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Geophysical signatures of copper-gold porphyry and epithermal gold deposits

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ABSTRACT

Geophysical data are presented for a number of deposits including the Batu Hijau, Elang, Grasberg, and Alumbrera porphyry deposits, the Martabe and Yanacocha high sulphidation epithermal deposits, and the Pajingo and Waihi low sulphidation epithermal deposits. The physical properties of the mineralisation and alteration are discussed with an emphasis on those properties that can be measured with common exploration techniques.

Mineralisation in porphyry Cu-Au deposits is commonly associated with magnetite that can produce strong discrete magnetic anomalies. This is usually within a zone of magnetite-destructive alteration that can be identified with a high resolution magnetic survey. Magnetic surveys are also useful in defining regional structure and geology. Strong chargeabilities due to sulphides are typically associated with porphyry systems. Mineralisation and clay-pyrite alteration can produce strong anomalies and late stage and post mineral intrusions can be mapped as chargeability lows within the system. These systems may be more conductive than the host rocks because of clay-pyrite alteration and sulphide veining, and airborne EM can be useful in locating and defining their extent. Gravity, radiometrics, remote sensing and topography may also be useful in exploration for porphyry Cu-Au deposits.

In high sulphidation epithermal systems gold is often associated with massive silica alteration. This alteration results in resistivities in the order of thousands of ohm-meters compared with background resistivities of tens of ohm-meters in argillic and prophylitic alteration. Both ground resistivity and airborne EM surveys have been successful in locating and defining these deposits. Alteration in high sulphidation epithermal deposits is magnetite destructive over a large area although it does not appear to have a large vertical extent as the subdued character of the underlying lithologies can be observed.

Typically, gold in low sulphidation epithermal deposits is in thin quartz veins that are associated with major structures. The alteration associated with the veins is magnetite destructive and high resolution magnetics can be a very useful and cost-effective technique to map the structures and alteration. Some deposits are associated with broad zones of magnetite destruction which is apparent in the regional magnetics. The mineralised quartz veins are within broader zones of silicification and resistivity surveying can be used to map these zones. Generally the high resistivity zones due to silicification are coincident with the structures identified in the magnetics.

High resolution magnetics and electrical surveys are the most useful geophysical techniques in exploration for porphyry and epithermal deposits. Airborne magnetic and EM surveys are fast and cost effective particularly in areas of rugged topography. Regional magnetics, gravity, remote sensed data and topographic data can also be used to identify major structures, intrusive complexes and alteration. Radiometric surveys can be used to map geology and alteration.

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INTRODUCTION

Geophysical data from a number of porphyry and epithermal deposits has been evaluated to determine the physical characteristics of the mineralisation and associated alteration. This paper presents the results of work on a number of deposits, including the Batu Hijau, Elang, Grasberg and Alumbrera porphyry deposits, the Martabe and Yanacocha high sulphidation epithermal deposits, and the Pajingo and Waihi low sulphidation epithermal deposits. Most of these deposits are located in the western Pacific (Fig. 1) with the exception of Alumbrera in northwest Argentina and Yanacocha in northern Peru.

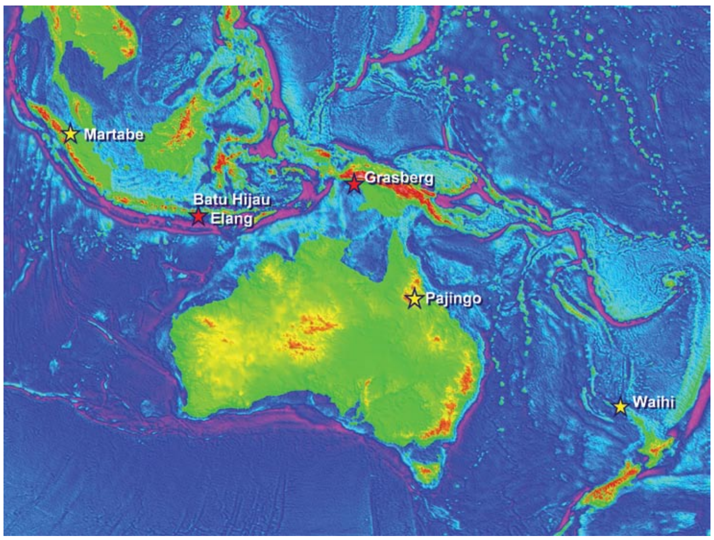

Figure 1. Location of the western Pacific deposits discussed in this paper.

PORPHYRY CU-AU DEPOSITS

Batu Hijau

Batu Hijau is a large porphyry gold copper deposit situated on Sumbawa Island in Indonesia. It has reserves of about 900 Mt at 0.53% Cu and 0.4 g/t Au.

Mineralisation is associated with a tonalite intrusive complex within diorite and andesitic volcanics. Alteration is potassic in the core, with magnetite and secondary biotite, and grades out to propylitic alteration. Both are overprinted by intermediate argillic and minor phyllic alteration. Chalcopyrite and bornite are coincident with the potassic zone within and adjacent to the tonalite stock (Maula and Levet, 1996)

A helicopter magnetic survey flown by Newmont in 1993 defined a large discrete magnetic anomaly associated with the potassic alteration zone which is characterised by biotite-magnetite-quartz alteration (Fig. 2). Sections through the deposit showing gold and copper grade and magnetic susceptibility

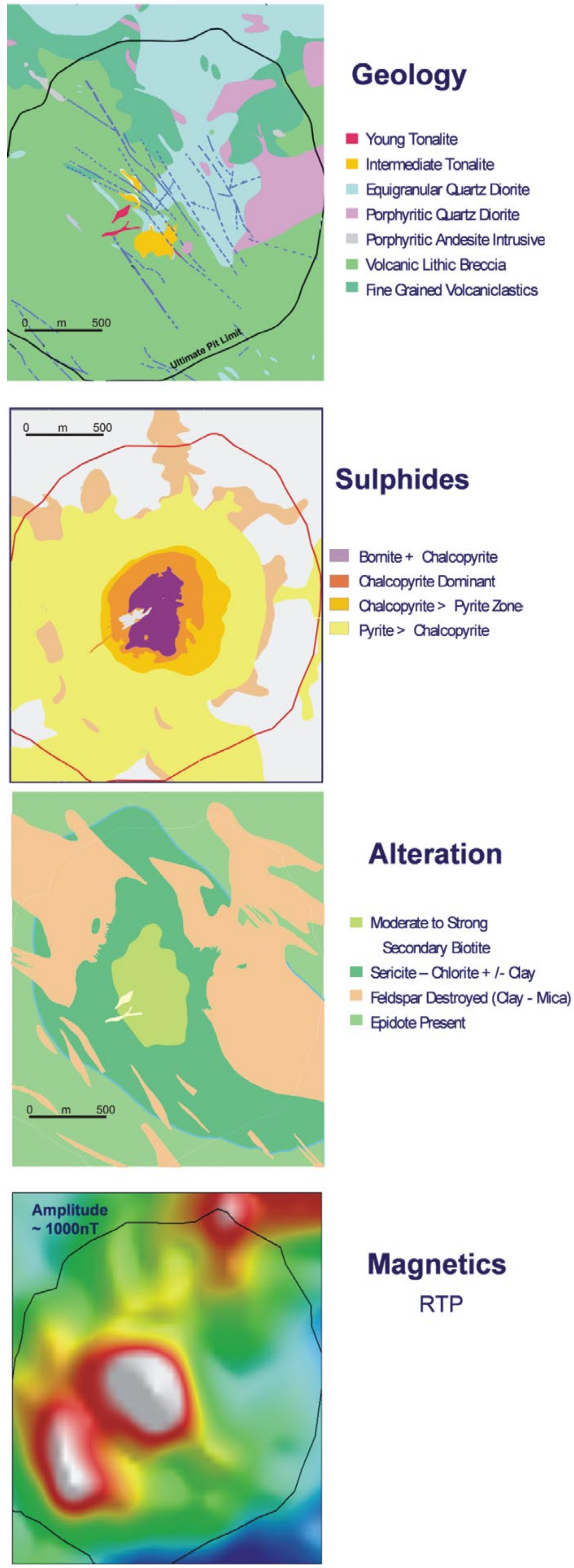

Figure 2 (right). Batu Hijau geology, sulphide content, alteration, and RTP magnetics.

demonstrate the clear relationship of mineralisation to magnetite (Fig. 3). The anomaly can be modelled using a vertical pipe-like body with a susceptibility of 0.006 cgs (the model is shown in Figure 3). A number of samples were selected for magnetic-property measurements and results indicate that the contribution of magnetic remanence is minor. This is because the main magnetic carrier is multi-domain magnetite with Kouningsberger ratios that are less than one. Palaeomagnetic measurements indicate that both polarities of remanence are recorded by the Batu Hijau system and this may lead to partial cancellation of normal and reverse components of remanence over large volumes of rock.

Induced Polarisation (IP) surveys were conducted over Batu Hijau in 1992 and 1995 and described by Wiles (1995). Three lines of 200m dipole-dipole IP, two lines of 300m dipole-dipole and a block of gradient array were surveyed over the deposit. The gradient array covered an area of 2km by 2km with 3km between transmitter electrodes and a 50m potential electrode spacing. The line spacing was 200m.

The gradient array chargeability clearly shows an anomaly greater than 60 milliseconds over the deposit which corresponds to the economic chalcopyrite bornite zone (Fig. 4). A chargeability annulus around the deposit is thought to represent a pyrite halo (Ferneyhough, 1998). Conductive zones in the resistivity correlate with overprinted argillic alteration.

All of the dipole-dipole and gradient array data were inverted using 3D algorithm by Geotomo Software. Chargeabilities and resistivities are not well defined away from the dipole-dipole lines at depth due to the lack of data. The 300m dipole-dipole lines are lacking resolution to define the chalcopyrite-bornite zone at depth as shown in an east-west section through the deposit (Fig. 4). The concentration of chalcopyrite and pyrite along this section is shown in Figure 4 and there is a good correlation with the gradient array chargeability.

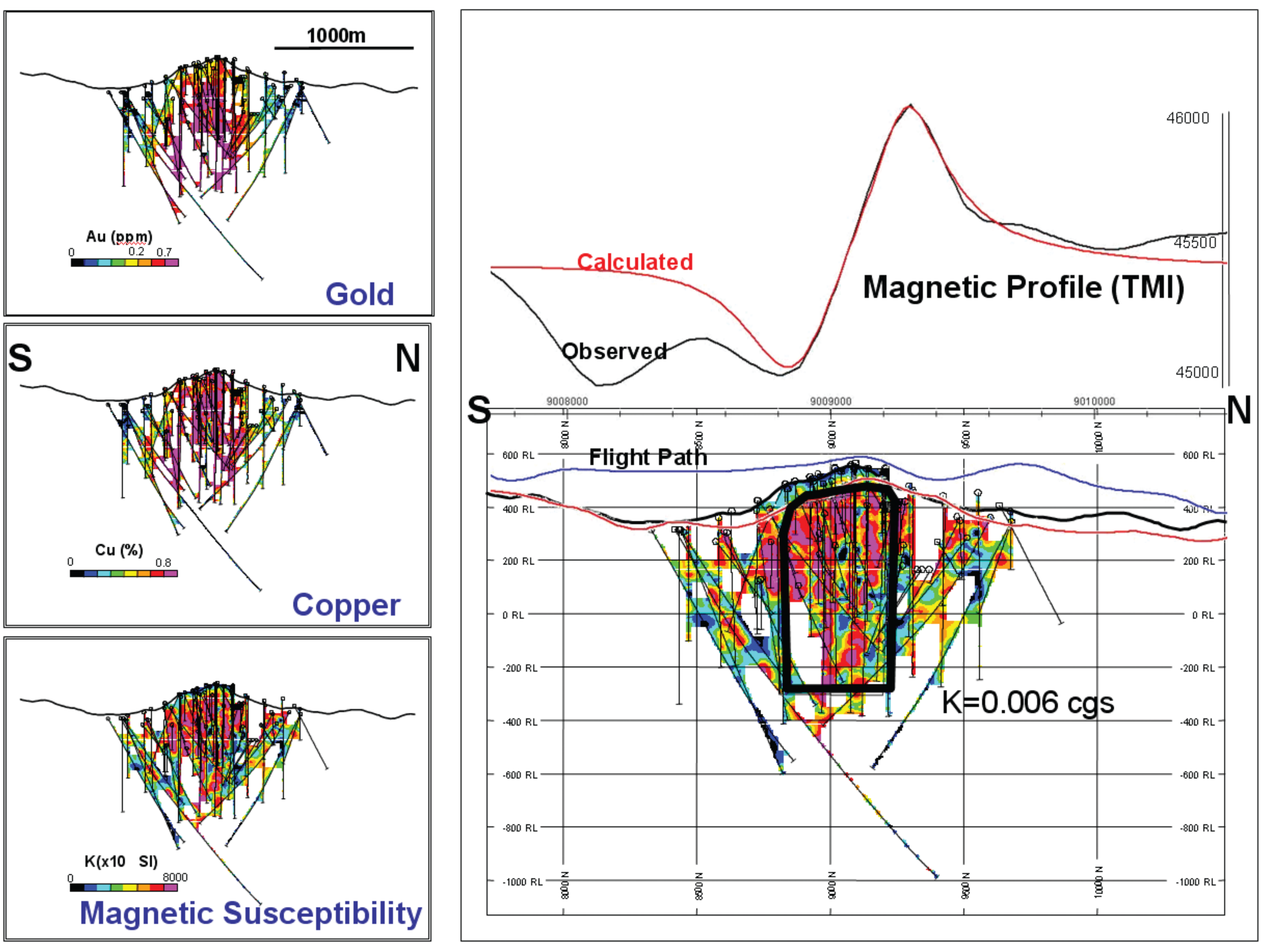

Figure 3. North-south section through Batu Hijau showing the relationship of gold and copper with magnetic susceptibility measured on drill core and the observed and calculated magnetic response of the deposit.

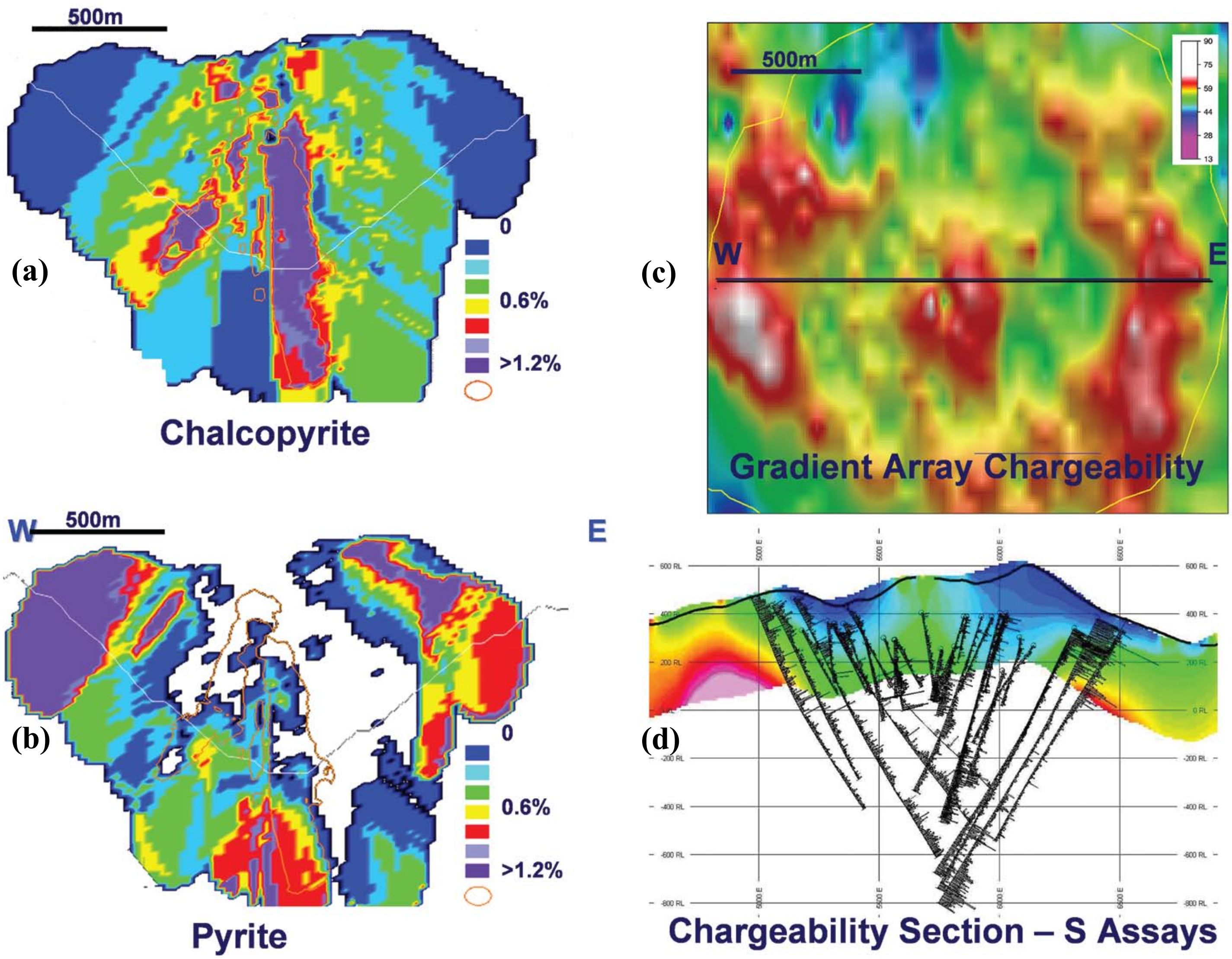

Figure 4. (a) Chalcopyrite and (b) pyrite concentrations on an east-west section through Batu Hijau (Arif, 2002). (c) Location of the section on the gradient array chargeability. (d) Chargeability section from a 3D inversion model of the gradient array and dipole-dipole IP with the drill-hole sulphur results.

Elang

Elang is a large porphyry Au-Cu deposit situated about 70 km east of Batu Hijau on Sumbawa Island, Indonesia. The deposit is associated with a series of tonalite porphyries that intrude andesitic volcanics. Mineralisation is associated with potassic alteration (chlorite-magnetite±biotite) which grades outward to propylitic alteration. This system is overprinted by intermediate argillic alteration and there is an advanced argillic lithocap, up to 200 m thick, covering much of the deposit.

The area was covered with a helicopter magnetic and radiometric survey in 1993 and Elang shows up as a discrete magnetic high of about 700nT. The anomaly is due to magnetite alteration in the potassic zone and can be modelled with two magnetic bodies. The magnetics and the outlines of the magnetic models are shown in Figure 5. The southern body is under the leached cap, about 200m below surface.

Three pole-dipole IP/resistivity surveys were conducted in the Elang Area with a potential electrode spacing of 100m and line spacing's of 100m and 200m. A 3D inversion was applied to the lines covering Elang. Figure 5 shows plans of chargeability and resistivity at 200m depth below topography. The resistivity clearly shows the extent of the alteration system with the porphyry alteration being relatively conductive at 10s of ohm-metres in a background of fresh volcanics in the 100s of ohm-metres. The highly resistive lithocap of 1000s of ohm-metres is well defined and is above the 200m depth slice shown in Figure 5. Very strong chargeabilities are associated with the porphyry alteration. A late dacite intrusion stands out as an area of low chargeability and some of the more subtle lows may be due to late intrusive phases of the porphyry that are less mineralised.

An airborne time domain electromagnetic survey (HoisTEM) of about 600 line kms was flown over Elang in 2004. The Elang alteration system clearly shows up as a conductive zone in a relatively resistive background. The

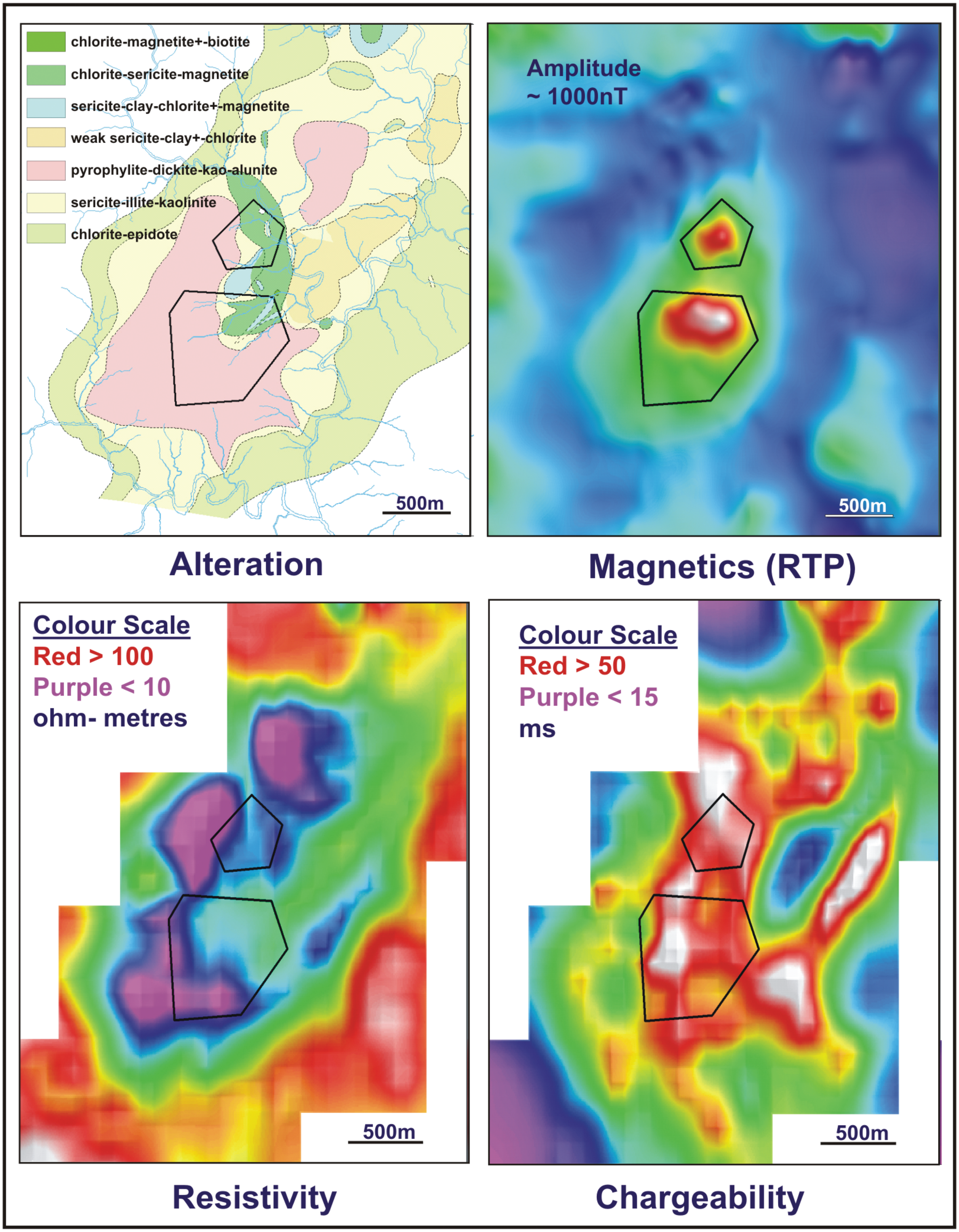

Figure 5. Elang porphyry showing a plan of alteration, RTP magnetics, 200 m depth slice of resistivity, and 200 m depth slice of chargeability. The polygons in black show the surface projection of the interpreted magnetic bodies.

lithocap is highly resistive and is clearly defined within the conductive zone by the HoisTEM.

Grasberg

Grasberg, situated in Irian Jaya, is the world's largest gold copper porphyry deposit. Including associated skarn mineralisation it has total proven and probable reserves of 2475 Mt of 1.06 g/t Au and 1.13% Cu (Coutts et al., 1999). The Grasberg intrusive complex is emplaced into a thick sequence of Tertiary carbonate sediments. Mineralisation is associated with the Grasberg and Kali intrusions which were emplaced within the Dalam Diatreme. The Dalam Diatreme is a funnel shaped structure composed of diorite, intrusive andesite breccias, and volcanics (Fig. 6). This is intruded by trachyandesites and quartz monzodiorites of the Grasberg and Kali intrusives (Cooke, 1996).

The orebody is about 600m in diameter and has a vertical extent of more than a kilometre. It coincides with a quartz stockwork zone containing more than 7% magnetite. This produces a strong magnetic anomaly of over 2000nT from helicopter magnetic surveys. The survey covering Grasberg and to the north was flown east-west with a 200m line spacing and the surveys immediately to the south were flown north-south with 100m and 200m line spacings. The Total Magnetic Intensity (TMI), topography and terrain clearance were gridded and a north-south profile was extracted for modelling. This profile and the model are shown in Figure 7.

Grasberg can be magnetically modelled using a vertical pipe-like body with a magnetic susceptibility of 0.015cgs and a minor component of steep remanence. A large magnetic body at depth helps to match the observed magnetic field. This is interpreted by Kavalieris (1999, personal communication) to be the Ertzberg Intrusion. The steep direction of remanence is difficult to explain as the magnetic field at the time of emplacement would be similar to the present field which has an inclination of about 25° from horizontal. A number of samples were selected for magnetic-property measurements and results show both normal and reverse components with Kouningsberger ratios generally less than one. It is possible that the normal and reverse components are not exactly opposite, producing a steep resultant.

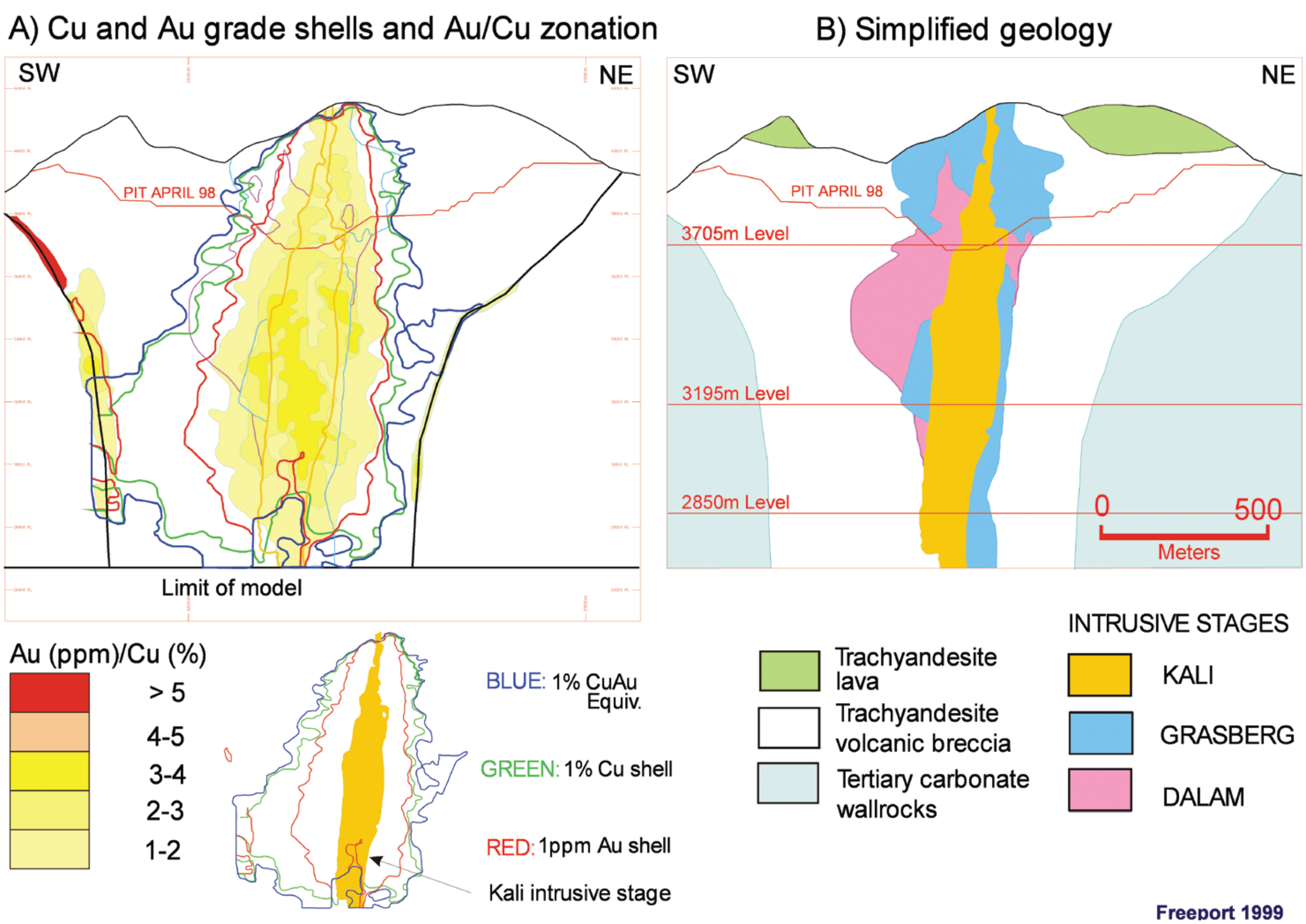

Figure 6. Grasberg Cu and Au grade shells with geology.

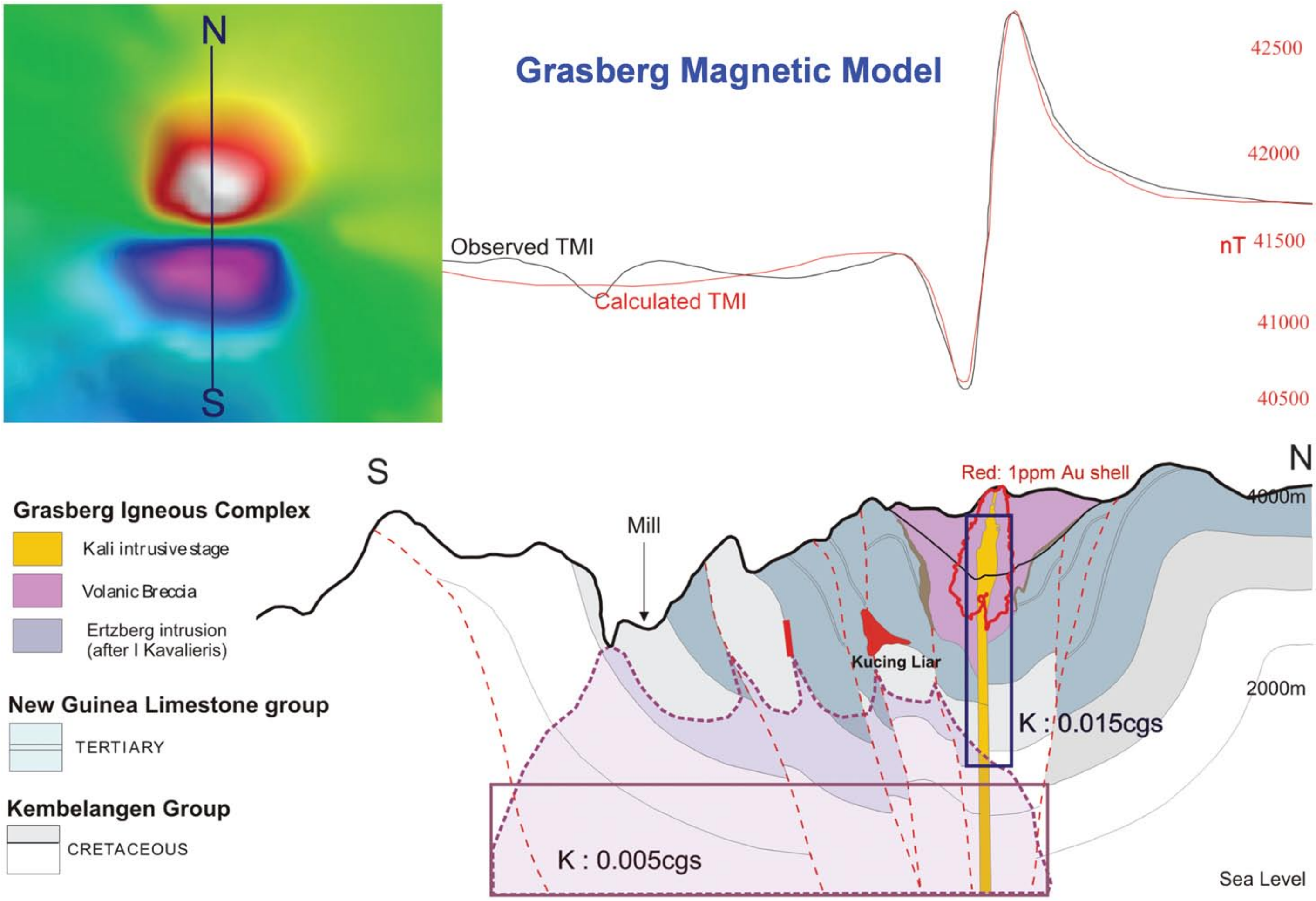

Figure 7. North-south section through Grasberg showing interpreted geology and the magnetic model with observed and calculated TMI.

There were no electrical survey data available at Grasberg and samples were sent to Systems Exploration in Sydney for conductivity tests. Results show conductivities generally in the 100s of ohm metres although some of the samples are very conductive at less than 10 ohm metres. These samples have chalcopyrite veining which is extensive in the deposit and high grade mineralisation would probably be conductive.

Alumbrera

Alumbrera is a large gold copper porphyry deposit in northwest Argentina. It is a gold-rich deposit with a total resource of 402 Mt of 0.64 g/t Au and 0.54% Cu. The deposit is Late Miocene in age and is hosted by high potassium calc-alkaline andesites of the Farallon Negro volcanic complex (Guilbert, 1995). The ore is centred on a series of closely spaced dacitic porphyry intrusions and extends into the surrounding andesitic rocks.

Alumbrera exhibits a symmetrical pattern of alteration and mineralisation. (Stults, 1985; Guilbert, 1995; Proffett, 1997). Early K-feldspar-magnetite-quartz alteration and secondary biotite and K-feldspar (±magnetite) are closely associated with the central porphyry stocks. This zone contains most of the copper and gold mineralisation. It is surrounded with biotite-altered andesite of about 1km by 1.7km in size which in turn is surrounded by an outer zone of epidote-chlorite alteration. Later phyllic alteration which contains pyrite surrounds the central potassic zone and copper mineralisation. Plans of geology and alteration are shown in Figure 8.

A combined helicopter-borne magnetic, radiometric, and electromagnetic (EM) survey was flown over the deposit by Aerodat in 1996 with north-south lines spaced 100m apart and a terrain clearance of about 100m. The concentric alteration patterns are clearly evident in the magnetic survey results, with the central potassic zone being highly magnetic and producing an anomaly of 2000nT. This can be modelled using a vertical pipe-like body with a magnetic susceptibility of 0.024cgs. Palaeomagnetic measurements of selected samples show both normal and reverse components and there is some evidence in these measurements of rotation of the deposit since formation. The remanence is not strong with Kouningsberger ratios generally less than one. Surrounding the potassic core, phyllic alteration has destroyed any magnetite. Outside these alteration zones, propylitically altered andesite appears to have a

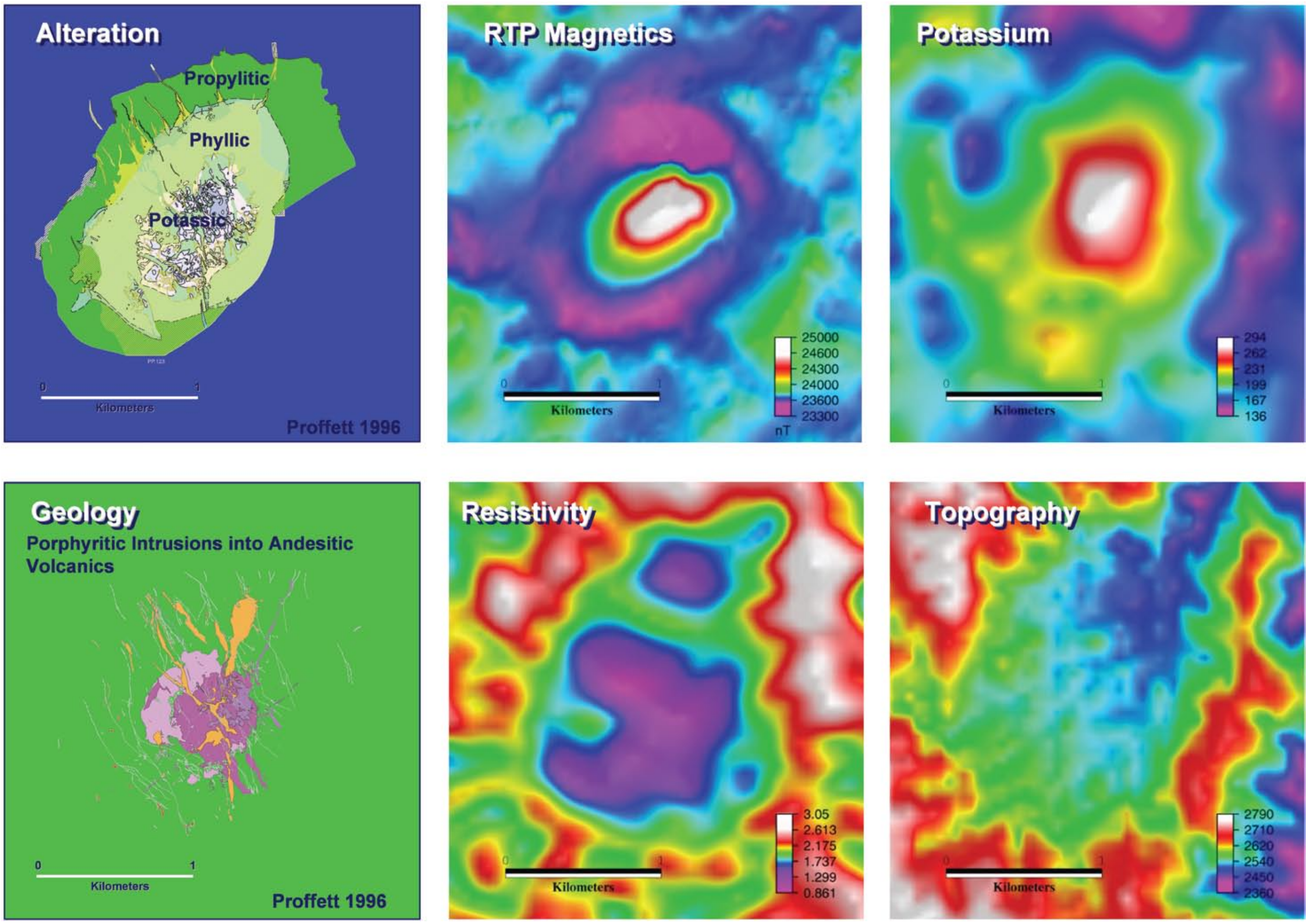

Figure 8. Alumbrera porphyry deposit with alteration, RTP magnetics, potassium, geology, resistivity, and topography.

similar susceptibility to that of the unaltered andesite.

Apparent resistivity results from the helicopter EM survey shows a zone of low resistivity corresponding to the phyllic alteration within which is a more conductive zone corresponding to the central potassic core (~10 ohm-metres). Conductivities were measured on the samples taken for palaeomagnetic measurements by Systems Exploration in Sydney. Most of the samples showed high resistivities and those with low resistivities had sulphide veining. It would appear that the main cause of the resistivity low associated with alteration is a network of sulphide veins as veining is observed to be extensive in the pit. It is thought that this is more likely than alternatives such as clay alteration or high porosity.

Four lines of 50m dipole-dipole IP were surveyed over the deposit and the IP results show strong chargeabilities in the potassic and phyllic alteration zones (Fig. 9). The propylitic alteration was poorly sampled but showed only background chargeability. The resistivity results are similar to the results of the EM survey with very low resistivities in the central potassic zone (areas of less than 10 ohm-metres) and higher resistivities in the phyllic zone(~30-50 ohm-metres). The background appears to be in the hundreds of ohm-metres.

The porphyry system also stands out as an obvious feature in satellite imagery and a clearly defined topographic depression is associated with the alteration system. There is also a significant potassium anomaly over the outcropping central potassic alteration zone.

HIGH SULPHIDATION EPITHERMAL DEPOSITS

Martabe

Martabe is a high sulphidation epithermal district located on the west coast of North Sumatra. Approximately three million ounces of gold resource have been discovered to date in two deposits, Purnama and Baskara, with 90 percent at Purnama (40.7 million tonnes at 2.26 g/t Au). The mineralisation is hosted by vuggy and massive silica and this alteration grades out to silica alunite and then to clay-rich argillic alteration (Sutopo et. al., 2003)

IP/resistivity surveys were conducted by Normandy in the late 1990s. Blocks of gradient array were surveyed over

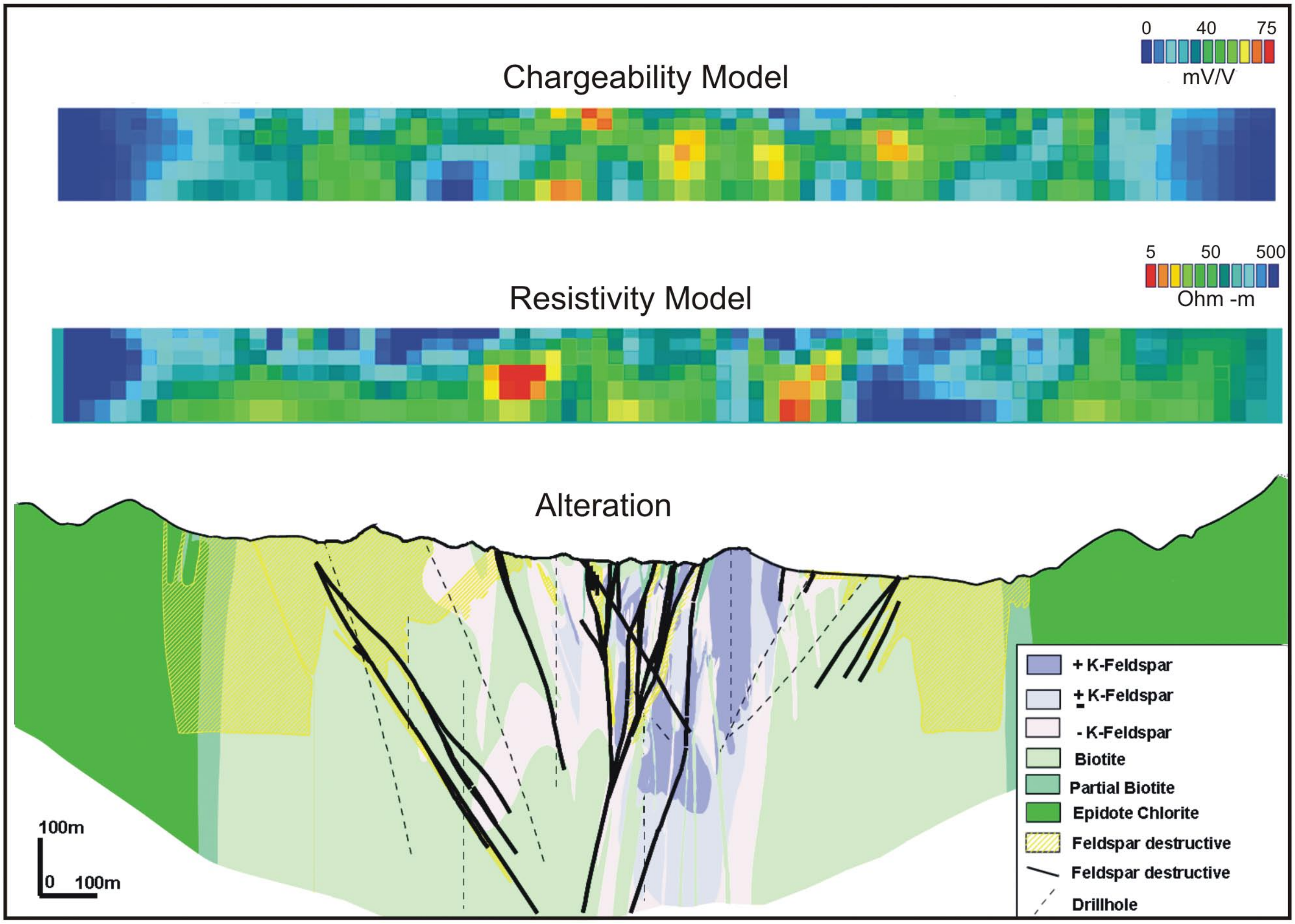

Figure 9. Alteration section with chargeability and resistivity through Alumbrera (IP results are from Fallon and Kangas, 1999).

Baskara and Pelangi and three short lines of 50m dipole-dipole were read over Gerhana and Baskara. No data was acquired over Purnama. The gradient array surveys did not prove particularly useful and were probably affected by topography and major variations in near-surface resistivity. The dipole-dipole resistivity was much more effective with the lines at Baskara clearly mapping the massive silica zones. This work indicated that massive silica alteration associated with gold mineralization has resistivities on the order of thousands of ohm-meters compared with a background of tens of ohm-meters within argillic and prophylitic alteration zones.

In 2004 a large IP/resistivity survey covered the area from north of Kejora to south of Purnama. Approximately 70 line kilometres of 50m pole-dipole was read with 100m between lines. The data was inverted using a 3D algorithm by Geotomo Software to produce a 3D block model of resistivity and chargeability. The silica bodies are clearly defined by the resistivity and a section of geology, alteration, gold grade and resistivity through Punama is shown in Figure 10. A plan of the 50m depth–slice- below-topography showing resistivity and gold from the Newmont block model (Jones et al., 2005) is presented in Figure 11. This shows the excellent correlation of gold with resistivity. The survey not only defined the known zones of electrically resistive silica alteration at Purnama and Baskara, it identified a new zone at East Baskara.

In 2004 Newmont conducted a helicopter electromagnetic survey (HoisTEM) over most of the contract of work to try to identify other high sulphidation systems. The survey was flown in an east-west direction with a nominal terrain clearance of 50m, 200m line spacing, and about 6500 total line kilometres. The correlation between the HoisTEM and pole-dipole resistivity results is excellent and the 100m depth slice from both surveys is shown in Figure 12. The known deposits are clearly identified in the resistivity depth slices and there are a number of other anomalies that have been selected for further work.

Magnetic data was also collected during the HoisTEM survey. The alteration at Martabe is magnetite destructive and the deposits are within a broad magnetic low. In addition to identifying potential areas of alteration, the magnetic data contains a significant amount of information that may reveal geological and structural features.

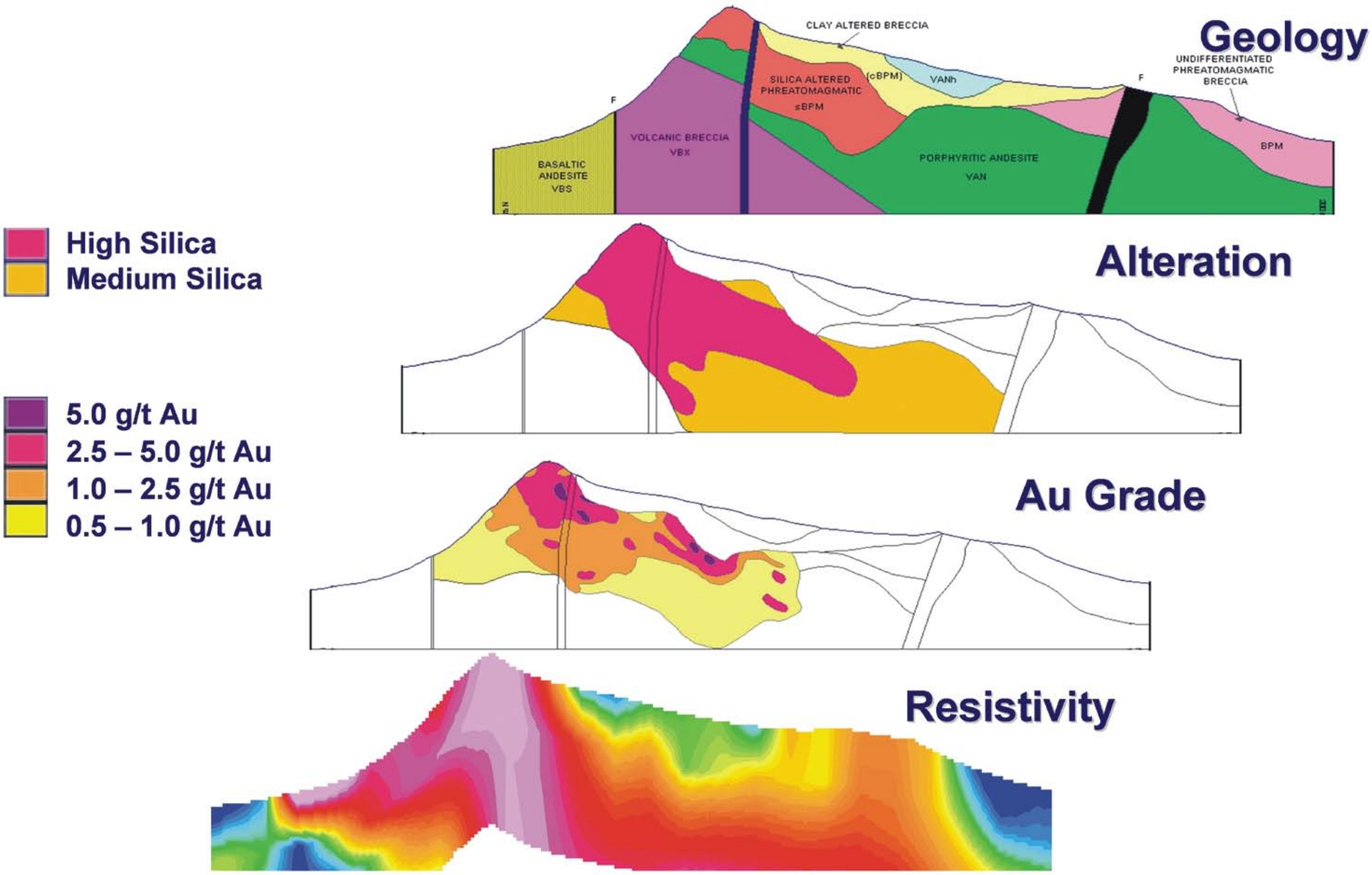

Figure 10 (above). East-west section through the Purnama deposit at Martabe.

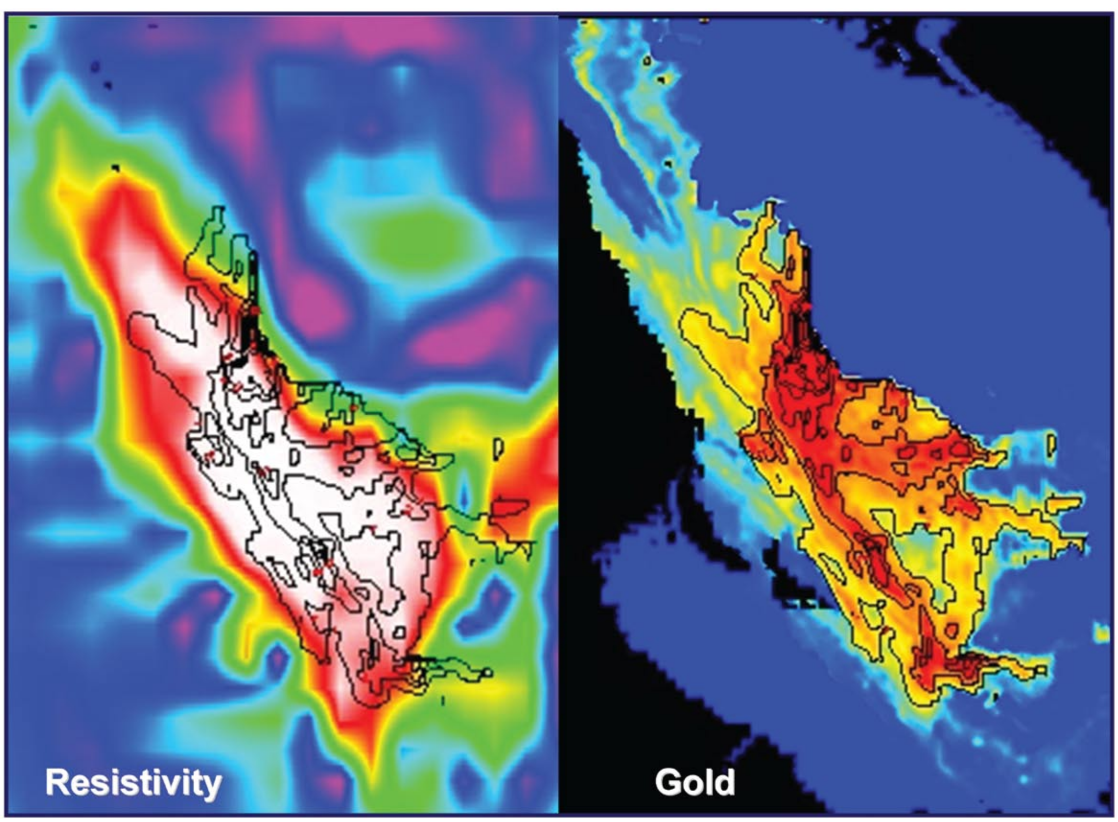

Figure 11. Depth slice of resistivity and gold 50m below topography through the Purnama deposit. (Contours represent gold concentration at intervals of 1 g/t.)

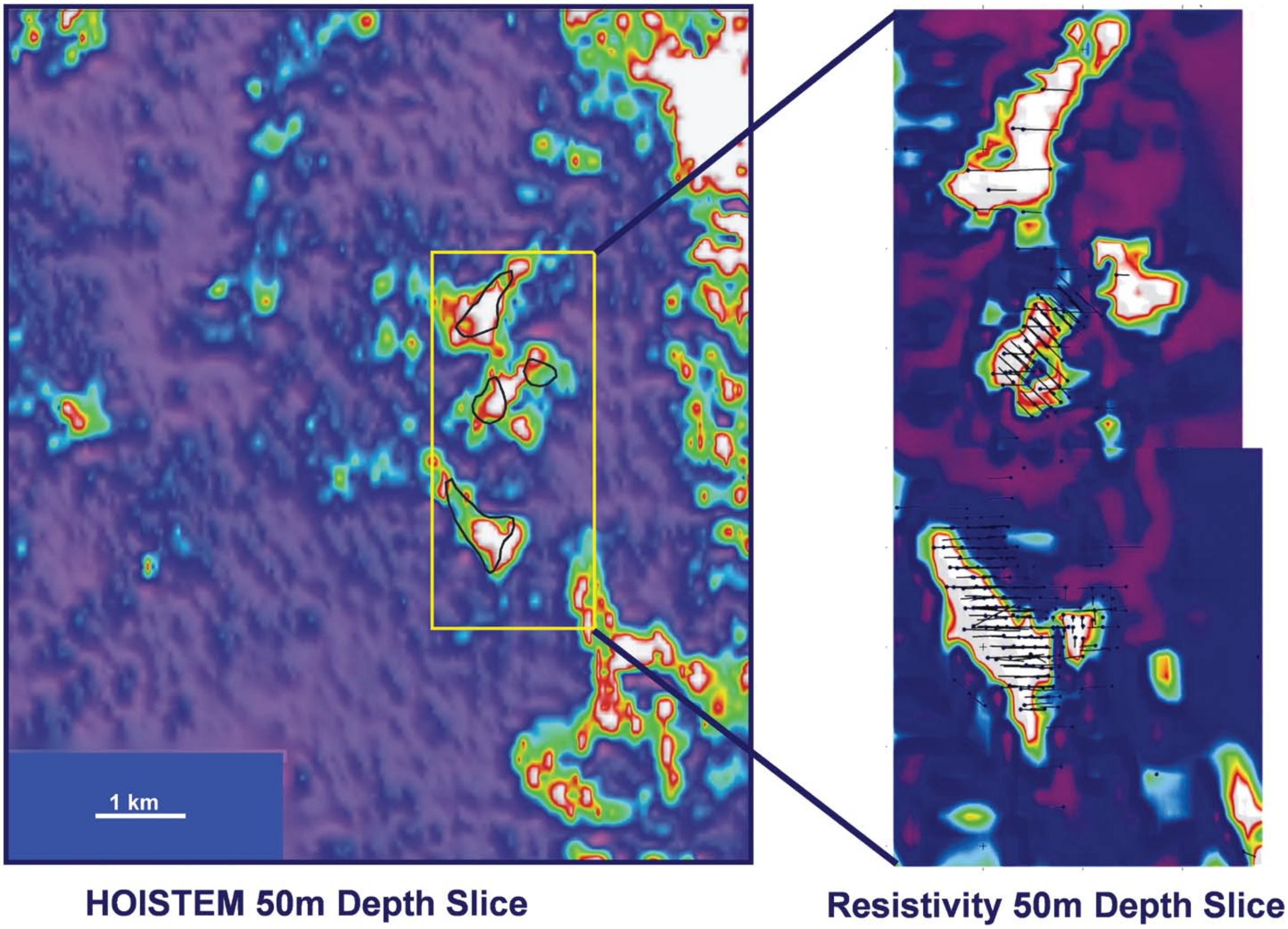

Figure 12. Comparison of airborne TEM resistivity with pole-dipole resistivity at Martabe.

Yanacocha

The Yanacocha district, located in northern Peru, contains a number of high sulphidation epithermal gold deposits. Current past production and resource/reserve is about 47 million ounces of gold. Gold is generally hosted by vuggy and granular silica and fractured massive silica. From this silica-rich core, alteration grades out to silica alunite and then to clay-rich argillic zones (Fig. 13; Bell et al., 2004). The silica-altered rock is highly electrically resistive and this is within relatively conductive clay alteration.

Resistivity methods have been used successfully in exploration for the silica bodies, the most useful techniques being IP/resistivity, TDEM and CSAMT surveys (Goldie, 2000). Resistivity from IP surveys was very successful in mapping near surface resistors. Figure 14 shows resistivity over a 100m depth slice from these surveys and the location of the known deposits. TDEM and CSAMT techniques were used to look for deeper targets and the Corimayo deposit was discovered under gravel and argillic alteration using TDEM soundings (Goldie, 2000).

An airborne geophysical survey was flown in 1994 and, as at Martabe, there is a broad area of subdued magnetics due to the magnetite-destructive nature of the alteration. There is a low radiometric response over the deposit due to the intense acid alteration.

LOW SULPHIDATION EPITHERMAL DEPOSITS

Pajingo

The Pajingo Epithermal System is situated 60 km south of Charters Towers in northeast Queensland (Figure 1). It is an area of low sulphidation epithermal veining and alteration about 15 km in diameter and is largely hosted by Late Devonian intermediate volcanic rocks of the Drummond Basin. Tertiary and younger conductive sediments, commonly containing quartz-vein detritus, cover about 80% of the area. These sediments are an impediment to exploration, particularly by surface geochemistry.

The gold mineralisation is within thin quartz veins and most of the ore bodies discovered to date are along the

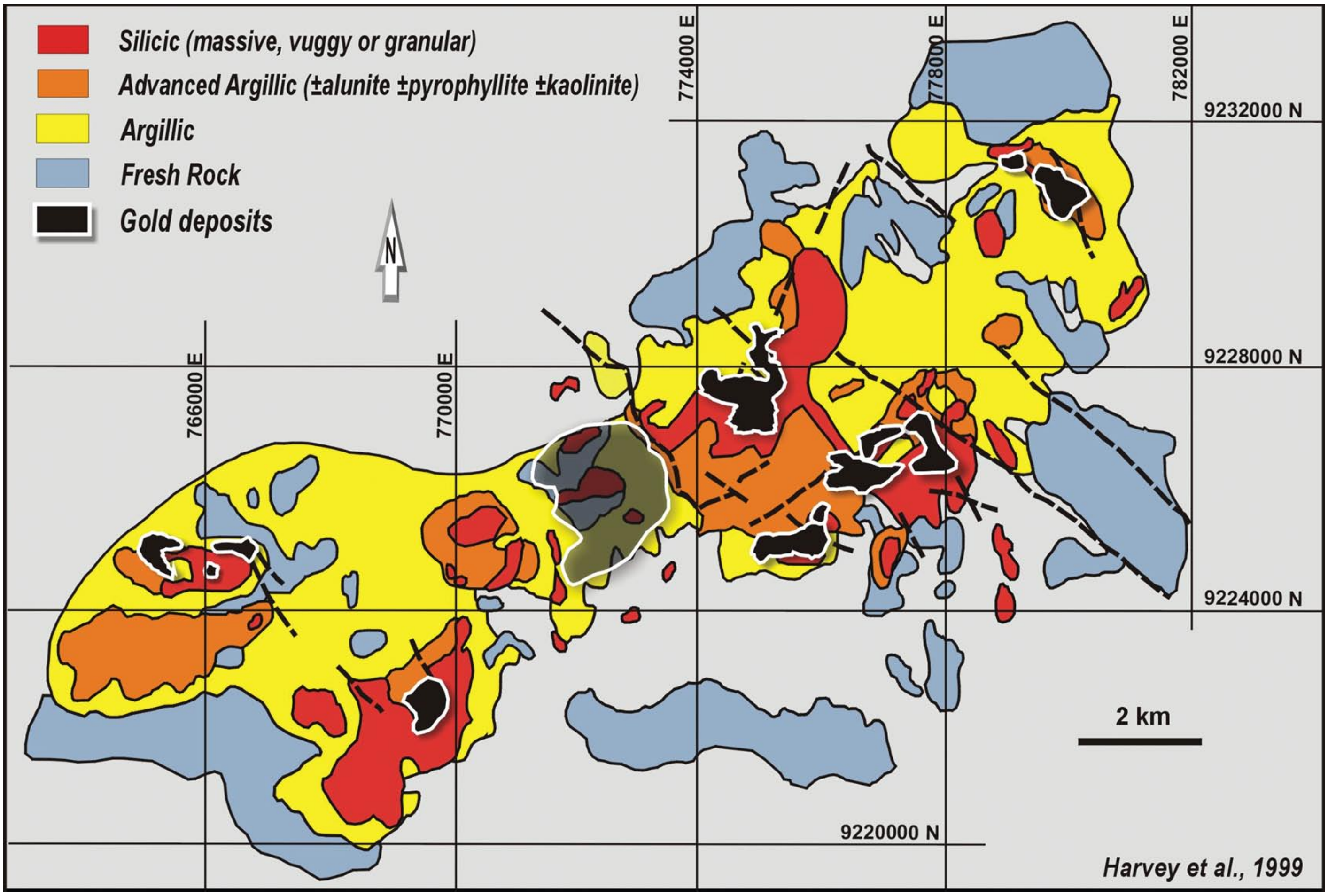

Figure 13 (above). Plan of Yanacocha alteration with the location of the gold deposits.

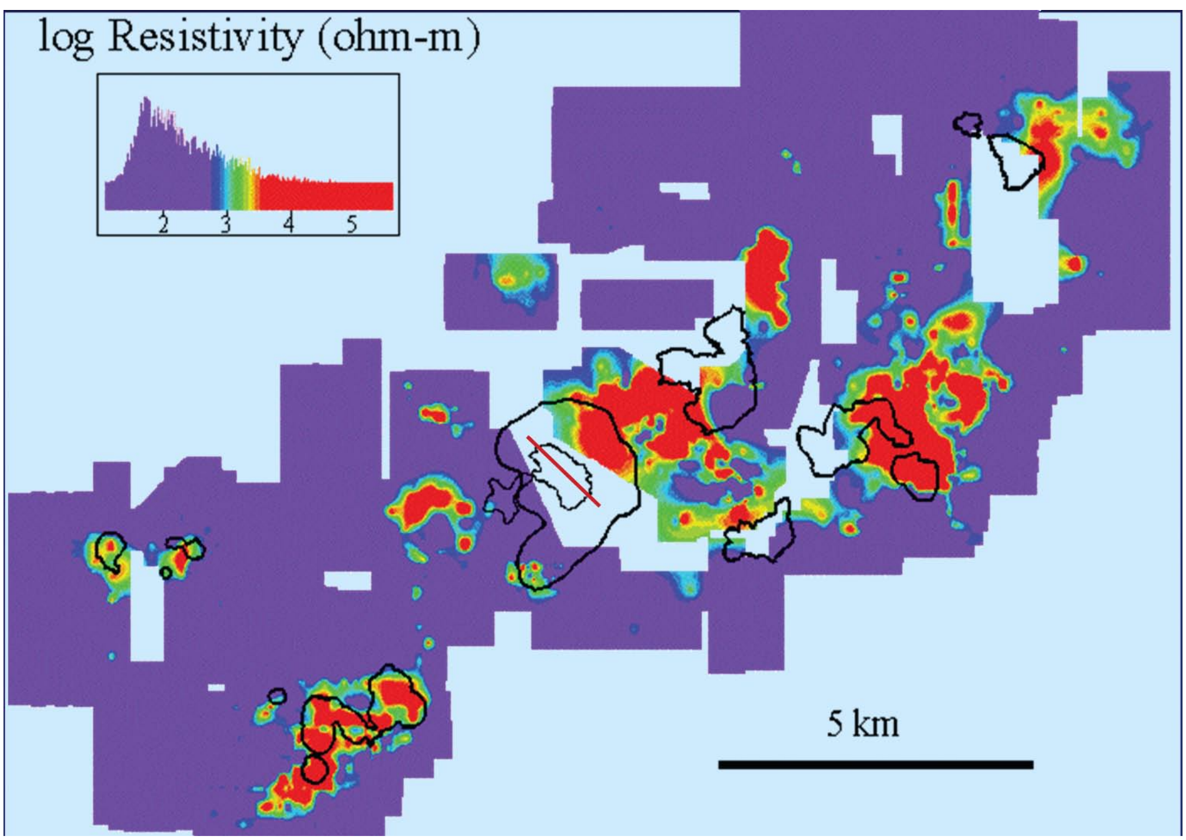

Figure 14. Yanacocha pole-dipole resistivity 100 m depth slice.

northwest-trending Vera-Nancy Structure. The host intermediate volcanics are magnetic and the epithermal alteration that extends up to 50m from the veins along the Vera-Nancy Structure is magnetite destructive. Results of a high resolution magnetic survey clearly delineate the major structures including the Vera-Nancy Structure (Fig. 15).

The quartz veins are within broader zones of silicification as can be seen in the alteration section shown in Figure 16. The quartz veins average a few metres in width and are generally too thin to be directly detected by geophysics. It is the silica alteration associated with veining that provides the target and gradient array resistivity surveying has been successful in mapping these zones (Fig. 15). Generally, high resistivity zones due to silicification are coincident with the structures identified in the magnetics.

High resolution magnetics and resistivity continue to be the most useful geophysical tools in the ongoing exploration of the Pajingo Epithermal System for additional mineralised structures.

Waihi

The gold deposits at Waihi are situated on the Coromandel Peninsula on the North Island of New Zealand. The Martha deposit is a large low-sulphidation vein system with total resource, reserves, and past production of about 6.4 Moz Au and 31 Moz Ag. There is no ground-geophysical data over Martha due to the pit, although CSAMT lines along the edges give the impression that the deposit would produce a broad resistivity anomaly.

The Favona deposit is a thin vein system along a north-south structure about two kms east of Martha. Figure 17 shows a section through Favona annotated with resistivities

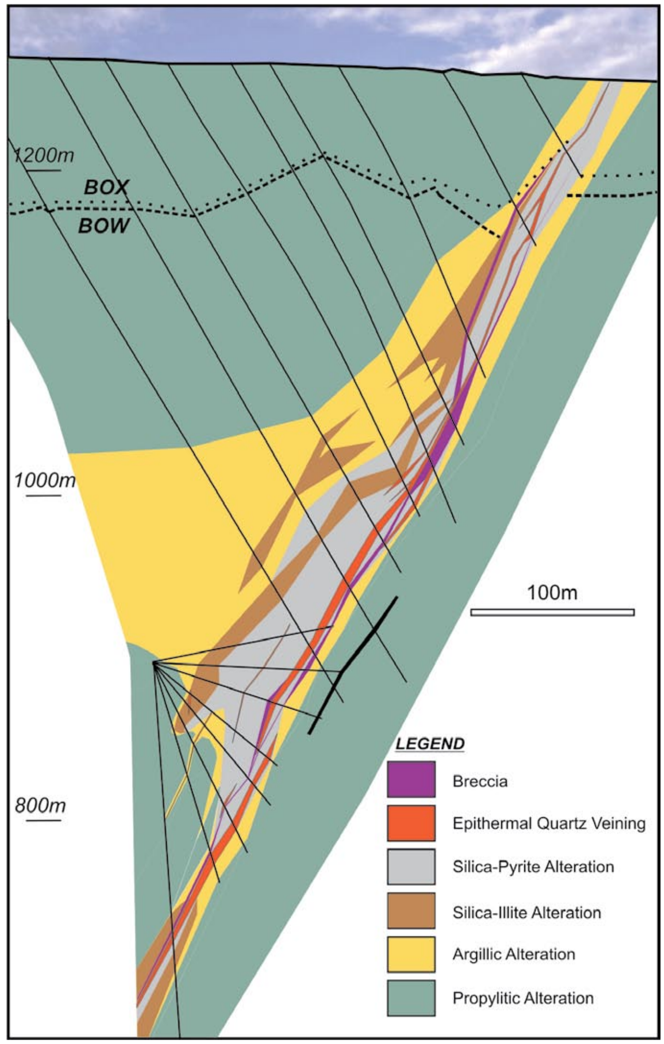

Figure 16 (above). Alteration section through the Vera deposit at Pajingo (Baker et al., 2002).

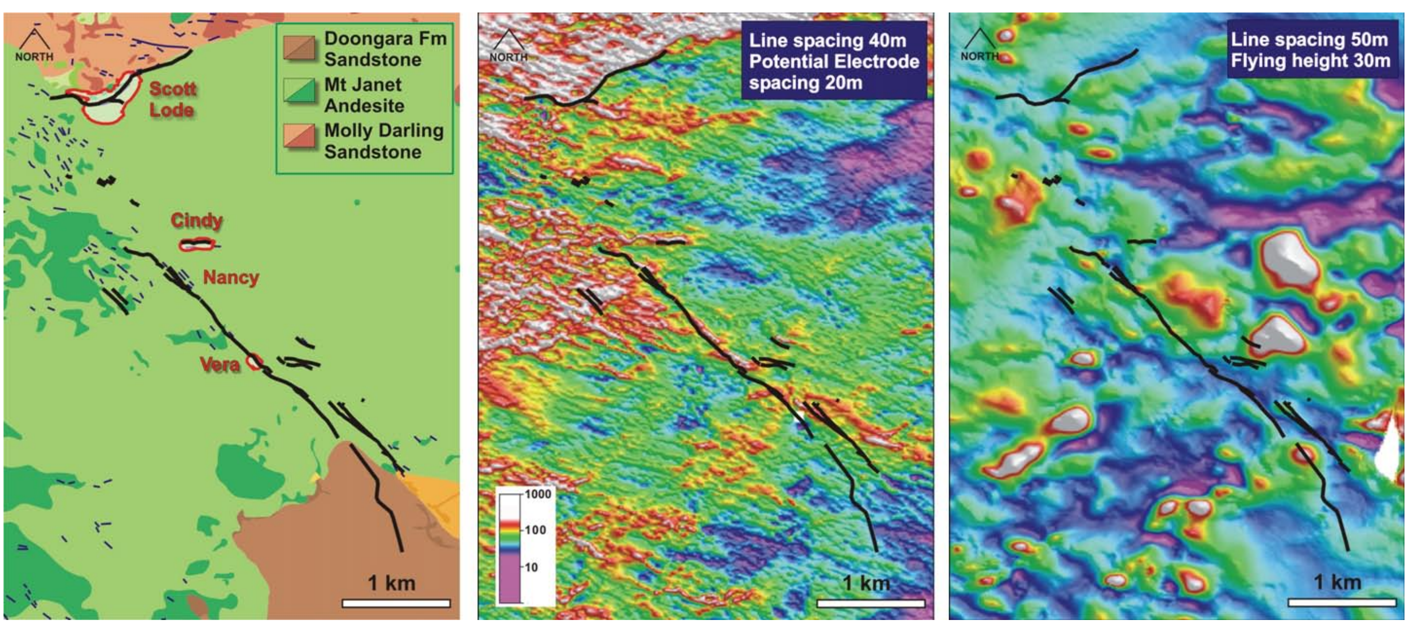

Figure 15. Location of the Vera-Nancy vein system with the geology, resistivity, and RTP magnetics.

thought to be typical of the alteration types. The veining and silicification have very high resistivities of thousands of ohm-metres. This sits on a structure with altered volcanics of hundreds of ohm-metres to the west and intense clay alteration of tens of ohm-metres to the east. On top of this are resistive ignimbrites and post-mineral dacites. The associated CSAMT section shows the silicification and this is not obvious on all sections across Favona. The CSAMT clearly maps the contact with the volcanics and the extensive clay alteration.

The mineralisation at the Golden Cross deposit, located about 5 km northwest of Waihi, is in a similar setting to Favona. Figure 18 shows an inverted resistivity section across the deposit, which also sits on the contact between altered volcanics and extensive clay alteration. The resistivity also maps the unaltered volcanic cover to the east of the deposit.

EXPLORATION IMPLICATIONS

In porphyry Cu-Au systems the mineralisation is associated with potassic alteration that usually contains magnetite. This can produce large discrete magnetic anomalies. Outside the potassic core the alteration is magnetite destructive and may be identified in magnetic survey data, particularly if the host to the porphyry is magnetic. Airborne magnetic surveys are fast and cost effective exploration techniques, particularly in areas of severe topography. Low resistivities observed in these systems can be due to sulphide veining or clay alteration and EM/resistivity can be used in exploration. Large volumes of disseminated sulphides are common in these systems and IP can be used to map these. Regional magnetics, remote sensed data and topographic data can also be used to identify major structures, intrusive complexes, and alteration. Radiometric surveys can be used to map geology and alteration.

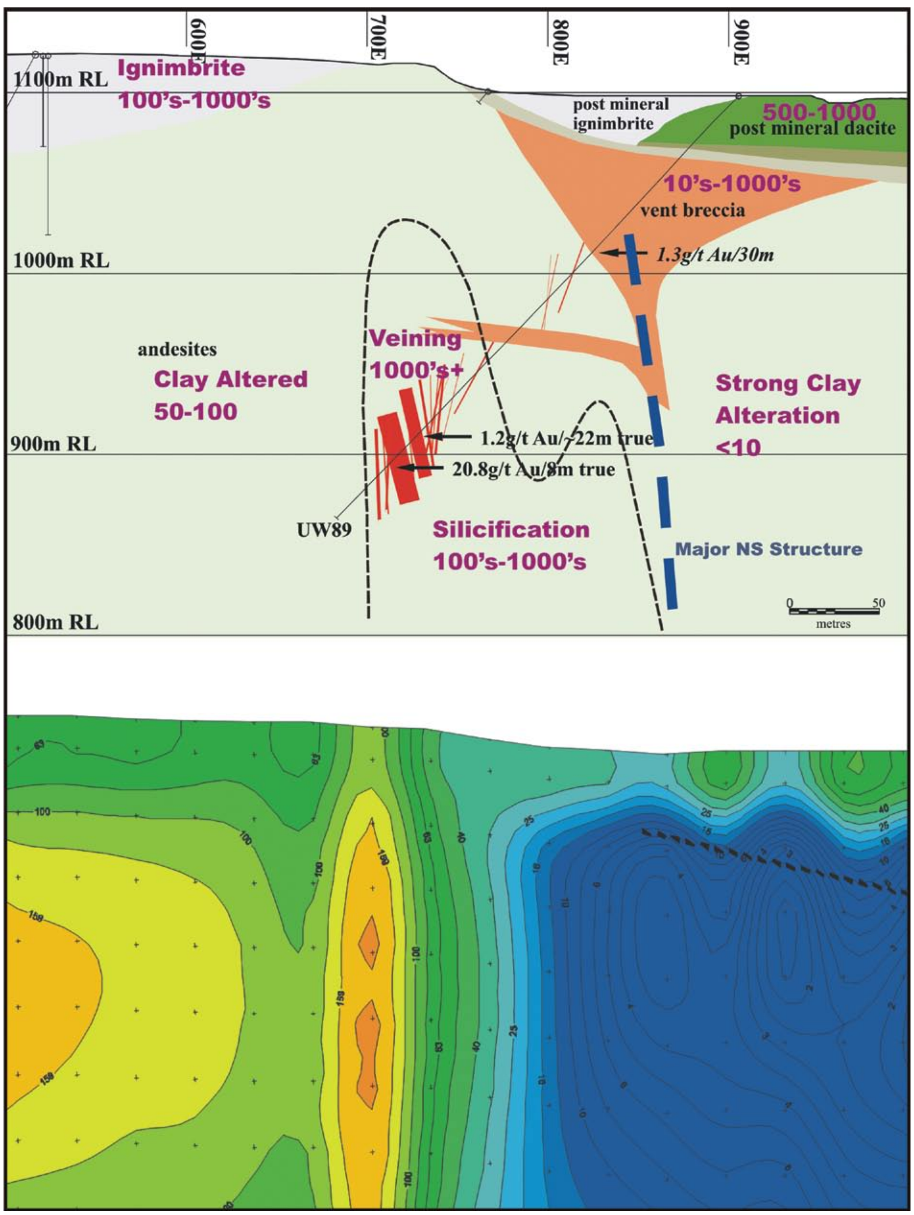

Figure 17. Type section through the Favona deposit showing typical resistivities of the alteration and 1D inversion of the CSAMT along the same section.

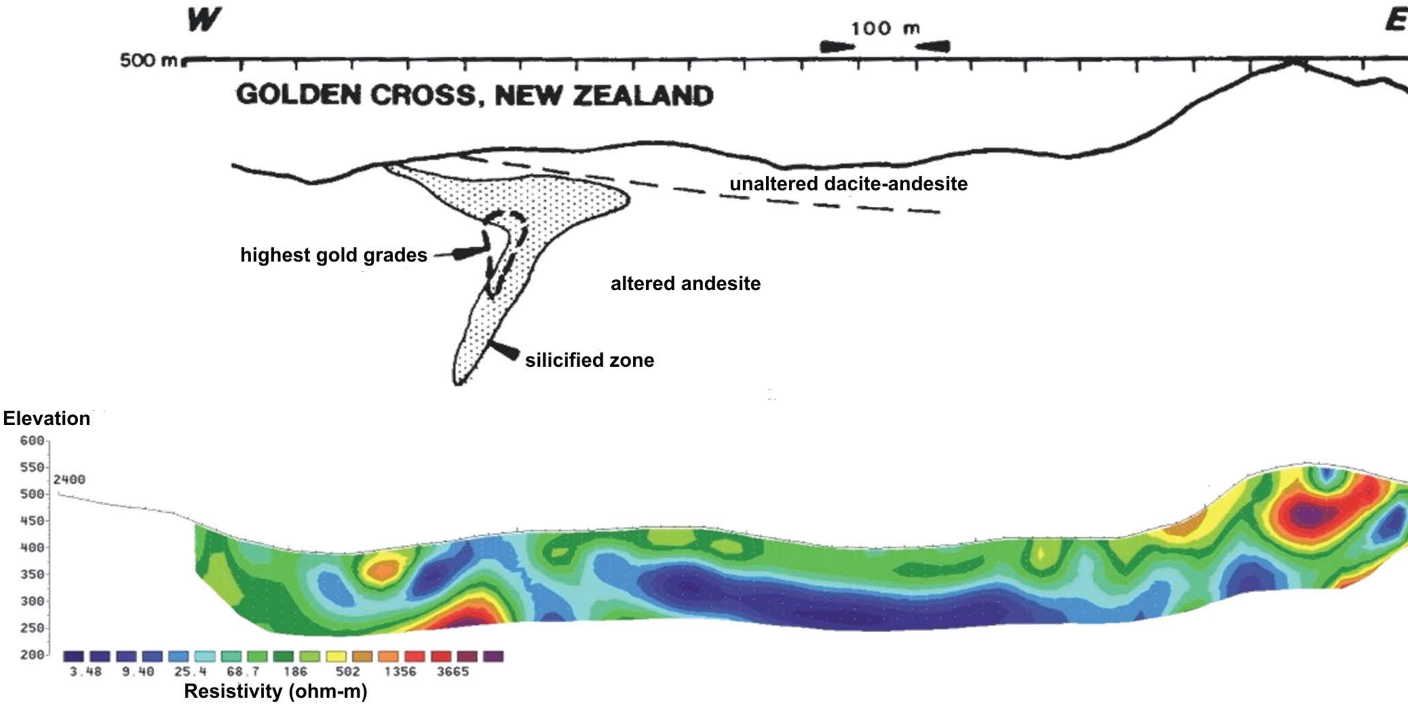

Figure 18. Section through Golden Cross showing a 2D inversion of the resistivity (after Hay, 2004).

In high sulphidation systems the gold is usually associated with vuggy or massive silica within a broad zone of clay alteration. The silica is electrically highly resistive and can be detected using resistivity techniques. The alteration is magnetite destructive and this leads to a subdued magnetic response over the system. To be economic the silica bodies usually have to be oxidised. Sulphides are present under the zone of oxidation and these can be mapped with IP. The silica bodies are resistant to weathering and may form ridges and cliffs. The intense acid leaching can lead to a low radiometric response over the alteration.

Typically low sulphidation deposits are extensive thin veins along major structures. The alteration associated with the veins is magnetite destructive and high resolution magnetics is a very useful and cost-effective technique to map both the alteration and major structures. The thin veins have an envelope of silica alteration which can be mapped with resistivity. This zone is usually thin (~20m) and is a difficult target, particularly at depth. A number of the Coromandel epithermal deposits in New Zealand are on the edge of a broad zone of conductive clay alteration which is easily detected by resistivity (e.g., Favona, Golden Cross). Associated alteration may contain pyrite and there can be chargeability anomalies associated with the mineralised system. This is often not a target in itself but may help rank resistivity and magnetic anomalies. The broad alteration zones associated with the Coromandel deposits are apparent as areas of subdued magnetics due to magnetite-destructive alteration. Gravity can also be useful to help define major structures and alteration. There may be a potassium response associated with the alteration.

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