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EPITHERMAL GOLD DEPOSITS: STYLES, CHARACTERISTICS AND EXPLORATION

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Epithermal ore deposits form at shallow depth. This conclusion was initially based on geologic reconstructions, ore mineralogy and related textures (Lindgren, 1933). It has subsequently been refined with fluid inclusion data to indicate that epithermal ores form over the temperature range of <150°C to ~300°C, from the surface to as deep as 1 to 2 km. Here we highlight the general characteristics of the two principal styles of epithermal mineralization in which gold is the dominant economic metal. We base our generalizations on observations of many deposits and prospects in the circum-Pacific region. Distinguishing between the two styles is crucial for effective exploration. Although they show similar alteration mineralogies, the distribution of the alteration zones is different, and the economic mineralization is associated with different parts of the system. The alteration zoning can be used as a pointer towards the most prospective part of the system, but only when the style has been correctly recognized. In addition, the two styles of mineralization have differences in their geochemical associations.

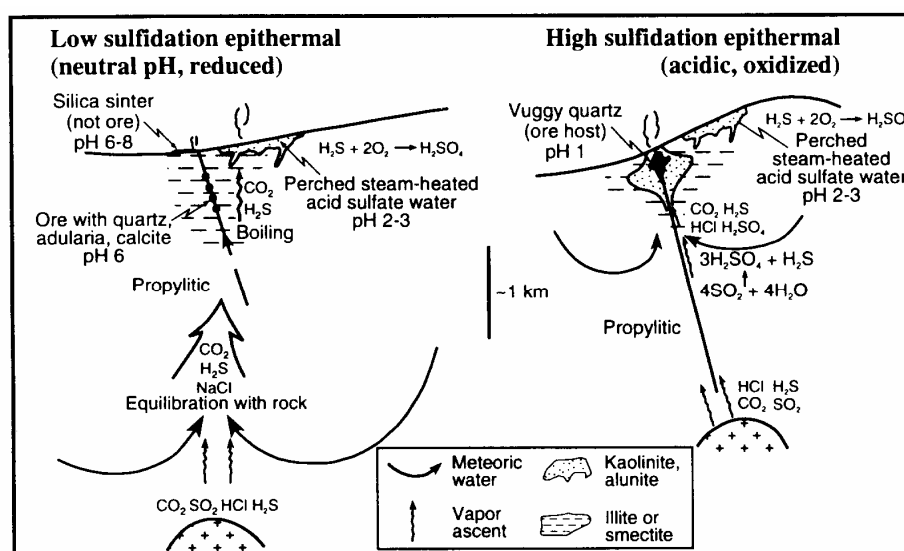


Figure 1. Generalized sketches showing the relation of fluid types to alteration zoning in the two styles of epithermal deposits. (a) In low-sulfidation systems, the fluid at 1-2 km depth is near-neutral pH and reduced, and in equilibrium with the host rocks at greater depths. The boiling fluid rises along permeable zones, depositing ore and gangue minerals, and may discharge from near-neutral pH hot springs. The separated vapor with CO₂ and H₂S condenses in the vadose zone to form a steam-heated water, acidic from oxidation of H₂S. (b) In high-sulfidation systems, magmatic volatiles ascend to the epithermal environment where they are absorbed by meteoric water, and the HCl and SO₂ form a highly acidic solution that leaches the rock outward from the fluid conduit. Ore metals may be introduced into this leached rock by later magmatic fluids (see Hedenquist *et al.*, 1994).

The two deposit styles are formed from fluids of contrasting chemistry (Fig. 1). In the **low-sulfidation** environment, the mineralizing fluids are those typically tapped by drilling into active geothermal systems (Henley and Ellis, 1983). The near-neutral pH and reduced fluids form low-sulfidation state sulfide minerals (Barton and Skinner, 1979). In contrast, **high-sulfidation** systems and their relatively high-sulfidation state minerals are associated with acidic and oxidized fluids formed in the magmatic-hydrothermal environment adjacent to young volcanoes (Ransome, 1907; Hedenquist *et al.*, 1994). These two styles of epithermal mineralization (White and Hedenquist, 1990) are also known as the adularia-sericite and acid-sulfate types, respectively (Heald *et al.*, 1987).

Isotopic studies have shown that the hydrothermal fluid in the low-sulfidation environment is dominated by meteoric water, but some systems contain water and reactive gases of magmatic origin (Hedenquist and Lowenstern, 1994). The fluids that rise from great depth have equilibrated with their host rocks, so are reduced and have a near-neutral pH (Giggenbach, 1992); this reaction results in NaCl, CO₂ and H₂S being the principal species in the fluid (Fig. 1). Boiling at shallow depth generates a CO₂- and H₂S-rich vapor which may condense near the surface in the vadose zone, forming steam-heated acid-sulfate waters from oxidation of H₂S (pH 2-3 waters with a temperature close to 100°C).

By contrast, in the high-sulfidation environment reactive components derived from an oxidized magmatic source ascend to the near surface with little water-rock interaction at depth. The HCl- and SO₂-rich vapor may become absorbed by groundwater (Rye, 1993), resulting in a hot (200-300°C), highly acidic (pH 0-2) and oxidized fluid that reacts extensively with and leaches the host rock at shallow depth. Thus one major difference between these two styles of fluids is the degree to which they have equilibrated with their host rocks below the level of ore deposition.

Table 1: EXAMPLES OF EPITHERMAL GOLD DEPOSITS

LOW SULFIDATION	HIGH SULFIDATION
McLaughlin, California, USA	Goldfield, Nevada, USA
Round Mountain, Nevada, USA	Summitville, Colorado, USA
Hishikari, Japan	Iwato, Kasuga and Akeshi, Japan
Emperor, Fiji	La Coipa, Chile
Golden Cross, New Zealand	El Indio, Chile
Waihi, New Zealand	Pueblo Viejo, Dominican Republic
Lebong Tandai, Indonesia	Chinkuashih, Taiwan
Porgera Zone VII, Papua New Guinea	Lepanto, Philippines
Pajingo, Australia	Lahóca, Hungary

To simplify our brief discussion, we examine epithermal mineralization in which gold is the principal economic metal, mainly hosted by or related to calc-alkalic or alkalic volcanic rocks. Both styles are widespread (Table 1), principally in convergent tectonic settings, and both have examples of major economic significance. A similar discussion could be made for epithermal systems rich in silver, base-metals (Pb, Zn) or even tin.

OBSERVATIONS

The most basic characteristics of any ore deposit are its form, mineralogy, textures and alteration zoning. Based on a variety of observations (Sillitoe, 1977; Buchanan, 1981; Heald *et al.*, 1987; White *et al.*, 1995), when we compare the low- and high-sulfidation deposits we see that there is considerable overlap in characteristics, but there are also many distinctive features. For example, the characteristic form of these two styles of epithermal deposit is different (Table 2). Most low-sulfidation deposits consist of cavity-filling veins with sharp boundaries, or stockworks of small veins. Veins may be important in high-sulfidation deposits, but the majority consist of disseminated ores that replace or impregnate leached country rock. Both styles are typically structurally controlled, though in high-sulfidation deposits the disseminated form may conceal this.

Table 2: FORM OF DEPOSITS

LOW SULFIDATION (Adularia-sericite)	HIGH SULFIDATION (Acid sulfate)
Open-space veins dominant	Veins subordinate, locally dominant
Disseminated ore mostly minor	Disseminated ore dominant
Replacement ore minor	Replacement ore common
Stockwork ore common	Stockwork ore minor

Ore and Gangue

The mineralogy of ores shows considerable overlap, but there are several pronounced differences, based on a compilation of mineral data for more than 130 epithermal deposits (White *et al.*, 1995; Table 3); these differences are mainly in the sulfide mineralogy, which reflects the different redox conditions of the hydrothermal fluid. One distinction is the common occurrence of sphalerite and arsenopyrite in low-sulfidation deposits, whereas sphalerite is scarce and arsenopyrite rare in high-sulfidation deposits (White *et al.*, 1995). Unlike low-sulfidation examples, high-sulfidation deposits commonly contain copper minerals, especially the high-sulfidation state sulfosalts enargite-luzonite. Such sulfides, including the relatively high-sulfidation state minerals tennantite-tetrahedrite (Barton and Skinner, 1979), are typically rare or absent in low-sulfidation deposits. The total abundance of sulfide minerals (dominantly pyrite) is not significant, as it can be high or low in either style.

The gangue minerals associated with the two styles of epithermal mineralization also show considerable overlap, but there are clear differences as well (Table 4), differences that reflect the reactivity (pH) of the altering fluid. Quartz is common in both styles. Adularia and calcite, both indicating near-neutral pH conditions, are common minerals in low-sulfidation deposits (the most common after quartz; Buchanan, 1981), but are absent from high-sulfidation deposits. Minerals formed under relatively acidic conditions, such as kaolinite and alunite (plus pyrophyllite, diaspore and P-, Sr-, Pb- and REE-bearing phosphate-sulfate minerals), are common but minor in high-sulfidation deposits. In low-sulfidation deposits kaolinite and alunite do not occur as gangue, except as an overprint (Vikre, 1985).

Table 3: ORE MINERALS IN Au-RICH ORES
shown as frequency of occurrence (abundance)

	LOW SULFIDATION	HIGH SULFIDATION
PYRITE	ubiquitous (abundant)	ubiquitous (abundant)
SPHALERITE	common (variable)	common (very minor)
GALENA	common (variable)	common (very minor)
CHALCOPYRITE	common (very minor)	common (minor)
ENARGITE-LUZONITE	rare (very minor)	ubiquitous (variable)
TENNANTITE-TETRAHEDRITE	common (very minor)	common (variable)
COVELLITE	uncommon (very minor)	common (minor)
STIBNITE	uncommon (very minor)	rare (very minor)
ORPIMENT	rare (very minor)	rare (very minor)
REALGAR	rare (very minor)	rare (very minor)
ARSENOPYRITE	common (minor)	rare (very minor)
CINNABAR	uncommon (minor)	rare (very minor)
ELECTRUM	uncommon (variable)	common (minor)
NATIVE GOLD	common (very minor)	common (minor)
TELLURIDES-SELENIDES	common (very minor)	uncommon (variable)

Textures

The textures that characterise the two types of deposits are very different. Low-sulfidation deposits show a wide variety of textures, including banded, crustiform quartz and chalcedony veins, druse-lined cavities, and spectacular, multiple-episode vein breccias. The latter reflect multiple episodes of mineral deposition and hydraulic fracturing, followed by explosive pressure release which may be associated with hydrothermal eruptions at the surface. Lattice-textured bladed calcite is common, formed as a result of boiling (Simmons and Christenson, 1994), though it may be replaced by quartz as the system cools. In areas that have experienced little erosion, distinctive silica sinters deposited at the paleosurface by neutral-pH hot-spring waters may still be present (Vikre, 1985; White *et al.*, 1989). The sinters are rhythmically banded, with vertical growth structures, and may contain plant fragments; they are easily distinguished from siliceous replacement of bedded sediments.

Table 4: MINERALOGY OF GANGUE
shown as frequency of occurrence (abundance)

	LOW SULFIDATION	HIGH SULFIDATION
QUARTZ	ubiquitous (abundant)	ubiquitous (abundant)
CHALCEDONY	common (variable)	uncommon (minor)
CALCITE	common (variable)	absent (except as overprint)
ADULARIA	common (variable)	absent
ILLITE	common (abundant)	uncommon (minor)
KAOLINITE	rare (except as overprint)	common (minor)
PYROPHYLLITE-DIASPORE	absent (except as overprint)	common (variable)
ALUNITE	absent (except as overprint)	common (minor)
BARITE	common (very minor)	common (minor)

By contrast, the typical textures of high-sulfidation deposits show relatively little variation, with the most characteristic texture being massive bodies of vuggy quartz typical of Nansatsu-type deposits, though locally veins and breccias may be important hosts to ore. The vuggy quartz is caused by acid leaching at pH <2 (Stoffregen, 1987), which leaves open spaces and mainly silica behind; this residue then recrystallizes to quartz, with additional quartz and pyrite deposited from solution. Massive to banded sulfide veins consisting of pyrite and enargite may also cut the vuggy quartz bodies. Silica sinters are never formed at the surface in this acidic environment because of kinetic factors inhibiting the polymerization and precipitation of silica from acidic solutions. On textural grounds alone, there is seldom much difficulty to distinguish the two styles of deposit.

Alteration mineralogy and zoning

In addition to gangue mineralogy, the mineralogy and zonation of hydrothermal alteration assemblages is another distinguishing characteristic. Many alteration minerals are stable over limited temperature and/or pH ranges, and thus provide important information to reconstruct the thermal and geochemical structure of the hydrothermal system. Because of the near-surface origin of these deposits, and the dynamic setting in which they form (including the possibility of significant erosion during hydrothermal activity; Reyes, 1990; Sillitoe, 1994), alteration that overprints the system must be distinguished from that associated with ore.

Table 5: HYDROTHERMAL ALTERATION

	LOW SULFIDATION	HIGH SULFIDATION
DEEP, MINERALIZING FLUID	near-neutral pH	acid (pH <1 to >3)
MINERAL ASSEMBLAGE	illite (sericite) interstratified clays	alunite, kaolinite, pyrophyllite, diaspore, zoned out to illite

The ore-associated alteration in low-sulfidation deposits is produced by near-neutral pH thermal waters, with temperature decreasing both with decreasing depth and with increasing distance from the conduit of fluid flow. In active systems alteration mineralogy and temperature are directly measured, thus indicating the range of thermal stability of temperature-dependant minerals (Henley and Ellis, 1983; Reyes, 1990; Fig. 2). During exploration of epithermal prospects this information allows paleoisotherms to be deduced from the distribution of alteration minerals, which in turn helps to locate conduits of paleoflow, and to determine the level of erosion. The former is significant because major ore accumulations must occur in conduit zones. The latter is significant as most epithermal ore is deposited over the range of 180 to 280°C, equivalent to a depth below the paleowater table from about 100 m to 800-1500 m (Hedenquist and Henley, 1985). Prospects with paleotemperatures low in that range are encouraging, whereas indications of temperatures >280°C suggest the prime epithermal potential has been eroded.

Variations in the basal spacing of clay minerals, which dominate alteration in the low-sulfidation

environment (Table 5) are among the best indicators of paleotemperature. With increasing temperature smectite (stable at $<160^{\circ}\text{C}$) gives way to interstratified illite-smectite, whereas illite by itself is generally stable at $>220^{\circ}\text{C}$ (Reyes, 1990). This progression in thermal stability commonly results in a clear upward and outward zonation of minerals from low-sulfidation ore bodies (Table 6). The ore zone contains minerals indicating the highest pH (adularia and calcite), as boiling in the conduits causes CO_2 loss and consequent increase in pH, though these minerals are relatively temperature insensitive (Fig. 2). Other temperature-sensitive minerals include zeolites (most stable at $<220^{\circ}\text{C}$, except for wairakite) and Ca-silicates such as epidote (stable above $200\text{--}240^{\circ}\text{C}$); hydrothermal biotite and amphiboles form at temperatures above about 280°C , near the base of the epithermal environment.

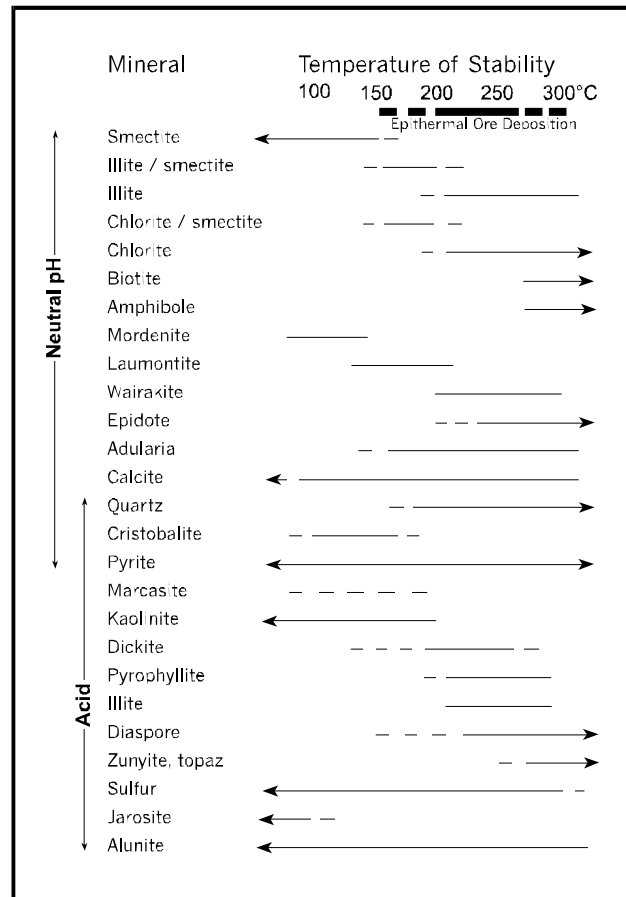


Figure 2. Temperature stability of hydrothermal minerals common in the epithermal environment (from Henley and Ellis, 1983; Reyes, 1990; E. Izawa and M. Aoki, personal communication, 1994). Some workers disagree on the absolute temperature of first appearance of some minerals, and the temperature of transition from one clay to another, but the relative stability is similar in geothermal systems throughout the world. It is useful to identify zones of mineral assemblages, as these may be more meaningful in indicating paleotemperatures than single minerals (Reyes, 1990). In low-sulfidation systems the principal gangue minerals are quartz, calcite, and adularia; in high-sulfidation systems the principal gangue mineral is quartz.

Izawa *et al.* (1990) deduced the paleotemperature-sensitive suite of hydrothermal minerals that are characteristic of the Hishikari district, Japan, and based on these alteration minerals the paleoisotherms were mapped using surface and drillhole samples. The presence of primary cristobalite or tridymite (from high-temperature devitrification of volcanic glass) indicates the least altered rocks affected by the lowest temperature hydrothermal fluid. Progressively higher temperature zones were mapped based on the presence of kaolinite, smectite, interstratified clays, and finally (beneath the present surface) chlorite abundance exceeding that of interstratified clays. These zones form an elongate halo centered on the vein

system, and in cross section drape over the vein system, the pattern expected for hydrothermal fluids ascending along fractures.

In contrast to neutral-pH alteration, minerals such as kaolinite, dickite, pyrophyllite, diaspore and alunite are stable under acidic conditions (Hemley *et al.*, 1969, 1980; Reyes, 1990), and several of these minerals are also temperature sensitive (Fig. 2). Pyrophyllite may form at a temperature <160°C if the silica concentration is high (i.e., forming chalcedony or amorphous silica); however its coexistence with dickite, illite or diaspore indicates paleotemperatures >200°C. Zunyite, topaz and andalusite also indicate acidic conditions and high temperatures of alteration, >260°C. These minerals comprise the advanced argillic alteration assemblage formed by high-temperature acidic fluids in high-sulfidation deposits. The host rock most commonly consists of leached silicic alteration (Meyer and Hemley, 1967), with advanced argillic alteration giving way outward to argillic alteration halos (Steven and Ratte, 1960); the illite or smectite becomes stable as the acidic water is progressively neutralized by reaction with the host rock away from the conduit (Figure 6).

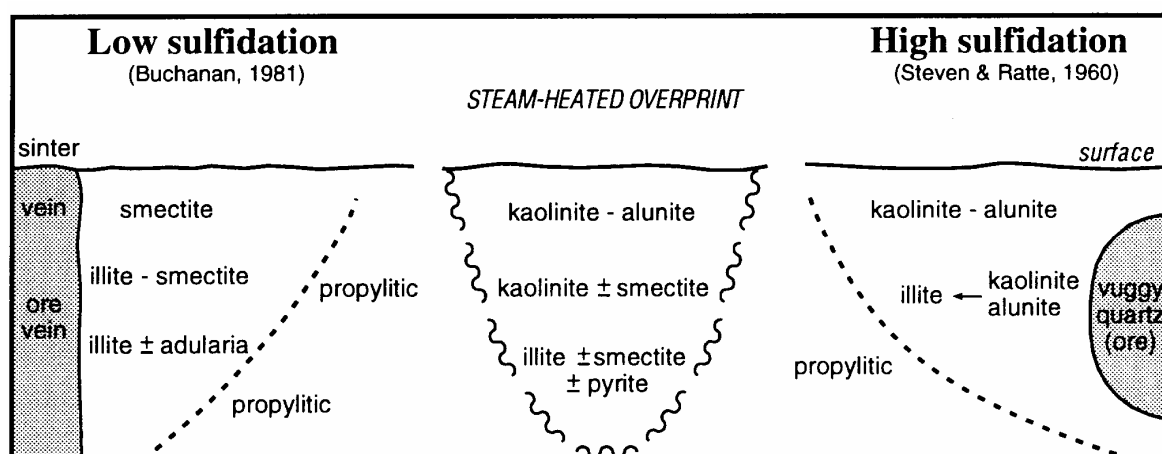


Figure 3. Distribution of hydrothermal alteration associated with high and low sulfidation deposits. The alteration mineralogy varies both vertically and laterally. Quartz is stable in all areas. Propylitic alteration occurs in regions of low water:rock ratios, i.e., outside conduit zones, and its mineralogy is controlled by rock composition. Typical minerals include albite, calcite, chlorite, epidote and pyrite. Steam-heated overprint can occur in either low or high sulfidation environments, though in the latter the hypogene and steam-heated mineralogies are similar. The effects of the steam-heated overprint are most apparent in the low sulfidation environment, as the alteration mineralogy is markedly different from that produced by hypogene fluids. In the low-sulfidation environment. Silica sinters may form where the neutral-pH thermal water discharges at the surface; in areas of high relief, however, this hot water may flow laterally a great distance before reaching the surface, becoming entrained in ground water and thus not liable to precipitate silica sinter. In areas of little erosion and low relief, veins may terminate at the paleosurface in sinter (e.g., McLaughlin, USA); by contrast, in areas of high paleorelief, the veins may pinch out upwards, perhaps into argillic-altered rock, deep below the surface (e.g., Hishikari, Japan). In the high-sulfidation environment, ore mineralization (if present) occupies part of the intensely acid-altered core of the alteration system. This core is typically very irregular in shape, but commonly pinches out above and below the main ore body.

Some of the lower temperature, acid-stable minerals, such as kaolinite and alunite, are also typical of alteration caused by near-surface steam-heated waters in low-sulfidation systems

(Fig. 1); these acid-sulfate waters form at near 100°C, but may be heated if they flow downwards along fractures (Reyes, 1990). Where hydrothermal kaolinite and alunite occur in these deposits, they are either overlying or overprinting ore; weathering of sulfides can also produce a similar alteration overprint, including jarosite.

These observations illustrate the necessity to distinguish these two styles of mineralization during exploration. In a high-sulfidation deposit the ore is typically closely associated with (usually IN) the zone of most acid alteration, and is surrounded by mineral assemblages indicating less acid conditions. By contrast, in low-sulfidation deposits the ore is associated with the LEAST acidic alteration (i.e., adularia and calcite or illite); if acid, advanced

argillic alteration is present (kaolinite and alunite only), it is an overprint of near-surface origin unrelated directly to ore mineralization (Table 6). Particular attention must be given to determining the origin of alteration minerals indicating acidic conditions, including 1) hypogene acidity due to magmatic HCl and SO₂, 2) steam-heated acid-sulfate waters formed near the surface, and 3) post-hydrothermal weathering of sulfide minerals.

From the perspective of understanding the controls on metal transport and deposition, knowledge of variables such as pH and redox state, along with temperature, fluid salinity, etc., are of fundamental importance. For example, in a low-salinity reduced fluid, gold is likely to be transported in solution as a bisulfide complex. Boiling, a common if not ubiquitous process operating in conduits at epithermal depths, will cause CO₂ to be lost from the liquid, resulting in an increase in pH. This initially increases the solubility of gold, but eventually the accompanying H₂S loss from the liquid causes the solubility to decrease, thus leading to the precipitation of gold (Henley *et al.*, 1984). By contrast, in an oxidized and acidic solution of moderate salinity, gold may be transported as a chloride complex, with different controls on its precipitation (Giggenbach, 1992; Hedenquist *et al.*, 1994).

EXPLORATION IMPLICATIONS

To assess an epithermal gold prospect effectively, it is essential to establish whether it is of low- or high-sulfidation style. The commonly extensive and conspicuous steam-heated acidic and/or weathering overprint on low-sulfidation systems has often been mistakenly identified as advanced argillic alteration related to a high-sulfidation system. This leads to wasted effort on an unprospective obscuring blanket. Fortunately the simple characteristics noted above allow the two styles to be, in most cases, easily distinguished. The distinct origins of the two styles results in differences in the geochemical signatures of the ores (Table 7). With use of these generalized chemical differences to guide the design of geochemical surveys, and correct application of alteration zoning to focus detailed assessment *towards* ore potential, we can explore these systems more efficiently.

Table 7: GEOCHEMICAL ASSOCIATIONS

	LOW SULFIDATION	HIGH SULFIDATION
ANOMALOUSLY HIGH	Au, Ag, As, Sb, Hg Zn, Pb, Se, K, Ag/Au	Au, Ag, As, Cu, Sb, Bi Hg, Te, Sn, Pb, Mo, Te/Se
ANOMALOUSLY LOW	Cu, Te/Se	K, Zn, Ag/Au

In exploration it is also important to consider the geological setting and hydrological conditions (e.g., relief) that prevailed at the time of mineralization. In high-sulfidation systems, ore-hosting structures are likely to be found near eruptive vents (i.e., above a subvolcanic magma chamber). The acidic waters generated in this environment may flow long distances before discharging at the surface, as indicated by the extensive distribution of surface features associated with active systems such as Nevaldo del Ruiz volcano in Colombia (Giggenbach *et al.*, 1990).

The very large hydrothermal systems that form low-sulfidation deposits are also strongly influenced by topography (Henley and Ellis, 1983). In relatively low-relief areas the major shallow conduits are likely to be distributed above a feeder zone extending into the basement; the hydrothermal system and resulting alteration commonly has an approximately symmetrical distribution in this setting due to mushrooming of the ascending thermal water. In high-relief areas (e.g., andesitic stratovolcanoes) there is a large degree of lateral flow in geothermal systems, up to 10 km or more, resulting in strongly asymmetric alteration zones relative to the upflow zone. For example, at the Palinpinon geothermal system, Philippines (Reyes, 1990), neutral-pH hot springs depositing silica sinter occur more than 5 km from the upflow zone, and at several hundred meters lower elevation than the steam-heated acidic water and associated alteration that are located over the upflow zone. The most favorable site for mineralization will probably be found associated with the upflow zone, which in this case may occur on the periphery of an extensive asymmetric alteration zone. Failure to recognise lateral flow may lead to misinterpretation of such apparently paradoxical features as flat-lying zones of intense alteration (associated with aquifers) sandwiched between little or unaltered volcanic rocks (aquicludes).

Reconstruction of the geological setting and topography of a prospective district must be combined with information on alteration mineralogy and zoning (Tables 5 and 6), geochemical anomalies (Table 7) and geophysical results to best interpret the potential for and location of epithermal mineralization.

In the past an explorationist had to rely on experience to identify alteration minerals in the field. Clays and other OH- and SO₄-bearing minerals have the most potential to indicate paleotemperature zoning, yet they are the most difficult to correctly characterize in the field, and waiting for X-ray diffraction results reduces the effectiveness

of combining alteration mapping with geological mapping and geochemical sampling. The recent availability of field portable infra-red spectrometers (such as the PIMA II) has revolutionized our ability to map alteration correctly and in detail (e.g., interstratified clays can be identified).

Lack of geophysical responses directly related to ore has limited the use of geophysics in gold exploration historically. Nevertheless, mineralizing processes cause changes in rock properties which can be detected by geophysical methods on both regional and prospect scale. When geophysical surveys are used in conjunction with geological and geochemical data (White *et al.*, 1995; Table 8), and with an understanding of mineralizing processes, they can be an important aid in exploration (Irvine and Smith, 1990). On a regional scale, aeromagnetic, radiometric and gravity surveys can assist in locating alteration systems and the structures that control deposits. At prospect scale, induced polarization, electromagnetic and resistivity surveys can locate changes in rock properties (e.g., pyritization, silicification and clay alteration), which may be related to ore-forming processes.

Unless they crop out at the surface, epithermal gold deposits of both high- and low-sulfidation styles are difficult exploration targets because they vary sharply in width and grade. Successful exploration must rely on integration of a variety of exploration techniques, guided by an understanding of the characteristics of deposits and the processes that form them. The style of mineralization, and environmental factors at the time of formation (e.g., controlling structures, topography, depth below the paleowater table) and today (e.g., topography, depth of erosion, vegetation, depth of weathering, rainfall) all change the effectiveness of different exploration techniques. There are no simple formulae for success: what works best has to be determined for each terrain and each prospect.

CONCLUSIONS

We have briefly discussed two distinct styles of volcanic-related epithermal gold deposits, and have noted the general characteristics of each style. Although both styles commonly share a similar geologic environment, the composition of the mineralizing fluid is very different. The acidic and oxidized high-sulfidation environment produces deposits with characteristics distinct from those formed in the neutral-pH and reduced low-sulfidation environment. These characteristics can be recognized easily in the field, and this recognition is crucial to the efficient exploration of an epithermal prospect.

Our generalizations have been based on our observations, and those made by other geologists in publications on ore deposit studies. Careful observation and reporting is essential if we are to improve understanding of various deposit types. As noted by Woodall (1993), "it is critical to understand ore-forming processes and to be able to recognize, from limited data, where those processes have been active". Careful observation, followed by informed interpretation based on an understanding of the ore-forming processes, will be essential in future exploration, especially for deposits that do not crop out.

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