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Advances in Geological Models and Exploration Methods for Copper ± Gold Porphyry Deposits

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ABSTRACT

This paper focuses on the relationships between the geological model and exploration techniques for porphyry Cu ± Au deposits, with reference to the discovery record and exploration practices over the past fifteen years. The porphyry model is built on a long record of study dating back to the 1960s which has been gradually refined to encompass differences and complexities in mineralization and hydrothermal alteration assemblages resulting from varying intrusion ('porphyry') chemistries, differing wallrock geochemical and structural controls, the upwards zonation into the lithocap environment, and the overprinting effects of deep weathering. The most recent advances of the model include:(i) an understanding of how changes to the prevailing tectonic regime are important in porphyry ore formation; (ii) better knowledge of the distinctive characteristics of the alkalic sub-type, and (iii) improved knowledge of fluid compositions and the history of magmatic-hydrothermal activity from fluid and melt inclusion and geochronological studies. Tabulation of potentially economically significant porphyry deposit discoveries over the past fifteen years shows secular trends in the application of the various exploration techniques. Long-established field geological and geochemical methods are still vitally important for successful discovery, but in both cases their application on drillhole samples is becoming relatively more important compared to surface samples. A new geochemical vectoring tool of potential significance is sulphur isotope geochemistry. The magnetic method has great applicability in the porphyry environment, both regionally and locally, because of the likely presence of varying amounts of magnetite in mineralization, alteration, intrusion and wallrock mineral assemblages. Thus the use of detailed magnetic data, acquired both from airborne and downhole surveys, has been significant in recent major discoveries. Gravity, for both cost and model-derived reasons has less use in porphyry exploration but may become more applicable as more covered terrains are explored and airborne costs decrease. Induced polarization (IP) has had a critical, but indirect role in several significant discoveries and its role as a sulphide distribution mapping tool has been enhanced by the development of better acquisition and inversion practices made possible by advances in computer technology. Spectral scanning is developing as a potentially significant tool for more efficient, objective core-logging. Drilling has become more recognised as a specific exploration tool, rather than just a target-testing method, and has been used successfully to find deposits both under poorly consolidated cover and to collect information in hard rock environments that has vectored to discoveries. Over the past fifteen years a higher proportion of discoveries are being made in covered geological settings, most of which are brownfields. Also, deposits are being discovered at greater depths. Outcropping deposits are being discovered largely in geological provinces that are underexplored for geopolitical reasons. There are no revolutionary exploration techniques that have created a surge in exploration success or refocusing of exploration approaches. Discoveries are still made using tried and true techniques that have naturally evolved with developments in technology and accumulating industry knowledge. The main trends of this evolution are that drillhole vectoring using downhole geological, geochemical and information, and geophysics methods are increasingly important in achieving exploration success. The challenge for explorers is to be the first to make discoveries in a competitive environment. We suggest that the successful explorers will be those who strive to make the most effective use of a broad combination of the exploration methods available.

INTRODUCTION

The ore deposit model for porphyry Cu ± Au deposits is universally recognised as one of the most well-developed and successful of all such models, both in its empirical and genetic aspects (e.g., recent reviews by Sillitoe, 2000a; Richards, 2003, 2005; Cooke et al., 2004; Seedorff et al., 2005; Sillitoe and Thompson, 2006). Porphyry deposits are amongst the world's major repositories of Cu, Au and Mo, and so remain one of the main targets for the global mineral exploration industry. Therefore, the continuing refinement of both the porphyry model and exploration techniques in general, and understanding of the relationships between them are of major importance to explorers. The model is used to select exploration techniques

and interpret the results of surveys. Those experiences and results are then fed back into improving the model from field data.

This paper summarizes the recent discovery history of porphyry Cu ± Au deposits, and discussing refinements to the porphyry model and new approaches and advances in geochemistry, geophysics, drilling and integrated interpretation over the past decade or so. Case study examples, including some from recent discoveries, are used to illustrate the state of the art of porphyry exploration.

THE PORPHYRY MODEL TODAY

Copper ± gold ± molybdenum porphyry deposits are large tonnage, low-grade hypogene resources. The deposit class is unified by a close spatial, temporal and genetic association between subvolcanic porphyritic intrusive complexes (the 'porphyry') and hypogene mineralization and hydrothermal alteration mineral assemblages that occur in and around them (Figure 1). The intrusions belong to the magnetite-series of Ishihara (1981) and range from calc-alkalic to alkalic compositions, with most porphyry deposits associated with the former. The degree of fractionation appears to have influenced metal tenor, with less fractionated calc-alkalic intrusions associated with Cu-Au mineralization, and more fractionated intrusions related to Cu-Mo mineralization. Alkalic porphyry deposits are uncommon, and are associated exclusively with copper-gold mineralization. Multiple intrusive phases are common in most porphyry deposits, with one intrusive phase typically contributing most of the magmatic-hydrothermal fluids and metals.

Porphyry deposits were originally described as "disseminated", although most workers used this term to refer to the homogenous distribution of sulfides that occur in a three dimensional volume of rock. Where examined in detail, the copper-iron sulfides reside primarily in veins and/or hydrothermal breccias, with lesser amounts occurring as disseminations in the altered wallrocks. A strong structural control is apparent in many porphyry deposits, with the vein 'stockwork' comprising two or more preferred orientations that developed due to local intrusion-related stress regimes or (in some cases) far-field stress regimes that prevailed at various times throughout the evolution of the deposit (e.g., Tosdal and Richards, 2001). In cases where the regional stress regime predominates, sheeted vein arrays may form (e.g., Cadia Hill, Australia; Wilson et al., 2007a, b).

Mineralization can occur in both the intrusive complex and the surrounding wallrock. The amount of mineralization that occurs in the intrusions compared to the adjacent wallrocks varies between deposits. Sulfide mineralization is typically zoned, with high-grade bornite-rich cores, surrounded by chalcopyrite-rich and outer pyrite-rich halos typifying some deposits. Other deposits lack bornite, and have chalcopyrite-rich cores. Isotopic and fluid inclusion studies typically confirm that magmatic-hydrothermal fluids cause mineralization, and that the sulfur and metals have predominantly magmatic sources (e.g., Hedenquist and Richards, 1998, and references therein).

Hydrothermal alteration assemblages associated with the high-grade core of calc-alkalic porphyry deposits include: 1) potassic (typified by abundant secondary orthoclase and/or biotite), and less commonly 2) phyllic (typified by abundant sericite, quartz and pyrite), 3) advanced argillic (characterized by quartz, alunite, kaolinite and/or pyrophyllite, potentially associated with high sulfidation state mineralisation) and 4) calc-silicate (skarn) assemblages, if carbonate wallrocks are present (characterized by combinations of garnet, pyroxene, epidote, calcite, chlorite, sulfides, quartz and anhydrite). In addition to potassic alteration, alkalic porphyry deposits can have calc-potassic-altered cores characterized by secondary orthoclase ± biotite ± garnet ± actinolite ± epidote). Most alkalic porphyry deposits lack significant volumes of phyllic or advanced argillic altered rock. Magnetite is an important vein and alteration mineral in the high-grade core of some gold-rich deposits, and can locally comprise up to 10 wt. % (e.g., Grasberg, Irian Jaya; Kavalieris et al., 1994). Unmineralized propylitic alteration halos (characterized by epidote – chlorite – carbonate ± pyrite ± actinolite; Figure 1) can extend away from the mineralized porphyry centres laterally for several kilometers, and propylitic sub-facies have been mapped in some deposits (actinolite-, epidote- and chlorite sub-facies; Norman et al., 1991; Garwin, 2002; Rae et al., 2003; Fig. 1a). The propylitic alteration zone is still part of the larger porphyry system, which includes both the ore deposit itself, the underlying intrusions and the unmineralized wallrocks that have undergone hydrothermal alteration.

Some porphyry deposits (e.g., Far South East, Philippines) occur beneath extensive domains of magnetite-destructive clay and quartz-alunite alteration ('lithocaps'; Sillitoe, 1995a; Figure 1a). A lithocap is a stratabound zone of advanced argillic and residual silicic alteration that can form above porphyry deposits. Lithocaps have structural roots that are defined by intense phyllic and/or advanced argillic alteration zones. These roots are centred on steeply-dipping faults, and may contain high sulfidation state mineralization (Sillitoe, 1999; Hedenquist et al., 2000, Einaudi et al., 2003).

Supergene enrichment has enhanced the economic viability of many Cretaceous and Tertiary porphyry copper deposits in the arid climates of southwestern North America and the Peruvian and Chilean Andes. Few of the Tertiary and Quaternary porphyry deposits in the southwest Pacific contain significant supergene resources due to unfavorable climatic conditions. Older (e.g., Paleozoic) porphyry systems could have significant supergene enrichment zones preserved, if plate motions carried them through more favorable semi-arid climatic zones during exhumation. This may explain the formation and preservation of the Cretaceous enrichment zone at Central Oyu Tolgoi, in the Gobi desert of Mongolia (Perelló et al., 2001).

The empirical characteristics of porphyry copper deposits summarised above were mostly well-established by the late 1970s, and only minor modifications have been made since that time. Keynote studies of porphyry deposits from South America (e.g., Gustafson and Hunt, 1975), the southwestern Pacific (e.g., Gustafson and Titley, 1978, and references therein), Canada (e.g., Sutherland-Brown, 1976, and references therein; Schroeter, 1995, and references therein; Lang et al., 1995) and the southwestern USA (e.g., Lowell and Guilbert, 1970; Sheppard et al., 1971; Taylor, 1974, Titley, 1982, and references

therein) provided the basis for much of our current understanding of porphyry systems. Richard Sillitoe's observations and interpretations (e.g., Sillitoe, 1972, 1973, 1979, 1985, 1989, 1995a, 1995b, 1997, 1998, 2000a, 2000b; Sillitoe and Gappe 1984) have helped us to understand many aspects of porphyry systems, including that the ore deposits can be significant resources of gold, and that epithermal and skarn deposits are genetically and spatially associated with porphyry deposits in many mineral districts. Other significant contributions that improved our understanding of porphyry ore genesis include Henley and McNabb (1978), Burnham (1979), Bodnar et al. (1985), Candela (1991) and Dilles and Einaudi (1992).
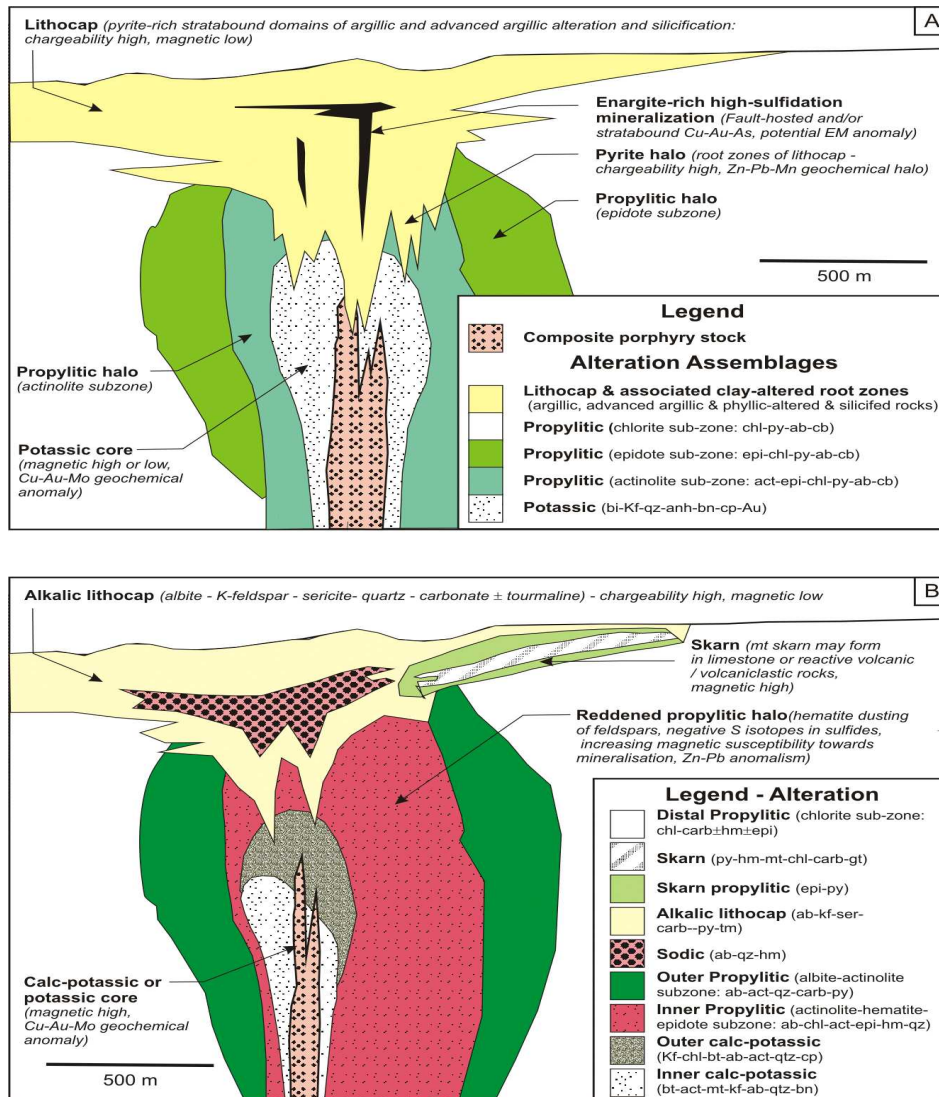
Figure 1A: Schematic illustration of alteration zoning and overprinting relationships in a calc-alkalic porphyry system. Mineralization occurs in potassically altered intrusions and adjacent wallrocks. Three propylitic alteration subfacies (actinolite, epidote and chlorite zones) can occur around the potassic-altered rocks. In this example, the porphyry has been partially overprinted by a lithocap (silicic and advanced argillic alteration assemblages) that contains a domain of high sulfidation epithermal mineralization. The roots of the lithocap can produce a pyrite halo to the porphyry system. The degree of superposition of the lithocap into the porphyry system is contingent on uplift and erosion rates at the time of mineralization. B: Schematic illustration of alteration zoning and overprinting relationships in an alkalic porphyry system, based on geological relationships from the Cadia East porphyry Cu-Au deposit (Tedder et al., 2001; Wilson 2003; Cooke et al., 2007). The alkalic equivalent of a lithocap contains less acidic alteration assemblages (albite – sericite – K-feldspar). The propylitic sub-facies are more complicated than in the calc-alkalic example, and calcium-bearing alteration minerals (calcite, actinolite, epidote, garnet) occur in the core of the deposit, in contrast to calc-alkalic porphyries. Inspirations for this diagram came from Sillitoe and Thompson (2006). Abbreviations: ab – albite; act – actinolite; anh – anhydrite; Au- gold; bi – biotite; bn – bornite; cb – carbonate; chl – chlorite; cp – chalcopyrite; epi – epidote; gt – garnet; hm – hematite; Kf – K-feldspar; lm – laumontite; mt – magnetite; pr – prehnite; py – pyrite; qz – quartz; ser – sericite; tm – tourmaline.

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Recent Advances

Over the past decade, significant advances in our understanding of porphyry deposit genesis has come from data obtained through new advances in microanalytical technology, particularly with regards fluid and melt inclusion studies. We also have new perspectives on the tectonic environments that are favourable to porphyry deposit formation, a better understanding of the alkalic sub-class of deposits and the timing and duration of porphyry mineralization through comprehensive geochronological and thermochronological investigations. These advances are discussed below.

Advances in understanding tectonic controls

Porphyry deposits have long been recognised to form in subduction–related environments (e.g., Sillitoe, 1972). Metallogenic belts defined by porphyry deposits have been recognised as forming late in orogenic cycles (e.g., Sillitoe, 1987). Porphyry deposits are known to have formed in oceanic island arcs, continental (Andean) arcs, accreted arc terranes and also in post-orogenic magmatic belts (e.g., SE China).

Several workers (e.g., Solomon, 1990; Sillitoe, 1997; Kay et al., 1999; Kerrich et al., 2000) have argued that changes to the prevailing tectonic regime are important in porphyry deposit formation. More specifically, Cooke et al. (2005) and Hollings et al. (2005) recently highlighted the spatial and temporal association between the formation of giant porphyry Cu-Mo and Cu-Au deposits and areas where subduction regimes have been perturbed by small collisions (e.g., subduction of ridges or seamount chains) or areas where oceanic plateaus have collided with subduction zones around the Pacific Ocean. From the perspective of regional targeting in Quaternary and Tertiary arcs and where the oceanic plate is still preserved off shore, a first-order tool is therefore to focus on regions where plate convergence angles are high (> 45°) and topographic anomalies on the oceanic plates have interacted with subduction zones In such environments, subduction angles may have shallowed and the subducting slab may have flexed or torn. The resultant compressional tectonic regime promoted a cessation of volcanism and initiation of plutonism, which in turn favored fractionation of magma chambers and generation of magmatic-hydrothermal fluids in shallow-crustal settings. Such environments can also be subjected to uplift and exhumation, which may result in the porphyry deposits, which form at depths of 1-3 km below the surface, to be brought closer to the present-day land surface, making them more attractive exploration targets (i.e. lower stripping ratios and mining costs). The challenge now for researchers and explorers is to find a way to use this knowledge in ancient environments. Can igneous fertility indices be determined that record the key geodynamic events? It may be that such indices will need to be terrain-specific, so that only similar ancient and modern environments are compared (e.g., the alkalic porphyry deposits of the Ordovician Lachlan fold belt are best compared in a modern context to a oceanic island arc setting such as Fiji, rather than the continental Andean arc).

Advances in the alkalic sub-type model

Alkalic porphyry deposits have long been recognized in the Canadian Cordillera (e.g., Barr et al., 1976) but they have received comparatively little attention through the 1970s and 1980s due to the size and remote locations of many of the Canadian deposits. Small alkalic porphyry Cu-Au systems were discovered by Geopeko / North Ltd. in the Goonumbla (now NorthParkes) district of New South Wales in the 1980s and early 1990s, but the significance of their alkalic character was not appreciated at the time.

Discovery of high-grade and large tonnage alkalic porphyry Cu-Au deposits in the Cadia district of NSW by Newcrest Mining Ltd. in the 1990s, and the discovery of the Didipio alkalic porphyry system in the Philippines by Climax Arimco in 1989 revitalised interest in exploration for alkalic porphyry systems. Newcrest recognised the importance of deep-drilling in order to fully evaluate these vertically elongated deposits. This exploration technique gave them considerable success with the discovery of the Cadia Hill, Cadia East, Ridgeway and Cadia Quarry alkalic porphyry systems in the 1990s. The success of their deep drilling program is now being emulated in the Canadian Cordillera, with deeper-drilling at Afton, British Columbia, resulting in discovery of a new high-grade ore zone.

The deep drilling programs at Cadia provided a wealth of information regarding the lateral and vertical zonation of mineral assemblages that has allowed for refinement of the alkalic porphyry model (e.g., Holliday et al., 2002; Wilson et al., 2003, 2007a, 2007b; Cooke et al., 2007). The Cadia East and Ridgeway deposits have high-level stratabound alteration zones characterized by albite, sericite and tourmaline-bearing alteration assemblages that may be the alkalic equivalents of lithocaps (Figure 1b). The propylitic alteration zones around many alkalic porphyry deposits are marked by pronounced reddening, caused by sub-micron sized hematite dusting of secondary feldspars. This is indicative of wall-rock oxidation by the mineralizing fluids. Recognition of the significance of 'reddening' was an important factor in the discovery of the Ridgeway deposit, as this feature helped with drillhole vectoring.

Alkalic porphyry deposits commonly occur in clusters, and the character of individual mineralized zones can vary markedly in a given cluster. Mineralization can be centered on narrow (< 200m diameter) pipes (e.g., Ridgeway, E26, E48) or dyke swarms (Cadia East), or may be hosted in larger plutonic complexes (e.g., Cadia Hill and Cadia Quarry, Australia; Afton, Red Chris and Mt Polley, British Columbia).

Cooke et al. (2007) provide a summary of the characteristics of the Australian alkalic porphyry systems. Lang et al. (1995) and Jensen and Barton (2000) provide synopses of this sub-class of porphyry Cu-Au deposits from the Canadian and global perspectives.

Use of geochronology to determine the timing and duration of porphyry systems

Over the past decade, improvements and new innovations in geochronological techniques, and the use of thermochronological techniques have helped to improve our understanding of the timing, duration and exhumation of porphyry copper deposits. The advent of Re-Os isotope analyses

has provided a direct dating method for molybdenite, one of the ore minerals that occur in porphyry systems (e.g., Stein et al., 2001). Recent studies have integrated U-Pb dating techniques to constrain the timing of intrusive activity, Re-Os techniques to date sulfide deposition, Ar-Ar techniques to date the initial cooling history of the deposit and U-Th-(He) thermochronology to constrain the low temperature cooling history of the deposit (e.g., McInnes et al., 1999; Stein et al., 2001; Cannell, 2004; Maksaev et al., 2004; McInnes et al., 2005; Cannell et al., 2005; Wilson et al. 2007a, Braxton et al., in press). U-Pb and Re-Os dating have demonstrated that several mineralizing events occurred in some porphyry districts (e.g., La Escondida – Richards et al., 1999; Tampakan – Rohrlach and Loucks 2005; Chuquicamata – Ballard et al., 2001, Campbell et al., 2006; Cadia – Wilson et al., 2007a). Several discrete episodes of mineralization occurred in 1-5 m.y. time periods at a number of porphyry deposits. The extreme end-member appears to have been the Cadia district, with two mineralizing events separated by approximately 18 m.y. (Wilson et al., 2007a). Despite the magmatic history and consequent thermal anomaly progressing for millions of years, metal input into these systems can occur on incredibly short time scales (e.g., < 300,000 years at Lepanto-Far South East – Arribas et al., 1995; < 1 m.y. at El Teniente – Maksaev et al., 2004; Cannell et al., 2005).

Advances in our understanding of fluid and melt compositions

In the last decade, fluid and melt inclusion research has been revolutionised by the development and application of new microanalytical technologies, including laser-ablation inductively-coupled plasma mass spectrometry (LA-ICPMS) and proton-induced X-Ray emission spectrometry (PIXE). Both of these techniques now allow for trace element concentrations to be analyzed from individual fluid and melt inclusions (including Cu, Mo and in the case of LA-ICPMS, Au). PIXE also has the capacity to generate concentration maps of fluid and melt inclusions that can be used to determine which phases (solids, liquids, gas) in individual fluid inclusions host the element of interest at room temperature (e.g., Harris et al., 2003; Davidson et al., 2005). Many modern electron microprobes and scanning electron microscopes can now generate detailed cathode luminescence images of the host quartz crystals, which help to constrain the timing of fluid inclusion formation (primary versus secondary) and allows for microanalytical studies to be better constrained (e.g., Redmond et al., 2004; Landtwing et al., 2005; Rusk et al., 2006) than could be achieved previously using the optical petrographic microscope.

Advances in microanalytical technologies have helped to significantly advance our understanding of the composition of melts and magmatic-hydrothermal fluids in porphyry systems (e.g. Audétat et al., 1998; Kamenetsky et al., 1999; Heinrich et al.; 1999; Harris et al., 2003; Halter et al., 2005). These studies have revealed extreme copper and gold concentrations dissolved in brines and vapours from deposits such as Grasberg and Bajo de la Alumbrera (Ulrich et al., 1999; Harris et al., 2003). These results have led to the realization that significant amounts of copper and gold could be transported in magmatic vapors at high pressures. This means that ore could be precipitated during decompression events, because the pressure drop causes metal solubilities to decrease markedly (Williams-Jones and Heinrich,

2006). This may have particularly significant implications for the formation of Cu-Au mineralization associated with phyllic and/or advanced argillic alteration assemblages, because the acidity required to form those alteration assemblages is produced by magmatic gases (e.g., HCl(g), SO2 (g); White, 1991), and those gas mixtures are now recognized to be capable of transporting copper and gold.

EXPLORATION FOR PORPHYRY DEPOSITS

Recent Discovery History

Table 1 lists porphyry deposit discoveries of potentially economic significance made since 1992, based on information from Sillitoe (2000b), Sillitoe and Thompson (2006), and the authors' own information. The information is most complete for the circum-Pacific region and less reliable elsewhere. The information is also more complete for the larger and less-recently discovered deposits than for the smaller, and especially very recently located occurrences. This is because the occurrences may not yet be well recognised as potentially economically significant discoveries.

Geology

Field geology remains an essential tool in porphyry exploration, as exemplified by the very recent porphyry system discoveries at Boyongan and Nugget Hill in the Philippines (discovered in part by mapping float trails – Waters, 2004) and Habo in China (discovered by bedrock mapping of new exposures created after a minor landslide - White et al., 2007). But with an ever-decreasing number of exposed or near-surface porphyry systems being discovered, especially in mature exploration terrains, geological mapping and core logging techniques are now integrated routinely with geochemical and geophysical techniques to help explore for concealed deposits.

Geochemistry

Geochemical exploration techniques for porphyry deposits have been well-established for several decades. Recognition of metal zonation patterns in and around porphyry deposits (e.g., Jerome, 1966; Chaffee, 1976; Jones, 1992) has guided geochemical surveys for porphyry deposits, irrespective of the techniques used (rock chip, stream sediment, soil, rotary air blast or other sampling methodologies), but new advances in exploration geochemical sampling technologies (e.g., mobile metal ions) are not known to have played any significant role in porphyry discoveries.

Sulfur Isotopic Zonation Patterns

Although commonly used as a research tool in ore genesis, recent studies of the sulfur isotopic compositions of sulfide minerals in porphyry systems have shown them to have potential as a tool in exploration vectoring. At the E26 (Heithersay and

Walshe, 1995; Radclyffe, 1995), Cadia (Harper, 2000; Wilson, 2003; Wilson et al., 2007b), Didipio (Wolfe, 2001), El Teniente (Cannell, 2004), Rio Blanco (Frikken et al., 2005) and Mt Polley (Deyell, 2005, Figure 2) porphyry deposits, detailed studies have shown that the sulfur isotopic compositions of sulfide minerals (bornite, chalcopyrite, pyrite) are zoned systematically around the high-grade core of each deposit. Most of these porphyry deposits have sulfides with strongly negative sulfur isotopic compositions in their cores, and with near-zero values on their peripheries. At Cadia East, Wilson et al. (2007b) detected a core zone of 34Ssulfide values below -3 ‰ centered on the intrusive complex that extended over 1.5km vertically, and for more than 300 m laterally. The anomalous 34Ssulfide halo defined by values lower than -2 ‰ extends for more than 600 m laterally at its widest point (Wilson et al., 2007b). The significance for exploration is that this discovery provides another vector toward the mineralized centre. Detection of negative sulfur isotopic compositions from pyrite encountered during drilling of propylitic-altered rocks is a favorable indicator of proximity to an oxidised fluid source, which has the potential to be a well-mineralized porphyry deposit. Sulfur isotopic analyses of sulfides can therefore be used to augment the information gained from drilling, and can provide encouragement for persistence in exploration.
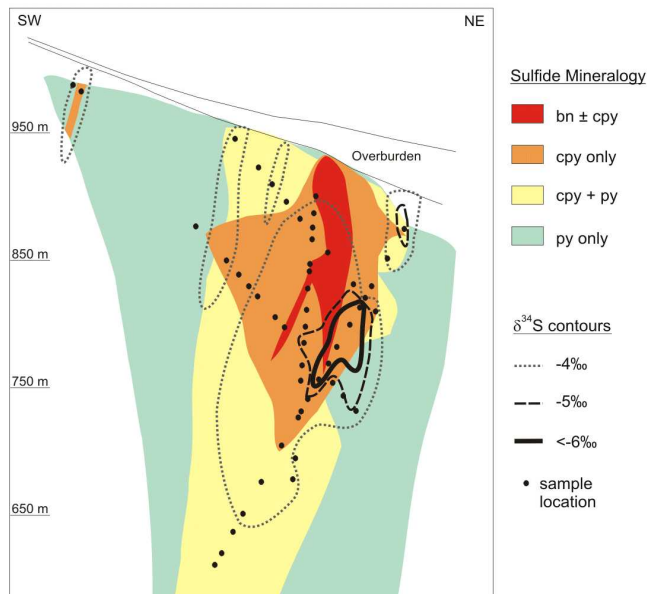
Figure 2: Schematic cross-section through the NE zone, Mt Polley, British Columbia, showing sulfide mineral zonation and contours of $\delta^{34}S_{cpy}$ data. Modified from Deyell (2005).

Geophysics

Geophysics has long been used in porphyry exploration. The porphyry model provides clear guidance (Figure 1) about the possible physical property contrasts caused by intrusive activity, hydrothermal alteration and mineralization during the formation of a porphyry deposit. Thus, the model provides a powerful guide for the selection of geophysical methods, their appropriate use and their interpretation.. However, the large scale of the alteration, metal and fracture zonation patterns about porphyry systems has had the effect that most known porphyry deposits, particularly exposed deposits, were found by combined geological/geochemical methods rather than geophysics (Sillitoe, 1995b). Geophysics has thus in the past been less relevant in porphyry exploration than, for instance, in the search for volcanogenic massive sulphide deposits, the latter which commonly provide discrete, high physical property contrast targets particularly suited for direct geophysical detection.

Magnetics

Magnetics has a dual role in exploration, firstly it serves as a tool for guiding geological mapping and secondly it is a direct detection tool for deposits with magnetic signatures. As a mapping tool, magnetics has the potential to greatly improve the coverage and quality of a standard geological map in all but areas of extensive, unweathered outcrop. Therefore, the use of detailed airborne magnetic data has advanced such that it has become a standard process in regional exploration in mature exploration areas such as Australia, with the data often provided by government geological survey groups or multi-client airborne contractor surveys. In the Lachlan Fold Belt (LFB) porphyry province of Eastern Australia an extensive, covered volcano-intrusive belt hosting the Goonumbla/Northparkes (Jones, 1985) and Marsden (Holliday et al., 2006) porphyry deposits would not have been discovered without regional aeromagnetic data (Figure 3).
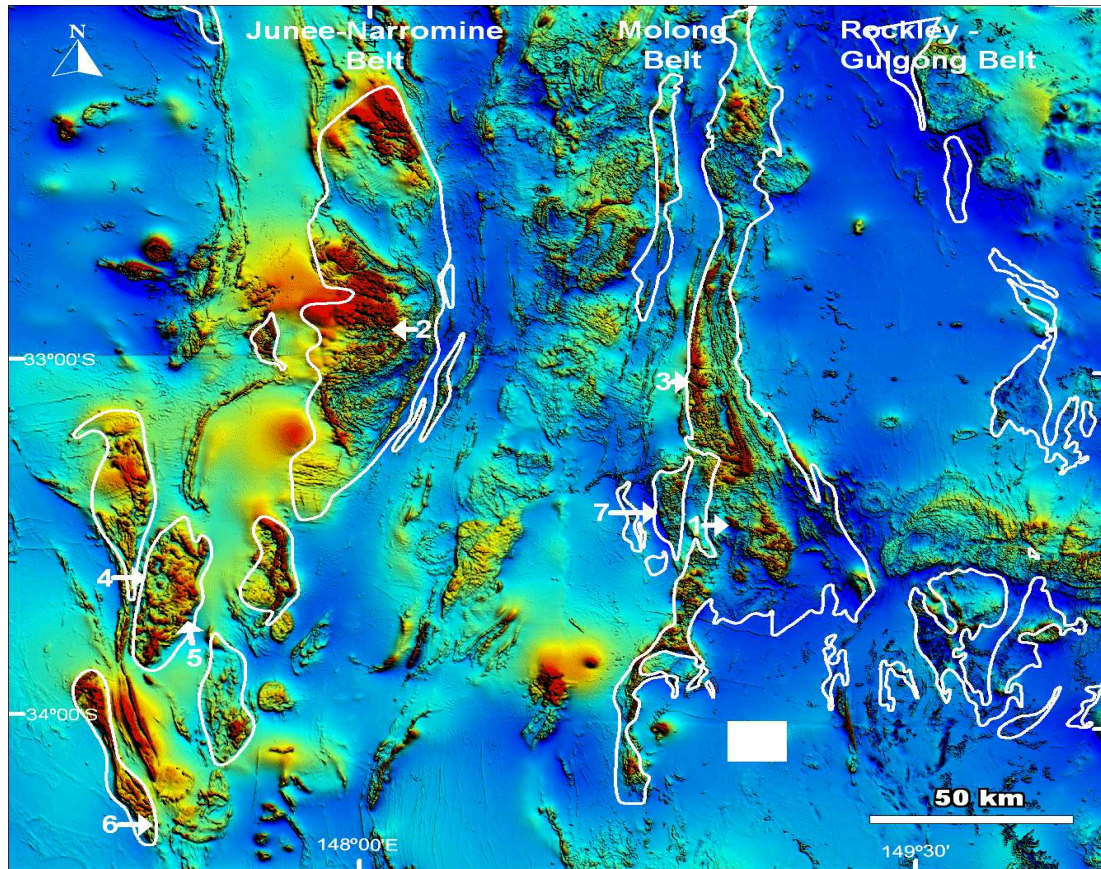
Figure 3: Total magnetic intensity image of the eastern Lachlan Fold Belt, Australia showing the Ordovician-early Silurian volcanic-intrusive belts and known porphyry deposits. The western Junee-Narromine Belt is almost totally without outcrop and was only recognised from the magnetic data. The largest and currently producing porphyry deposits are Cadia (1) and North Parkes (2). Other porphyry deposits are Copper Hill (3), Cowal E39 (4), Marsden (5), Gidginbung-The Dam (6) and Cargo (7). Magnetic data from Australian and NSW governments. Colour range is red for high TMI to deep blue for low TMI.

At the district and prospect scale magnetic physical property contrasts predicted by the porphyry model include those related to intrusive activity, as many of the intrusive complexes driving porphyry mineralization will be to some extent magnetic and will contrast either positively with volcanic and sedimentary host rocks, or negatively with highly magnetic volcanic host rocks. Hydrothermal alteration in porphyry systems can provide distinct signatures for instance, magnetite in K silicate alteration zones in the core of the system (e.g.: Oyu Tolgoi), intense magnetite replacement in peripheral skarns (e.g.: Grasberg district, Ok Tedi, Cadia district), and magnetite alteration or destruction in volcanic rocks adjacent to intrusions.

The Cadia district helimagnetics survey (Figure 4) illustrates all these features. Distinct strong highs occur over the outcropping Big and Little Cadia skarns. To the west the Cadia Ridgeway deposit lies in a strong magnetic complex, which originally drew exploration attention to that area because the complex was thought to possibly be caused by a concealed skarn. It is now known that the complex is predominantly caused by magnetic intrusions and magnetite alteration of volcanics in the upper 250 m and that the deposit at 500 m depth does not give a response recognizable at surface despite the intensity of the magnetite alteration within it (Close, 2000). The magnetic

anomaly immediately east of Cadia Hill is caused by the contrast in susceptibility between the slightly magnetic Cadia Hill Monzonite and the roof pendant and surrounding magnetite altered host volcanic rocks. At Cadia East the only magnetic anomaly is caused by relatively near-surface magnetite alteration of volcanic rocks just to the north of the deposit. The Cadia East deposit, whilst magnetic at depth, has no magnetic response because of intense, magnetite-destructive phyllic alteration in its upper part and 60-200 metres of non-magnetic cover.

Despite the complexity of anomaly sources, the magnetic survey at Cadia proved to be at least equally important as geological mapping as a guide in the early drilling of the deposits, and the data are much more revealing of the district structural patterns than outcrop mapping. This indicates that a detailed district-scale magnetic survey (airborne or ground) is a sound investment at an early stage of a porphyry exploration program, and the increasing use of these surveys is a clear evolutionary advance in recent porphyry exploration. Waters (2004) noted the usefulness of aeromagnetic data in a porphyry exploration program in the Baguio District, Philippines and Kirwin (2003) mentioned the use of magnetic surveys at Oyu Tolgoi, Mongolia.
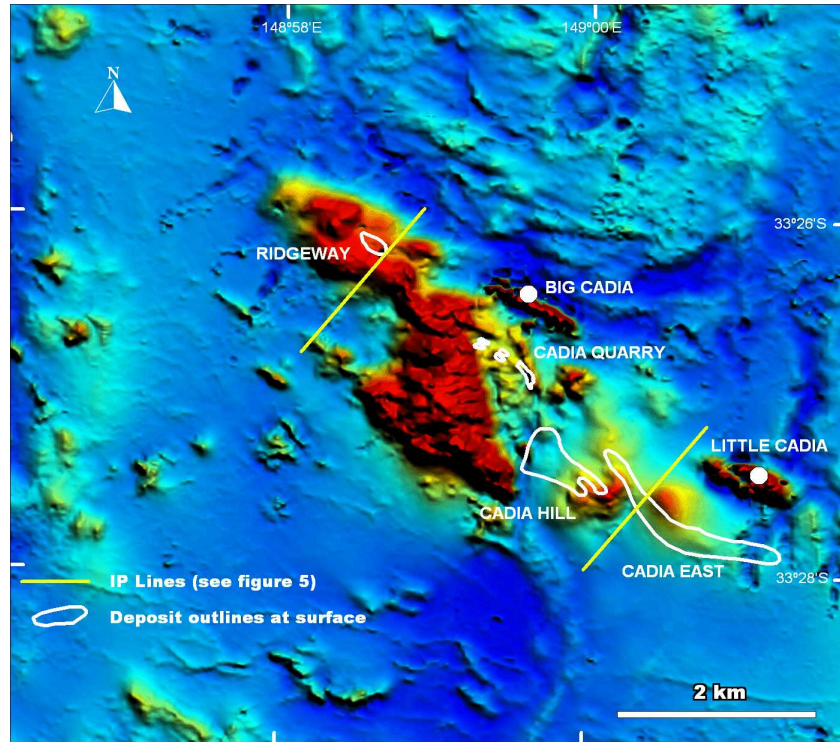
Figure 4: Reduced-to-the-pole magnetic image of the Cadia District, Australia showing the position of the Cadia deposits. For discussion of the relationships between the deposits and the magnetic features see the main text. Flight line spacing is 50m at 30m flying height. Data from Newcrest Mining Limited. Colour range is red for high TMI to deep blue for low TMI.

One clear limitation of magnetics, illustrated by the Cadia survey, is the declining resolution of the method at depth. With increasing depth below surface, more pronounced and extensive susceptibility contrasts between sources are required to produce anomalies readable at or above surface. One way to partially overcome this issue as exploration proceeds is to measure downhole magnetic susceptibility either by downhole probe logging or by magnetic susceptibility meter on drill core or chips. Three-dimensional patterns of susceptibility established by these means enable or assist correlation of lithology between holes and help build a pattern of overall magnetite zonation which will usually be a reliable guide to the general hydrothermal alteration pattern in a porphyry system. State of the art porphyry core logging and interpretation systems now incorporate this approach.

An area of ongoing development with magnetic data in porphyry exploration is the increasing use of forward modelling and inversion software to produce a predictive model from the initial survey data set. Oldenburg et al. (1997) give an early example of this from the Mt Milligan, British Columbia porphyry deposit. Research is now focusing on constraining magnetic models with geological and susceptibility information obtained during drilling campaigns.

Gravity

The porphyry model can be used to predict that there may be significant, sharp density contrasts between intrusive and country rocks, but that recognizable contrasts related directly to alteration and mineralization are much less likely because these features usually have disseminated character and diffusive boundaries. As well as these interpretation issues, there are the practical difficulties that, gravity data can be adversely affected by topographic and/or bouger correction noise. Further, these data cannot be collected relatively cheaply in as detailed a pattern as, for example, magnetic data. For these reasons the gravity method is not commonly a significant part of porphyry exploration programs except at the regional geological interpretation level. As an example of this, in the LFB, Jones (1985) suggested that a broad gravity low over the Goonumbla porphyry field is due to the density contrast between monzonites and andesites, and since then gravity lows have been considered a positive prospectivity indicator in that geological province. Regional gravity data also can aid in defining tectonic features such as covered basins and in interpreting the thickness of the cover and structures underneath the cover. In this role it may become increasingly used in areas such as the Andes and south-west USA as outcropping areas become fully explored.

A major increase in the use of detailed gravity data in porphyry exploration is only likely to occur if the method can be used as cheaply and effectively as magnetics. For ground gravity the advent of differential geographical positioning system (GPS) surveying and digital gravity meters has improved the cost situation by eliminating the need for theodolite leveling and greatly speeding up the rate of data collection. However, it is airborne gravity which holds the most promise if the cost per line kilometre decreases significantly over time, which is likely to happen in the long term. The airborne gravity gradiometer systems recently commercially available have demonstrated the

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effective collection of detailed data in a wide range of exploration applications and could potentially be very useful in porphyry settings at both the regional and prospect scale. If detailed airborne gravity datasets were commonly collected it would then become useful to interpret them with the assistance of forward model case studies of deposits. These could be created by using the commonly large specific gravity measurement databases acquired on deposits for resource modelling purposes.
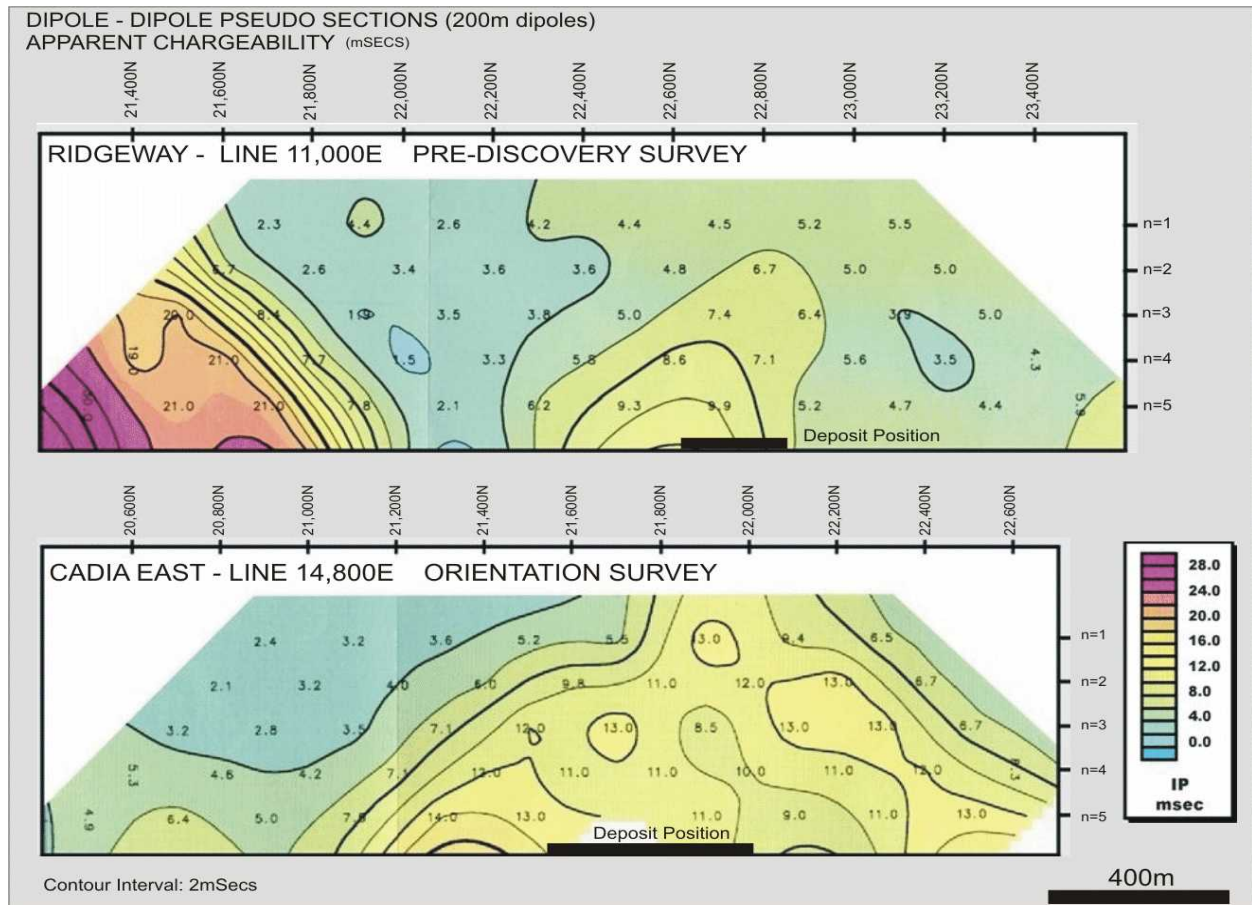
Induced Polarization (IP)

Induced Polarization has a long history of use in porphyry exploration because it is particularly suited to detecting large bodies of disseminated sulphide mineralization and, if used extensively, to producing a three-dimensional sulphide distribution map of a prospect area. It is an excellent method for detecting sub-surface phyllic zones within porphyry systems because these zones usually have the highest sulphide content, mainly pyrite.

Despite this it has never been credited as the major discovery method for a porphyry discovery since 1970 (Sillitoe,

1995b, Sillitoe, 2000b), but in two recent discoveries (Cadia Ridgeway, Hugo Dummett, Table 1), drill targeting of IP anomalies led to the drillhole geological/geochemical vectoring that made the actual discoveries. Induced Polarization anomalies, interpreted in sound geological terms in accordance with the porphyry model have, therefore, been the trigger for successful drilling programs.

At Cadia Ridgeway a 200 m dipole-dipole survey conducted and processed in a conventional fashion was interpreted with the goal of looking for deep, subtle chargeability anomalies possibly indicative of a large, Cadia East-type phyllic alteration sulphide assemblage. The best such anomaly when subsequently drilled (Figure 5) has since been recognized to be largely due to a sulphide halo well above the deposit (Holliday et al., 1999; Close, 2000), and the deposit itself has proven to be much smaller and to have a different alteration zonation than Cadia East (e.g., Wilson et al., 2007a, b). Model work by Close (2000) has shown that the deposit is likely to have contributed to the target anomaly, but because the deposit is 500 m below surface, its contribution to the anomaly is unrecognizable in the real exploration context.
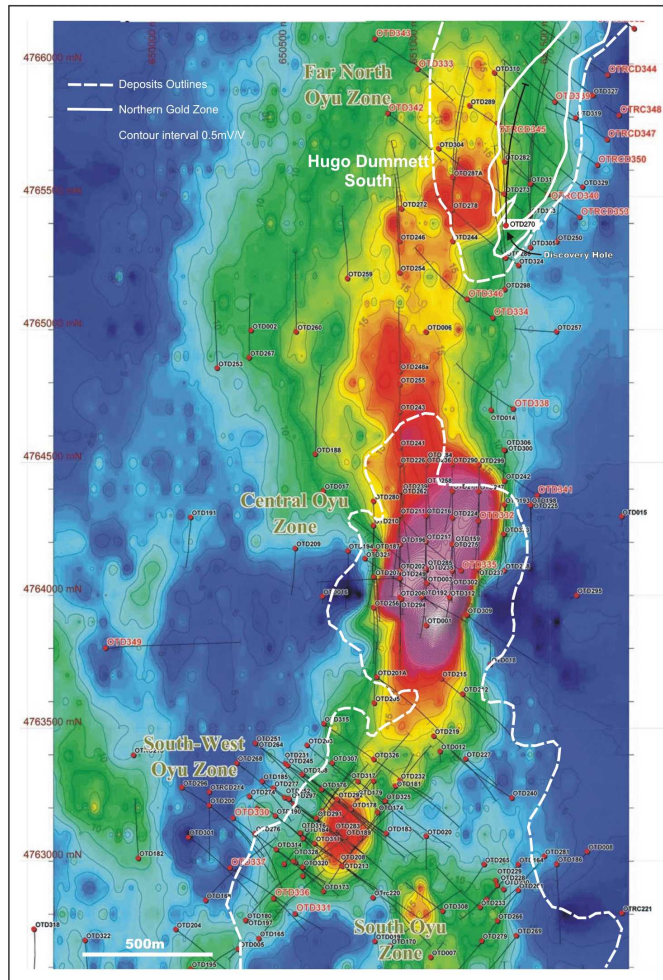

Figure 5: Induced Polarisation chargeability pseudo-sections from the Cadia deposits, Australia showing an orientation survey over Cadia East and a subsequent survey over Cadia Ridgeway prior to its discovery. The anomaly at Ridgeway was interpreted to be a Cadia East type response and consequently was drill-tested. Data from Newcrest Mining Limited.

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At Oyu Tolgoi, Mongolia an early gradient array IP survey on north-south lines recorded an annular chargeability anomaly which was the focus of a follow-up drilling program. The last hole of the program, extended northwards beyond its target depth for stratigraphic reasons, is credited as the discovery hole for the Hugo Dummett South deposit. A subsequent gradient array survey on E-W lines produced a very different anomaly extending the length of the Oyu Tolgoi field (Figure 6). The anomaly flanks the western side of the Hugo Dummett deposit and is caused by pyrite-rich mineralization (Kirwin et al., 2003).

Recent and emerging technological advances with the IP method include 3D pole-dipole acquisition (Collins and White, 2003), distributed data acquisition (Ritchie and Sheard, 1999, Goldie, 2007), and 3D forward modelling and inversion (Oldenburg et al., 1998). A combination of these advances used in conjunction with astute geological interpretation holds the promise of significant improvement in the usefulness of IP for porphyry exploration. Distributed acquisition IP is known to have been used recently with success over porphyry systems at Kemess North, British Columbia (Figure 7), and also at Resolution, Arizona although the results remain proprietary.

An early example of the use of inversion at the Mt. Milligan, British Columbia porphyry deposit is provided by Oldenburg et al. (1997), who show how 2D IP inversions (composited to 3D) compare with geology and bulk Au content. They also present a cooperative inversion of magnetic and IP data, but do not present a cooperative geology and IP inversion. Cooperative geology and IP inversions are presently a cutting edge research topic, but hold the promise of significant improvement in interpretation at exploration sites where drilling has advanced sufficiently that down hole rock property information is available. For IP this information can be from down hole sulphur assays obtained inexpensively by ICP analytical methods, or by visual estimates of sulfide contents made during core logging. The rock property information can be used in conjunction with geological interpretation and porphyry model concepts to provide constrained starting models for the inversion process and thus a more realistic outcome.

Figure 6: Induced Polarisation gradient array chargeability map from the Oyu Tolgoi deposits, Mongolia showing drillholes and deposit outlines. Survey details are: current electrode separation 4800m, potential electrode separation 100m on 100m-soaced east-west lines. Data from Ivanhoe Mines Ltd.
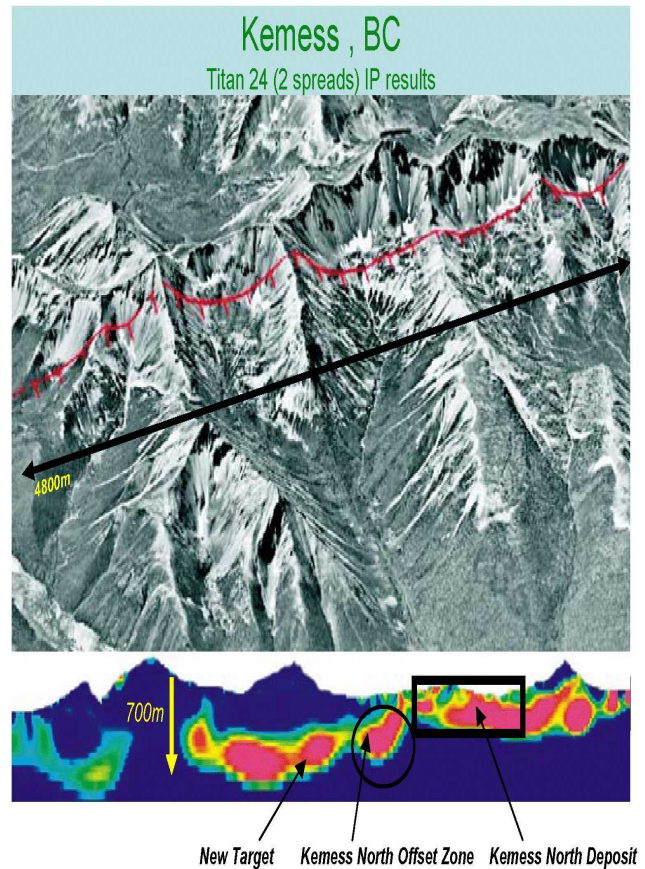
Figure 7: Induced polarisation results from Kemess North, British Columbia collected by the Quantec Titan proprietary distributed acquisition system. The survey outlined new targets for drilling at considerable depths to the east (left on the figure) of Kemess North. Data from Northgate Minerals Corporation.

Radiometrics

Radiometric data, usually collected in conjunction with magnetic data during airborne surveys, are an excellent aid to geological mapping, and in porphyry settings a radiometric survey can quickly identify both potassic intrusions and potassic alteration zones if they are at surface. Generally, however, in areas of good outcrop these indicators have already been detected by geological work, so surface radiometric methods have rarely, if ever, had a major role in porphyry exploration.

Spectral Scanning Methods

Airborne multi-spectral scanning methods have also not had a major role in porphyry exploration, although this technique can discriminate complex phyllosilicate alteration assemblages much more efficiently than any geological mapper, something which can be very important in porphyry lithocap settings. The more standard approach in these settings is to use hand-held devices (e.g., PIMA® or ASD Fieldspec Pro®) on rock samples and drill core.

A significant development in this direction is the HyLogger™, a semi-automated core logging device which combines rapid hyperspectral mapping of mineralogy and very high resolution imaging of cores (Huntington et al., 2006). The device can identify phyllosilicates, amphiboles, carbonates, sulfates and iron oxides, and with the recent addition of scanning in the thermal infra-red spectral range will recognise quartz, feldspars, garnets, olivines and pyroxenes. The ability to rapidly

(~100 core trays per day) and objectively collect such data (Figure 8) and then interpret these data in terms of alteration zones utilizing the porphyry model would be a significant advance for exploration targeting in an advanced porphyry exploration project, and may be of particular benefit for targeting mineralized zones within or beneath lithocaps.

Other Geophysical Methods

Resistivity has always been an adjunct measurement during IP surveys for porphyry exploration but it has not been a significant discovery tool because conductivity contrasts tend to be moderate and diffusive in the porphyry environment. For the same reason, EM methods have not been extensively used in porphyry exploration.

A recent development is the co-acquisition, during distributed acquisition IP surveys, of DC resistivity and magnetotelluric (MT) resisitivity data. Unsourced reports claim that large, known porphyry systems at greater than 1000 m depth below surface can be detected by this method, but the MT data from these surveys remains proprietary.

Holliday et al. (2006) document a rare use of seismic methods in porphyry exploration to aid in locating the faulted-off lower portion of the Marsden, Australia porphyry deposit. It is possible that the use of seismic methods will increase in covered areas where strata generally dip less than 45º, with the aim of determining cover thickness, volcanic architecture beneath the cover and overall structural architecture.
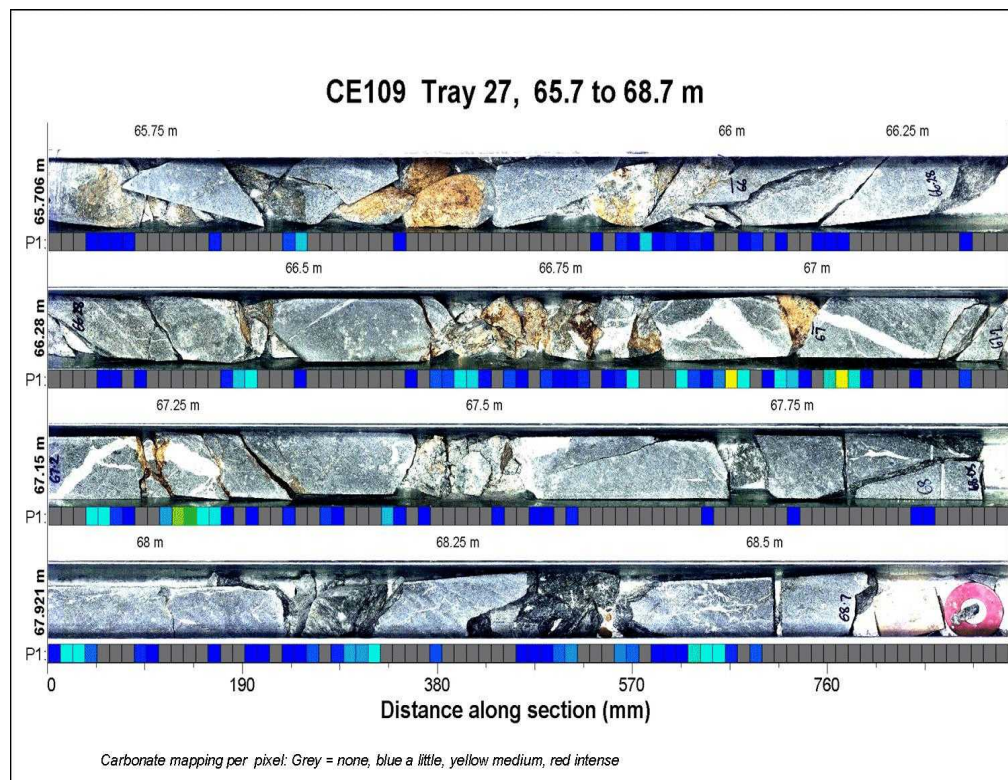
Figure 8: High resolution scanned core from the Cadia East deposit, Australia showing carbonate distribution as semi-automatically mapped using the Hy-Logger core logging device. Data from CSIRO Australia.

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Drilling

The large alteration, metal and fracture zonation patterns associated with porphyry deposits, together with the understanding of them provided by the porphyry model, facilitate the effectiveness of drilling as an exploration data collection technique (as compared to a purely target testing technique) in porphyry exploration more than in the exploration for most other deposit types.

Drilling methods used include soft cover drilling (air core, rotary air blast, rotary with muds) to collect what are effectively a pattern of rock chips samples from hard basement rocks, to hard rock drilling (reverse circulation, core) in patterns where cover sequences are hard or the mineralized areas are suspected to be at considerable depth. Deposits found by these methods include Marsden, Australia (Holliday et al., 2006) and Spence, Chile (Rio Algom, 1999).

Drilling has also been very successfully used in an information gathering sense to vector ongoing drilling towards the economically mineralized zones at the major discoveries at Cadia Ridgeway (Holliday et al., 1999), Cadia East (Tedder et al., 2001), Resolution (Manske and Paul, 2002), Hugo Dummett, Mongolia (Kirwin et al., 2003), Pebble East, Alaska (Rebagliati and Payne, 2005) and Bayugo, Philippines (Waters, 2004). In all these cases it was the geological (alteration patterns, fracture and veining intensities) and geochemical information collected by drilling and then interpreted with varying skill and degrees of success that led to the commitment to continue to drill additional holes either deeper or laterally towards the ultimate ore discovery.

As specific examples, Figure 9 shows the pattern of drilling as it progressed to depth at Cadia Ridgeway. RC hole 1 (RGRC1) targeted at an IP anomaly intersected a "leakage" vein some 400 m above the deposit. Follow-up core drilling progressed deeper based on following increasing Cu contents, quartz veining and alteration patterns (particularly hematite reddening of feldspars) until the discovery with core hole NC498. Figure 10 shows the 2004-2006 drilling at Pebble East. The recognition in 2004 drillholes of increasing quartz stockwork, potassic alteration and Cu-Au-Mo grades at the edge of Pebble West suggested to the exploration team that there was a new porphyry system to the east under thick Tertiary cover. The 2005-2006 drilling proved this prediction.

Significant recent improvements in drill ancillary tools for locating and orienting downhole information can greatly assist in applying porphyry model concepts. Specifically, the development of reliable mechanical (e.g., Ballmark™) and accelerometer-based devices for core orientation has made it possible to map vein and fracture orientations over long core intervals if the core recovery is high. Also, gyroscopic downhole surveying has enabled downhole positions to be accurately determined in magnetic parts (e.g., the potassic zone core) of porphyry systems.

Integrated Interpretation

Leading edge exploration and mining software packages with 3D and 4D visualization capability are fast becoming the industry norm and they are particularly applicable for porphyry exploration because of the large scale of porphyry deposits and the extensive range of data that can be acquired within them for interpretative purposes utilizing porphyry model concepts. Full integrated interpretation requires a commitment to the scanning or digitizing of all pre-digital era data from a property and the ongoing digital collection of all mapping, geophysical and drillhole information. A significant issue is the need to always distinguish objective (factual) data from subjective (interpreted) data, particularly with geological information.
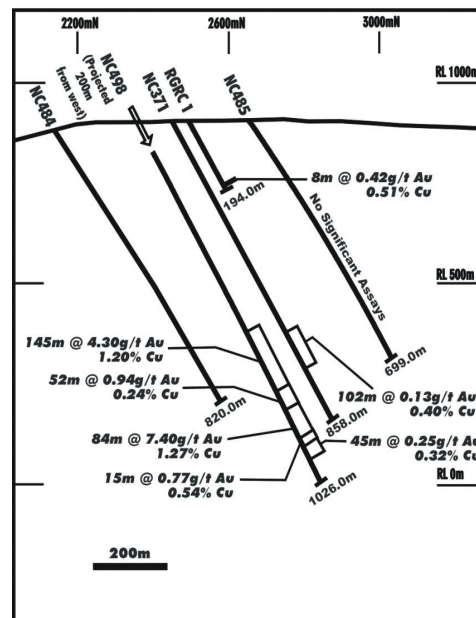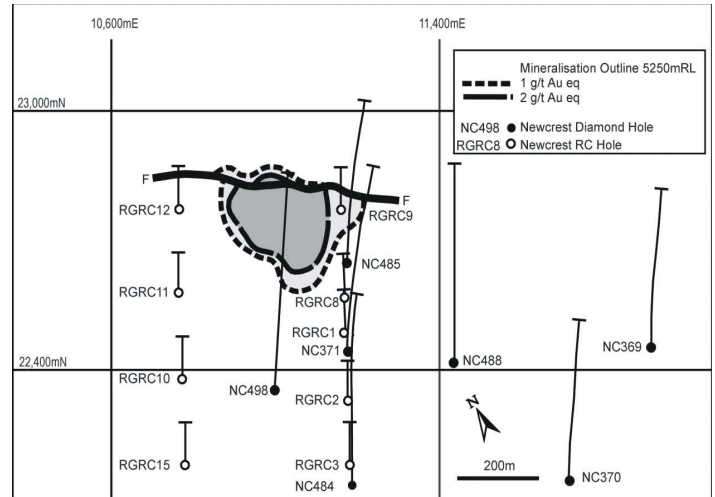
Figure 9: Drill plan and section from the Cadia Ridgeway deposit, Australia from Holliday et al., 1999. The RGRC holes were targeted on an IP anomaly, but only one hole (RGRC1) obtained a significant intersection. The next key hole was NC371, drilled under RGRC1, which initially went to 513.6m, but because of increasing copper grades at the bottom was subsequently deepened to 858.4m, intersecting 102m of near-economic grades. Step-out drilling on roughly 200m centres around NC371 resulted in the discovery on the fourth step-out hole (NC498).
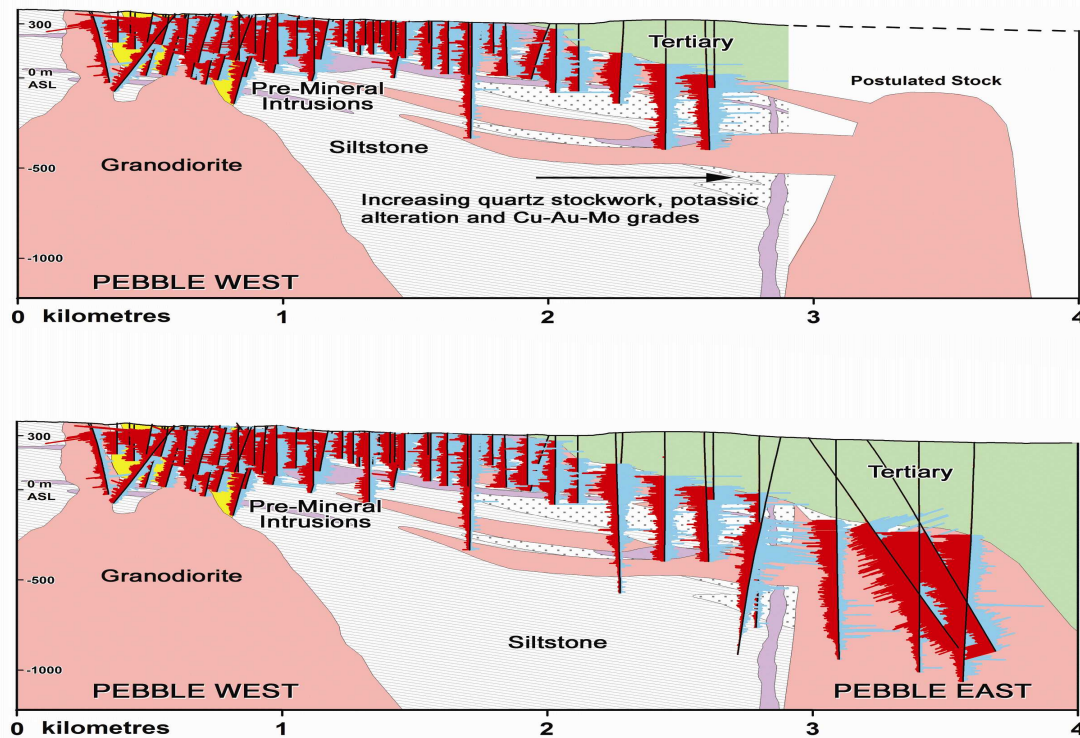
Figure 10: Drill sections across the Pebble West and Pebble East deposits, Alaska from the 2004 season (upper) and 2005-2006 seasons (lower) showing the progression of drilling eastwards based on recognised porphyry indicators, resulting in the Pebble East discovery under thick Tertiary cover. The red bars on the drillholes show the relative Cu grades and the blue bars show the relative Au grades. Data from Northern Dynasty Minerals Ltd.

CONCLUSIONS

A number of observations about porphyry discovery can be made from the above summaries and Table 1, particularly when they are compared with the information covering a longer timeframe provided in Sillitoe and Thompson (2006).

- More discoveries of porphyry deposits have been made in covered geological settings (e.g.: Spence, Toki, Cadia East, Pebble East, Hugo Dummett) than in the past.
- These covered deposits are mostly being discovered in near-mine (brownfields) areas (e.g.: Toki, Cadia East, Pebble East, Hugo Dummett) rather than virgin (greenfields) areas.
- Deposits are being found at greater depths based on vectoring information only obtainable by drilling (e.g.: Cadia Ridgeway, Resolution). This suggests an increasing use of drilling for data gathering rather than specifically for target testing.
- Exposed deposits are discovered predominantly only in geological provinces that are very under-explored because of their less-favourable geo-political setting.

- Some recent discoveries have unusually high hypogene grades (e.g.: Cadia Ridgeway, Hugo Dummett, and Resolution).

No revolutionary exploration techniques have resulted in a surge in exploration success or refocusing of exploration approaches, rather, discoveries are still made using tried and true techniques that have naturally evolved with developments in technology and accumulating industry knowledge. This is essentially the same conclusion as that drawn by Sillitoe (2000b).

The main trends of this evolution are that drillhole vectoring using downhole geological and geochemical information, and geophysics methods appear to be increasingly important in obtaining exploration success. This is to be expected because as exploration terrains become more mature (e.g.: south-west USA, LFB, Andes) the effectiveness of surface geological and geochemical methods declines markedly as all the outcropping and near surface deposits are found. Further, in the brownfields environment there is a greater commitment to explore and therefore to conduct geophysics surveys and to drill for vector information. In covered environments there is no alternative to these methods apart from purely wildcat drilling.

Table 1

Deposit	Exposed/ concealed	Brownfields/ greenfields	Discovery year(s)	Primary discovery method(s)	Contributory discovery method	Reference
Tampakan, Philippines	Exposed	Greenfields	1992	Geology		Rohrlach & Loucks, 2005
Mt. Bini, Papua New Guinea	Exposed	Greenfields	1992	Geochemistry, geology		Leaman, 1996
Endeavour 48, Australia	Concealed	Brownfields	1992	Magnetics, Drilling through cover		Hooper et al., 1996
Cadia field, Australia Cadia Hill Cadia Ridgeway Cadia East	Exposed Concealed Concealed	Brownfields Brownfields Brownfields	1992 1996 1994-96	Geology, geochem Drillhole geology/geochem Drillhole geology/geochem	IP, magnetics Magnetics	Wood & Holliday, 1995; Holliday et al., 1999, Tedder et al., 2001
Rio Blanco, Peru	Exposed	Greenfields	1994	Geochemistry	Geology	Monterrico Metals Plc, 2007
Sierra Gorda, Chile	Exposed	Greenfields	1992-96	Geology, geochem		Ristorcelli & Ronning, 2005
Spence, Chile	Concealed	Greenfields	1996	Drilling through cover		Sillitoe, 2000b
Gaby Sur, Chile	Concealed	Greenfields	1996	Geology, geochem, drillhole geology/geochem	Magnetics	Sillitoe, 2000b
Resolution, USA	Concealed	Brownfields	1996	Drillhole geology/geochem		Manske & Paul, 2002
Reko Diq, Pakistan	Exposed	Brownfields	1996	Geology, geochem	Magnetics, IP	Tethyan Copper Company reports to ASX
Galeno, Peru	Exposed	Brownfields	1997	Geology		Northern Peru Copper Corp., 2007
Marsden, Australia	Concealed	Greenfields	1997	Drilling through cover	Magnetics	Holliday et al., 2006
Antapaccay, Peru	Concealed	Brownfields	1998	Drilling	Geology, geochem, magnetics, TEM	Sillitoe, 2000b
Esperanza, Chile	Exposed	Greenfields	1999	Geology	Magnetics	Perello et al., 2004
Oyu Tolgoi field, Mongolia Southern Oyu Hugo Dummett	Exposed Concealed	Greenfields Brownfields	1997-2001 2002	Geology, geochem Drillhole geology/geochem, IP	Magnetics Magnetics	Kirwin et al., 2003
Toki cluster, Chile Toki Quetena Genoveva Genoveva Deep Opache	Concealed	Brownfields	1999-2005	Drilling through cover	Geology interp,	Rivera, 2004 Rivera & Pardo, 2004 Rivera et al., 2003 Sillitoe & Thompson, 2006 Camus & Rivera, 2006
Boyongan, Philippines	Concealed	Greenfields	2000	Geology, drilling through cover		Waters, 2004
La Fortuna, Chile	Exposed	Greefields	2000-2001	Geology	Magnetics, IP, geochemistry	Lightner, 2001
Bayugo, Philippines	Concealed	Brownfields	2003	Drilling through cover, drillhole geology/geochem		Waters, 2004
Pebble East, USA	Concealed	Brownfields	2005	Drillhole geology/geochem		Rebagliati & Payne, 2006
Inca de Oro, Chile	Concealed	Brownfields	2005	Drilling through cover	Reinterpretation of old data	Rivera, 2007
Xietongmen, China	Exposed	Greenfields	2000-05	Geology, geochem		Rebagliati & Laing, 2006

IP = induced polarization; TEM = transient electromagnetics; geochem = geochemistry.

The challenge for all explorers is to not only make a discovery, but to react competitively to industry trends so as to make the discovery ahead of all others. We suggest that the successful explorers will tend to be those who strive to make the most effective use of a broad combination of the exploration methods available. In this regard we suggest that, not only in covered provinces, but also in areas of abundant outcrop and/or less explored porphyry provinces (e.g.: Andes, central Asia) the earlier acquisition and use of semi-detailed regional geophysics, particularly airborne magnetics and radiometrics, integrated with geological interpretation will result in more rapid discovery rates for porphyry systems.

In newly discovered districts or brownfields settings, approaches such as early surface magnetic and sulphide mapping (IP), downhole magnetic and sulphide logging, comprehensive drillhole geochemistry (broad analytical suites, sulphur isotopes), and objective geological logging of a full range of lithological, alteration and fracture information (including scanned data) will enable a much more efficient exploration of the system, guided by the porphyry model, than would result without this information.

ACKNOWLEDGEMENTS

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