TWELVE

Deposits Related to Subaerial Volcanism

Many of the world's most spectacular and historically significant deposits are shallowly buried or crop out in or near subaerial, commonly intermediate to silicic volcanic rocks. They are generally related to volcanic processes and to the emplacement, cooling, and consolidation of the volcanic rocks that contain them. They have a tectonic position, as might be expected. Many of them result from extravasation of the intermediate to felsic igneous systems discussed in the last chapter; they occur along convergent plate boundaries and are therefore related to orogenic belts much as are porphyry, skarn, and granitic deposits and Cordilleran Vein and pegmatite deposits. Associated rock types are basalts, dacites, rhyodacites, latites, and rhyolites in pyroclastic, welded pyroclastic, and flow regimes associated with ignimbrites, cauldron and caldera complexes, and other volcanic symptoms of the volcanic belts of the world.

Deposits considered in this chapter include the classic epithermal type, essentially as defined by Burbank, Nolan, and Lindgren (1933), Wisser (1966), and others before them. Epithermal deposits include the bonanza precious metal districts for which Europe and the Americas are so renowned; in North America, old names like Comstock Lode–Virginia City, Tonopah, Creede, Cripple Creek, Guanajuato, Pachuca, and Potosí are being joined by new ones like Round Mountain, McDermitt, Delamar, Summitville, and Oatman and Creede reawakened. We will also consider a relatively recently recognized subtype, the so-called "invisible gold" deposits

of the Carlin-Cortez, Nevada, type, and develop the idea of "bulk low-grade" epithermal precious-metal gold or silver deposits—broad, altered-mineralized volumes of volcanic pyroclastic rocks and even associated lake-bed volcaniclastic sediments. Waterloo, California, and Candelaria, Nevada (Watson, 1977), are examples of those deposits. Although they do not involve hydrothermal transport, we will also examine the volcanic magnetite flows of Durango, Mexico; El Laco, Chile; and elsewhere, occurrences presumably related to magnetite deposits like those on the Kola Peninsula of Fennoscandia-U.S.S.R. The tin-rhyolite association mentioned at the close of Chapter 11 could be considered here. In a review article, Sillitoe (1977) included stratiform "manto" occurrences of native copper-chalcocite-bornite in flow-top vesicles and ash flow tuffs in some South American calc-alkaline volcanic rocks in this group. Similar occurrences are known in Sonora and near Arivaca, Arizona. Most economic geologists would also include the famous deposits of native copper in propylitized basalts and interbedded conglomerates of the Keweenaw Peninsula in northwestern Michigan as epithermal. Lastly, the Senator antimony deposit in west central Turkey (Bernasconi, Glover, and Viljoen, 1980) is probably epithermal.

▸ EPITHERMAL SILVER-GOLD DEPOSITS

Epithermal deposits as originally defined are products of volcanism-related hydrothermal activity at shallow depths and low temperatures. Deposition normally takes place within about 1 km of the surface in the temperature range of 50 to 200°C, although temperatures to 300°C are now known to be common. Most deposits are in the form of siliceous vein fillings, irregular branching fissures, stockworks, breccia pipes, vesicle fillings, and disseminations. Replacement textures are recognized in many of the ores, but open-space fillings are common and in most deposits are the dominant form of emplacement. Drusy cavities, comb structures, crustifications, and symmetrical banding are generally conspicuous. Colloform, agatelike textures also characteristic of epithermal environments presumably reflect moderate temperatures and free hydrothermal fluid circulation. The fissures have a direct connection with the surface, which allowed the ore-bearing fluids to flow with comparative ease; in fact, some modern hot springs and steam vents are almost certainly surface expressions of underlying epithermal systems (White, 1955; White, Muffler, and Truesdell, 1971; Bernasconi, Glover, and Viljoen, 1980). Barton, Bethke, and Toulmin (1971) deduced flow rates to have been at the rapid rate of 0.2 to 1 cm/second in the OH vein at Creede, Colorado. They found flecks of hematite on the upper surfaces of quartz crystals protruding into veins, and calculated the rate of flow necessary to carry them upward.

A few epithermal deposits can be related directly to deep-seated intrusive bodies, but this relationship is demonstrable only where especially deep erosion has occurred. Many epithermal deposits have no observable association with plutonic rocks. Most ores are in or near areas of Tertiary volcanism, especially near volcanic necks and other structures that tap underlying source materials and reservoirs. Because these deposits are formed near the surface and in tectonically rising areas, they are susceptible to destruction by almost immediately subsequent erosion. They occur, then, in young volcanic rocks, and are nearly unknown in pre-Cenozoic rocks. Wisser (1960) emphasized that district-scale gentle doming is almost universal in epithermal districts. The volcanic environment and continuing hot spring activity engender hot waters in some mines; for example, caustic hot waters were encountered at depth in mines in the Comstock Lode of Nevada and in several of the mercury mines of California.

The country rocks near epithermal veins commonly are extensively altered, even though the vein walls may be sharply defined. Relatively high porosity and open-channel permeability allow fluids to circulate in the wall rocks for great distances, and favorable temperature gradients promote reactions between cool host rocks and warm to hot invading solutions. As a result, wall-rock alteration is both widespread and conspicuous, as is shown in Figure 5-11. Among the principal alteration products are chlorite, sericite, alunite, zeolites, clays, adularia, silica, and pyrite. Chlorite is probably the most common alteration mineral in this zone. Propylitization is the dominant alteration process, *propylite* being an aggregate of secondary chlorite, pyrite, epidote, sericite, carbonates, and albite or adularia in mafic to intermediate volcanics like basalts, andesites, and dacites (Chapter 5). Studies in the late 1970s revealed widespread inconspicuous potassium feldspathization associated with epithermal districts (Howell, 1977); sericitization, silicification, and K-feldspathization are the most common alteration products flanking veins in the more felsic rhyodacite, latite, and rhyolite host lithologies. The silica, sericite, chlorite, and pyrite of epithermal alteration halos are generally fine-grained. Carbonate minerals, especially calcite, dolomite, ankerite, and rhodochrosite, are also alteration products. Furthermore, kaolin and montmorillonite clay minerals may be abundant and conspicuous (Sudo, 1954), forming zones of different colors parallel to the walls of veins. The gangue minerals in epithermal veins include white, clear, greenish, or amethystine quartz, chalcedony, adularia, calcite, dolomite, ankerite, rhodochrosite, barite, and fluorite. Typical "high-temperature" minerals such as tourmaline, topaz, and garnet are absent.

Sulfosalt ore minerals are characteristic of epithermal deposits. They include the silver sulfantimonides and sulfarsenides polybasite, stephanite, pearceite, pyrargyrite, proustite, and others, all combinations of Ag, As, Sb, and S; the gold and silver tellurides petzite [$(Ag,Au)_2Te$], sylvanite ($AuAgTe_4$), krennerite (Au_4AgTe_{10}), calaverite ($AuTe_2$), hessite (Ag_2Te), and so on; and stibnite, acanthite, cinnabar, and native mercury. Some of the world's richest concentrations of native gold and electrum, the natural gold-silver alloy, were deposited under epithermal conditions; the famous bonanza deposits at Goldfield, Nevada; Cripple Creek, Colorado; and Hauraki, New Zealand, are examples. Most epithermal deposits have "bottoms" which must be physicochemical in nature; the structures and gangue mineral fillings such as quartz and carbonates continue downward, but ore values drop sharply below a given level, which may be related to a zone of boiling. In some deposits, however, typical epithermal mineralogies merge downward with galena, sphalerite, chalcopyrite, and other sulfides commonly found in mesothermal or Cordilleran Vein deposits. This interdigitation is found at Creede and Silverton in Colorado, at Pachuca, Mexico, and elsewhere. Graton (1933) proposed the term *leptothermal* to describe ores representing the transition between moderate and low temperatures of formation, the prefix *lepto* meaning small or weak. Recent fluid inclusion studies have so blurred thermal distinctions between epithermal, leptothermal, and mesothermal, however, that leptothermal is now applied generally just to base-metal mineralization and gangue minerals that continue below epithermal precious-metal occurrences.

It is not uncommon to find large, highly colored supergene gossans, or iron oxide cappings, covering epithermal ores. During weathering, the wide-spread pyrite in the altered wall rock is oxidized to limonite—goethite, jarosite, and hematite—forming a conspicuous guide to ore deposits. Supergene enrichment to the extent found in copper deposits is absent, although minor enrichment in silver and gold is reported. Just as epithermal deposits have a discrete bottom or base, they also appear to have upper assay limits which may parallel the lower ones and lie at or a few meters below the surface. The tops almost certainly also represent chemical-physical thresholds related to surface effects with or without surface-related leaching.

Epithermal deposit articles by Schmitt (1950), Wisser (1966), White (1955, 1967), and Sillitoe (1977) have added to definitions and understandings developed decades ago when many epithermal districts now considered "worked out" were still active. They include the observations that silver and gold minerals are texturally younger than base-metal sulfides, with gold normally youngest; that veins close to the subvolcanic basement are base-metal- and silver-rich, lower in quartz, and narrow, while veins higher in the average system are gold-rich, quartz-rich, and wide; that fluid inclusion filling temperatures range from less than 100 to 330°C with an average more nearly 250°C than 200°C; that salinities are typically low at less than 2% NaCl equivalent; and that low $\delta^{18}O$ at -16 to $+4$ ‰ and low D/H values of from -90 to -140 ‰ suggest dominance of meteoric fluids, with magmatic fluid input discerned at several deposits (O'Neill and Silberman, 1974). It appears that near-surface boiling is a trigger of precipitation, generally in the 230 to 260°C range, in systems that may be periodically sealed by precipitation of quartz, then reopened by increased pressure or seismic activity.

The genesis of epithermal precious-metal deposits has been a subject of lengthy discussion. The elements of that debate can be summarized best in Figures 12-1 to 12-3. Zies pointed out in 1929 that epithermal mineralization and broad-scale, fumarolic or solfataric kaolinite-alunite-pyrophyllite alteration can occur even in flows that are removed from a source conduit. He described geothermal springs in a series of volcanic rocks that flowed into a U-shaped valley at Katmai, Alaska, to produce the renowned Valley of Ten Thousand Smokes, with thousands of "rootless" epithermal fumaroles. Schmitt (1950) generalized Zies' ideas with the suggestion that epithermal deposits might be generated totally by shallow circulation of meteoric fluids even without a magmatic component (Figures 12-1 and 12-2). On the other hand, it cannot be controverted that in some districts the base and precious metals are essentially all delivered by magmatic fluids (Figure 12-3) with variable degrees of dilution, precipitation, and redistribution influenced by concurrent or late incursions of meteoric waters. It is certain that meteoric waters could hardly be excluded from the well-developed fault-vein systems that intersected the surface at the time of epithermal activity.

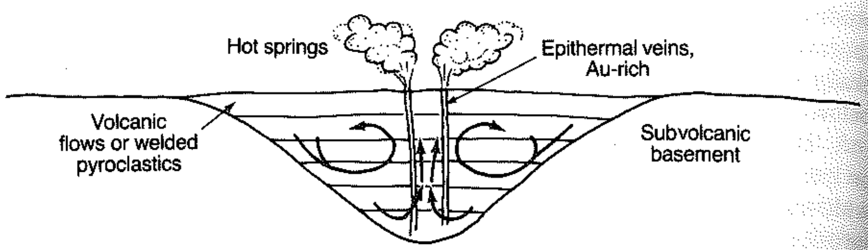

Figure 12-1. Meteoric waters convecting through a cooling volcanic pile dissolve silica, alkalies, halogens, and precious metals and deposit them in veins beneath active hot springs or fumaroles. Patterned after Katmai, Alaska (Zies, 1929), and ideas of Schmitt (1950).

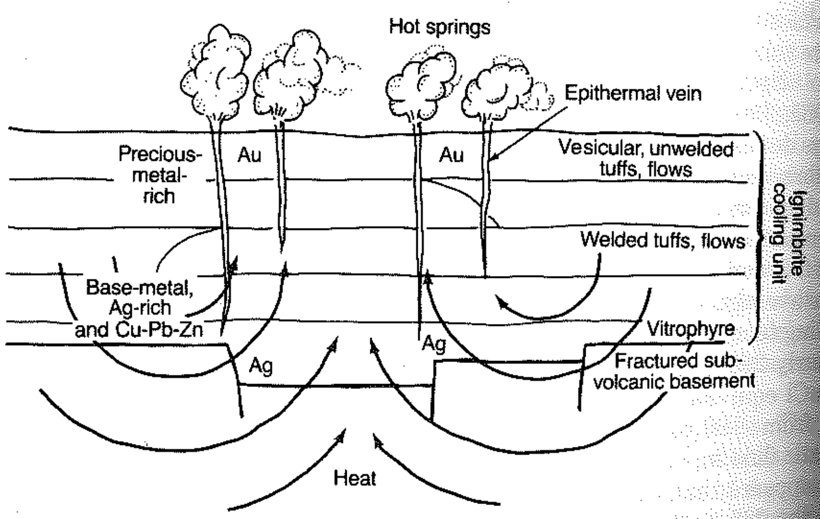

Figure 12-2. Deep circulation of meteoric fluids down through an ignimbrite cooling unit 1 km thick into subvolcanic basement rocks. Leaching of silica, alkalies, base metals, and precious metals supplies epithermal veins above. Similar circulation could be imposed upon a stratovolcanic edifice with an anhydrous subjacent stock. Patterned on possible relationships at Creede, Colorado.

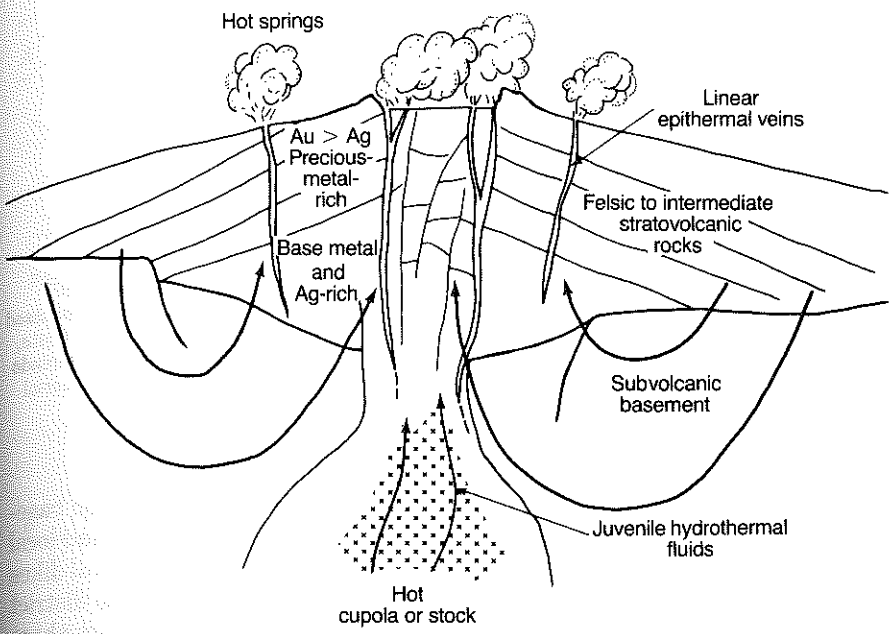

Figure 12-3. Combined juvenile (magmatic) and meteoric fluids. The magmatic component may be either early, as at the Comstock Lode, or late, as in several Peruvian deposits. The relative amounts of juvenile versus leached metal values is thought to vary widely, as from 100% at Tayoltita, Mexico, to low at Pachuca (Dreier, 1976) and Guanajuato (Gross, 1975). It is suggested by some that no meteoric component is necessary and by others that no juvenile component is required. Methods of defining the ratio for particular districts or mines are still imprecise.

Pachuca–Real del Monte, Mexico

The famous bonanza silver districts of Pachuca and Real del Monte are 100 km north-northeast of Mexico City (Figure 12-4); they are typical epithermal deposits. They would represent a single district and have a single name were the two ends not effectively separated by the crest of the Sierra de Pachuca. Pachuca lies along the west flank of the mountain range; Real del Monte is on the east flank, only about 1 km away. Because Real del Monte receives about twice as much rainfall as Pachuca, their physical geographies differ considerably. But geologically they represent two ends of a single mineralized volume (Ordoñez, 1902; Wisser, 1937, 1942, 1966; Winchell, 1922; Geyne, 1956; Geyne et al., 1963; Dreier, 1976).

The Sierra de Pachuca is made up of Tertiary volcanic rocks overlying Cretaceous sedimentary rocks. Thick andesite flows and associated tuffs