au 0.3, Background 0.01
Intrusives older than Cretaceous	Source of heat and metals in relation to cover rocks.	NZMIntFelsInt	Cover 0.1, Intrusive 0.2, Host 0.01
P2: Migration to Trap			
Second Order Faults	Structural control.	NZM2OFaultBuf	Fault 0.2, Cover 0.1, Rock 0.01.
Carbonate rich host lithology	Chemical trap with reactive host rock.	NZMCarbHost	Carbonate 0.5, Rock 0.01, Cover 0.1.
Fault Jogs	Mineralisation controlled by fault jogs as interpreted using MI-SDM fault analysis tool.	NZMFaultJogBuf	Rock 0.01 , Jog 0.3, Cover 0.1.
P3: Formation of Trap			
Cu rich or porphyritic intermediate intrusive rocks.	Source of metals or fluids.	NZMFertileDiorite	Cover 0.1, Fertile 0.9, Host 0.01
Rock and soil anomalous Au	Geochemical pathfinder for gold, which has a larger geochemical signature within alteration halos around gold deposits.	NZMAuSoilRock	Anomalous Au 0.4, Background 0.01, Cover 0.1.
Rock and soil anomalous Cu	Geochemical pathfinder that can define areas of anomalism. Widespread areas of low level anomalism increase the probability of continuous large tonnages of economic mineralisation.	NZMCuSoilRock	Cu>120ppm 0.9, Background 0.01, cover 0.1.
Rock and soil anomalous Mo	Geochemical pathfinder that can define areas of anomalism. Widespread areas of low level anomalism increase the probability of continuous large tonnages of economic mineralisation.	NZMMoSoilRock	Mo>15ppm 0.9, Background 0.01, cover 0.1.
P4: Deposition of Metal			
Rock and drill sample	Geochemical measure of extent of high grade	NZMAuGrade	Economic 0.45,

Spatial Variable	Measure	Theme Code	Fuzzy Value
economic grade Au	mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.		Background 0.1, Cover 0.1.
Rock and drill sample economic grade Cu	Geochemical measure of extent of high grade mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.	NZMCuGrade	Economic 0.95, Background 0.1, Cover 0.1.
Rock and drill sample economic grade Mo	Geochemical measure of extent of high grade mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.	NZMMoGrade	Economic 0.95, Background 0.1, Cover 0.1.

A decision tree illustrating the model is shown in Figure 1. The predictive maps for the model in this study were initially combined using the fuzzy OR operator to create four resultant predictive maps representing the source, migration, traps, and deposition sub–processes within the mineral system. These predictive mineral system maps were then combined using the fuzzy SUM operator. The fuzzy OR operator combines the model themes so that the maximum value of any location from the inputs is carried through to the next level in the model. The fuzzy SUM operator combines the mineral system predictive themes so that the evidence for each phase of the mineral system reinforces the others where they overlap. Overlapping themes therefore increase the model results.

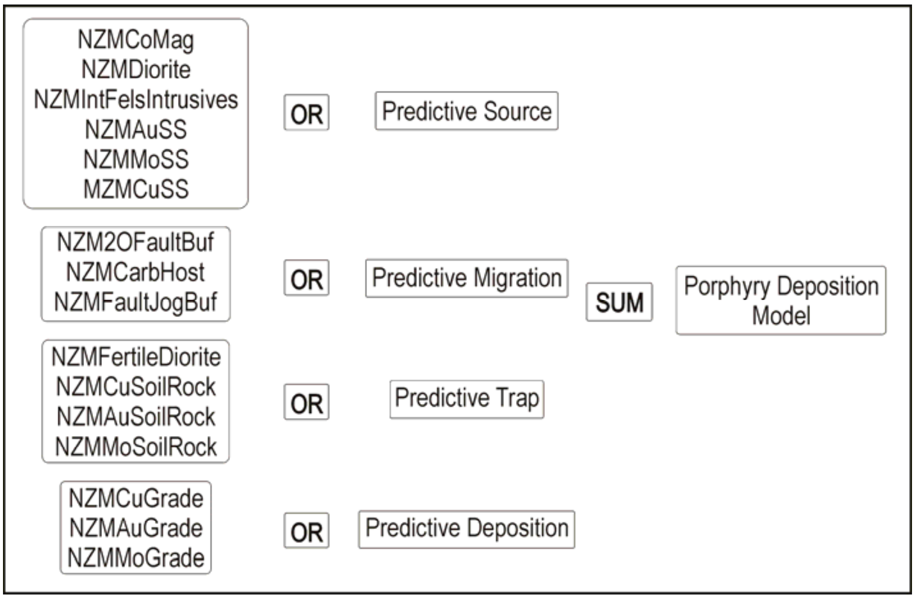

Figure 1. Decision tree for porphyry Cu–Au model listing model themes (for codes see Table 1).

Mafic Ni–Cu–PGE mineralisation model

Deposits containing nickel, copper and platinum group elements occur as sulphide concentrations associated with a variety of mafic and ultramafic magmatic rocks. The magmas originate in the upper mantle, below the Earth's crust, and contain small amounts of nickel, copper, PGE, and variable amounts of sulphur. As the magmas ascend upward through the crust, they cool as they pass through crustal rocks. If the original sulphur content of the magma is sufficient, or if sulphur is added from crustal wallrocks, a separate sulphide liquid forms as droplets dispersed through the magma. Nickel, copper, PGE, as well as iron favour the sulphide liquid. When sulphide droplets form they sink towards the base of the magma because of their greater density and concentrations of the sulphide liquid crystallises as the magma cools to form the ore deposits. Sulphide–rich Ni–Cu–PGE deposits achieve their concentrations mostly through the settling effects of gravity. Consequently in virtually all magmatic bodies the sulphide–rich ores are most likely to be found at the base of these bodies. Ore bearing intrusions can be found in deeply eroded terrains, where mid-crustal magma chambers were intruded into host rocks containing sulphide-rich bands. Subsequent erosion reveals remnants of these now-solidified magma bodies at the surface (Candela and Piccoli, 2005).

Mafic Ni–Cu–PGE mineralisation in Southland is associated with the Permian mafic intraoceanic suites. Potential sources of metals and energy have been confirmed by the presence of sills, dykes or plutons of mafic to ultramafic composition between 300-245Ma. There is only limited magnetic data available for the area so consequently the potential for zones of ultramafic lithologies within the mafic bodies could not be assessed nor could the location or extent of intrusive lithologies concealed by cover units in the region. Metals in mafic mineral systems are transported to their site of deposition by sulphides, which can be formed due to fractional crystallisation, magma mixing or host rock contamination. The detail of the geological data in the Southland region does not allow for confirmation of magma mixing or concentration of sulphide in mafic melts. However, in this study fractional crystallisation has been inferred from the presence of cumulate lithologies, mafic pegmatites, and layering in the mafic intrusions. There are also sulphide rich country rocks that may have provided additional sulphur by host rock contamination during magma movement.

Potential trap sites for mafic Ni–Cu–PGE mineralisation in the region have been modelled in a similar way to the porphyry mineral system. Unfortunately the detail of the geological mapping is not sufficient to target potential trap sites or identify the basal contact zones of the mafic intrusions. In fact, one of the major exploration challenges for finding basal sulphide deposits is determining the pre–deformational geometries and younging directions of the intrusions (Hoatson et al., 2006). The geological data were sufficient enough to identify those intrusions with sufficient size to produce the volumes of magma required to deposit mineralisation. The potential size and distribution of mafic Ni–Cu–PGE mineralisation was assessed using a combination of anomalous rock, stream sediment and soil values for Ni, Pt, Pd, Cu and Co. Copper and cobalt were particularly useful as they can usually be associated directly with hard rock mafic mineralisation. The best evidence for the efficiency of metal distribution comes from economically significant geochemical anomalism of nickel, platinum and copper as well as rock units that are enriched in the platinum group elements.

As for the porphyry Cu–Au model, forty-four themes were derived from the digital databases, and fifteen of those (Table 2) were selected for use in the model and a decision tree (Fig. 3) was developed. The predictive maps for this model were initially combined using the fuzzy OR operator to create four resultant predictive maps representing the mineral system elements and these were then combined using the fuzzy SUM operator.

Table 2. Fuzzy membership functions and themes in the Mafic Ni–Cu PGE model.

Spatial Variable	Measure	Theme Code	Fuzzy Value
P1: Extraction from Sources			
Presence of sills, dykes or plutons of mafic to ultramafic composition 300-245Ma.	Presence of mantle derived melt.	NZMMafics	Mafic 0.5, Rock 0.001, Cover 0.1.
Presence of hard rock or	Evidence of PGE, Ni and Cu metal	NZMMaficMinOcc	MinOcc 0.5,

Spatial Variable	Measure	Theme Code	Fuzzy Value
alluvial PGE mineralisation.	present.		Rock 0.001, Cover 0.1.
Stream Sed. anomalous Ni	Geochemical pathfinder that has a larger signature due to dispersion down rivers.	NZMNiSS	Ni>66ppm 0.55, Background 0.001
Stream Sed. anomalous Pt	Geochemical pathfinder that has a larger signature due to dispersion down rivers.	NZMPtSS	Pt>0.04ppm 0.6, Background 0.001
Presence of rocks with continental tholeiitic or komatiitic compositions > 18% MgO or < 1% TiO2.	Presence of mantle derived melt.	NZMMgRich	MgRich 0.95, Rock 0.001, Cover 0.1.
P2: Migration to Trap			
Presence of layering.	Fractional Crystallisation	NZMMaficLayered	Layered 0.85, Rock 0.001, Cover 0.1
Presence of cumulates (dunite, peridotite, picrite, wehrlite, harzburgite, lherzolite & websterite, pyroxenites, anorthosite, troctolite, norite).	Fractional Crystallisation	NZMMaficCumulates	Cumulate 0.75, Rock 0.001, Cover 0.2
P3: Formation of Trap			
Rock and soil anomalous Cu	Geochemical pathfinder that can define areas of anomalism. Widespread areas of low level anomalism increase the probability of continuous large tonnages of economic mineralisation.	NZMCuSoilRock	Cu>120ppm 0.75, Background 0.01, cover 0.1.
Rock and soil anomalous Ni	Geochemical pathfinder that can define areas of anomalism. Widespread areas of low level anomalism increase the probability of continuous large tonnages of economic mineralisation.	NZMNiSoilRock	Ni>116ppm 0.8, Background 0.001, cover 0.1.
Rock and soil anomalous Pt	Geochemical pathfinder that can define areas of anomalism. Widespread areas of low level anomalism increase the probability of continuous large tonnages of economic mineralisation.	NZMPtSoilRock	Pt>0.05ppm 0.9, Background 0.001, cover 0.1.
Presence of mafic intrusives > 300m thick	Evidence for sufficient volume of magma to allow fractional crystallisation and possible sulphur enrichment.	NZMMaficSize	Mafic 0.7, Rock 0.001, Cover 0.1.
P4: Deposition of Metal			
Evidence for magma enriched in PGE, Cu or Ni	Evidence for metals of interest being present in mafic magma.	NZMMaficMineralised	Mineralised 0.6 Rock 0.001, Cover 0.1.
Rock and drill sample economic grade Cu	Geochemical measure of extent of high grade mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.	NZMCuGrade	Economic 0.85, Background 0.001, Cover 0.1.
Rock and drill sample economic grade Ni	Geochemical measure of extent of high grade mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.	NZMNiGrade	Economic 0.9, Background 0.001, Cover 0.1.
Rock and drill sample economic grade Pt	Geochemical measure of extent of high grade mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.	NZMPtGrade	Economic 0.95, Background 0.001, Cover 0.1.
Rock and drill sample economic grade Pd	Geochemical measure of extent of high grade mineralisation with larger zones of economic grades increasing the probability of continuous shoots of high grade mineralisation.	NZMPdGrade	Economic 0.9, Background 0.001, Cover 0.1.

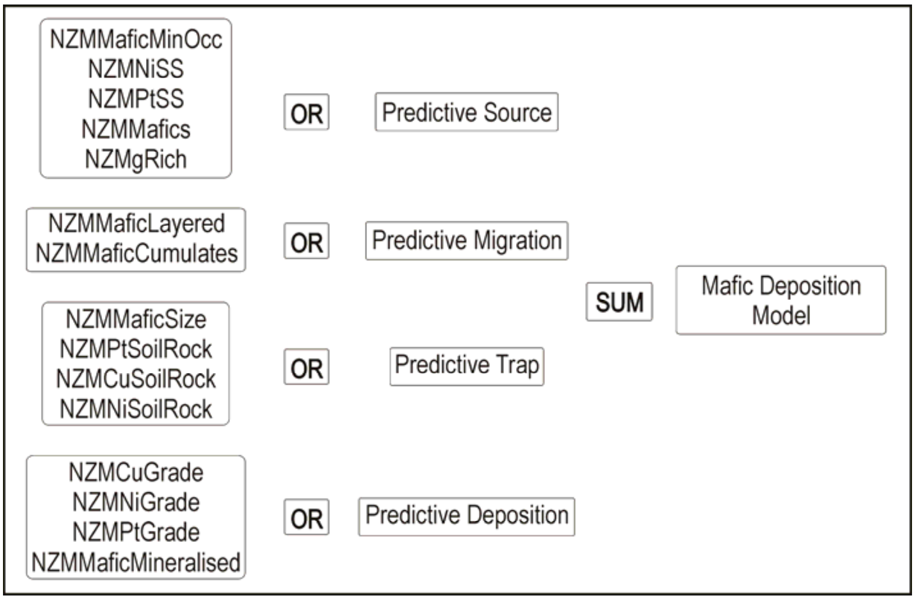

Figure 2. Decision tree for Mafic Ni–Cu–PGE model listing model themes (for codes see Table 2).

Results

After all the themes have been combined using the fuzzy membership functions the resulting map shows the probability of the particular mineral system having been present in the study region (Fig. 3). The two models for mineralisation in Southland have identified the most prospective areas for porphyry Cu–Au and mafic Ni–Cu–PGE mineralisation. The modelling has successfully identified known areas for both types of mineralisation in the Longwood Range, Otama, and the Greenhills area supporting the validity of this model as a predictor for mineralisation in Southland. The results have reduced the search area in Southland down to 3% of the study area for porphyry mineralisation and to 6% for mafic mineralisation. All of these areas at the time of this paper are being actively explored and are covered by prospecting or exploration permits. This study has enabled mineral explorers to target their exploration more effectively, ensure they are using the right exploration tools, and to make more objective management decisions while quickly moving closer toward finding an ore deposit.

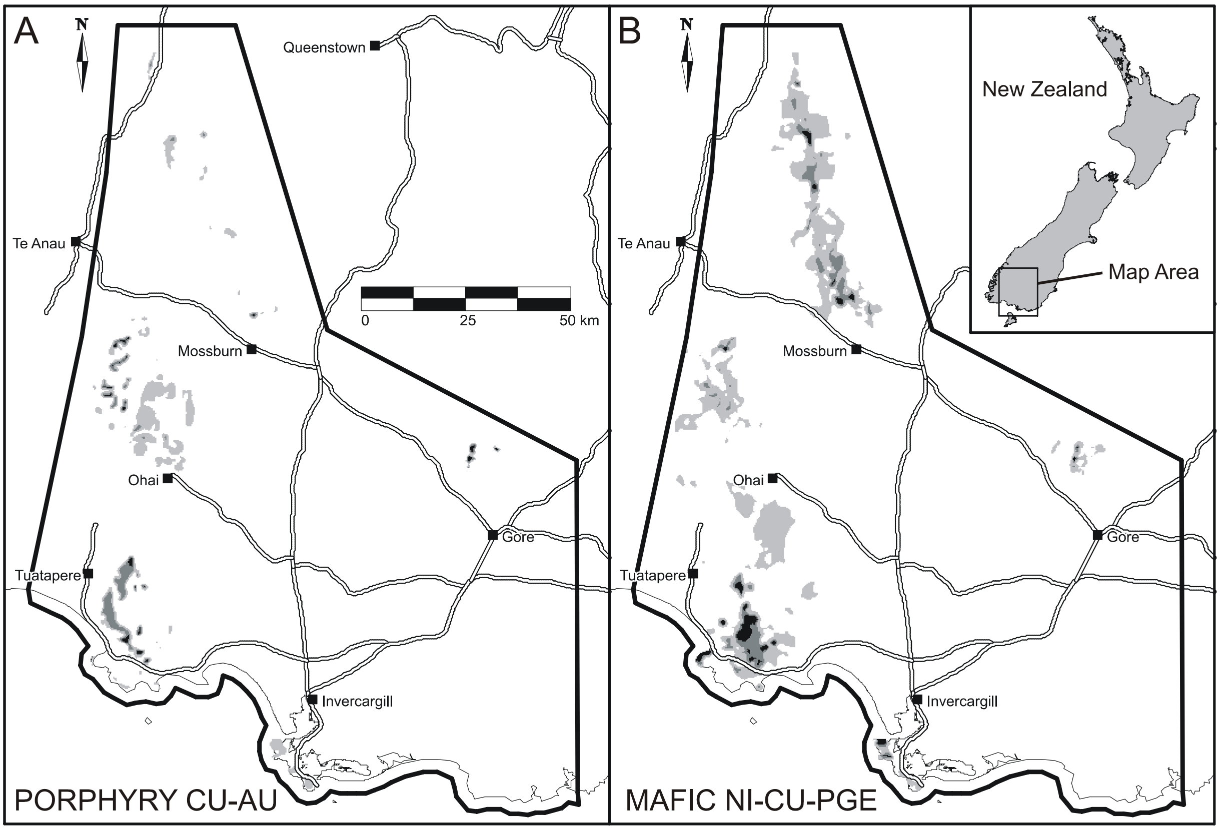

Figure 3. Prospectivity modelling results for the Southland region. A. Map of porphyry Cu–Au mineralisation. B. Map of mafic Ni–Cu–PGE mineralisation. Results shown by filled regions with prospectivity increasing from prospective (light grey regions) to highly prospective (black regions). Study region (bold black line) shown with major roads and place names for reference.

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