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CUMULATIVE FACTORS IN THE GENERATION OF GIANT CALC-ALKALINE PORPHYRY Cu DEPOSITS

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Abstract - The formation of porphyry Cu deposits in calc-alkaline magmatic arcs is considered to be the cumulative product of a wide range of processes beginning with dehydration of the subducting oceanic slab. No single process is key to the formation of large deposits, but the absence or inefficient operation of any contributory process, or the action of a deleterious process, can stunt or prevent deposit formation.

A starting premise is that normal calc alkaline arc magmas have the potential ultimately to form a porphyry Cu deposit (i.e., arc magmas are inherently "fertile"). This characteristic is ascribed to the relatively high oxidation state and high H_2O, Cl, and S contents of typical arc magmas (metal contents do not need to be anomalously enriched). Given the availability of such magma, the next most important factor in the formation of large porphyry Cu deposits is the flux of this magma reaching the upper crust. The supply of magma must be sufficiently voluminous and localised to maintain an active upper crustal magma chamber of $\geq$100 km^3 in order for enough Cu (and S) to be available for extraction by magmatic hydrothermal fluids. These requirements imply a long-lived magmatic system rooted in the supra-subduction zone mantle wedge, with the formation of an extensive lower-crustal melting and assimilation (MASH) zone. Compressional tectonic regimes are thought to favour the formation of such magma bodies as sill complexes deep in the lithosphere. Relaxation of compressional stress permits the voluminous rise of buoyant, evolved magmas to upper crustal levels, and explains the common occurrence of porphyry Cu deposits at the end of protracted tectono-magmatic events. Pre-existing zones of structural weakness in the crust facilitate magma ascent, and dilational volumes at transpressional jogs and step-overs in strike-slip fault systems provide optimal conditions for focused flow and emplacement. The geometry of the upper crustal magma chamber so formed includes a cupola zone (commonly $\leq$2 km depth) into which bubble-rich, buoyant magma rising from depths of >5 km convectively circulates, releasing its volatile load into the overlying carapace. This fluid dynamic mechanism enables efficient partitioning of metals from a large volume of magma into the exsolving hydrothermal fluid, and achieves focused delivery of that fluid into the carapace zone. Cooling of the fluid and wallrock reactions result in efficient precipitation of metals in association with potassic and, in some deposits, phyllic alteration.

Ore-forming potential may be spoiled by tectonic conditions and histories that do not focus magma generation and emplacement, crustal conditions (such as the presence of reduced lithologies in the deep crust) that cause early sulphide saturation and segregation, or catastrophic explosive volcanism that destroys the magmatic-hydrothermal ore-forming process by venting fluids directly to the surface.

Exploration indicators for large porphyry Cu deposits include the development of a well-established magmatic arc with concentrations of sub-volcanic plutonic centres, localised by large-scale structural features.

Introduction

Porphyry Cu-(Mo-Au) deposits, henceforth referred to as porphyry Cu deposits, are formed by hydrothermal fluids exsolved from subduction-related arc magmas. Porphyry Cu deposits are found in association with magmatic arcs worldwide, but large deposits tend to be clustered in both space and time (Clark, 1993). The host magmatic systems tend to be of felsic to intermediate calc-alkaline composition, although these upper crustal magmas are derivative from more mafic, ultimately mantle-derived, sources. Indeed, more mafic (dioritic) host rocks commonly occur in island arc settings where the crust is thinner (implying less differentiation and crustal interaction), and more alkaline (shoshonitic) intrusions occur in back-arc settings where rapid magma ascent from depth is facilitated by extensional tectonics. There is a general tendency, with many exceptions, for the latter two deposit associations to be relatively Au-rich (Kesler, 1973; Kesler *et al.*, 1977; Jones, 1992; Sillitoe, 1989, 1993, 1997, 2000; Lang *et al.*, 1995).

A fundamental tenet of this paper is that the formation of calc-alkaline porphyry Cu deposits is a normal, if rare, product of arc tectono-magmatic processes (Burnham, 1981; Cline and Bodnar, 1991; Cline, 1995). The rarity of large porphyry Cu deposits is interpreted to be not so much a function of unique events, as a fortuitous convergence of common processes that act together or cumulatively to optimise conditions for ore formation. In this paper the terms "large" and "giant" deposits are used in a general sense to describe unusually large systems in terms of their metal content. Note, however, that the word "giant" has been given specific meaning by Clark (1993; following the National Academy of Sciences, 1975), and refers to deposits containing 3.2 to 10 Mt (ie. million tonnes) of Cu ("super-giant" deposits contain 10 to 31.2 Mt Cu, and "behemothian" >31.2 Mt Cu). Examples of porphyry Cu deposits containing >10 Mt Cu include Chuquicamata, El Abra, La Escondida and El Teniente in Chile, Cerro Colorado in Panama, Grasberg in Indonesia, Sar Cheshmeh in Iran, Cananea in Mexico, and Bingham Canyon in the USA (Clark, 1993).

This paper reviews the range of processes that affect arc magmas and their exsolved hydrothermal fluids from magmagenesis to mineral precipitation, and discusses how these factors contribute to ore-forming potential. Such processes control the total metal content of the deposits, and also the hypogene grade and metal ratios. Ultimately however, the economic value of a porphyry Cu deposit may have little to do with the size of the hypogene system, but instead may be controlled by post-emplacement processes such as uplift, erosion, and weathering history. These secondary aspects of ore deposit evolution are beyond the scope of this paper.

Sources and Characteristics of Primary Arc Magmas

Slab Dehydration, Mantle Metasomatism, and Partial Melting

Calc-alkaline arc magmas are believed to be derivative from primary melts generated in the asthenospheric mantle wedge above a subducting oceanic plate (Fig. 1; Tatsumi *et al.,* 1986; Peacock, 1993; Arculus, 1994). The unique chemical characteristics of arc magmas, such as their high H_2O and sulphur contents, high large-ion lithophile element (LILE: Rb, K, Cs, Ba and Sr) concentrations, enrichments in Li, B, Pb, As and Sb, and relative depletions in Ti, Nb and Ta, are attributed to metasomatism of the mantle wedge by fluids released from the subducting slab (e.g., Davidson, 1996; Noll *et al.,* 1996; de Hoog et al., 2001). High-pressure (~3 GPa), low-temperature (700-800°C) metamorphic conversion of the oceanic crust from blueschist to eclogite facies rock at a depth of ~100 km involves the breakdown of hydrous minerals such as serpentine, amphibole, zoisite and lawsonite (Tatsumi, 1986; Schmidt and Poli, 1998; Winter, 2001; Forneris and Holloway, 2003) with the release of a fluid phase enriched in water-soluble elements (LILE, sulphur, halogens). These fluids infiltrate and hydrate the

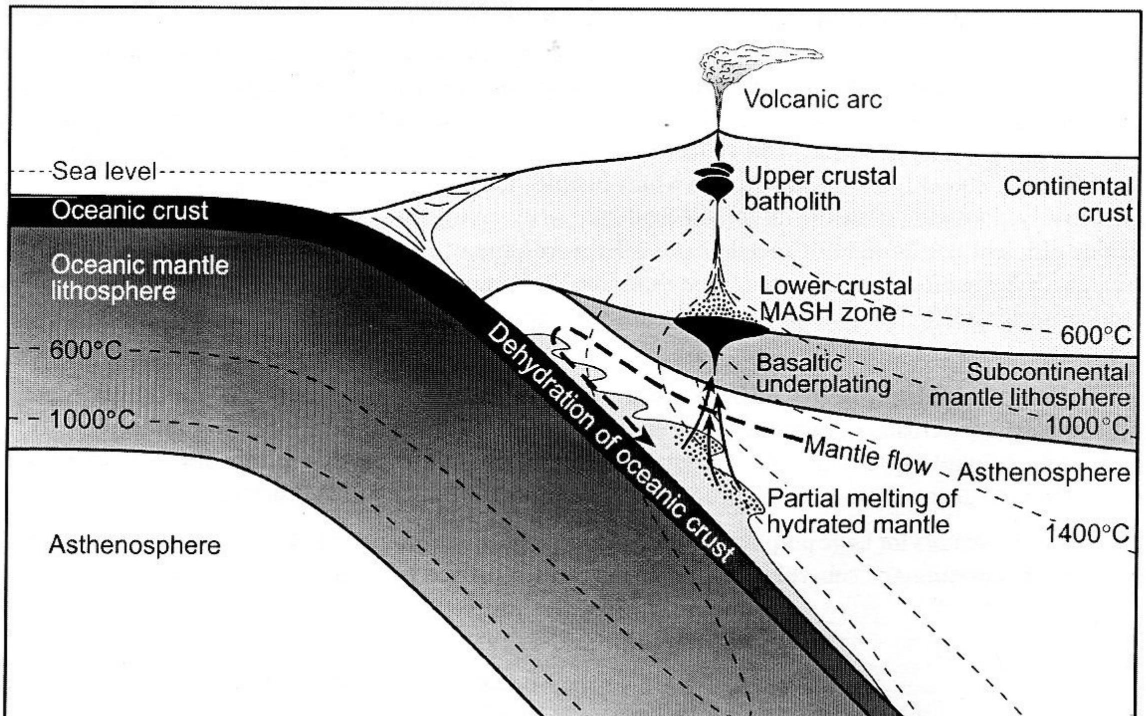

Figure 1: ***Structure and processes in a subduction zone and continental arc*** (modified from Winter, 2001, and Richards, 2003a). Primary arc magmas are derived from partial melting of the metasomatised mantle wedge. Pooling of these mafic magmas at the base of the overlying crust results in crustal melting and assimilation, with storage and homogenisation in large lower crustal sill complexes (MASH process). After evolution to less dense compositions, intermediate-composition magmas rise to upper crustal levels. 20% of these magmas may crupt at the surface.

overlying mantle, thereby lowering its solidus temperature and making it more susceptible to melting. Convection of this hydrated material into warmer parts of the mantle wedge (>1000°C), or direct fluid infiltration, results in partial melting to form primary arc magma.

Analyses of primitive (minimally evolved) magmas from island arcs suggest that the primary magma composition is a high-Mg basalt with 1.2-2.5 wt. % H_2O (Arculus, 1994; Sobolev and Chaussidon, 1996).

Slab Melting (Adakites)

Primary magmas in subduction zones may also be generated under certain conditions by direct melting of subducting oceanic crust, producing adakites. Adakitic magmas have recently been implicated in porphyry Cu deposit formation by some authors (e.g., Thiéblemont et al., 1997; Oyarzun *et al,* 2001). Normally, the geothermal gradient followed by the slab does not reach high enough temperatures at shallow enough depths for melting to occur, and the slab instead undergoes dehydration (as described above). However, under conditions of high-temperature, shallow, or stalled subduction, wherein the slab resides at shallow depths for extended periods of time and warms more extensively, melting of the metamorphosed basaltic crust has been proposed to occur (Defant and Drummond, 1990). Such conditions are favoured by the subduction of young (≤25 m.y.-old) and therefore buoyant oceanic lithosphere (Defant and Drummond, 1990; Peacock et al., 1994), where the plate is torn at discontinuities in subduction angle (Yogodzinski *et al.,* 2001), or during tectonic reconfigurations such as subduction zone reversal, arc migration, or arc collision.

Slab melts have been modelled as having high-alumina andesitic to dacitic bulk composition, and are characterised by low Y and heavy rare earth element (HREE), and high Sr concentrations, due to the presence of residual hornblende and garnet in the eclogitic source rock (e.g., $SiO_2 \geq 56$ wt.%, $Al_2O_3 \geq 15$ wt.%, MgO usually < 3 wt.%, Y ≤ 18 ppm, Yb ≤ 1.9 ppm, Sr ≥ 400 ppm; Defant and Drummond, 1990).

Defant and Drummond (1990) based their model of adakite petrogenesis primarily on island arc magmas where contamination from continental crustal sources was absent. However, these same geochemical characteristics can be generated by partial melting of garnetiferous (eclogitic or garnet amphibolitic) lower continental crust, and so the identification of rocks with adakitic chemical signatures in continental arcs is not a proof of origin by slab melting. Oyarzun et al. (2001) proposed that magmas involved in the formation of large Eocene-Oligocene porphyry Cu deposits in northern Chile were derived from slab melts because of their high Sr/Y and La/Yb ratios, but Rabbia *et al.,* (2002) and Richards (2002) argued that these geochemical signatures were imparted by deep crustal processes resulting from progressive thickening of the Andean crust (see also Haschke *et al.,* 2002; Garrison and Davidson, 2003). At present, there is no clear indication that slab melts are critical to the formation of porphyry Cu deposits.

Primary Arc Magmas: Factors Affecting Metallogenic Potential

Porphyry Cu deposits are typically associated with suites of normal calc-alkaline arc magmas, for which partial melting of the metasomatised mantle wedge is the generally accepted origin. Dilles (1987) and Cline and Bodnar (1991) have argued that such magmas are inherently capable of forming economic porphyry Cu deposits (i.e., they are "fertile"), and that special magmas or special magmatic processes are not required.

The chief characteristics that make calc-alkaline arc magmas fertile derive ultimately from the slab dehydration process, which transfers water, sulphur, halogens, LILE, and possibly metals into the mantle wedge. Porphyry Cu deposits are characterised primarily by extreme enrichments in sulphur and potassium (Hunt, 1991) introduced by exsolved saline magmatic fluids, and as such the primary enrichment of arc magmas in these metasomatic components gives them an obvious advantage as potential sources over other common magma types, such as relatively alkali- and volatile-poor mid-ocean ridge basalts (MORB) or ocean island basalts (OIB).

In addition to these elemental characteristics, arc magmas are also relatively oxidised, commonly up to two log f_{O2} units above the fayalite-magnetite-quartz buffer (FMQ+2; Brandon and Draper, 1996; Parkinson and Arculus, 1999; Einaudi *et al.,* 2003). Oxidation of the mantle wedge is another product of aqueous fluid metasomatism. Oxidation state is important because it affects the speciation and solubility of sulphur in the melt, as well as the stability of residual sulphide phases in the mantle. Under oxidising conditions, sulphide phases are increasingly destabilised, and sulphur solubility, as dissolved sulphate species, increases in the melt (Carroll and Rutherford, 1985). For example, Jugo *et al.,* (2001, 2003) have shown experimentally that the solubility of S as sulphate in basaltic melts at mantle pressures can be as high as 1.5 wt. % S under oxidising conditions (≥FMQ+2). The effect is that chalcophile elements (e.g., Cu and Au, which normally partition strongly into sulphide phases relative to silicate magma) will behave as incompatible elements and will dissolve into the melt. Thus, primary arc magmas should contain relatively high concentrations of chalcophile metals compared with other more reduced mantle-derived magmas.

Mungall (2002) has taken this argument a step further and has proposed that adakitic slab melts are particularly effective mantle oxidising agents because they might contain a high content of ferric iron derived from oxidised sea floor basalts. Although this model seems unlikely to be a general cause of metal enrichment in normal calc-alkaline porphyry Cu deposit-forming magmas for the reasons outlined above (i.e., slab melts are of rare and restricted occurrence), such a mechanism may well apply to the formation of unusually Au-rich porphyry deposits formed in atypical arc settings, such as during arc reversal or arc collision, where stalled slabs might undergo partial melting (cf. Solomon, 1990; McInnes and Cameron, 1994; Richards, 1995; Sillitoe, 1997).

Deep Lithospheric Processing of Arc Magmas

Porphyry Cu deposits form both in island arcs with relatively thin mafic crust, and continental arcs with variable to thick felsic crust. This first order relationship suggests that the composition and character of the upper plate lithosphere is not a primary control on the fertility of arc magmas (although it may affect ore metal ratios; e.g., Kesler, 1973). Nevertheless, all arc magmas, even the most primitive, undergo some degree of interaction with the lithosphere during their ascent towards the surface, and in continental arcs it has been estimated that evolved magmas entering the upper crust have undergone tens of percent of crustal contamination (McBirney *et al.*, 1987; Hildreth and Moorbath, 1988). Thus, it is important to consider how processes of crustal interaction might affect the evolution of potentially ore-forming magmas.

In continental arcs, Hildreth and Moorbath (1988) envisaged primitive basaltic magmas intruding the overlying dense mantle lithosphere until they reach the base of the crust (Fig. 1). Being denser than crustal rocks, the magmas pool in sill complexes at this level and conduct heat into the overlying crust as they begin to crystallise. If the magmatic flux is sustained, temperatures at the base of the crust will rise and cause partial melting of crustal rocks. These felsic crustal melts will mix with the evolving mantle-derived melts to form hybrid intermediate-composition magmas, with densities that are now lower than typical crustal rocks (see Richards, 2003, for a review). These magmas can then rise buoyantly towards the surface. Hildreth and Moorbath (1988) termed this combination of crustal melting and assimilation by primary basaltic magmas, magma storage at the base of the crust, and magma homogenisation, the MASH process.

The MASH Zone: Factors Affecting Metallogenic Potential

MASH processing enhances the fertility of arc magmas by further concentrating volatiles and incompatible elements (including chalcophile metals in oxidised magmas) in the evolved melts. It is likely, although not essential, that some metallic components will also be added to the magma from assimilated crustal materials, and such processes may explain second-order variations of metal contents and ratios in ore deposits derived from contrasting basement terranes, as observed for example in Arizona (Titley, 1987, 2001). In addition, fractionation of sulphide melt or minerals at any point during the evolution of these magmas could have a significant effect on chalcophile metal ratios due to the much lower abundance of Au and its higher partition coefficient in sulphides, compared with Cu (Campbell and Naldrett, 1979). Residual or fractionated sulphide phases would thus remove much of the Au from the melt, but would not significantly affect Cu concentrations unless the volume of sulphide was large (Fig. 2). It may be partly for this reason that Au-rich porphyry deposits are commonly formed from more mafic and more oxidised magmas, in which sulphide saturation and fractionation has not occurred (e.g., Hamlyn *et al.*, 1985; Bornhorst and Rose, 1986; Richards *et al.*, 1991; Spooner, 1993; Wyborn and Sun, 1994; Richards, 1995; Sillitoe, 1997, 2000).

Just as MASH-zone processes may affect metal ratios in derived magmas, they may also affect the mass of metals available for later mineralisation. The build-up and storage of large volumes of magma at the base of the crust during prolonged MASH episodes increases the overall volume of fertile magma that can subsequently rise into the upper crust. If it is accepted that the metals and S in porphyry Cu deposits are derived primarily from the associated magma, then the more magma available, the larger the potential ore deposit. Thus, large porphyry Cu districts tend to be associated with large, long-lived, magmatic events.

Following Takada (1994) and others, Richards (2003a) argued that periods of compression in an arc may promote extensive MASH zone development by favouring deep crustal sill formation over vertical dyke propagation. Porphyry Cu deposits are commonly observed to form late in any given tectono-magmatic cycle in the arc (e.g., Maksaev and Zentilli, 1988; McKee and Noble, 1989; McCandless and Ruiz, 1993; Richards *et al.*, 2001; Richards, 2003b), corresponding to periods of stress relaxation and large-volume ascent of evolved magmas into the upper crust. Although magmas derived at other times in the tectono-magmatic cycle from less well developed MASH zones are probably still fertile, they may not be emplaced into the crust with sufficient flux (i.e., volume and rate) to trigger or sustain effective ore-forming systems.

Arc Magma Ascent and Emplacement

The MASH process generates evolved (andesitic) magmas that are more buoyant than the surrounding crustal rocks. Buoyancy forces will drive magma ascent through the crust, perhaps initially as diapirs in the hot, ductile lower crust,

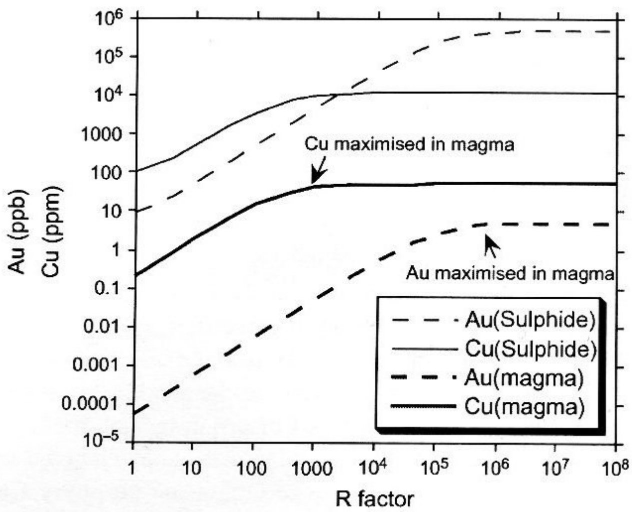

Figure 2: ***Variation of Cu and Au concentrations in sulphide melt coexisting with silicate melt as a function of R = (mass of silicate melt)/(mass of sulphide melt)*** (Campbell and Naldrett, 1979). Cu is only depleted in the magma if large amounts of sulphide remain in the mantle (>0.1 wt. %; $R \leq 1000$), whereas Au-rich magmas can only form when sulphide abundance falls below ~1 ppm ($R \geq 10^6$). Assumed sulphide/silicate melt partition coefficients are $D_{Cu} = 1000$, $D_{Au} = 10^5$; assumed metal concentrations in magma in absence of sulphide: Cu = 50 ppm, Au = 5 ppb.

but predominantly as dykes in the cooler middle and upper crust (Fig. 3; see review by Richards, 2003a). Dykes are magma-filled fractures, held open by hydraulic pressure transmitted from the buoyant magma column. Where large volumes of vertically-connected buoyant magma exist, these forces can easily exceed the lithostatic pressure plus the tensile strength of crustal rocks at the top of the dyke, resulting in upward propagation through the crust (Lister and Kerr, 1991; Clemens and Mawer, 1992).

Like faults and fractures, dykes propagate in the σ_1-σ_2 plane perpendicular to σ_3. Thus, ideal conditions for vertical dyke formation are tensile or shear tectonic stress, with σ_3 oriented horizontally. In contrast, horizontal compressional stress (σ_3 vertical) will favour sill formation (Parsons et al., 1992). It is for this reason that periods of voluminous upper crustal plutonism tend to follow compressional orogenic episodes, during which large volumes of magma are built up in lower crustal sill complexes (McNulty *et al.*, 1998; Simakin and Talbot, 2001). Upon relaxation of compressional stress or a switch to shear stress, dyke propagation is facilitated and vertical magma flow ensues. Because of the ability of dykes to become self-propagating, and due to the progressive warming of the conduit as fresh magma continues to pass through it, this process is likely to accelerate so long as a sufficient magma supply exists. Thus, it has been estimated that dyke-supplied mid-to-upper crustal plutons can be filled on time scales of 10^4-10^6 years (Paterson and Tobisch, 1992; Petford, 1996; de Saint-Blanquat et al., 2001). These filling rates are comparable to or exceed the expected convective cooling rates of upper crustal plutons (e.g., $\leq 10^4$ years; Cathles, 1981), such that a continuously molten magma chamber can be maintained while magma supply lasts.

Although magma buoyancy forces may be sufficient to form self-propagating dykes, suitably oriented pre-existing fractures and faults in the crust will provide paths of lower

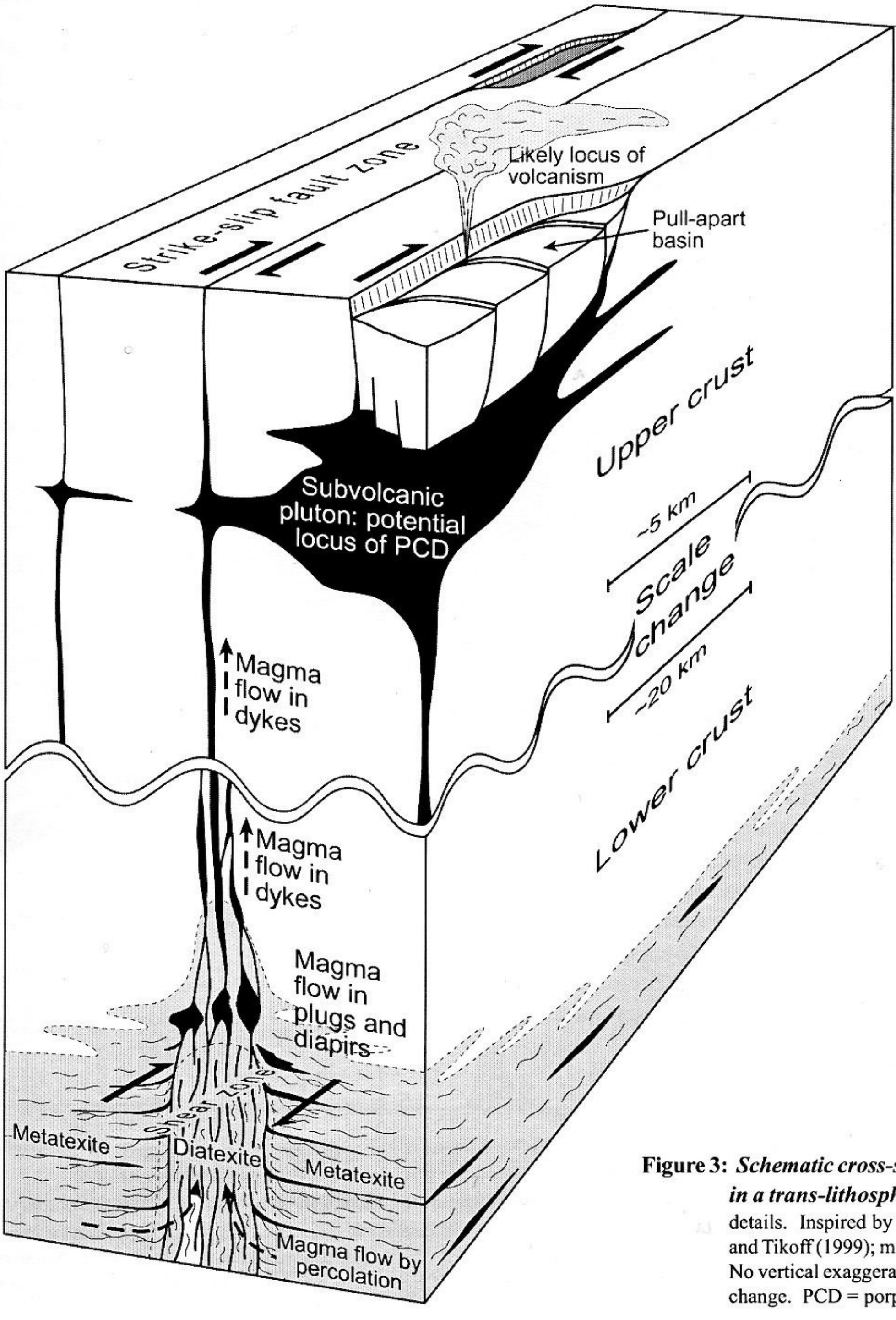

Figure 3: ***Schematic cross-section of magma transport in a trans-lithospheric shear zone;*** see text for details. Inspired by Brown (1994) and Vigneresse and Tikoff (1999); modified from Richards (2003a). No vertical exaggeration, but note mid-crustal scale change. PCD = porphyry copper deposit.

resistance for magma ascent. For this reason, large-scale crustal fracture zones, or lineaments, commonly focus the ascent of deeply derived magmas (Richards, 2000, and references therein). Especially favourable loci for magma ascent occur at jogs or step-overs on strike-slip fault systems, where vertically-oriented extensional volumes may form (Fig. 3; Brown, 1994).

Magma Ascent: Factors Affecting Metallogenic Potential

In sufficiently large trans-lithospheric magmatic systems, the mineralising potential of the magma is unlikely to be lost on ascent through the crust, because, once started, the transfer of mass from the lower to the upper crust is rapid (ascent rates of 10^{-2} to 10^{-3} m/s have been estimated by Clemens and Mawer, 1992, and Petford, 1996). However, the ability to construct a mid-to-upper crustal magma chamber of sufficient volume to sustain an ore-forming magmatic-hydrothermal system depends critically on the magma flux. If the supply rate is too slow, magma will tend to freeze in dykes en route to the surface (Clemens and Mawer, 1992), but if the flux is high and is sustained over a significant period of time, large, long-lived magma chambers can be constructed. There is now considerable evidence that large porphyry Cu deposits form, perhaps in pulses, over periods of time significantly greater than that expected for simple cooling of the small host plutons (diameters commonly <1 km, cooling <<1 m.y.), suggesting that recharge of the underlying mid-to-upper crustal parental magma chamber from a deeply-rooted lower crustal magmatic system may be essential to producing large ore-forming systems (e.g., Damon, 1986; Marsh *et al.*, 1997; Richards *et al.*, 1999, 2001; Ballard *et al.*, 2001).

The apparent necessity of a sustained, voluminous magma supply for formation of large porphyry Cu deposits means that optimum ore-forming conditions may occur at the end of prolonged periods of tectonic compression and lower crustal MASH processing, when stress relaxation facilitates magma ascent. This timing is consistent with the late appearance of porphyry Cu deposits in many arc cycles around the world (e.g., Richards, 2003a,b, and references therein).

In addition to these timing constraints, the locations of maximum magma flux into the upper crust may be controlled by pre-existing crustal-scale faults, and particularly by fault intersections or deflections in strike-slip fault systems where pull-apart volumes may be created by transpression or transtension. The emplacement of large porphyry Cu deposits at or near such loci has been proposed in several instances, such as Chuquicamata (Maksaev and Zentilli, 1988; Lindsay *et al.*, 1995), La Escondida (Richards, 1999; Richards *et al.*, 1999, 2001; Padilla Garza *et al.*, 2001), and Bajo de la Alumbrera (Sasso and Clark, 1998; Chernicoff *et al.*, 2002).

In combination, therefore, constraints of timing (at the end of tectono-magmatic epochs) and location (at or near major fault intersections or deflections) provide powerful tools for predicting the locations of large porphyry Cu deposits in magmatic arcs. These considerations do not prohibit deposits from forming at other times and in other places within the arc, but under non-optimal conditions large deposits are less likely to form. It should also be noted that the surface expressions of deep crustal fault systems typically occupy broad structural zones several kilometres wide, in keeping with the vertical scale (tens of kilometres) of such systems (Richards, 2000; Chernicoff *et al.*, 2002). Predicting the locations of porphyry-forming systems within these fault zones on this basis to better than a few kilometres is likely, therefore, to be difficult. Nevertheless, even at this distance one is likely to be able to observe distal hydrothermal alteration effects (e.g., propylitic alteration), which can extend >5 km from the core of a large magmatic-hydrothermal system. Thus, the potential of such structural zones can be rapidly assessed using remote sensing and field reconnaissance methods.

Upper Crustal Magmatic and Hydrothermal Processes

Development of Upper Crustal Magma Chambers

The focus of this review so far has been on the generation of fertile magmas at depth and their transport into the upper crust. A problem arises, however, if these magmas do not stop within the crust (as intrusions) but erupt at the surface. Voluminous eruption is obviously not conducive to the formation of pluton-related ore deposits. However, despite the impressive appearance of large stratovolcanoes, it has been estimated that only ~20% of the magma generated in an arc actually reaches the surface (Carmichael, 2002). The remaining 80% either freezes en route from the lower crust, or forms plutons within the upper crust. In addition, the most voluminous volcanic eruptions associated with

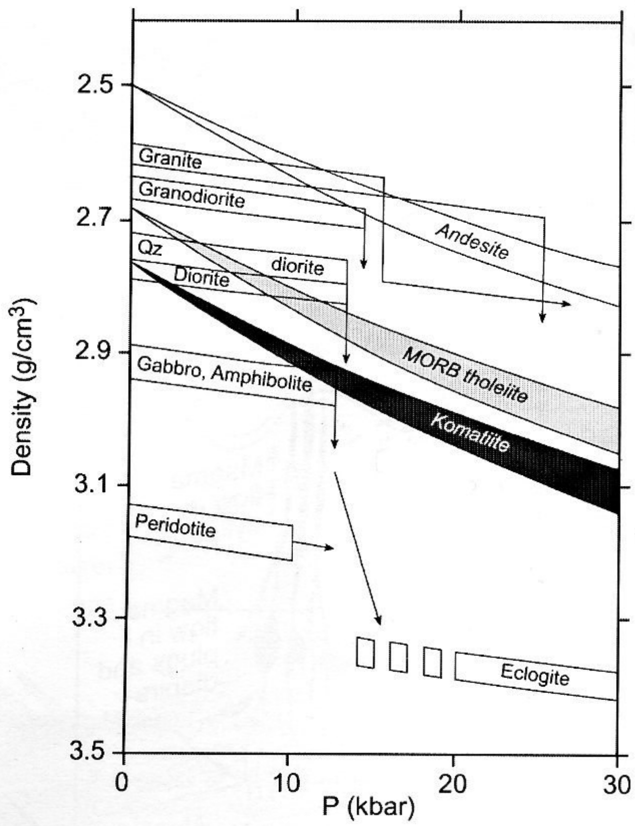

Figure 4: ***Variation of densities of magmas and rocks with pressure*** (after Herzberg *et al.*, 1983). Whereas basaltic magmas are denser than most crustal rock types, andesitic magmas are lighter and may rise to the surface driven by buoyancy forces alone.

magmatic arcs probably do not involve subduction zone magmas or their differentiates, but instead involve crustal melts formed after prolonged periods of crustal thickening and heating (e.g., the Altiplano-Puna volcanic complex; de Silva, 1989). Such magmatic systems are not prospective for porphyry Cu deposits.

Although intermediate composition (andesitic to dacitic) arc magmas are less dense than typical crystalline crustal rocks, unvesiculated magmas are more dense than many supracrustal lithologies (Fig. 4; Herzberg *et al.,* 1983). Thus, in the absence of vesiculation or excess magma pressure (from hydrostatic head), magmas will tend to pool at their level of neutral buoyancy, which is typically close to the basement/supracrustal contact where rock density decreases (Fig. 5; Glazner and Ussler, 1988; Walker, 1989; Lister and Kerr, 1991). Alternatively, their ascent may be checked by rheological boundaries, such as the brittle-ductile transition zone (10-15 km depth, or shallower in regions of high heat flow such as active magmatic arcs; Vigneresse, 1995). Plutons will form at these levels by lateral propagation and inflation of sills to form laccolithic (by roof lifting) or lopolithic (by floor depression) magma chambers (Cruden, 1998; de Saint-Blanquat *et al.,* 2001). Patanè *et al.* (2003) have recently described such a system beneath the active Mount Etna volcano, in which a large, structurally-located, sill-dyke-complex at 6-15 km depth feeds a shallower magma reservoir 3-5 km beneath the volcano. Roof lifting due to magma chamber inflation is indicated by GPS measurements and seismic records of normal faulting from 0-5 km depth beneath the edifice.

If the supply of magma is maintained at a sufficient flux, the magma chamber will remain molten and the pluton will expand. In contrast, a lower flux will result in freezing of the pluton, with any later magma injections forming separate small intrusions from which heat and fluids will be dissipated ineffectually. Progressive development of a large upper crustal magma chamber will likely involve at least some volcanism, and also the emplacement of shallow-level sub-volcanic stocks or apophyses inflated by evolved, volatile-rich, low-density magma (Fig. 5; Damon, 1986). The three-dimensional form of stocks associated with porphyry Cu deposits is characteristically vertically elongate, resembling a narrow finger (1-2 km-diameter) extending to within ~1 km of the surface from a source pluton several kilometres below (Norton, 1982).

Volatile Exsolution

Volatile exsolution is an inevitable result of the cooling and fractionation of hydrous arc magmas (water contents in hornblende-phyric andesitic and dacitic magmas exceed 4 wt.% H_2O; Burnham, 1979, 1997; Naney, 1983; Hedenquist *et al.,* 1998). The large volume increase

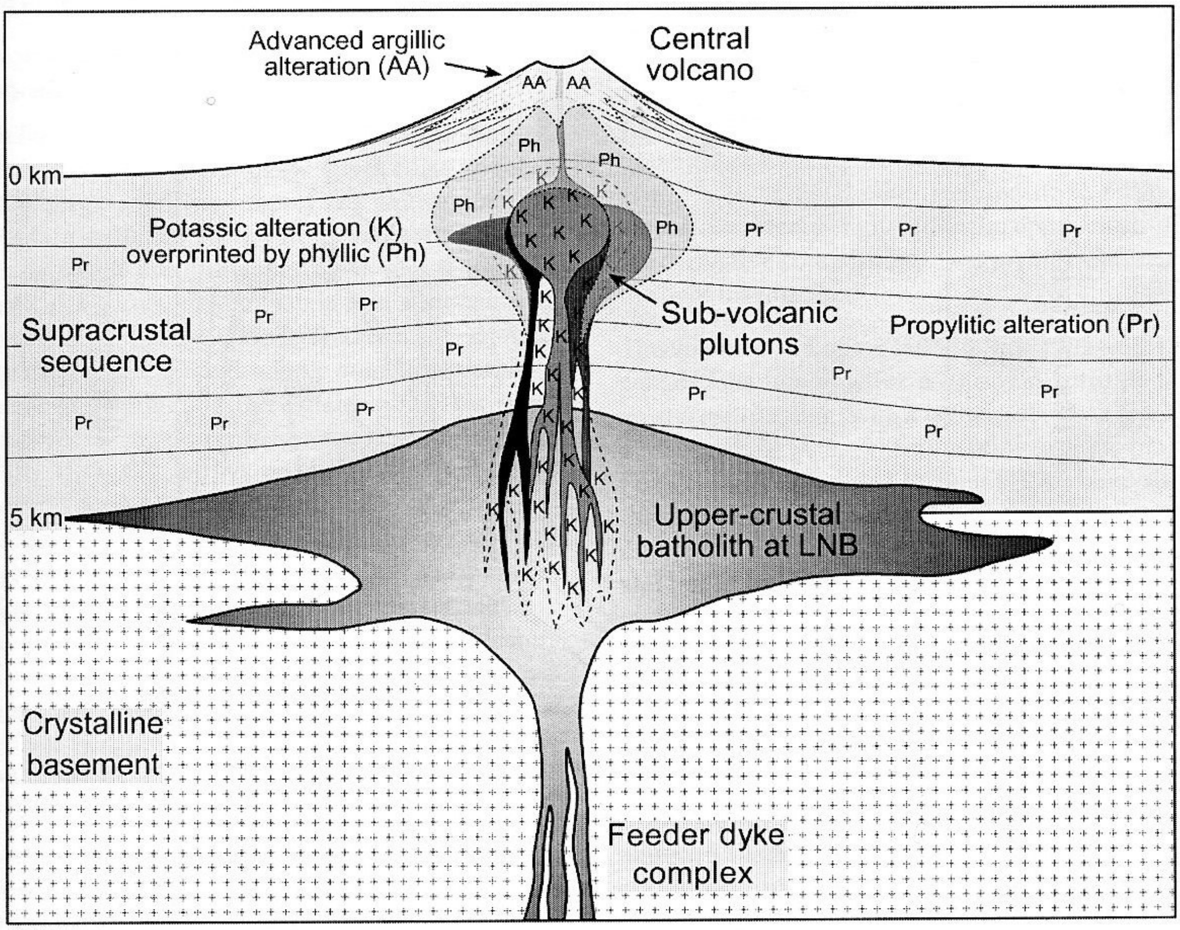

Figure 5: ***Schematic cross-section through a porphyry Cu forming volcano-plutonic system*** (modified from Richards, 2003a) After pooling at an upper crustal density or rheological barrier (LNB = level of neutral buoyancy), intermediate composition magmas continue to evolve and inject apophyses to shallow levels (some magma may erupt). Evolved, bubble-rich magma is convected into the cupola zone where it releases volatiles, with resultant potassic (K) alteration. As these fluids cool, they progressively deposit metal sulphide minerals, and alteration becomes hydrolytic (phyllic: Ph). Intense hydrolytic (advanced argillic: AA) alteration develops near surface. Propylitic alteration (Pr) is developed in the surrounding country rocks by the convective circulation of heated groundwaters.

resulting from this process, combined with the greatly lowered bulk density of vesiculating magma, is a major cause of volcanic eruptions (Eichelberger, 1995). These same volatiles, however, if separated from the magma without direct eruption to surface, will cause hydrothermal alteration and, potentially, porphyry Cu-style mineralisation. To form an economic deposit, large volumes of this fluid must be channelled through and reacted with small volumes of rock in order to focus mineral deposition. Wide dispersion of fluids, or venting to surface prior to cooling, will not result in porphyry-type ore formation.

Volatiles exsolve initially from magma as small bubbles (Candela, 1991). Although much less dense than the magma, escape of these bubbles is hampered by melt viscosity and the presence of crystals (Cloos, 2001). Instead, the bubble-rich magma may rise convectively to the top of the chamber as a buoyant plume (Shinohara *et al.*, 1995). As the magma rises, the bubbles will expand further in response to pressure decrease, and may eventually coalesce to form a volatile-rich carapace (Whitney, 1975). The degassed, denser magma will sink away to make room for fresh, hot, buoyant magma in a convective process that continually releases new volatiles and heat into the carapace. In this way, Shinohara et al. (1995) and Cloos (2001) envisage that the exsolution of volatiles from a large volume of magma could be spatially focused in the apical portions of the magma chamber, and, moreover, that this cupola zone could be maintained at magmatic temperatures for as long as convective overturn continues. This condition is considered to be a prerequisite for porphyry Cu formation, because the volumes of syn-mineralisation intrusive rocks exposed in most such mines are insufficient to explain the large quantities of metals and sulphur if typical magmatic concentrations of these elements are assumed. These components must instead have been efficiently extracted from much larger volumes of magma at depth, and transported into the apical zones by convection (Cloos, 2001).

The chemical and physical state of the exsolved magmatic fluid varies significantly with depth, and is a primary factor in controlling the partitioning of metals from the magma into the fluid phase. Kilinc and Burnham (1972) showed that chloride contents of initially exsolved aqueous fluids

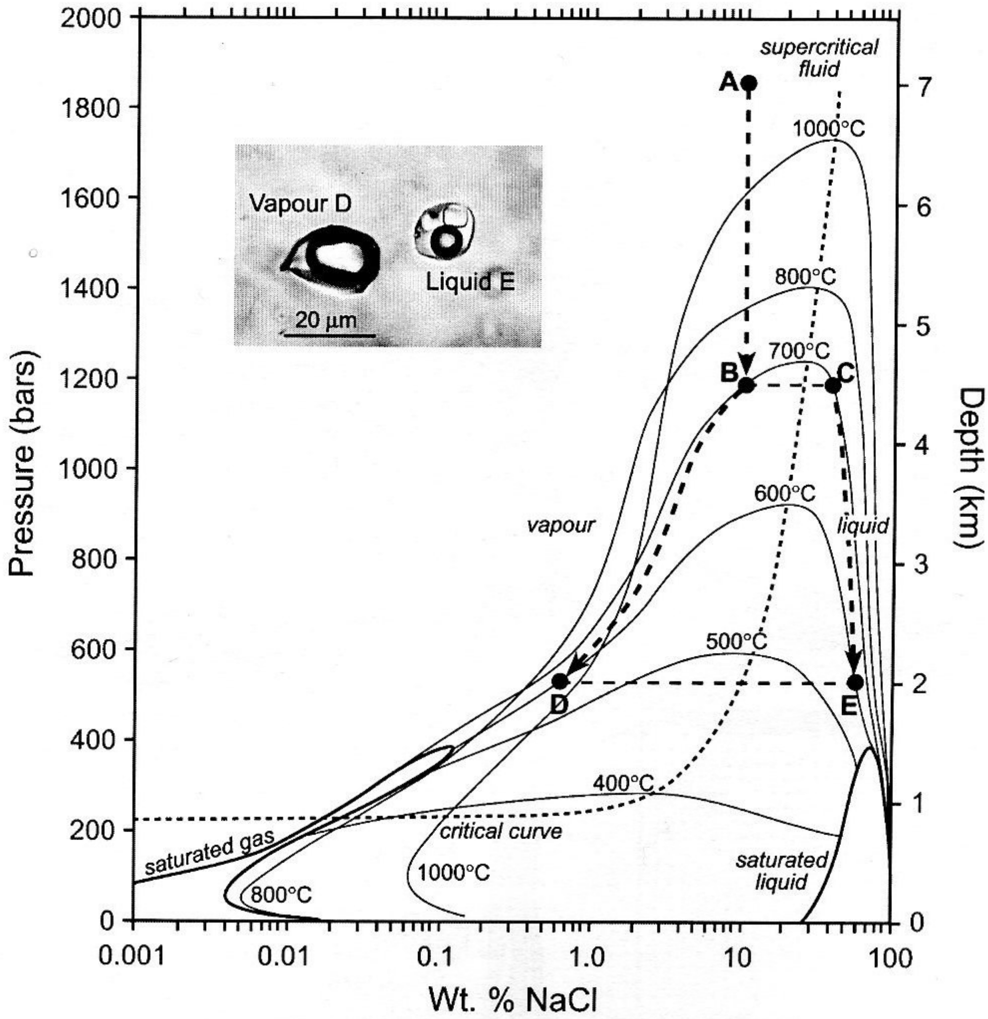

Figure 6: ***Isotherms in P-X space for the NaCl-H2O system*** (after Pitzer and Pabalan, 1986). Depth is plotted on the right-hand axis assuming lithostatic pressure and a crustal density of 2.7 g/cm^3. A supercritical aqueous fluid with 10 wt. % NaCl exsolves from magma in a chamber at 700°C and 7 km depth (point A). As it rises into the cupola zone in a convecting plume of bubbly magma, it undergoes aqueous phase separation from ~4.6 km depth (point B), condensing a saline brine (C) from a vapor that rapidly decreases in salinity as it continues to rise and cool (dashed line B-D). By 2 km depth, the two-phase fluid at 600°C will consist of a low density vapour (~0.6 wt. % NaCl; point D) and a high salinity brine (~60 wt. % NaCl; point E). Cu is initially transported by the supercritical fluid, and then deposited as the fluid begins to phase separate and cool. Inset shows fluid inclusions from the Bigham Canyon porphyry, Utah, which have trapped coexisting vapour and liquid phases similar to fluids D and E.

increase with pressure, and Candela and Holland (1984) showed that Cu solubility in these fluids increases with Cl content. Thus, optimum conditions for partitioning of Cu into a saline magmatic hydrothermal phase appear to be at pressures ≥1 kbar (depths ≥4 km; Cline and Bodnar, 1991; Cline, 1995). This result implies that initial segregation of metalliferous fluids from the magma must occur well below the level of the shallow-level apophyses that typically host ore (1-2 km), and that these fluids then rise, in a buoyant bubble-rich magma plume, into the cupola zone. Efficient sequestering of metals by the aqueous phase would be expected during ascent of this intimately mixed bubbly plume.

Phase relationships in the H_2O-NaCl system and experimental models indicate that fluids exsolved at ~700°C and pressures ≥1.2 kbar will be supercritical (single phase), and with salinity near 10 equiv. wt. % NaCl (Fig. 6; Sourirajan and Kennedy, 1962; Pitzer and Pabalan, 1986; Cline and Bodnar, 1991; Cline, 1995). Upon ascent and depressurisation however, these fluids will undergo phase separation to form a high salinity brine and a lower salinity vapour, the latter becoming rapidly more dilute as pressure falls (Fig. 6; Henley and McNabb, 1978). The bulk of the Cu is probably transported by the saline brine, although some metal also appears to be transported in the early high-temperature vapour phase (Lowenstern *et al.*, 1991; Heinrich *et al.*, 1999; Williams-Jones *et al.*, 2002, 2003).

Magmatic-hydrothermal Processes: Factors Affecting Metallogenic Potential

Maintaining metallogenic potential of the ascending arc magmas is, until their arrival in the upper crust, largely a function of magma flux (i.e., supply rate and volume). In other words, a sufficient volume of metal-bearing magma must be delivered into the upper crust, and it must be delivered quickly enough to maintain it in a molten state while metals are partitioned into a hydrothermal fluid phase. Once the magma is emplaced, a large number of variables play a role in determining the efficiency of this metal transfer process, including magmatic volatile content (especially H_2O, Cl, and S), oxidation state, depth of emplacement, form of the sub-volcanic apical region, and eruptive history. These are variables that are largely unique to any given body of magma and its crustal environment (including rheological, structural, and tectonic regime), and are therefore hard to predict. Nevertheless, these factors may all or individually exert absolute control on ore formation. For example, if the aqueous fluid phase is exsolved late or in small volumes, minimal hydrothermal transport of metals will occur, and no ore deposit will be formed (Cline and Bodnar, 1991).

Of major and overriding importance is the need for the hydrothermal fluid phase to interact with a large volume of magma, because Cu concentrations in intermediate composition magmas are quite low (10-150 ppm Cu; Gill, 1981). Cline and Bodnar (1991) and Cline (1995) have suggested that a moderate-sized porphyry Cu deposit could be formed from as little as 30-50 km^3 of magma, although larger volumes (perhaps 300 km^3) might be required to form a behemoth such as El Teniente. [Note that Cloos (2001) suggested that a magma volume ten times this size would be required to supply all the metal in the El Teniente porphyry Cu deposit (>93 Mt Cu; Skewes *et al.*, 2002), but in personal communication Mark Cloos (2003) agrees that there was an order-of-magnitude error in this calculation.] A simple mass balance calculation supports this view:

Average [Cu] in andesitic magma	= 60 ppm Cu
ΣCu in super-giant ore deposit	= 10 Mt Cu
Requires 10 Mt / 60 ppm of magma	
	≈ 1.7 x 10^{11} t of magma
Magma density	= 2.7 g/cm^3 = 2.7 t/m^3
Magma volume required	= (1.7 x 10^{11}/ 2.7) m^3
	≈ 6.3 x 10^{10} m^3
Assuming 100% extraction efficiency	= 63 km^3

Accepting that extraction efficiencies will be well below 100%, minimum volumes of at least 100 km^3 of magma are therefore probably required to form super-giant (>10 Mt Cu) orebodies.

Similar mass-balance calculations for sulphur, if based on typical sulphur solubilities in felsic magmas (100 ppm), suggest that volumes in excess of 4800 km^3 would be required to form the 30 Mt Cu Bingham Canyon porphyry deposit (Hattori and Keith, 2001). However, as these authors point out, the volume decreases by more than an order of magnitude (to 152 km^3) if a more mafic source magma with higher sulphur solubility is used in the calculation (see also Wallace, 2001). The latter scenario seems logical in the light of the preceding discussion of arc magma evolution, in which magma compositions were shown to evolve from primary high-Mg basalts generated in the mantle wedge (containing up to 1.5 wt. % S; Jugo *et al.*, 2001, 2003), to the intermediate to felsic magmas that are ultimately emplaced in the upper crust. The latter are derivative compositions, and are not representative of the bulk magma flux.

The volumes of magma (10^2-10^3 km^3) suggested by these calculations imply active connection between the upper crustal cupola zone (with a volume of only a few km^3) and a mid-crustal magma chamber of batholithic proportions. For example, Dilles and Proffett (1995) have shown that the Yerington porphyry district was underlain by a differentiating batholith of >1000 km^3, and Ballantyne et al. (1995) suggested that the Bingham Canyon porphyry was underlain by a batholith of >5000 km^3. Although batholiths are a common feature of arcs, they are mostly constructed slowly from individual plutons over several millions of years (e.g., Cobbing, 1982), and so may not provide the degree of continuous magmatic activity required to source a large porphyry system. Active magma chambers of sufficient size may be quite rare in the history of an arc, although evidence for the present-day existence of a large mid-crustal magma chamber (~20 km depth) has recently been found beneath the Altiplano-Puna region of the central Andes (Schilling and Partzsch, 2001; Zandt *et al.*, 2003). The rarity of formation of magma sources of this volume may partially explain the rarity of large porphyry Cu provinces. However, when conditions *are* suitable for the formation of regionally extensive mid-crustal magma chambers, then the evolution of multiple porphyry Cu systems might be expected. This condition could explain the common clustering of such deposits, both in space and time (e.g., Sillitoe, 1988).

Summarising the above discussion, the construction of large, active magma chambers requires a high magma flux from depth, which brings us back to the necessity of developing a large-volume MASH zone as a precursor for giant porphyry Cu deposit formation.

Mafic Magma Recharge

Recently, Hattori and Keith (2001) have argued that recharge of upper crustal felsic magma chambers by primitive mafic melts might be an essential step in the formation of large porphyry Cu deposits, because of the higher concentrations of chalcophile metals and sulphur in mafic magmas compared with felsic melts. In support of this theory, Hattori and Keith (2001) pointed to the Bingham Canyon porphyry Cu deposit and the 1991 Mt. Pinatubo eruptions, where evidence for mingling of felsic and mafic magmas can be found.

Magma mixing is a common feature of eruption products from arc volcanoes, and has been suggested to be a trigger for some explosive volcanic eruptions (Walker, 1989; de Silva, 1991; Feeley and Davidson, 1994; Eichelberger, 1995; Straub and Martin-Del Pozzo, 1996; Murphy *et al.*, 2000; Schmitt *et al.*, 2001). However, in most such cases the mafic end-member is not "primitive" in the strict sense of the word (i.e., a minimally evolved magma with high Ni and Cr content), but merely a less evolved mafic-to-intermediate magma from the same deep-seated magmatic system. The ascent of truly primitive magmas to shallow crustal levels is uncommon in volcanic arcs, and is particularly rare in continental arcs, where the thick felsic crust acts as a density filter (Hildreth and Moorbath, 1988; Carmichael, 2002). Primitive mafic magma recharge, therefore, seems to be an unlikely and unsystematic mechanism for forming porphyry Cu deposits, which are highly reproducible in form, space, and time within magmatic arcs (Sillitoe, 1988, 1992). It is also not clear why such a special mechanism should be required, when normal magmatic evolution of oxidised, hydrous arc magmas can potentially achieve the same result.

Despite these misgivings about the applicability of this model for forming normal porphyry Cu deposits, it may yet have validity in the formation of less common Au-rich porphyry systems, of which Bingham Canyon is an example. As discussed above, primitive mafic magmas may well retain higher Au/Cu ratios than more evolved magmas, especially if the latter have evolved in the presence of, or have fractionated, sulphide phases (Richards, 1995). Richards (1997) noted that mafic magmas related to alkalic-type Au deposits are commonly emplaced in post-subduction, collisional, or back-arc settings. A feature of such settings is the existence of localised extensional or transtensional structural domains, which facilitate the shallow ascent of primitive magmas. Some of the largest Au-rich porphyry Cu deposits, such as Bingham Canyon, Grasberg, and Bajo de la Alumbrera, also formed in back-arc or off-arc settings. Here, extensional tectonics (e.g., Guilbert, 1985; Ballantyne *et al.*, 1995; Luck *et al.*, 1999) may have played a similar role in enabling the shallow ascent of primitive Au-rich magmas, which then mixed with, or "spiked", more felsic magma chambers in the upper crust.

Porphyry Cu Ore Formation

General Model

Landmark studies by Meyer and Hemley (1967), Lowell and Guilbert (1970), Gustafson and Hunt (1975), and Hollister (1975) defined the characteristic framework of hydrothermal alteration and mineralisation in porphyry Cu deposits (Fig. 5; see review by Hedenquist and Richards, 1998). Three decades of additional research have modified these original descriptions only in detail, and have served to underline the remarkable reproducibility of these large ore forming systems. In their simplest form, porphyry Cu deposits are formed by precipitation of Cu-Fe-sulphide minerals during cooling, phase separation, and reaction of the exsolved magmatic-hydrothermal fluid with wallrocks. Early high temperature potassic alteration (700-350°C; Einaudi *et al.*, 2003) produces an assemblage similar to that present in the igneous source rocks (e.g., quartz, K-feldspar, biotite, ± magnetite) because the fluid is still close to equilibrium with the near-solidus magma. As the fluid cools (towards ~350°C), however, disproportionation of sulphur, predominantly dissolved as SO_2 at high temperature, begins to generate H_2S and sulphuric acid:

$$4\ SO_2 + 4\ H_2O \Leftrightarrow H_2S + 3\ HSO_4^- + 3\ H^+ \qquad (1)$$

This acidity, combined with the increasing reactivity of other species such as HCl and HF (Hedenquist, 1995), produces hydrolytic alteration of increasing intensity as the fluids rise through the carapace and cool. In addition, the generation of H_2S combined with falling temperatures leads to rapid precipitation of sulphide minerals (Burnham, 1997). The classic alteration zonation from potassic to near-surface advanced argillic alteration (clay, alunite, diaspore; <200°C), with lateral overprinting phyllic alteration (sericite-pyrite; 350-200°C), can be viewed broadly as a product of this evolution from hot neutral to cooler highly acidic fluid conditions (or low to high sulphidation states; Einaudi *et al.*, 2003). In detail however, the situation is more complex, and fluid evolution must be viewed in both space and time.

Depending on the depth of exsolution, the magmatic hydrothermal fluid will exist initially either as a homogeneous supercritical fluid (e.g., at pressures >1.2 kbar, ~700°C), or as separate brine and vapour phases (pressures <1.2 kbar, ~700°C; Fig. 6). Cline and Bodnar (1991) and Cline (1995) have shown that this distinction is important, leading to early extraction of Cu from the magma in the first instance, but later and possibly less efficient Cu extraction in shallower systems. The process of retrograde volatile phase separation in deeper systems also appears to exert an important but poorly understood control on ore deposition, significant sulphide mineralisation commonly appearing just after the first evidence for immiscibility in the fluid inclusion record (e.g., Gustafson and Quiroga, 1995; Arancibia and Clark, 1996).

A model for independent physical evolution of the brine and vapour phases was presented by Henley and McNabb (1978), who suggested that a low density vapour plume would ascend to shallow levels in the system, leaving the denser brine at depth. It is this vapour plume, rich in acidic volatiles, that gives rise to the shallow level advanced argillic alteration, broadly coeval with potassic alteration at depth (Hedenquist *et al.*, 1998). There is mounting evidence that these vapours may also be capable of transporting significant quantities of metals, particularly at depth (Lowenstern *et al.*, 1991; Heinrich *et al.*, 1999; Williams-Jones *et al.*, 2002, 2003).

The origin of phyllic alteration has been debated extensively, because of conflicting stable isotope results that indicate an important role for meteoric groundwater in some systems, but evidence for formation from magmatic fluids in others (Sheppard *et al.*, 1971; Dilles *et al.*, 1992; Harris and Golding, 2002). Shinohara and Hedenquist (1997) and Hedenquist *et al.*, (1998) argued that later fluids to exsolve from the cooling magmatic system might follow a low-temperature path towards the surface that would not intersect the fluid solvus, thus giving rise to moderately saline (~5 equiv. wt. % NaCl) low-temperature (300-350°C) liquids that could cause sericitic alteration. Stable isotopic indications of the involvement of meteoric groundwater in some systems might then be explained by later overprinting.

Circulation of groundwater heated by magmatic intrusion causes coeval propylitic alteration in huge volumes of country rock extending many kilometres around large systems (Taylor, 1974; Norton, 1982). Continuation of convective groundwater circulation long after solidification of the source pluton commonly results in propylitic overprinting of earlier high-temperature alteration styles, and local formation of argillic alteration (Sheppard *et al.*, 1969).

Ore minerals such as chalcopyrite, bornite, molybdenite and pyrite are precipitated from the earliest stages of magmatic-hydrothermal fluid evolution, but highest concentrations of hypogene Cu and Mo (and Au) tend to be found towards the outer edges of the potassic alteration zone where temperatures are cooling towards 350°C (the "ore shell" of Lowell and Guilbert, 1970; Giggenbach, 1997). Ore deposition in this region is primarily a function of solubility reduction due to cooling, combined with an increase in the activity of aqueous sulphide species due to the disproportionation of SO_2 (equation 1). Pyrite is the dominant sulphide mineral precipitated from the cooler, more acidic fluids generating phyllic alteration.

Fluid Pathways

In order to deposit an economic concentration of metals, fluid flow must be focused through relatively small volumes of rock where sulphide mineral precipitation is promoted. Highest grades of ore may be achieved where these rocks are also reactive with the fluid, such as carbonate or mafic volcanic rocks. Short-circuiting of fluid flow directly to the surface (e.g., by catastrophic explosive eruption or volcano sector collapse, as occurred at Lihir Island; Moyle *et al.*, 1990; Müller *et al.*, 2002; see also Sillitoe, 1994), or broad dissipation throughout a large volume of country rock, will reduce the porphyry ore-forming potential of the system (although it may enhance epithermal ore formation, as at Lihir). In contrast, relatively focused flow may be achieved by brecciation of the carapace zone, and highly focused flow may correspond to breccia pipe formation.

The textures of porphyry ores indicate that they were formed near the brittle-ductile transition temperature. Early K-silicate-stable veins which formed at temperatures over ~400°C (Fournier, 1999) display evidence of plastic deformation and vuggy cavities are rare (e.g., "A" veins), whereas later veins associated with lower-temperature potassic or phyllic alteration are linear, and preserve open cavities and breccia textures ("B" and "D" veins of Gustafson and Hunt, 1975). Phillips (1973), Burnham (1979), and Burnham and Ohmoto (1980) discussed the mechanics of brittle failure in the partially solidified carapace zone in response to increasing pressure from the expanding fluid volume, and concluded that this was an effective way of releasing fluid pressure while at the same time reacting these fluids with large surface areas of cool overlying rocks. The classic three-dimensional stockwork texture of many porphyry ore zones is a product of hydraulic fracturing by this expanding, over-pressured fluid (Fig. 7). Pre-existing structures in the cover rocks, or extensional faults generated by the stress of pluton emplacement, may further focus the flow of fluids to form vein deposits or breccia pipes, in which rich pockets of ore may be deposited in response to rapid fluid depressurisation and cooling (Perry, 1961; Sillitoe and Sawkins, 1971; Fletcher, 1977; Skewes *et al.*, 2002). The majority of breccia pipes are barren, however, suggesting that rapid fluid venting may have prevented ore deposition, rather than focusing it.

Au in Porphyry Cu Deposits

Zonation of Mo and Cu within porphyry Cu deposits is common but not systematic, with higher Mo/Cu ratios occurring in the cores of some systems and as haloes in others (e.g., John, 1978; Williams and Forrester, 1985; Sillitoe, 1997). Of greater current economic interest, however, is the zonation or variation of Au abundance in porphyry Cu deposits because, although typically a minor component of the ore, Au credits can significantly affect the overall value of a mining operation. Several recent studies have attempted to explain the anomalous Au-enrichment of some deposits, and Kesler *et al.*, (2002) have shown that Cu/Au atomic ratios vary over a wide range from ~5000 to ~5 000 000, with a mode near 40 000. Much of this variability in normal porphyry Cu deposits is likely to be related to late magmatic or hydrothermal effects, rather than any fundamental source composition difference (e.g., Sillitoe, 1979; Muntean and Einaudi, 2000, 2001; Halter *et al.*, 2002; Kesler *et al.*, 2002). However, as noted previously, the supra-subduction zone mantle oxidation state exerts a strong control on the stability of residual sulphide phases, which in turn controls the behaviour of siderophile and chalcophile elements. Under unusually oxidising conditions or during multi-stage melting events in which residual sulphides in the mantle are destroyed (e.g., during cessation of subduction, subduction reversal, or arc collision), relatively oxidised alkalic magmas may be generated that have the potential to generate Au-rich porphyry and alkalic-type epithermal deposits (e.g., Hamlyn *et al.,* 1985; Bornhorst and Rose, 1986; Richards *et al.,* 1991; Spooner, 1993; Wyborn and Sun, 1994; Richards, 1995; Sillitoe, 1997; see also Mungall, 2002).

Muntean and Einaudi (2000, 2001) argued that gold-rich porphyry deposits in the Oligo-Miocene Maricunga belt of northern Chile formed in response to shallow emplacement (<1 km) of magma, resulting in flashing of high temperature magmatic fluids and deposition of characteristic auriferous banded quartz veinlets. Loss of sulphur species to the vapour phase during flashing would have inhibited Cu-Fe-sulphide precipitation and promoted Au deposition.

Simon *et al.,* (2000) and Kesler *et al.,* (2002) presented a different model in which they suggested that initial Cu/Au ratios in porphyry ores might be a function of temperature (and oxidation state) at the time of initial sulphide mineral precipitation. They showed that experimental high-temperature (600°C) bornite-magnetite assemblages contain an order of magnitude more Au (>1000 ppm) than lower temperature chalcopyrite-pyrite assemblages. The extent of formation and preservation of early high-temperature sulphide assemblages may therefore control the bulk Cu/Au ratio of the deposit, but overprinting and replacement by lower temperature assemblages may redistribute Au, or even remove it from the system altogether (perhaps into the epithermal environment).

In contrast, Halter *et al.,* (2002) argued that Cu/Au ratios in magmatic-hydrothermal fluids might be controlled by the presence of a late-stage sulphide melt, into which chalcophile metals would be partitioned. They argued that this sulphide melt would rapidly destabilise upon exsolution of a volatile phase from the magma, releasing metals to the fluid. It is not clear, however, how chalcophile metal ratios are affected by this process, nor why the sulphide sequestration step is necessary when volatile exsolution can also effectively scavenge metals from the magma.

Finally, the possibility that magma chamber recharge by primitive mafic magmas might "spike" the system with Au (e.g., Hattori and Keith, 2001) has been considered above. Although such a mechanism is plausible, it remains to be shown that this is a necessary and universal step in the formation of Au-rich porphyry Cu deposits.

Conclusions

Giant Porphyries: Extreme, Not Special, Cases

Shallow-level calc-alkaline plutons are common features of subduction-related magmatic arcs, but the majority are not intensely hydrothermally altered, and even fewer are mineralised. Economic porphyry-type deposits are rarer still, and "super-giant" porphyries are numbered globally in the teens (Clark, 1993). There is a temptation to look for a magic bullet that will explain the generation of giant ore deposits, but from the information reviewed above it would seem that Alan Clark was correct when he concluded that "there are no systematic qualitative differences between outsize and smaller examples of the porphyry clan" (Clark, 1993, p 213). Instead, it is clear that at every step of the way from initial dehydration of the downgoing slab to exsolution and evolution of a magmatic-hydrothermal fluid, multiple and commonly independent processes can either preserve the ore-forming potential of the system, or destroy it. The odds are clearly in favour of spoiling, because at any stage once the overall process is disrupted it will be difficult for it to regain its full potential.

Thus, it may be argued that the following criteria and processes all have to be met or optimised for a giant porphyry to be formed. Omission or partial fulfilment of any one step can be sufficient either to destroy completely the system's ore-forming potential, or to result in the formation of a more modest-sized deposit:

1. Subduction must be maintained at a uniform angle and relatively rapid rate for a considerable period of time (perhaps ≥10 m.y.) to build up a large and localised volume of underplated mafic magma near the crust-mantle boundary of the overlying plate.
2. Development of a mature MASH zone at this level requires a period of sustained compressional stress across the arc, which encourages magma pooling in lower crustal sill complexes rather than early escape via dykes.

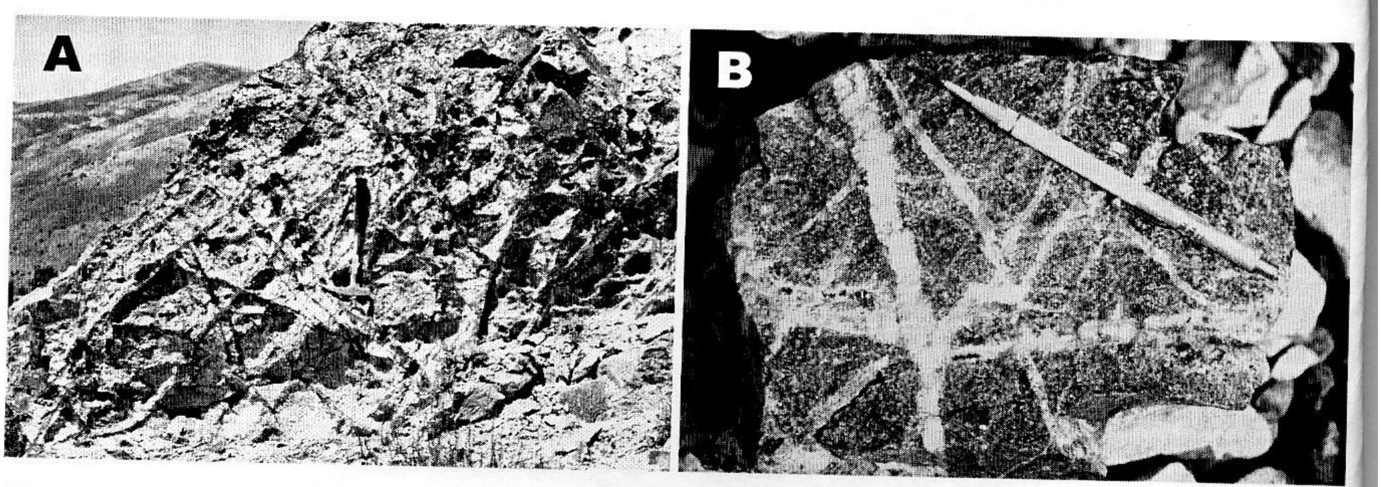

Figure 7: (A) ***Weathered outcrop showing stockwork veining in potassic alteration, Kuh-e-Panj porphyry copper deposit, Kerman belt, Iran.*** **(B)** ***Stockwork quartz veins with chalcopyrite and molybdenite in biotite-rich potassic alteration, Bingham Canyon porphyry copper deposit, Utah.***

3. Following an extended period of MASH processing, stress relaxation or change to moderate shear conditions will promote dyke formation, and ascent of large volumes of evolved, volatile-rich (including H_2O, Cl, S), metalliferous magma. A high magma flux is perhaps the most critical element in this process because it ensures that sufficient heat and ore-forming components are delivered to the upper crust.
4. Pre-existing structures in the crust, especially extensional offset zones along trans-lithospheric strike-slip fault systems, will serve to focus magma ascent.
5. Magma flux from the lower crust must be sufficient and sustained for long enough to construct a large volume (≥100 km^3), at least partially continuously molten, mid-to-upper crustal magma chamber.
6. Volatile exsolution should begin at depth within this magma chamber (>5 km), causing convection of bubble-rich, buoyant magma into tall apical stocks, where volatiles can be released. A sustained flux of heat and ore-forming components entering the chamber by recharge from depth and convected into the cupola, will prolong and maximise the magmatic-hydrothermal exchange process.
7. Volatiles should be released in a controlled, focused and prolonged fashion, allowing the progressive build up of large concentrations of economic minerals in depositional sites.

Conversely, specific processes that can destroy ore-forming potential include:

1. Tectonic changes that alter the rate or angle of subduction: reducing or shifting the supply of primary magma to the base of the overlying crust will hinder development of an extensive MASH zone (although the *onset* of changes in tectonic configuration, if accompanied by stress change, may provide opportunities for voluminous magma ascent from previously-developed MASH zones).
2. Stress conditions in the upper plate that are not conducive to MASH zone formation (e.g., tension).
3. Interaction of ascending magmas with reducing lithologies in the crustal column, which might cause early sulphide saturation and removal of chalcophile metals.
4. Catastrophic explosive (volcanic) bulk release of volatiles to the surface, which will short-circuit the porphyry ore-forming process. Thus, large calderas are unlikely to be prospective for porphyry deposits, although they may be prospective for epithermal systems.

If these various favourable criteria have operated and negative influences are absent, it should then be possible for an ordinary calc-alkaline arc magmatic system to form an economic porphyry Cu deposit, as suggested by Cline and Bodnar (1991). The formation of a giant porphyry is probably the cumulative result of optimisation of each step, and not of the action of any single or unique process.

Exploration Indicators

There is a significant amount of serendipity involved in the discovery of any large ore deposit, and many of the factors listed above that control the size of porphyry Cu deposits are beyond prediction. More difficult still is prediction of the *exact* location of a large porphyry system (i.e., to within 1 or 2 km). Nevertheless, there are some general features that should characterise prospective arc terranes, and some specific features that might be used to focus target selection for first-pass exploration:

1. Large porphyry Cu deposits are likely to be found in well-established arcs, featuring voluminous magmatism developed in narrow belts (≤50 km-wide) over a significant period of time (>5 m.y.).
2. Crustal-scale structural architecture (observed as lineaments) may focus the ascent of arc magmas, and lineament intersections where they form pull-apart structures are likely to be particularly prospective. Large-scale lineaments commonly represent the boundaries of basement domains, and can be recognised from regional-scale gravity or magnetic surveys and remote sensing (e.g., Chernicoff *et al.*, 2002). Such lineaments and lineament intersection zones may define broad areas of prospectivity, a few tens of kilometres square.
3. Clusters of shallow-level dioritic plutons (within an area 10-30 km square) indicating voluminous, focused magma supply, can be recognised from regional mapping or airborne geophysics (e.g., Behn *et al.*, 2001; Richards *et al.*, 2001). Porphyry Cu deposits may occur near the centre of such clusters, where magmatic flux was greatest.
4. Caldera and ignimbrite complexes are probably not prospective for porphyry Cu deposits, despite their evidently large magma flux. Rhyolitic ignimbrites are derived predominantly from less fertile crustal melts (lacking key arc components such as sulphur and chalcophile metals), and large caldera eruptions likely destroy deeply rooted magmatic-hydrothermal systems.
5. Regional erosion and weathering history must be appropriate for exposure and possible supergene enrichment of shallow level porphyry systems.

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