Mineralium Deposita (2002) 37: 4–13
DOI 10.1007/s00126-001-0227-6

ARTICLE

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Some metallogenic features of gold and copper deposits related to alkaline rocks and consequences for exploration

Received: 8 June 2001 / Accepted: 21 August 2001 / Published online: 11 December 2001

Abstract Porphyry copper-gold, skarn copper-gold, sediment-hosted (Carlin-style) gold, breccia pipe, low-sulphidation epithermal gold, pluton-related (mesothermal or orogenic) gold vein and volcanogenic massive sulphide deposits associated with alkaline rocks are commonly broadly similar to those hosted by their calc-alkaline counterparts. In contrast, porphyry molybdenum-gold deposits are confined to alkaline igneous centres. Alkaline suites are notably deficient in high-sulphidation epithermal gold deposits and even in the advanced argillic lithocaps which host them. This is surprising, given that the required oxidised sulphur species are seemingly more abundant than in calc-alkaline igneous centres. Highly efficient buffering of acidic fluid by metasomatised alkaline rocks may offer a viable explanation. All types of intrusion-related zinc deposits also appear to be poorly developed in alkaline provinces. The characteristics of several gold and copper deposits associated with alkaline rocks, including the giant Porgera, Cripple Creek, Ladolam, Olympic Dam and Phalaborwa examples, are judged to diverge appreciably from their most closely related deposit types, rendering them arguably unique. Most of these aberrant mineralisation styles may be due to variations in magmatic-fluid compositional and liberation characteristics consequent upon the extreme diversity of ore-related alkaline magmas. Most types of gold and copper deposits developed in calc-alkaline provinces also constitute exploration targets in and around alkaline igneous centres, although porphyry copper-gold and low-sulphidation epithermal gold deposits are considered to possess the greatest potential. Perhaps of even greater interest, however, is the possibility of encountering unconventional giant gold and copper deposits which lack closely analogous examples. If already-defined aberrant deposits are truly unique, then exploration designed specifically to detect additional examples is pointless. Furthermore, exploration for new unique deposits is difficult because their defining geological parameters are unknown. Alkaline rocks within or behind calc-alkaline arcs at convergent plate boundaries probably offer the greatest exploration potential, although anorogenic intracontinental extensional settings should not be ignored.

Keywords Alkaline · Gold · Copper · Porphyry-epithermal transition

Introduction

The spectrum of gold and copper deposits related to alkaline rocks has attracted much recent attention (Mutschler and Mooney 1993; Richards 1995; Jensen and Barton 2000), apparently because of the distinctive compositions and settings of the magmatism, the commonly clear-cut genetic connection between the magmatism and mineralisation, and the evidence for transitions between the porphyry and epithermal environments. Furthermore, mineralisation related to alkaline magmatism in arc terranes apparently also includes a disproportionately large share of the world's giant gold deposits when the small volume of alkaline relative to calc-alkaline rocks is taken into account (Sillitoe 1993; Müller and Groves 1993). Nevertheless, it should be remembered that the majority of deposits related to alkaline rocks, like those in calc-alkaline belts, are small, as exemplified by the numerous past-producers in the central Montana and New Mexico alkaline provinces of the western United States (Giles 1983; McLemore 1996; Kelley and Ludington 2001, this volume).

Alkaline rocks for the purposes of this general discussion are taken to be those with combined potash and soda contents high enough to plot in or above the basanite, trachybasalt, shoshonite, latite and trachyte fields in the IUGS classification scheme for volcanic rocks (Le

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Maitre et al. 1989), although stricter definitions are employed elsewhere (e.g. Blevin 2001, this volume). Ore-related alkaline rocks span broad compositional ranges, from ultramafic to felsic, silica-saturated to silica-undersaturated and potassic to sodic, although the last distinction may be somewhat blurred by the effects of potash metasomatism (e.g. Jensen and Barton 2000). As a suite, the ore-related alkaline rocks are clearly transitional to their calc-alkaline counterparts. Most gold- and copper-bearing alkaline igneous centres occur in arc terranes, where emplacement takes place either during or immediately following subduction. Back-arc sites, extensional settings and post-subduction timing are especially favourable for such mineralised centres. Nevertheless, a minority of the alkaline rock-related copper-gold deposits occurs in anorogenic and extensional intraplate settings, mainly of Precambrian age.

Although gold and copper deposits related to alkaline rocks have been isolated as a class, most of their fundamental geological characteristics, as summarised by Richards (1995), Jensen and Barton (2000) and Kelley and Ludington (2001, this volume), are essentially the same as those of deposits accompanying calc-alkaline magmatism. Only certain mineralogical features, such as occurrence of roscoelite (vanadian mica), unusually elevated telluride and fluorite contents, unusually intense and widespread development of potassic alteration and deficiency of quartz gangue, are truly distinctive (Bonham 1988; Jensen and Barton 2000), although none of these attributes is displayed by all alkaline rock-related deposits.

Notwithstanding the overall similarities between gold and copper mineralisation in alkaline and calc-alkaline igneous centres, a few widely recognised deposit types tend to be either poorly represented in, or largely restricted to alkaline provinces. Furthermore, alkaline igneous centres apparently include a disproportionately large number of unusual, arguably unique gold and copper deposits. These aberrant deposits are considered important and worthy of special emphasis, not only because of the exceptionally large metal contents of several of them and their intrinsic scientific interest, but also because of the potential difficulties in recognition which they may present at the exploration stage.

Some of the salient metallogenic features of alkaline rock suites and their exploration consequences are the subjects of this short introductory essay. Comments focus on gold and copper deposits hosted by potassic igneous rocks, but also encompass those formed in association with more sodic magma compositions as well as with the carbonatite component of a potassic suite.

Traditional deposit types

Most of the usual types of gold and copper deposits defined in calc-alkaline provinces are readily recognisable in association with alkaline rocks. These include porphyry copper-gold deposits, calcic copper-gold skarns, pluton-related (mesothermal or orogenic) gold veins, gold-bearing breccia pipes, sediment-hosted (Carlin-style) gold deposits, low-sulphidation epithermal gold veins and polymetallic volcanogenic massive sulphide (VMS) deposits (Table 1). Bonanza gold grades characterise a few of the low-sulphidation vein deposits. As an example, porphyry copper-gold deposits related to both calc-alkaline and a few alkaline intrusions are typified by potassic alteration, quartz-veinlet stockworks and low-sulphidation state, chalcopyrite ± bornite assemblages, including elevated magnetite (±hematite) and native gold contents (Sillitoe 2000a).

The only deposit type – defined as several broadly similar mineralised occurrences possessing widespread geographical distribution – which is associated with alkaline rocks, but not with their calc-alkaline counterparts, is the porphyry molybdenum-gold class. As pointed out by Jensen and Barton (2000), these fairly uncommon deposits are hosted by felsic alkaline rocks, typically latite porphyries, as documented at Golden Sunlight, Montana (Spry et al. 1996) and Central City and Jamestown, Colorado (Rice et al. 1985; Saunders 1991) in the United States, and Kisladag in Turkey

Table 1 Traditional gold and copper deposit types related to alkaline rocks

Deposit type	Example	Metals	Related alkaline rocks	Selected reference
Porphyry Cu–Au	Cadia, NSW, Australia	Au–Cu	Monzodiorite-quartz monzonite porphyry stock	Holliday et al. (2001), this volume
Skarn	Lukas Canyon, New Mexico	Au–Cu	Monzonite and latite porphyry stocks	Maynard et al. (1990)
Sediment-hosted (Carlin-style)	Foley Ridge and Annie Creek, South Dakota	Au	Monzonite porphyry, quartz monzonite porphyry and phonolite dykes and sills	Lessard and Loomis (1990)
Breccia pipe	Golden Sunlight, Montana	Au	Latite porphyry intrusions	Spry et al. (1996)
Low-sulphidation epithermal vein	Emperor, Fiji	Au	Absarokite-shoshonite shield volcano and monzonite stocks	Eaton and Setterfield (1993)
Pluton-related (mesothermal or orogenic) vein	Dongpin, China	Au	Syenite pluton, latite porphyry and lamprophyre dykes	Zhang and Mao (1985)
Volcanogenic massive sulphide (VMS)	Rea, British Columbia	Cu–Zn–Pb–Ag–Au	Alkaline basalt tuffs	Höy (1991)

(R.H. Sillitoe, unpublished data, 2000). However, Kisladag, because of its much higher gold content, is the only member of the porphyry molybdenum-gold class known to the writer to possess economic potential, bearing in mind that the gold mined at Golden Sunlight is hosted by an epithermal breccia pipe which overprints the porphyry-type mineralisation (Spry et al. 1996; Table 1). The previously exploited Gilt Edge gold deposit, hosted by trachyte porphyry intrusions in the Black Hills of South Dakota, United States, may also be assigned to the porphyry category, although there both molybdenum and copper contents and, as at Kisladag, quartz-veinlet stockworks are relatively minor (MacLeod and Barron 1990).

Notable is the apparently poor development of the high-sulphidation epithermal environment in alkaline volcanic centres. Only minor examples are known, the best described being the Navisi 3 prospect alongside the Emperor low-sulphidation epithermal vein gold-telluride deposit, Fiji. There, minor gold concentrations are hosted by alunite-rich, advanced argillic alteration and underlain by low-grade porphyry copper-gold mineralisation (Eaton and Setterfield 1993; Fig. 1a). This sort of downward transition from the high-sulphidation epithermal to porphyry copper-gold environment is typical of calc-alkaline volcano-plutonic arcs (e.g. Sillitoe 2000a). By contrast, most of the documented porphyry-epithermal transitions in alkaline igneous centres involve low- rather than high-sulphidation gold mineralisation. Low-sulphidation mineralisation above or overprinting deeper-level environments is described, for example, at Porgera (Richards and Kerrich 1993; Fig. 1b) and

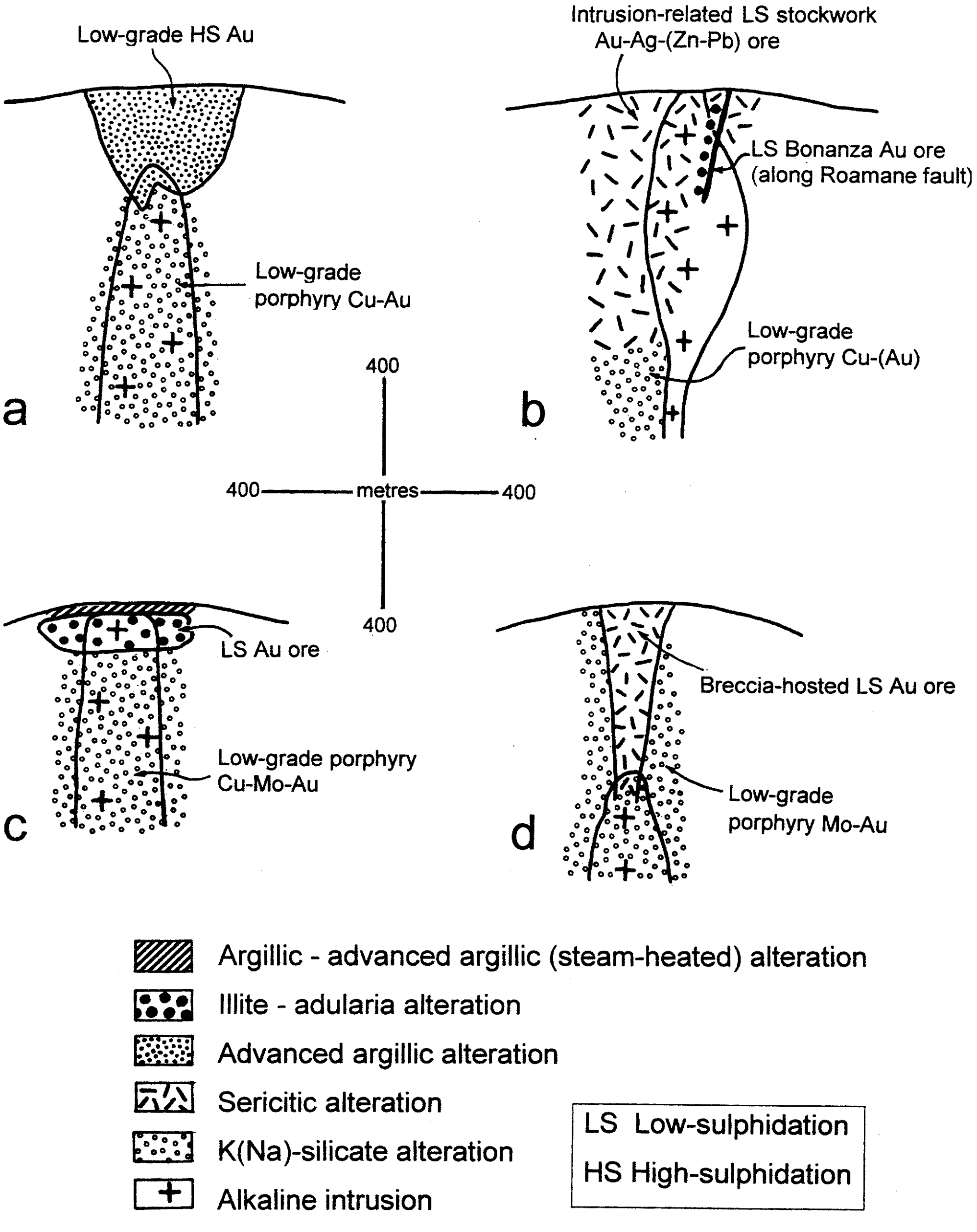

Fig. 1a–d Cartoons to show the generalised nature of the porphyry-epithermal transition in four gold ± copper systems related to alkaline rocks. **a** Navisi 3, Fiji (inspired by Eaton and Setterfield 1993). **b** Porgera, Papua New Guinea (inspired by Richards and Kerrich 1993, and Ronacher et al. 1999). **c** Ladolam, Papua New Guinea (inspired by Moyle et al. 1990). **d** Golden Sunlight, Montana, United States (inspired by Spry et al. 1996; personal observations, 1980). Existence of the high-sulphidation epithermal environment at Navisi 3 is unusual in alkaline igneous centres, which appear to be typified by low-sulphidation epithermal mineralisation above or overprinting the porphyry environment

Ladolam (Moyle et al. 1990; Müller et al. 2001, this volume; Fig. 1c) in Papua New Guinea as well as at Golden Sunlight (Spry et al. 1996; Fig. 1d). This situation may be explained by assuming either that advanced argillic alteration – the porphyry lithocap – and any subsequent high-sulphidation mineralisation were not developed or simply that the host lithocap environment has already been lost to erosion. The former explanation is preferred because the broad range of paleo-depths observed in alkaline igneous centres worldwide is difficult to reconcile with the consistent deficiency of lithocaps and attendant high-sulphidation mineralisation.

Groundwater absorption of SO_2- and HCl-rich magmatic volatiles in the epithermal environment generates the highly acidic fluid responsible for advanced argillic alteration, the ubiquitous host to high-sulphidation mineralisation (e.g. Hedenquist 1987). Therefore, in view of clear evidence for higher SO_2 contents in volatiles derived from alkaline as opposed to calc-alkaline magmas (Bailey and Hampton 1990; Hedenquist 1995), and enhanced chlorine solubilities in alkali-rich, silica-poor magmas (e.g. phonolite; Signorelli and Carroll 2000), the paucity of advanced argillic lithocaps and high-sulphidation deposits in alkaline igneous provinces does not appear to reflect a prevalence of unsuitable volatile compositions. The profusion of magmatically derived SO_2 is further emphasised by the greater abundance of anhydrite and, locally, even celestite in the low-sulphidation epithermal deposits of alkaline parentage (e.g. Cripple Creek, Colorado, United States; Thompson et al. 1985). It may be proposed, therefore, that the highly efficient acid-buffering capacities of alkaline igneous rocks subjected to intense and commonly widespread alkali and carbonate alteration may offer a viable explanation for the restricted development of advanced argillic alteration and high-sulphidation mineralisation (cf. Jensen and Barton 2000). The alkali- and CO_2-rich aqueous fluid which produced these alteration effects may perhaps be considered more akin to that responsible for the extensive zones of sodic and potassic fenitisation around carbonatite-bearing alkaline igneous complexes (e.g. Morogan 1994) than to the magmatic fluid exsolved from typical calc-alkaline magmas or, at least, to lie somewhere between these two end-member types.

By the same token, the newly named intermediate-sulphidation class of epithermal deposits (Hedenquist et al. 2000) is also sparsely developed in alkaline provinces. This epithermal class, intermediate in sulphidation state between classical high- and low-sulphidation deposits, but locally transitional to the former, is characterised by elevated base-metal sulphide, manganoan carbonate and silver contents, as exemplified by Comstock Lode, Nevada, United States. Most epithermal vein deposits associated with alkaline rocks are true low-sulphidation deposits, in which the common presence of minor quantities of arsenopyrite defines the low sulphidation state. Some workers, however, prefer to separate alkaline rock-related epithermal deposits into a distinct category because of their special mineralogical features, particularly the elevated telluride and roscoelite contents (Bonham 1988).

Based on known examples, it seems reasonable to conclude that magmatic-hydrothermal deposits associated with alkaline rocks are relatively poor in zinc, lead and silver compared with those in calc-alkaline rocks. There are no major zinc-rich skarn or carbonate-replacement deposits associated with either barren intrusions or porphyry copper/molybdenum-gold-bearing stocks of alkaline composition, although this absence may result from a paucity of carbonate rocks in some alkaline provinces. Alkaline rock-related epithermal veins are also typically characterised by both low zinc and lead contents and low Ag/Au ratios. Given the relatively high salinities revealed by fluid-inclusion studies of epithermal deposits related to alkaline rocks (Richards 1995), this paucity of zinc, lead and silver is taken to reflect a lower availability of these chloride-transported metals than in many calc-alkaline magmatic systems. Nevertheless, low-grade zinc and lead, rather than copper, concentrations accompany the stockwork gold mineralisation at Porgera (Richards and Kerrich 1993) as well as occurring in a deep zone of dispersed mineralisation at Cripple Creek (Jensen and Barton 2000).

Aberrant deposits

Several giant gold and/or copper deposits related to alkaline rocks may be considered unique, in the sense that even minor examples displaying the same key geological characteristics are unknown beyond their general vicinities (Sillitoe 2000b). Cripple Creek, Ladolam, Porgera and Olympic Dam, all containing >20 million oz Au, and the Phalaborwa copper deposit are prime examples (Table 2). Subeconomic mineralisation showing similarities to Ladolam occurs elsewhere in the Tabar-Feni alkaline volcanic chain (Licence et al. 1987), to Porgera at nearby Mount Kare (Richards and Ledlie 1993) and to Olympic Dam at nearby Acropolis and Wirrda Well (Parker 1990), but not further afield. Assignment of Cripple Creek, Ladolam and Porgera to the low-sulphidation epithermal category, or Olympic Dam and perhaps even Phalaborwa (Groves and Vielreicher 2001) to the iron oxide-copper-gold category, although correct in a strictly classificatory sense, tends to obscure this uniqueness. Some might claim that one or more of these selected deposits are not unique, as may be implied, for example, by perceived genetic similarities between Cripple Creek, Emperor and second-stage mineralisation at Porgera (Ronacher et al. 1999). Nevertheless, it is the unique empirical, rather than strictly genetic, attributes of these and other deposits which are of greatest concern to explorationists.

The Cripple Creek gold-telluride deposit is centred on a large diatreme complex (Table 2), within and immediately beyond which ore shoots confined to steep,

Table 2 Aberrant gold and copper deposits related to alkaline rocks

Deposit	Metal content	Related alkaline rocks	Age (Ma)	Tectonic setting	Selected reference
Cripple Creek, Colorado	834 t Au	Phonotite to alkali basalt (lamprophyre) diatreme complex	31–28	Extensional back arc, preparatory to Rio Grande intracontinental rift	Kelley et al. (1998)
Ladolam, New Papua Guinea	1,190 t Au	Trachyandesite-latite stratovolcano, monzodiorite stocks	< 1	Post-subduction extension	Moyle et al. (1990)
Porgera, Papua New Gunea	660 t Au	Minor alkaline gabbro and mafic porphyry stocks	6	Fold-thrust belt linked to continent-island arc collision	Richards and Kerrich (1993)
Olympic Dam, Australia	20 Mt Cu, 1,200 t Au, 1 Mt U	Syenogranite pluton, felsic and alkaline mafic-ultramafic dykes	~1590	Intracontinental rift	Reeve et al. (1990)
Phalaborwa, South Africa	4.25 Mt Cu + Au	Foskorite and carbonatite intrusions	~2060	Intracontinental extension	Verwoerd (1986)
Zortman-Landusky, Montana	120 t Au	Quartz monzonite and syenite phases of laccolith, tinguaite dykes	~62	Extensional back-arc above flat slab	Russell (1991)

Fig. 2 Typical sheeted vein zone cutting diatreme breccia in the Cripple Creek gold deposit, Colorado, United States (extracted from a drawing of the Captain vein in the Portland mine by Lindgren and Ransome 1906). Individual seams are vuggy and lined with crystalline aggregates of quartz, fluorite, dolomite, pyrite, calaverite and minor amounts of other minerals. Note the marked contrast with normal low-sulphidation epithermal quartz veins

generally narrow (0.6–3 m) sheeted zones were exploited to depths of up to 1,000 m, more than three times that typical for low-sulphidation epithermal veins. Individual seams, 2–15 cm wide, in the sheeted zones tend to be vuggy and composed of minor amounts of intergrown quartz, fluorite, dolomite, pyrite and calaverite which lack crustiform banding and are quite unlike normal low-sulphidation epithermal quartz ± carbonate veins (Lindgren and Ransome 1906; Fig. 2). Currently, the low-grade envelopes to the main sheeted zones hosted by diatreme breccia constitute open-pit ore (Kelley et al. 1998).

Markedly different is the broadly tabular and subhorizontal Ladolam gold deposit (Fig. 3), lying beneath the collapse amphitheatre of a small alkaline stratovolcano (Table 2). The deposit comprises a complex array of hydrothermal breccias which overprint low-grade porphyry copper-gold mineralisation hosted by potassic-altered monzodiorite porphyry (Moyle et al. 1990; Müller et al. 2001, this volume; Fig. 1c). The breccias underwent biotite-magnetite followed by illite-adularia-pyrite alteration which, in turn, was cut by a stockwork of quartz-illite-adularia-pyrite veinlets (Carman 1995; Müller et al. 2001, this volume; Fig. 3). Much of the gold is refractory and occurs as submicroscopic inclusions within arsenian pyrite in the breccias. The orebody, the youngest known intrusion-related deposit (Davies and Ballantyne 1987), is the only major example of gold mineralisation triggered by sector collapse of a volcano, thereby telescoping low-sulphidation epithermal over pre-collapse porphyry environments (Moyle et al. 1990; Sillitoe 1994; Carman 1995; Müller et al. 2001, this volume).

The Porgera gold deposit, centred on a cluster of small mafic intrusions (Table 2), may be subdivided into two discrete, partly overprinted mineralisation stages (Richards and Kerrich 1993; Fig. 4). The first is an unusual stockwork of quartz-poor, sulphide-carbonate veinlets hosted dominantly by carbonaceous and calcareous siltstone in which gold, much of it refractory, accompanies pyrite, sphalerite and galena. The second, possessing the hallmarks of a classic ‘alkalic-type’ gold deposit (Richards 1995), is a fault-localised zone of vuggy quartz veins and hydrothermal breccias containing a roscoelite- and telluride-bearing, low-sulphidation

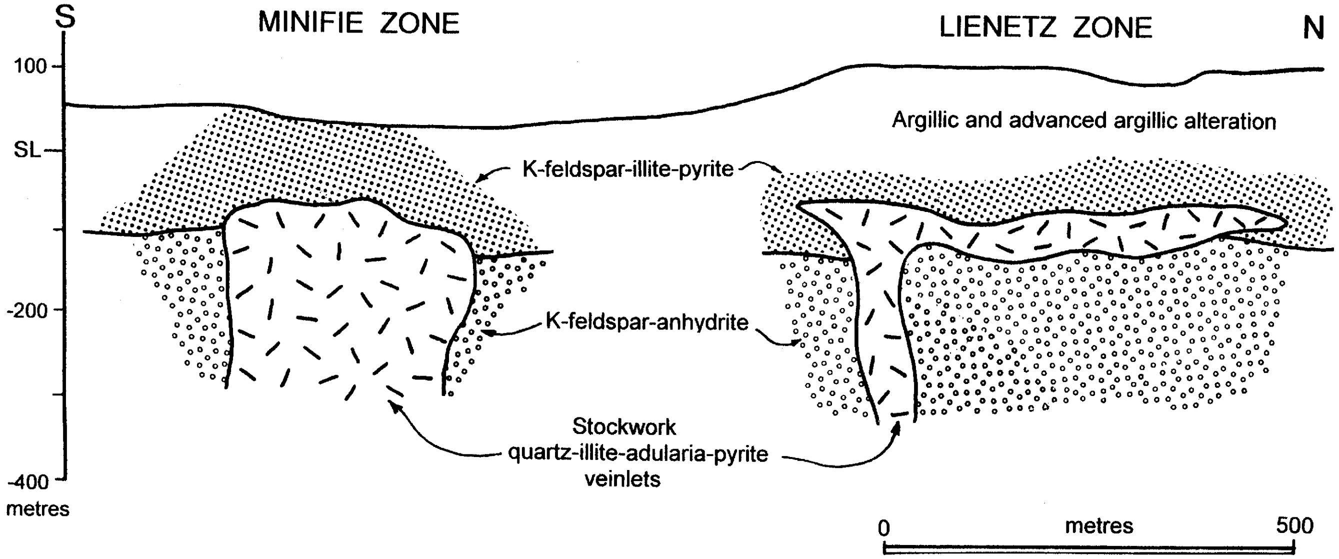

Fig. 3 Generalised post-porphyry copper alteration pattern in the Ladolam gold deposit, Lihir Island, Papua New Guinea (extracted from Carman 1995). Alteration and hydrothermal brecciation affect trachyandesitic volcanic rocks cut by monzodiorite intrusions displaying potassic alteration and low-grade porphyry copper-gold mineralisation. Much of the gold accompanies the K-feldspar-pyrite assemblage above the anhydrite-sealed zoned, although a lesser proportion is present in the overprinted quartz-veinlet stockwork. Argillic and advanced argillic alteration of steam-heated origin occurs at the shallowest levels, especially in the Lienetz zone

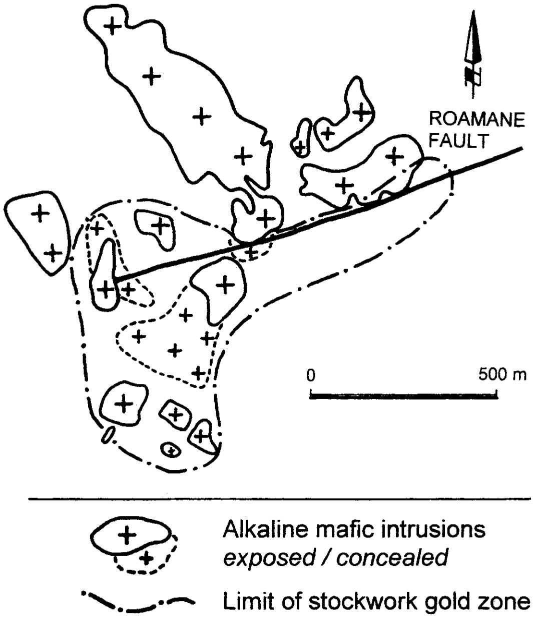

Fig. 4 Sketch of the outcropping and concealed extents of the balloon-shaped alkaline mafic intrusions and associated gold mineralisation in the Porgera deposit, Papua New Guinea (extracted from Richards and Kerrich 1993). The late, bonanza-stage quartz vein and breccia gold ore is controlled by the Roamane fault and overprints the stockwork gold-silver ore

epithermal assemblage. Recent drilling has encountered magnetite-chalcopyrite-pyrrhotite mineralisation associated with biotite and actinolite alteration at depths of ~1,000 m (Ronacher et al. 1999), strongly suggestive of the porphyry environment (Fig. 1b).

The Olympic Dam copper-uranium-gold-silver deposit occurs in a pervasively sericitised, hematitic breccia complex hosted by quartz-poor syenogranite (Table 2; Fig. 5). Sulphide disseminations, microveinlets and fragments within the ore-bearing breccias are zoned from pyrite at depth, upwards to chalcopyrite, then bornite and chalcocite which, in turn, are capped by sulphide-free rock (Reeve et al. 1990; Fig. 5), a pattern more reminiscent of strata-bound, sediment-hosted rather than intrusion-related copper deposits. Pitchblende, fluorite and light REEs are intimately associated with the hematite and sulphide minerals. Highly altered felsic and alkaline mafic-ultramafic dykes, the latter enriched in incompatible elements and similar to ultramafic lamprophyres (cf. Cripple Creek), intruded the breccia complex during the brecciation and mineralisation, and are believed to be genetically related to ore formation (Johnson and McCulloch 1995; Reynolds 2000). The volume of exposed alkaline igneous rock at Olympic Dam is minimal as, indeed, it also is in the Bingham porphyry copper-gold deposit, United States, where melanephelinite magma is invoked as a major source of both sulphur and metals (Keith et al. 1998; Maughan et al. 2001, this volume). The Olympic Dam breccias are locally overlain by, as well as contain subsided fragments of hematitic epiclastic and tuffaceous rocks which are thought to have originated in an overlying fluvio-lacustrine environment (Reeve et al. 1990; Fig. 5). A maar-diatreme complex has been invoked as a likely setting for the unusual combination of geological features at Olympic Dam (Sillitoe 1988; Reeve et al. 1990; Johnson and McCulloch 1995).

The Phalaborwa copper deposit, from which magnetite, gold, platinoids and other commodities, including baddeleyite, uranothorianite and apatite, are by-products (Verwoerd 1986), is hosted by a composite, concentrically zoned, pipe-like pyroxenite-carbonatite intrusion nested within a larger pyroxenite-syenite-carbonatite complex (Palabora Mining Company 1976; Table 2; Fig. 6). Blebs and veinlets of chalcopyrite, bornite and subordinate cubanite and valleriite occur over a >1,200-m vertical interval in phoskorite (magnetite-olivine-apatite rock) and banded and end-stage transgressive carbonatite (Palabora Mining Company 1976). Both potassic and sodic fenites developed in wall-rock granitic gneiss (Palabora Mining Company 1976).

Smaller aberrant deposits also occur in association with alkaline rocks. An example is the bulk-tonnage, low-grade Zortman-Landusky deposit, Montana, United States, where broad fault zones cutting quartz monzonite and syenite within a laccolithic complex contain tinguaite (phonolite) dykes and breccia-hosted stockwork and disseminated gold mineralisation. The gold occurs as electrum, native gold and auriferous tellurides associated with pyrite, marcasite, dolomite and fluorite, but relatively minor quartz, in illite alteration zones (Russell 1991). The illite overprints widespread, but poorly defined potassic alteration. The Zortman-

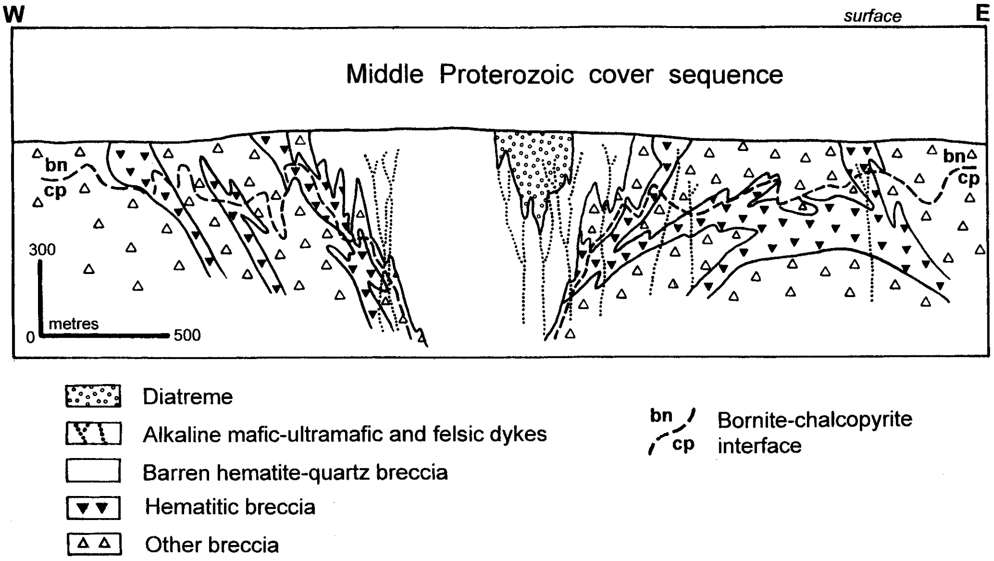

Fig. 5 Simplified section of the Olympic Dam deposit, South Australia, showing the distribution of the ore-bearing hematitic and barren hematite-quartz breccias and late diatremes within the breccia complex (extracted from Reeve et al. 1990). Note the close association between diatremes and alkaline ultramafic dykes. The overall funnel-shaped form of the sulphide zoning pattern is highlighted by the abrupt boundary between chalcopyrite and bornite. The hematite-quartz breccia is sulphide-free

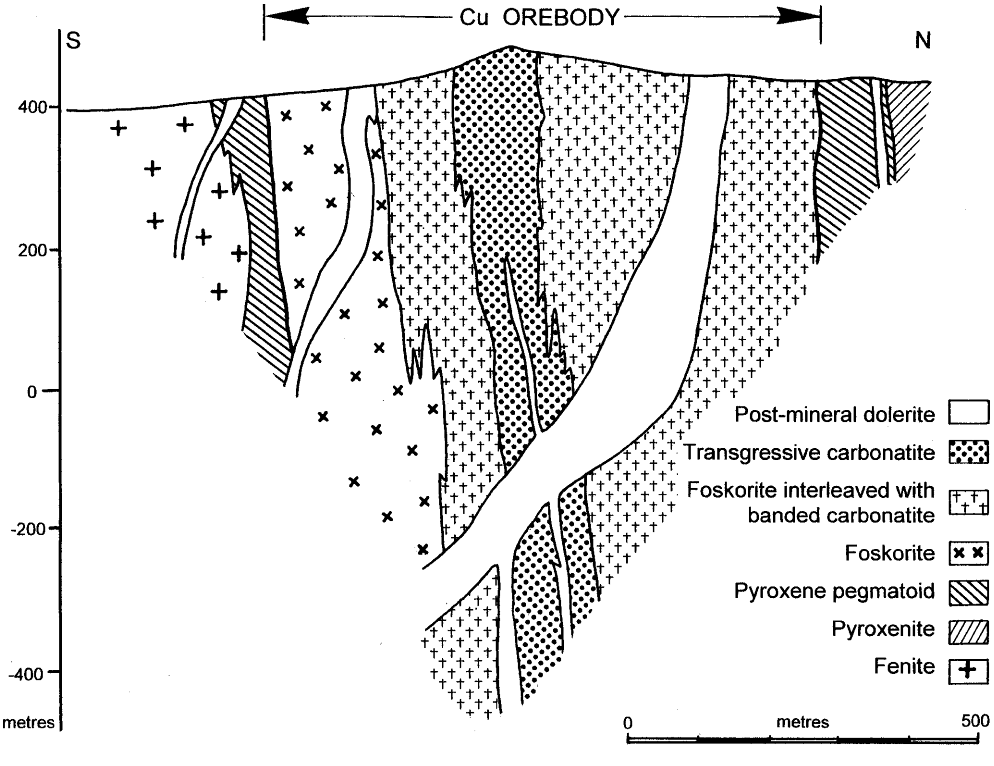

Fig. 6 Simplified section of the Phalaborwa copper deposit, South Africa, showing the steep, concentric disposition of the ore-bearing phoskorite, interleaved phoskorite and banded carbonatite and centrally located transgressive carbonatite units (extracted from Palabora Mining Company 1976). The last contains the highest average copper content (~1%)

Landusky deposit appears to possess a low-sulphidation epithermal affiliation rather than being of porphyry type.

In addition to these individual deposits, a number of alkaline rock-hosted copper-gold deposits assigned to the porphyry category in the Intermontane belt of British Columbia contain few stockwork veinlets, especially quartz-bearing ones, besides possessing prominent calcic and sodic alteration suites, represented by minerals like garnet, scapolite, actinolite, diopside and albite, in combination with or in addition to more typical potassic assemblages (Barr et al. 1976; Lang et al. 1995a, 1995b). Sulphide minerals generally occur as clots and disseminated grains as well as hydrothermal breccia cements. This combination of features, when combined with the abundance of hydrothermal magnetite, might be considered more reminiscent of some iron oxide-copper-gold deposits than of porphyry copper-gold deposits (Sillitoe 2000a). However, the Intermontane belt and other veinlet-poor porphyry copper-gold deposits are all centred on composite porphyry stocks rather than, as in the case of most iron oxide-copper-gold deposits, being hosted by wall-rock lithologies, and are difficult to assign unambiguously to specific intrusions.

The reason for the formation of these aberrant deposit styles is unclear. It may be significant, however, that the ore-related alkaline rocks are characterised by extreme compositional diversity and, moreover, that several of the aberrant deposits, including Porgera, Cripple Creek and Phalaborwa, are related to alkaline rocks with potash-poor compositions rather than to the more usual potassic, including shoshonitic, end members. Unusual magma types, especially silica-undersaturated examples, may differ from their more conventional counterparts in the details of magmatic fluid composition, salinity and temperature as well as in the timing of fluid liberation and its ensuing evolution (cf. Lang et al. 1995a), factors which could be important determinants of deposit style. Certainly, in general, alkaline magmas are richer in SO_2, CO_2 and halogens and poorer in H_2O than their calc-alkaline counterparts (Bailey and Hampton 1990). In the case of Olympic Dam, however, admixture of a specialised external fluid with that of magmatic parentage may be invoked to explain many of the aberrant features (e.g. Haynes et al. 1995).

Silica-undersaturated magmas appear to be those most likely to generate porphyry and epithermal deposits deficient in hydrothermal quartz (Jensen and Barton 2000), which is certainly the case at Cripple Creek, Phalaborwa and in stage 1 at Porgera. Nevertheless, other alkaline magmas gave rise to quartz-poor deposits at Zortman-Landusky and, during early mineralisation stages, at Ladolam, Olympic Dam and elsewhere (e.g. Dinkidi porphyry copper-gold deposit, Philippines; Wolfe et al. 1999). Essentially all the Intermontane belt porphyry copper-gold deposits lack hydrothermal quartz, irrespective of whether the host stocks are saturated or undersaturated in silica (Lang et al. 1995b). The absence of hydrothermal quartz in many of these alkaline rock-related gold and copper deposits, especially those of epithermal type, is rather enigmatic because the silica content of magma seems unlikely to directly influence the amount of silica in a derivative hydrothermal fluid at relatively low temperatures. One possible explanation, however, is that a fluid buffered by quartz-free rock is initially highly alkaline, a condition conducive to suppression of quartz deposition (Rimstidt 1997).

Exploration consequences

Alkaline igneous provinces offer obvious potential for porphyry copper-gold and low-sulphidation epithermal gold deposits and may also contribute relatively minor amounts of gold and/or copper from porphyry molybdenum-gold, skarn, sediment-hosted (Carlin-style), breccia pipe, pluton-related vein and VMS sources. However, alkaline provinces are apparently unfavourable for high- and intermediate-sulphidation epithermal gold/silver deposits and for zinc concentrations of all types. Nevertheless, it is their potential to host unique gold and/or copper deposits which should perhaps be of greatest interest to the exploration community.

Exploration is generally guided mainly by geological parameters, which are typically those emphasised by empirical or descriptive ore-deposit models. Hence, occurrences which lack key geological attributes of particular models run the risk of being discarded at an early exploration stage or, worse, even ignored entirely. For example, porphyry copper-gold deposits lacking quartz- and sulphide-veinlet stockworks may not attract the attention they deserve outside the Intermontane belt of British Columbia. Sheeted vein zones without prominent quartz, as at Cripple Creek, would not meet the criteria of many explorationists seeking bonanza-grade, low-sulphidation epithermal gold veins. Stockwork sulphide mineralisation, containing low-grade zinc and lead values, in carbonaceous and calcareous siltstone cut by small mafic intrusions, as at Porgera, would not be an immediate gold target for many explorers. And how many geologists would realise that the barren hematitic epiclastic-pyroclastic sequence which seems originally to have capped the Olympic Dam deposit could be underlain by a giant copper-uranium-gold breccia body? Furthermore, the quartz-deficient deposits which are commonplace in alkaline igneous centres are unlikely to resist erosion and crop out prominently. For example, Lindgren (1933, p. 859) remarked that the sheeted zones at Cripple Creek '... oxidize to brownish clayey material in which the original vein structure is no longer apparent.' Hence, the quartz-deficient deposits will tend to underlie recessive topography and to be concealed beneath surficial cover. Fortunately, however, conventional geochemistry remains effective, at least where concealment is incomplete.

Exploration for additional examples of aberrant giant deposits related to alkaline rocks (or, indeed, in any environment) is difficult and, if they are indeed unique, manifestly a waste of time and money. In this context, is all the effort expended worldwide, so far unsuccessfully, in search for 'another Olympic Dam' really justified? Even more difficult, however, is mounting a geological programme to explore for aberrant giant deposits unlike those currently known, because the key geological parameters remain undefined (Sillitoe 2000b). Obviously, the geological characteristics which define Porgera or Ladolam, for example, were unimagined prior to discovery. Realistically, only basic prospecting and regional geochemistry and geophysics can be used to target unique giant deposits. An added complexity is introduced by the fact that several aberrant giant deposits are not (Cripple Creek, Phalaborwa) or, at the time of discovery, were not (Porgera, Ladolam, Olympic Dam) parts of well-defined ore districts or belts – in which most exploration activity is normally concentrated.

Therefore, notwithstanding recent emphasis on alkaline igneous provinces as prime exploration targets, particularly for gold, subtle expressions of unconventional deposits and deposit types may have easily been missed. Therefore, it is concluded that major gold and copper deposits remain to be found in the numerous alkaline provinces around the world, and perhaps not just in those generated at convergent plate boundaries. Both saturated and undersaturated alkaline igneous rocks in anorogenic intraplate settings, better known as repositories for niobium, tantalum, uranium, tin, tungsten and REEs (e.g. Kinnaird and Bowden 1991), should not be ignored as hosts for isolated and possibly unusual gold and copper deposits. Intraplate gold and copper mineralisation seems most likely to occupy intracontinental extensional (rift or hot-spot) settings, like those inferred for Olympic Dam and Phalaborwa, but oceanic alkaline magmatism under subaerial and/or shallow-marine conditions could perhaps also possess unsuspected potential.

Acknowledgements Daniel Müller is thanked for the invitation to contribute this introductory essay. Reviews by Jeff Hedenquist, David Groves, Eric Jensen, Daniel Müller and John Thompson improved the content. Robert Fournier and Jeff Hedenquist provided counsel on silica solubility.

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