EXPLORATION FOR EPITHERMAL AU-AG DEPOSITS IN THE PACIFIC RING OF FIRE: THE ROLE OF GEOCHEMISTRY FROM A NEW ZEALAND PERSPECTIVE

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Introduction

Epithermal deposits form at depths of less than 1.5 km below the water table (mostly 50 to 700 m depth) and at temperatures <300°C (mostly 160-270°C). They are typically associated with subaerial calc-alkaline to alkaline volcanism in volcanic arcs and hence the majority are found around the Pacific Rim along the “Ring of Fire” (Figure 1). Mining of epithermal gold deposits accounts for about 12% of the world’s total gold production and some deposits achieve bonanza grades (e.g. Hishikari, Japan) and very large size (e.g. Ladolam, PNG and Yanacocha, Peru).

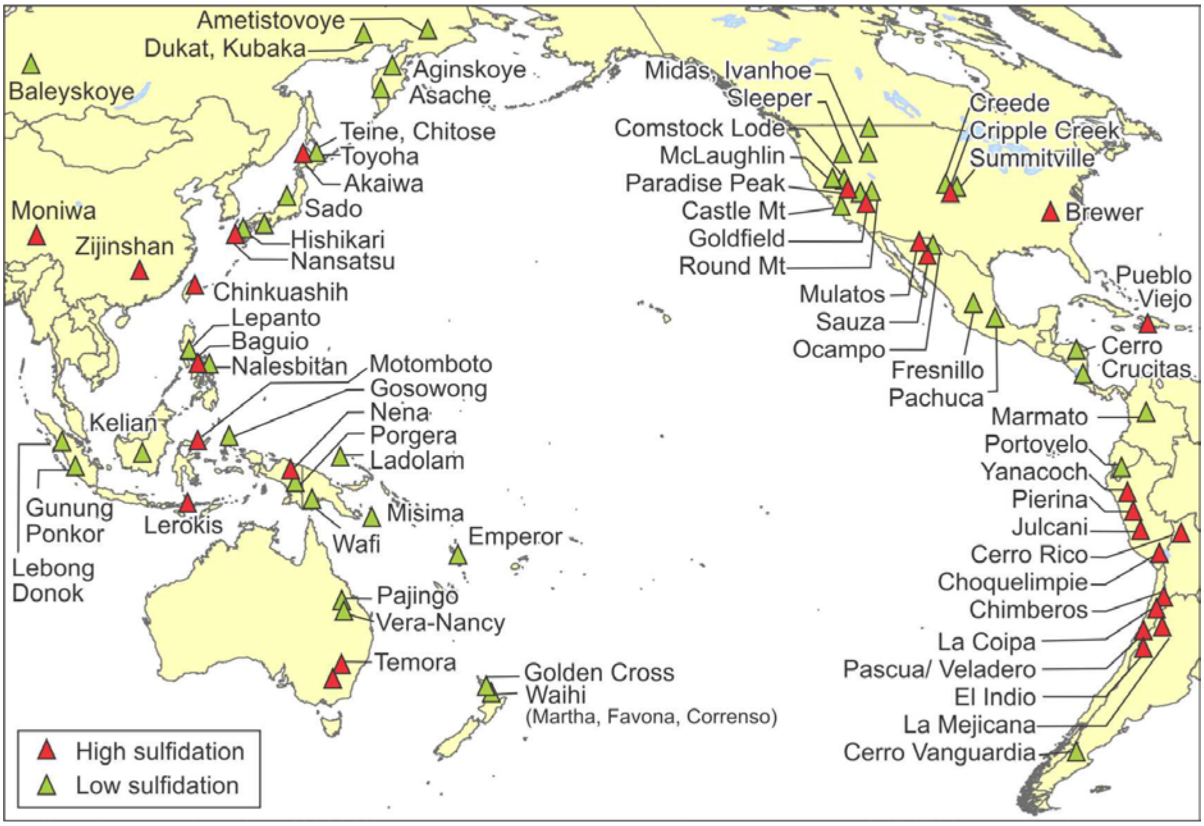

Figure 1. Locations of principal epithermal deposits in the circum Pacific rim (modified after Fig. 6a of Hedenquist et al. 2000).

There are a wide variety of classification schemes for epithermal deposits (e.g. see Table 1 of Simmons et al. 2005) although most recognise two end members: low-sulfidation (LS) deposits formed from near neutral pH, reduced (H_2S

rich) hydrothermal fluids and high sulfidation (HS) deposits formed from acidic hydrothermal systems with a relatively oxidised state of sulphur. Many deposits exhibit features between these two and are grouped in a third category of intermediate sulfidation (IS) deposits. A spatial and genetic relationship to porphyry systems and magmatic intrusions has been suggested, whereby HS deposits occur proximal whereas LS form more distally.

Previous reviews of exploration for epithermal deposits (e.g. Williams 1997; Hedenquist et al. 2000; Simmons et al. 2005) emphasised the need for the explorer to have a good understanding of epithermal deposit characteristics and ore forming processes. This has been aided by the recognition of modern analogues in geothermal systems (e.g. Ohaaki-Broadlands, Waiotapu in New Zealand) for LS deposits, and volcanic systems (e.g. White Island, New Zealand) for HS deposits. Explorers can see epithermal processes in action and experience the size and some components of the systems by visiting these active systems. Research on epithermal and geothermal systems has demonstrated that as a function of the wide range of physical conditions (e.g. T and P) and dynamic processes in the epithermal environment, epithermal deposits may display vertical and lateral zonation in a number of features that can assist exploration. These include hydrothermal alteration minerals and their compositions (particularly clays and chlorite; e.g. Reyes 1990), vein textures (Dong et al. 1995), vein minerals, and paleofluid temperatures and compositions recorded by fluid inclusions and stable isotopes (particularly O and D/H). Another important exploration feature is evidence of boiling (e.g. bladed calcite or quartz textures, and abundance of adularia; Saunders 1994; Etoh et al. 2002), because boiling is an efficient mechanism for gold deposition (Brown 1986). These various features may in turn result in geochemical zonation, typically with Cu, Pb and Zn more abundant at depth and Hg, Sb, and Tl more abundant in the upper parts of the systems.

This paper reviews some exploration techniques for epithermal deposits and describes exploration for epithermal deposits in New Zealand (NZ) where all of the known epithermal Au-Ag deposits are LS types.

Exploration techniques

Desktop data mining, area selection and targeting

Many jurisdictions have legislation that requires companies to submit reports of their exploration and these are made publicly available, possibly following a period of confidentiality. Some geological surveys compile digital databases that they make available online so that an explorer can assess geological and exploration information, and carry out a first pass area selection in the form of a desktop study. Many governments fund the acquisition of new regional geochemical (typically stream sediments) and airborne geophysical (typically magnetics and radiometrics) survey data to provide additional information to raise the apparent prospectivity of their areas, “reduce exploration risk” and attract new exploration investment. The data is assembled and assessed by the explorer in a GIS environment and may also be used in prospectivity assessment software (e.g. weights of evidence and fuzzy logic) to aid in area selection. A mineral systems approach (i.e. assessing metal and fluid source, metal transport and active fluid pathways, physical and chemical deposition drivers, and preservation factors) has been recommended for this type of assessment, but a rigorous application is often not possible because of problems in defining diagnostic parts of the mineral system, such as the source of the mineralising components and/or the parameters of the depositional environment. Nevertheless, even in these cases, the method helps to get the explorer thinking about aspects of the system which may provide insights to help guide exploration.

At a more detailed stage, drillcore libraries can also provide information for desktop prospecting. Drill logs and assay data, photos and in rare instances hyperspectral logs (e.g. Hylogger or CoreScan) may be available online.

NZ examples of desk-top data mining, area selection and targeting

In NZ, company exploration reports are filed with NZ Petroleum & Minerals (NZP&M) and available from their web site. Data from the open file reports have been used to assemble digital databases of geochemical and airborne geophysical survey data (e.g. Crown Minerals, 2009). The exploration geochemical data were incorporated in an epithermal gold data package and prospectivity weights of evidence study by Crown Minerals (2003), which showed the most prospective areas for epithermal deposits based on the data available at that time. Many of the airborne geophysical surveys with publicly available data (Christie et al. 2012), including Government-funded surveys of the Northland region, have radiometric data (in addition to magnetic data) that is useful in mapping geology and hydrothermal alteration (i.e. K-alteration).

Some exploration companies have also carried out extensive data compilations and studies. For example, in 2004 Glass Earth Gold Ltd carried out an extensive study in the Taupo Volcanic Zone (TVZ). They compiled previous exploration and research data in a 3D database for 3D interpretation of the TVZ geology and structure and to determine data gaps to plan follow-up reconnaissance exploration (Henderson et al. 2005). In 2005, the company flew airborne geophysical surveys (magnetics, radiometrics and gravity) over a large part of the TVZ and using the resulting data in their expanded 3D database, they identified 22 targets for follow-up ground exploration. Their GIS analysis of the data included weights of evidence GIS prospectivity analysis, a technique that enables large quantities of exploration and research data to be integrated, prioritised and viewed as a single prospectivity map (Bonham-Carter et al. 1989). The targets were mostly coincident negative magnetic anomalies and positive gravity anomalies, in addition to encouraging geochemistry (Henderson et al. 2006). Payne et al. (2014) also carried out a weights of evidence prospectivity assessment of the TVZ, using geochemistry as one of their eight themes to rank prospectivity. Subsequently, they conducted a 3D weights of evidence prospectivity analysis of the Ohakuri prospect using Au grade shells along with five other criteria to rank volumes of prospectivity.

Ground-based exploration

Prospecting for the epithermal quartz veins in the late 19th and early to mid-20th centuries was by traditional methods of panning and examination of float and outcrops. The veins were tested by trenching and underground workings excavated with hand tools and explosives. Drilling was rarely used except in the larger prospects and mines.

Even in today's age of computerised exploration, prospecting and field mapping of outcrops are still important techniques in characterising the style and footprint of mineralisation, e. g. mapping the geological setting (e.g. providing guides to primary permeability and rheological properties for hosting veins), structure (an important host control), hydrothermal alteration, and features such as veins, hydrothermal breccias, silica blankets and sinters (c.f. Cerro Negro in Shatwell et al. 2011). For example, vein textures may provide information on paleodepth and boiling (e.g. bladed quartz or calcite), breccia textures can help interpret multiphase events, and vuggy silica textures can be a diagnostic feature of HS systems. Aerial photography, Lidar and hyperspectral mapping surveys can assist the ground mapping of structure and hydrothermal alteration, especially in arid climates where there is little vegetation. Many epithermal deposits have an elevated topographic expression because the quartz vein and siliceous alteration are resistive to erosion. The application of pXRF and semi-portable infrared spectrometers to analysing field samples, as well as drill hole samples, has greatly assisted mapping of hydrothermal alteration through mineralogy and geochemistry (e.g. Halley 2014; Halley et al. 2015). Portable XRD instruments are also now available and will be useful for quickly determining hydrothermal alteration mineralogy.

Regional geochemical surveys have been one of the major discovery techniques for epithermal deposits from the 1960s (e.g. Batu Hijau, Gosowong and Gunung Pongko in Indonesia, Mt Bini in PNG, and Yanacocha in Peru) (c.f. Sillitoe 1995; 2010). Float inspection and sampling has also helped discover some deposits (e.g. Tolukuma, Chatree, Wafi, Miwah). Many systems have free gold, and thus some deposits have been discovered by traditional panning for gold (e.g. Porgera, Tavatu, Kelian and Emperor). Regional-scale geochemical surveys typically use stream sediment geochemistry: conventional (-80 mesh), or low sample density bulk cyanide leach (BLEG). Panned concentrate geochemical surveys are also sometimes used.

As follow-up, or for smaller areas, conventional stream sediment surveys and rock chip surveys are common. Follow-up exploration is commonly by grid-based soil surveys (and geophysical surveys such as magnetic, IP, resistivity and CSAMT). In rugged terrain where grids would be impractical, ridge and spur soil sampling is commonly used.

Trenching is used in target areas with some cover to enable rock-chip or channel sampling of the bedrock. Once the sources of anomalies have been located, drilling is used to test the targets at depth.

Halley (2014) noted that geochemical analyses of exploration samples have undergone a major evolution over the last 40 years from AAS to INAA to ICP-AES to ICP-MS, with decreasing detection limits and availability of a larger number of elements for similar cost. In the 1960s and 1970s, typically only a few elements were analysed (e.g. Ag, As, Cu, Pb, Zn). Gold and Ag had high limits of detection relative to analyses today and therefore, if analysed for Au and Ag, a high percentage of samples returned assays below the limits of detection. Commercial laboratories now offer packages of 30 or more elements for their ICP-MS analyses. However, fire assay is still a popular method of Au analysis and unfortunately some drill programmes will assay only for Au and Ag, and maybe a few selected other elements. Halley (2014) recommended routinely using a 4 acid digest and ICP-MS/AES analyses of a large suite of elements in exploration samples to provide data for interpreting geology and hydrothermal alteration, as well as metal assays.

Whole rock geochemistry and mineral chemistry (e. g. chlorite, adularia and pyrite) in samples (usually drill core) may be used to identify the zonation of hydrothermal alteration and vector toward higher grade alteration, and hopefully Au mineralisation (Gemmel 2006). Alteration indices such as the Alteration Index (AI; Ishikawa et al. 1976) and chlorite-carbonate-pyrite index (CCPI; Large et al. 2001) using major element geochemistry (e.g. K_2O, Na_2O, MgO, S and LOI) typically increase toward mineralisation. Similarly, a study by Booden et al. (2011) at Waitekaui in the Hauraki Goldfield, NZ, suggested that K/Sr, Rb/Sr, and M K/(K+Na+2Ca), and K/Al vector toward adularia rich rocks. Chlorite chemistry changes from Fe-chlorite to Mg-Fe chlorite to Mg chlorite with increasing hydrothermal alteration grade in some deposits (note that this property may also be determined by infrared analyses). Adularia shows an increase in Ba, Pb and to a lesser extent Cs, and pyrite shows an increase in Pb, Bi and Mo, towards mineralisation (Gemmel 2006). Logging of the occurrence of adularia and its abundance in drill core is aided by staining for potassium.

New Zealand examples of ground-based exploration

In the Hauraki Goldfield (including the Coromandel Peninsula) (Figure 2), stream sediment geochemical surveys were first used in the 1960s and since then they have been the major reconnaissance prospecting technique used on a routine basis, together with selected application of rock and soil geochemistry methods. Most stream sediment sampling programmes used conventional sampling techniques and analysed the -80 mesh fraction, however in the 1980s, many companies began using panned concentrate and BLEG techniques.

Detailed exploration has used close spaced rock and soil geochemical sampling, and geophysical surveys (e.g. ground magnetic, IP, resistivity, and CSAMT surveys; and helicopter borne EM) generally on a grid pattern, to outline drill targets. Trials have been carried out using biogeochemical surveys (e.g. Dunn & Christie 2014) and soil gas surveys (e.g. Christenson et al. 1988), but these have not been adopted in routine exploration.

Diamond drillhole (DDH) drilling has been the most common drilling type, usually employing the wireline technique, although reverse circulation (RC) drilling has been used on some prospects.

A phase of intensive mineral prospecting began in the Hauraki Goldfield in 1976 with Amoco's (subsequently Cyprus Minerals and Cyprus Gold) reconnaissance survey of the goldfield. Airborne geophysical surveys were conducted followed by stream sediment and rock chip geochemical surveys. Other companies including Amax, Austpac, ACM, ANZECO, Barrack, BP, BHP, Freeport, Gold Mines of New Zealand (GMNZ), Heritage, Homestake, Mineral Resources, Newmont Waihi Gold, NZ Goldfields, Otter, and Renison Goldfields Consolidated (RGC), also carried out reconnaissance and/or detailed prospecting programmes.

Most of the old mining centres and new targets defined by reconnaissance prospecting were investigated with detailed exploration programmes, resulting in the definition of new Au-Ag resources in previously mined deposits at Monowai, Karangahake (Talisman), and Waihi (Martha), and discovery of previously unknown vein systems during brownfields exploration at Golden Cross (Empire stockwork-discovered in 1981 and deep Empire vein system-1982) and Waihi (Favona-2001, Trio-2003 and Correnso-2009).

There are large areas of unexplored ground in the Hauraki Goldfield for prospecting under cover, but little greenfields exploration has been done to date in these areas, although brownfields discoveries have been made under cover at Waihi (Favona and Correnso).

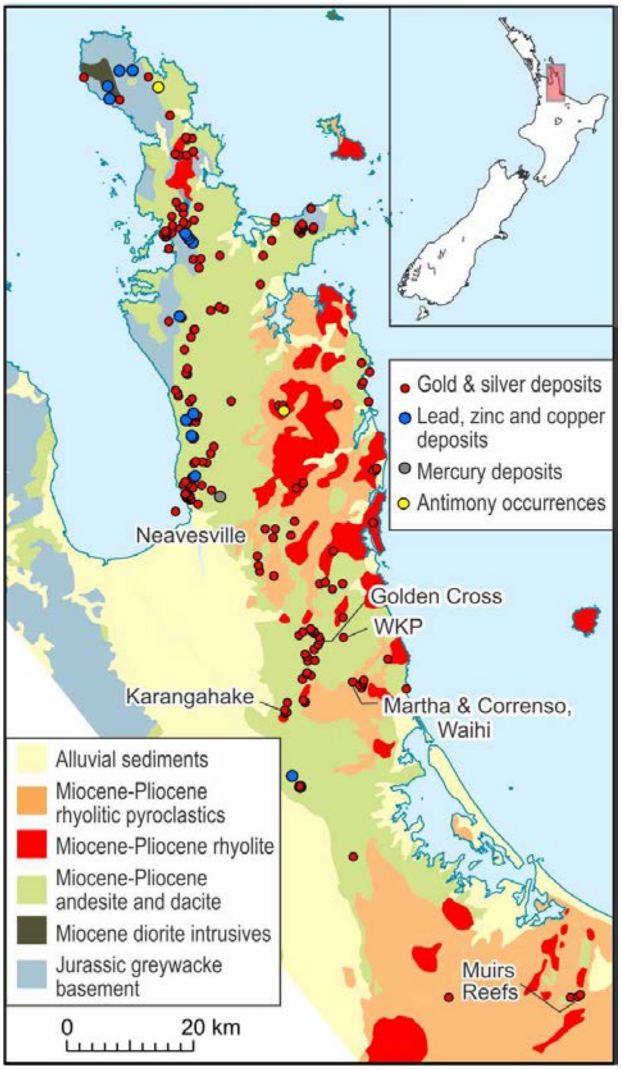

Figure 2. Geology and location of Au-Ag mines and prospects in the Coromandel Volcanic Zone – Hauraki Goldfield (note that Muirs prospect is located south of the map area)

The TVZ (Figure 3) was prospected from the 1970s, and most reconnaissance ground exploration was carried out in the early 1980s by AMOCO, Newmont and ANZECO, followed by ACM, Amax, BP, Foxwell Mining, Max Resources, and Mintago Investments. This identified a number of epithermal Au-Ag prospects based on the presence of epithermal mineralisation features (e.g. sinters, silicified hydrothermal breccias, quartz veins, and quartz-adularia altered rocks), and/or geochemical and geophysical anomalies. The work included geological mapping, geochemical surveys, ground magnetic surveys, regional aeromagnetic surveys (BP and ACM), and IP/resistivity surveys. Early reconnaissance geochemical surveys showed that the widespread presence of volcanic ash and other cover rocks, particularly Taupo Pumice, limited the usefulness of conventional stream sediment samples, and therefore most subsequent stream sediment sampling utilised panning (with visual determination of gold "colours"), panned concentrate sampling with chemical analysis of the concentrate, or BLEG geochemistry. Also, because of limited erosion and exposure of the epithermal systems, there has been considerable emphasis on geophysical prospecting in the TVZ.

The main prospects followed up by detailed exploration and drilling include Forest Road, the Matahana Basin - Horohoro area, Ohakuri, Thomsons, Tikorangi, Umukuri and Wharepapa (Barker & Christie 2013), as well as a lesser prospect at Puhipuhi, west of Kawerau. Three prospects were identified at Ohakuri: Ohakuri North, East and West. At Ohakuri North, more than 40 holes were drilled returning a best grade of 4.05 g/t Au over 5.5 m (DDH OH8) and a gold resource estimate of more than 7 Moz Au at a cut-off grade of 0.1 g/t (Hamilton & Soengkono 2009). Most of the resource is sub-economic with a grade of <0.2 g/t Au.

The 22 targets identified by Glass Earth Gold following their 2005 airborne geophysical surveys were followed up with ground mapping, geochemical sampling, CSAMT resistivity surveys, ESCAN 3D resistivity surveys, and drilling at Thomsons and the principal prospect Tahunaatara (Henderson et al. 2006).

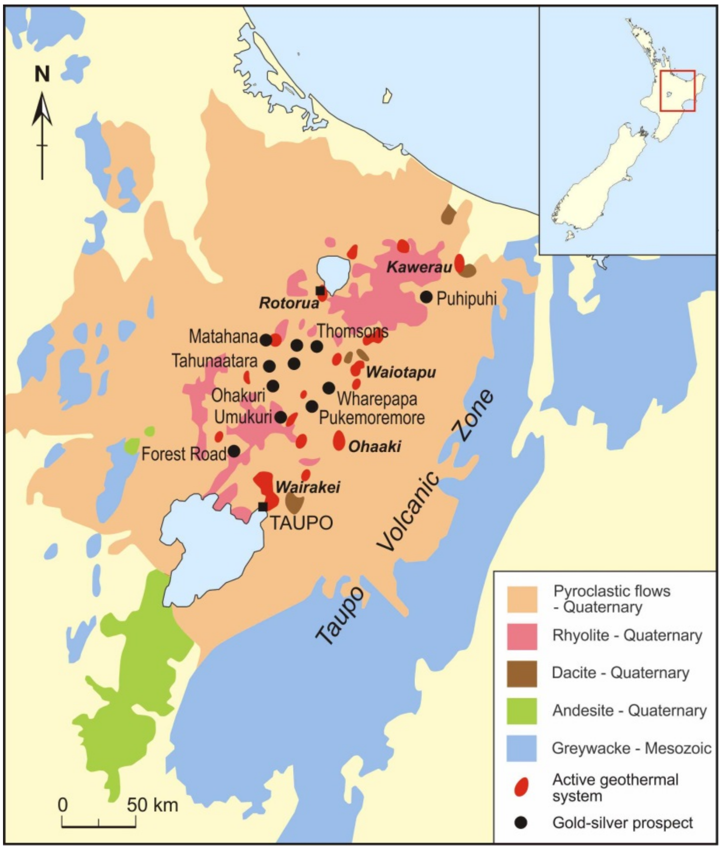

Figure 3. Geology, and location of Au-Ag prospects and geothermal fields in the Taupo Volcanic Zone.

In Northland (Figure 4), reconnaissance exploration programmes were carried out in the 1980s and 1990s by several companies. These included panning, stream sediment and panned concentrate surveys, and rock chip sampling. In addition to the previously known Puhipuhi prospect, several new prospects were identified by geochemical anomalies and mapping of hydrothermal alteration and epithermal mineralisation features, particularly hydrothermal eruption breccias. Soil geochemical surveys were undertaken at several prospects. Follow up drilling at Huia (including Aurora's Backyard prospect), Te Pene and Puketotara intersected generally low values of Au and Ag. However, at Puhipuhi, drilling by Homestake intersected veins and hydrothermal breccias with best values of 5.3 g/t Au and 18.5 g/t Ag over 10 m. In 2011, the Government funded an airborne magnetic and radiometric survey of the entire Northland region and this data is publicly available and was described and interpreted by Stagpoole et al. (2012).

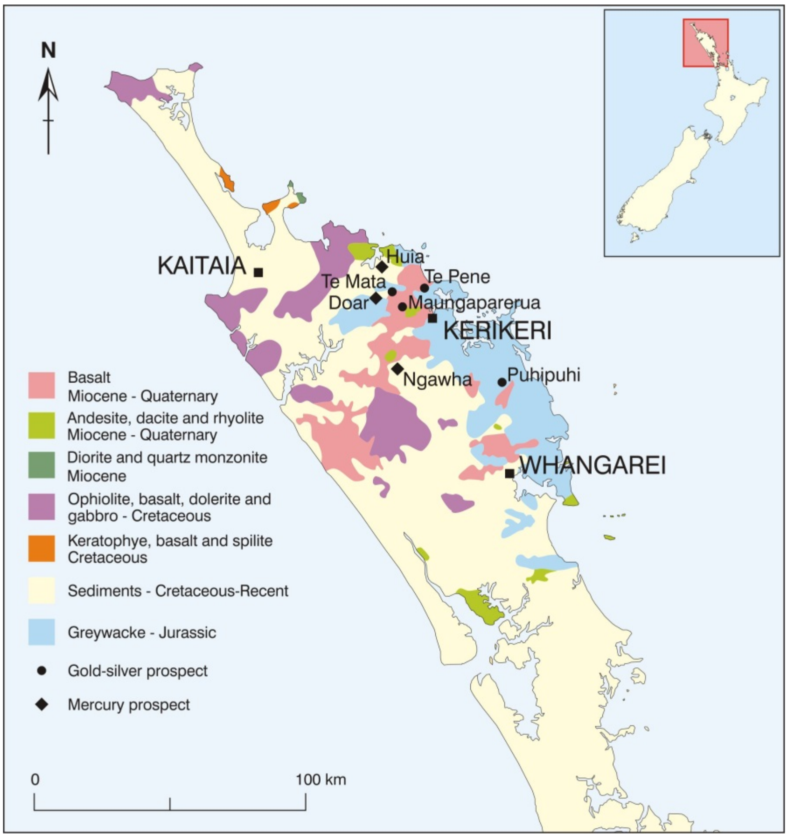

Figure 4. Geology, and location of Au-Ag prospects Northland.

Discussion and Conclusions

Legacy geochemical exploration data are an important component in desk-top area and target selection using GIS analyses and GIS prospectivity studies. On the ground, geochemical surveys continue to be a major exploration technique for epithermal Au-Ag deposits. Reconnaissance exploration typically begins with stream sediment surveys along with rock chip sampling of interesting stream float and outcrops. Airborne radiometric and hyperspectral surveys can provide useful data for mapping hydrothermal alteration, particularly in areas with little vegetation.

Detailed exploration typically involves soil and rock chip geochemical surveys to identify drill targets. Portable XRF and infrared (e.g. Terraspec) analysers are increasingly being used and help identify and map hydrothermal alteration. They are particularly useful in logging drill core or analysing drill chips and powders. Portable XRD instruments are becoming available and will also assist in these applications. Hyperspectral core loggers such as Hylogger and Corescan will see increasing application as costs are reduced. More sophisticated interpretation of geochemical data such as the use of alteration indices can provide information to help vector toward mineralisation, especially if used in association with other techniques such as infrared analyses.

In NZ, exploration since the late 1970s has revived gold production in the Hauraki Goldfield with new discoveries and mining at Waihi and Golden Cross and advanced prospects at Karangahake (Talisman), WKP, Neavesville and Muirs. However, greenfields exploration has so far not resulted in any new significant discoveries away from former pre-1950s mining areas. In contrast, exploration in the TVZ and Northland, particularly in the 1980s, has successfully identified many new epithermal prospects and large low grade resources have been defined at Ohakuri. However, identifying former fluid upflow zones has proven challenging because of the generally shallow depths of erosion of the deposits in these regions.

Research on epithermal processes in active geothermal systems of the TVZ, and the ability of local exploration staff to visit and readily see surficial features of these geothermal systems has encouraged them to seek a better understanding of the former hydrothermal systems in their exploration prospects. This led to the early application in NZ exploration of petrological and XRD studies of the mineralogy of hydrothermally altered rocks and fluid inclusion studies of veins to help define areas of fluid upflow and Au deposition. Infrared and pXRF analyses have also been recently used to identify hydrothermal alteration trends and vector toward mineralisation. The recent availability of high resolution airborne geophysical survey data over most of the prospective regions will encourage more use of geophysical data (including radiometric data) in future targeting, but geochemistry will continue to be a fundamental tool in exploration in NZ.

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