Overview of the Yerington Porphyry Copper District: Magmatic to Nonmagmatic Sources of Hydrothermal Fluids, Their Flow Paths, Alteration Affects on Rocks, and Cu-Mo-Fe-Au Ores

JOHN H. DILLES,
Department of Geosciences, Wilkinson Hall 104, Oregon State University, Corvallis, Oregon 97331

MARCO T. EINAUDI,
Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305

JOHN PROFFETT,
Geological Consultant, P.O. Box 772066, Eagle River, Alaska 99577

AND MARK D. BARTON
Department of Geosciences, University of Arizona, Tucson, Arizona 85721

Abstract

The Yerington district, Nevada, hosts at least four porphyry copper deposits and several small Fe oxide-copper-gold lodes within a middle Jurassic batholith and its volcanic cover. The contact aureole of the batholith contains early garnet-pyroxene hornfels and endoskarn, later copper-bearing andradite skarn deposits, and latest-stage large Fe oxide-copper-gold replacement deposits. The Jurassic host rocks have been faulted and tilted 60° to 90° W by Cenozoic normal faulting (Proffett, 1977) so that the modern exposures represent cross sections of a complex paleohydrothermal system from the volcanic environment to about 7 km depth.

This paper summarizes field, petrologic, and geochemical data that support the origin of hydrothermal wall-rock alteration and ore deposition due to two different types of fluids. Magmatic brines were derived from the crystallization of the youngest equigranular intrusion of the Yerington batholith, the Lahr Hill granite. Brines separated from the granite and were emplaced upward together with granite porphyry dikes to produce copper-iron sulfides and associated K silicate alteration in the porphyry copper deposits and copper skarns. In the upper part of the hydrothermal system, magmatic fluids are an important source of acids and sulfur that produced sericite and advanced argillic alteration.

A second type of ore fluid is brine derived from formation waters trapped in the Triassic-Jurassic sedimentary section intruded by the batholith. These fluids were heated by the batholith and circulated through its crystalline parts. Hornfels and endoskarn were produced along the contact of an early intrusion. Following intrusion of the porphyry dikes, sedimentary brines circulated up to 3 km into the batholith and upon heating produced sodic-calcic alteration there. Ascent of these brines, particularly after the waning of magmatic fluid input, may have caused shallow-level chlorite-dominated alteration in igneous host rocks and Fe oxide-Cu-Au lodes and replacement deposits in the batholith and its contact aureole, respectively.

Introduction

The Yerington district, Nevada, contains porphyry Cu(Mo), Cu skarn, Fe oxide, and Cu sulfide ores in metasedimentary rocks, and shallow batholith-hosted Cu-Au-Fe oxide lodes. In aggregate, the geologic resource and production of the district includes 6 Mt Cu in sulfide ores and >100 Mt of Fe in oxide ores (Dilles and Proffett, 1995). All these deposits are directly associated with the Jurassic Yerington batholith, which serves as either host rock or as source for heat and materials that produced contact metasomatism in the aureole to the batholith. Hydrothermal alteration has affected more than 100 km³ of rock and was produced by a similar volume of hydrothermal fluids. Jurassic rocks are superbly exposed in cross section from the subvolcanic environment to ca. 7 km paleodepth, due to Cenozoic normal faulting and westward tilting (Proffett, 1977), so that the three-dimensional geometry of a large upper-crustal paleohydrothermal system can be described in detail.

The purpose of this paper is to summarize the current state of knowledge and viable theories for the sources of these hydrothermal fluids, their flow paths through the Yerington batholith and its wall rocks, and the evolution of the fluids in both space and time. These features are summarized by a series of maps and cross sections illustrating the temporal evolution and three-dimensional geometry of a batholith-related hydrothermal system. This is necessarily a brief progress report drawn from 35 years of geologic research sponsored by the Anaconda Company, research universities, and the National Science Foundation.

The focus below is on two significantly different sources of fluids that have both different point sources and different time-temperature-position flow paths. Magmatic fluids are closely related to the youngest and central intrusion of the
Yerington batholith, the Luhr Hill granite, and associated granite porphyry dikes (Proffett, 1979; Dilles, 1987; Dilles and Proffett, 1995). The flow paths of these fluids were generally upward and outward from porphyry centers.

The second major type of fluids includes sedimentary brines or formation waters genetically related to water trapped within the evaporite-bearing Jurassic-Triassic sediments at Yerington. These brines were heated by the Yerington batholith and convectively circulated through the contact aureole and the crystalline parts of batholith. The flow paths were generally inward toward the batholith, and then upward and locally outward.

Geology

Early Mesozoic rocks

The rocks of the Yerington district include Mesozoic crystalline rocks, Cenozoic volcanic rocks, and Quaternary alluvial deposits (see Proffett and Dilles, 1984). The oldest rocks consist of a sequence of late Triassic or older intermediate and silicic volcanic rocks intruded by middle to late Triassic age plutons (Dilles and Wright, 1988). Unconformably overlying these rocks are a series of marine sedimentary and volcanioclastic rocks, from bottom to top as follows: limestone and black argillite; tuffaceous and limy beds; a dacitic tuff; a thick upper Triassic (Norian) limestone; tuffaceous siltstones and argillites; a thin marble; an evaporite gypsum; and an aeolian sandstone (Fig. 1). These rocks are overlain by the Artesia Lake Volcanics, a ca. 1-km-thick sequence of intermediate to silicic lavas, tuffs, and volcanioclastic rocks, which represents the first of a voluminous series of Middle Jurassic igneous rocks.

Yerington batholith

The Artesia Lake Volcanics are thought to represent the early, extrusive part of the magmatic system that developed into the Yerington batholith. Thus, the Yerington batholith is emplaced into the base of the Artesia Lake Volcanics. The batholith consists of three major equigranular intrusions, each progressively smaller in volume, more deeply emplaced, and more silicic in composition (Dilles, 1987). The batholith was emplaced and crystallized in about 1 m.y. based on the U/Pb zircon ages of 169.4 Ma for early McLeod Hill quartz monzodiorite and of 168.5 Ma for a late, mineralized granite porphyry dike (Dilles and Wright, 1988).

McLeod Hill quartz monzodiorite contains hornblende and biotite and was emplaced as a series of dikelike bodies into the overlying volcanics and into the adjacent hornfels. Early endoskarn and metasedimentary hornfels in the contact aureole are closely associated with this intrusion. There are numerous internal, steeply dipping contacts within the unit.

The second is the Bear intrusion, which generally was emplaced into the McLeod Hill body, but locally was emplaced into volcanics and possibly into older hornfels (Fig. 1). It is a compositionally zoned body, ranging from a fine-grained, graphic-textured granite roof and border a few hundred meters thick downward into a medium-grained, relatively homogeneous body of hornblende quartz monzonite. Hydrothermal alteration of the granite and its roof is widespread and consists of weak K silicate and sericitic alteration associated with minor pyrite mineralization; it is unclear if there is any associated Cu or Au mineralization.

The youngest equigranular unit of the batholith is the Luhr Hill intrusion, which consists of a deeply emplaced, medium-to-coarse-grained K feldspar megacrystat-bearing hornblende-biotite granite. A series of granite porphyry dikes are cogenetic with the Luhr Hill. The dikes contain about 50 vol percent phenocrysts of plagioclase, biotite, hornblende, quartz, and 1-cm-long K feldspar in an aplitic groundmass of ~0.02-mm-diameter K feldspar, quartz, and minor plagioclase. The porphyries were derived from the Luhr Hill granite, because they are compositionally and mineralogically very similar and because they grade downward into granite via an increase in grain size of the groundmass. Most porphyries intrude upward through cupolas of the granite from source areas within a few hundred to a thousand meters of the upper contact (Fig. 1). Porphyry copper deposits at Ann-Mason and the Yerington mine are associated with dike swarms that consist of a series of separate dikes emplaced through a granite cupola. At the Yerington mine at least five separate dike intrusions (designated QMP-N, 1, 2, 2.5, and 3; Proffett, 1979; Einaudi et al., pers. commun., 2000) have been mapped and identified. At least three temporally separate intrusions are mapped at Ann-Mason (Dilles, 1987). The Cu skarns near the Mason Valley, Bluestone, and Douglas Hill-Casting Copper-Ludwig mine areas are all associated with porphyry dikes. In addition, numerous aplitic and pegmatite dikes cut the upper contact of the Luhr Hill granite and are in turn cut by younger porphyry dikes.

Younger Jurassic igneous rocks

Following the emplacement of the Yerington batholith, a series of subareal intermediate- to silicic-composition lavas, domes, ignimbrites, and volcanioclastic sedimentary rocks that form the Fulstone Spring Volcanics were deposited. These are preserved in the western part of the Yerington district in the Buckskin Range (Proffett and Dilles, 1991). A U/Pb zircon age of 166.5 Ma was obtained from a dome in the upper part of the Fulstone (Dilles and Wright, 1988). However, it is possible that the base of the Fulstone section may be age-equivalent to youngest granite porphyry dikes related to the Luhr Hill Granite because the Fulstone contains quartz latite lava flows, breccias, and ignimbrites that somewhat resemble the porphyries (20 to 40 vol % phenocrysts of plagioclase, hornblende, biotite, quartz, and local 1- to 2 cm-long K feldspar).

A series of quartz monzodiorite porphyry dikes traverse the Yerington district, strike east-west, dip steeply, and have a U/Pb zircon age of ca. 165 Ma. They intruded the Fulstone volcanics and commonly were emplaced along faults that bound and downdrop the Yerington batholith ca. 1 km relative to the surrounding rocks (Proffett and Dilles, 1984). The dikes are inferred to be older than the Shamrock batholith (U/Pb zircon age of 165 Ma), which is a large body of hornblende-biotite granite that lies south of the Yerington batholith.

Cenozoic rocks and structure

Following a long period of erosion or nondeposition, a series of Oligocene and early Miocene ignimbrites and some lava flows blanketed the Yerington district (0.5–2 km thick: Proffett and Proffett, 1976). These rocks are overlain by middle Miocene-age andesitic lavas. During andesitic magmatism,
rapid extension via closely spaced, east-dipping normal faults began and terminated about a million years later (Proffett, 1977; Dilles and Gans, 1995). These oldest faults are cut and offset by two sets of east-dipping normal faults, the younger of which include the active fault system bounding the modern basins and ranges in the area. As a consequence of the down-to-the-east normal faulting, the pre-Miocene rocks, including the mineralized Mesozoic rocks, were tilted approximately 60° to 90° W (Proffett, 1977; Geissman et al., 1981) so that the current exposures represents cross sections of the Jurassic palaeohydrothermal systems at paleodepths ranging from the volcanic environment (Buckskin Range) to about 7 km depth.

**Magmatic Fluids**

**Genesis of fluids**

The Yerington batholith represents a relatively typical, shallowly emplaced differentiated granoid suite with an alkali-calcic geochemistry. The magmas were water-rich (2.5–4 wt. %) on the basis of hornblende crystallization early during solidification; strongly oxidized (NNO buffer + 2 to 3 log units) on the basis of Fe oxide compositions of the assemblage magnetite + sphene + quartz; and contained abundant sulfate (>1000 ppm) based on S-content ofapatite (Dilles, 1987; Dilles and Proffett, 1995; Streck and Dilles, 1998). Thus, crystallization of each major intrusion of the batholith generated magmatic-derived aqueous fluids.

Magmatic-hydrothermal alteration, and porphyry Cu-Fe ± Mo sulfide mineralization are closely associated temporally and spatially with emplacement of granite porphyry dikes (these were previously called quartz monzonite porphyry in Proffett and Dilles, 1984). Porphyry copper deposits at the Yerington mine (Proffett, 1979) and at the Ann-Mason prospect (Dilles and Einaudi, 1992) are well-studied, and Bear and MacArthur deposits represent separate centers that are similar. Petrologic evidence indicates the Luhr Hill granite reached water-saturation during cooling at about 50 percent crystallinity, and that the resultant magmatic aqueous fluids that separated were rich in dissolved Cl, Na, K, Fe, S, and Cu (Dilles, 1987; Dilles and Proffett, 1995). These fluids accumulated in the cupolas of the Luhr Hill granite (Dilles, 2000) and ultimately were released via fluid overpressuring or tectonic fracturing. The released fluids hydrofractured overlying rock and allowed upward movement of both the hydrothermal fluids and porphyry magmas. Most porphyry dikes were emplaced upward from the cupola regions of the Luhr Hill granite and these dikes served to focus magmatic-hydrothermal fluid-flow. During emplacement of most dikes, the least principal stress was apparently oriented in a southwest-northeast direction, and thus fracturing and most dike emplacement occurred along a prominent joint set striking northwest-southeast and dipping steeply. In the modern, west-titled exposures, these dikes and fractures now strike N 70° W and generally dip an average of 45° N.

**Magmatic-hydrothermal alteration associated with the McLeod Hill and Bear intrusions**

Magmatic-hydrothermal fluids were apparently released during crystallization of the McLeod Hill quartz monzodiorite and Bear quartz monzonite, but the role and importance of these fluids in hydrothermal alteration and mineralization is not clear. The advanced argillic and sericitic alteration in the overlying Artesia Lake Volcanics could be in part due to fluids released during crystallization of the McLeod Hill and Bear intrusions, and these alteration zones in part pre-date some shallowly emplaced porphyry dikes. Certainly, magmatic fluids containing sulfur, acids, and alkalies were released from the granitic roof of the Bear intrusion and produced relatively low temperature, widespread hydrothermal mineral assemblages that include K feldspar, sericite, chlorite, and pyrite in the granite and overlying McLeod Hill quartz monzodiorite and Artesia Volcanics in the central Singatse Range.

The emplacement and crystallization of McLeod Hill and possibly the Bear are closely related to formation of garnet-pyroxene hornfels in the contact aureole (Einaudi, 1977, 2000; Harris and Einaudi, 1982) and pyroxene-plagioclase endoskarn within the batholith near its contact (Harris and Einaudi, 1982; Dilles and Einaudi, 1992). The role of the magmas, as a material source compared to a heat source, is unclear. The hydrothermal fluids were apparently dominated by saline sedimentary brines heated by the McLeod Hill and possibly Bear intrusions (see below). However, these intrusions may have contributed considerable amounts of magmatic water to the metasomatic fluids, which dominantly flowed upward along the contact and within the sedimentary-volcanic sequence. The nearly isochemical nature of the metasomatic alteration that produced the garnet-pyroxene hornfels (Einaudi, 2000) suggests that magmatic fluids that would have contributed alkalis, sulfur, and iron were subordinate to sedimentary brines.

**Magmatic-hydrothermal alteration associated with the Luhr Hill intrusion**

The magmatic-hydrothermal fluids related to the Luhr Hill granite produced a series of porphyry dike-centered alteration and mineralization zones. Along the porphyry dike swarms immediately above the Luhr Hill granite cupolas, the hydrothermal alteration and Cu(-Mo) sulfide mineralization is most intense and produced at least four porphyry copper deposits: Yerington, Ann-Mason, Bear, and MacArthur (cupolas are not identified for the latter; Figs. 2, 3). Fluids of magmatic origin are responsible for K silicate alteration and in mixtures with local ground waters for both sericitic and advanced argillic alteration. Oxygen and hydrogen isotope data indicate waters for K silicate alteration were entirely magmatic whereas sericitic waters were about half magmatic (Dilles et al., 1992). Sulfur isotope compositions in K silicate and sericitic alteration are similar and indicate a magmatic origin for sulfur (Dilles et al., 1995).

The magmatic fluids were high salinity and produced the high-temperature K silicate alteration (biotite ± K feldspar) and bornite ± chalcopyrite ± magnetite mineralization characteristic of both the central parts of the Yerington and Ann-Mason porphyry deposits. Apparently, magmatic aqueous fluids were focused along the dike swarms and resulted in the highest water:rock ratios, and where fluids cooled they produced the most intense metasomatism, highest quartz vein densities, and highest percentages of Cu-bearing sulfides. Granite porphyries dikes emplaced off-axis of the major dike swarms or in the upper part of the dike swarms typically were
FIG. 2. North-south cross section of generalized hydrothermal alteration zones in the Yerington batholith (Dilles and Einaudi, 1992; J.H. Dilles, unpub. data) and contact aureole (Einaudi, 1982, 2000; Harris and Einaudi, 1982) based on exposures in the Ann-Mason-Ludwig, Blue Hill, and MacArthur areas.
FIG. 3. Generalized plan map of selected hydrothermal alteration zones projected to the Lower Tertiary erosion surface from about 1–4 km below the Jurassic paleo-surface (or 0–3 km below the LTS). The geologic contacts are from John Prof- fett (fig. 1 of Dilles and Proffett, 1995), and are shown in plan view at the elevation of the LTS (ca. 1 km Jurassic paleodepth). Because Jurassic rocks were tilted ca. 10° W prior to formation of the LTS, this is a slightly inclined plan view. Zones shown include K-silicate alteration (and Cu-Fe sulfide) located near porphyry Cu centers, sodic-calcic alteration, and shallow Fe oxide Cu-Au lodes in the batholith, and endoskarn, hornfels, Cu skarn, and Fe oxide Cu-Au replacements in the contact aureole. Widespread propylitic-actinolite, shallow sericitic and chloritic alteration are not illustrated. Mine numbers cor- respond to deposits whose class and resources are listed in table 1 of Dilles and Proffett (1995).
accompanied by lesser amounts of magmatic fluids. Nonetheless, all dikes in the 1 to 6 km depth range in the Ann-Mason and other Yerington district exposures contain some hydrothermal biotite and minor Cu-Fe sulfide, attesting to the passage of magmatic hydrothermal solutions. Distal dikes locally intrude the contact aureole of the Yerington batholith (e.g., the Ludwig area) where they are closely associated with andradite, hedenbergite, and actinolite-rich skarn that contains chalcopyrite and pyrite (Figs. 1, 2; Einaudi, 2000). The iron, copper and sulfur-rich ore fluids were apparently derived from these porphyry dikes.

The magmatic fluids were released as a series of pulses accompanying dike emplacement. Within the main Yerington mine orebody, at least five granite porphyries (designated QMP) have been identified. The oldest, QMP-1 accompanies the strongest K silicate alteration and Cu-Fe sulfides. Porphyry QMP-N post-dates QMP-1, and it is itself poorly mineralized. Porphyry QMP-2 is younger than QMP-N and accompanies moderate K silicate alteration and Cu-Fe sulfides. Porphyries QMP-2.5 and QMP-3 record progressively less K silicate alteration and Cu-Fe sulfide mineralization apparently because they contained less magmatic fluid (J.M. Proffett and M.T. Einaudi, unpub. data). Sericitic alteration accompanies pyrite-quartz 2D veins (Gustafson and Hunt, 1975) and postdates porphyry QMP-2.5 in the Yerington mine (Proffett, 1979). Throughout the Yerington district, within each porphyry copper deposit there is both a time evolution at a single point from early K silicate with Cu-Fe sulfides to late sericite alteration with pyrite; similarly, although we must infer age relations, it is quite possible that at any given time hydrothermal alteration evolved from deep K silicate to shallow sericitic or advanced argillic alteration (Fig. 4).

Sericitic alteration is widespread both above the Ann-Mason and MacArthur porphyry deposits (Fig. 2) and in the overlying Artesia Lake Volcanics in the Buckskin Range. In the latter (oxidized) exposures, the most intense alteration includes advanced argillic assemblages with pyrophyllite, quartz, alunite (hypogene?), pyrite, and sericite (Hudson, 1983; Dilles and Proffett, 1991; Lipske and Dilles, 2000). Although age relations are not clear in most exposures, locally, D veins with sericite envelopes postdate and crosscut pyrophyllite-bearing advanced argillic alteration. Pyrophyllite-bearing assemblages are cut by porphyry dikes (that may be late dikes related to the Luhr Hill granite, or possibly related to the Fulstone Spring Volcanics) that are in turn cut by younger D veinlets with selvages of hematite-sericite-pyrite alteration (Lipske and Dilles, 2000).

One interpretation of the temporal-spatial relationships of K silicate, sericitic, and advanced argillic assemblages follows. Two assumptions are made. All these alteration types are assumed to have been produced by fluids with large magmatic components, based on the stable isotopic data and the ability of magmatic fluids alone as potential ore fluids to provide abundant acids and sulfur. The second assumption is that each pulse of magmatic fluid is directly related to porphyry dike emplacement. The Ann-Mason, Yerington mine, and Buckskin data suggest that early magmatic-hydrothermal fluids produced a high-temperature plume of brine that rose and produced K silicate and Cu-Fe sulfide mineralization (with local, later molybdenite) in the individual porphyry centers. Due to depressurization at high temperature, on ascent these fluids would have intersected the brine-vapor immiscibility field in the system water-NaCl (Sourirajan and Kennedy, 1962). A buoyant, low-density vapor likely separated from brine (cf. Henley and McNabb, 1978) may have risen to the subvolcanic environment where it condensed and mixed with local ground water to produce the acid fluids responsible for the pyrophyllite-sericite assemblages. Alternatively, these two environments may not have been linked, or may have been linked by sericite alteration lying in an intermediate position between deep K silicate and shallow advanced argillic zones. This process of hydrofracturing, ascent of fluids, immiscibility, and coupled deep K silicate and shallow advanced argillic alteration may have occurred numerous times accompanied by successive granite porphyry dike emplacements that represent the main dike swarms in individual porphyry centers. As the Luhr Hill magma crystallized and degassed the late porphyry dikes were emplaced from a deeper source into cooler wall rocks. These fluids were apparently sulfur-rich but copper-poor and they cooled and depressurized along a path such that they did not intersect the water-NaCl immiscibility field. Instead, at the level of the porphyry copper orebody, they produced sericitic alteration and pyrite mineralization. As fluids ascended to the subvolcanic environment they produced some sericite-pyrite alteration, but may have lost most of their acids and sulfur and so did not produce strong alteration in the late porphyry dikes emplaced at this level. Rather, they may have mixed with local ground waters to produce the weak K metasomatism and the chlorite + hematite ± sericite ± K feldspar assemblages observed in the base of the Fulstone Spring Volcanics (Fig. 2; Dilles and Proffett, 1991; Lipske and Dilles, 2000).

**Sedimentary Brines**

The Triassic-Jurassic sedimentary section at Yerington represents a late Mesozoic marine sequence that ended with deposition of an evaporite and an aeolian sandstone, which indicates that marine conditions gave way to subaerial conditions through time. The lower Jurassic evaporite—sandstone association is widespread in western Nevada, and represents a time of marine regression, formation of closed marine basins, drying of these marine basins, and subaerial dune sand and fluvial sand deposition (Speed, 1974, 1978). The Triassic-Jurassic section at Yerington thus would have contained a large volume of marine and possibly meteoric pore fluids restricted by impermeable sedimentary units (shales, etc.). Although evaporite in the upper part of the section now contains only gypsum, it is likely that originally the gypsum beds would have contained saline brines and very likely evaporitic halite and other salts. Thus, the sedimentary section intruded by the Yerington batholith contained a vast volume of trapped pore fluids that likely ranged from halite-saturated brines to low-salinity sea water. When the batholith was emplaced these fluids were heated and convectively circulated, leading to extensive sodic-calcic alteration and associated Fe oxide-bearing mineralization.

**Early hornfels and endoskarn**

A contact metasomatic aureole surrounds the Yerington batholith and is well-developed in sedimentary lithologies
FIG. 4. Time-space evolutionary model for hydrothermal alteration of the Yerington batholith. A. Proximal to porphyry centers. B. Distal to porphyry centers. Note that alteration in the distal batholith environment is linking to alteration in the contact aureole, where protolith composition and resultant assemblages differ (see text and Fig. 5). Abbreviations are: quartz monzodiorite (QMD), quartz monzonite (QM), porphyritic granite (PG), and granite porphyry (GP). Granite porphyry is divided into early dikes (GP-1 equivalent to QMP-1 in Yerington mine), intermediate age dikes (GP-2, equivalent to QMP-2 of Yerington mine), late porphyries (GP-L, equivalent to QMP-2.5 and 3 of Yerington mine), and porphyries that may be feeders to the base of the Fulstone Spring Volcanics in the Buckskin Range. See text for details.
within about 4 km of the Jurassic paleosurface. The contact metasomatic aureole south of the Yerington batholith contains a huge volume of garnet-pyroxene hornfels and smaller volumes of garnet-pyroxene and plagioclase-pyroxene endoskarn within sills and dikes of the McLeod Hill quartz monzodiorite (Harris and Einaudi, 1982; Einaudi, 2000; Fig. 2). As noted above, large volumes of thin-bedded mixed clastic, carbonate, and tuffaceous lithologies have been broadly chemically homogenized. Such a process must have accompanied metasomatic fluid flow, which as documented by Einaudi (2000) must have been broadly up along the McLeod Hill quartz monzodiorite contact and outward away from the batholith along permeable sedimentary beds. These fluids accomplished broad-scale chemical homogenization and extraction of large amounts of carbonate and water from the sedimentary rocks at temperatures in excess of 400°C. The paucity of alkal, iron, and acid metasomatism and hydrothermal sulfides suggests the principal metasomatic fluid was a Ca-rich brine derived from the sedimentary section. Endoskarn in the McLeod Hill quartz monzodiorite has seen large additions of calcium and loss of iron and potassium during metasomatism. Strontium isotopic analyses of endoskarn in the McLeod Hill intrusion (Dilles et al., 1995) suggest that two-thirds of the strontium in these samples is derived from the Triassic-Jurassic sedimentary section as transferred into the batholith via the sedimentary brines.

Sodium-calcium metasomatism

Sodium-calcium alteration is widespread within the Yerington batholith and is closely associated in time with emplacement of the Luhr Hill granite and the related granite porphyry dikes. This alteration represents strong sodium and or calcium metasomatism as characterized by addition of sodic plagioclase, actinolite, epidote, and sphene to rocks. A variety of arguments suggests that this alteration represents influx of sedimentary brines into the Yerington batholith following hydrofracturing and porphyry dike emplacement produced by rise of magmatic fluids. These observations include presence of radiogenic strontium derived from the Triassic-Jurassic sedimentary rocks within altered batholithic rocks (Dilles et al., 1995); alkali exchange phase equilibria that indicate sodium metasomatism was produced by a heating (or prograde) fluid (Carten, 1987; Dilles and Einaudi, 1992); and numerous porphyry dike age relations with sodic-calcic alteration veins, which indicate that dikes cut veins but are cut in turn by younger veins (Carten, 1987; Dilles and Einaudi, 1992). The scenario of sodic-calcic metasomatism is that sedimentary brines moved laterally through the contact aureole into the batholith at 2 to 6 km depth, traversed into the batholith for 1 to 3 km along joint sets and granite porphyry dikes, and then flowed upward along the dikes and joints. The main upward flow occurred along porphyry dikes immediately outside of the main upward flow path of the magmatic-hydrothermal fluids (Figs. 1–3). Alteration effects are maximum where sedimentary fluids reached their highest inferred temperatures (~400°–450°C) along the deep parts of the porphyry dikes near the apices of the Luhr Hill granite cupola (Dilles and Einaudi, 1992). In these areas, sodic-calcic alteration is superimposed on earlier K silicate alteration within a porphyry representing a single dike emplacement, but younger dikes are observed to cut off the older alteration types and be affected by a younger paired set of K silicate and sodic-calcic alteration (Carten, 1987). In the center of the Ann-Mason and Yerington orebodies, relatively late fluid dominated by sedimentary brine produced assemblages with sodic plagioclase, hydrobiotite or chlorite, local sericite, and rutile. These assemblages cut and replace earlier K silicate assemblages. Causative fluids were likely sedimentary brines that acquired a moderately low pH, (necessary to produce rutile, sericite, and chlorite), as a result of either fluid cooling and resultant dissociation of HCl or by mixing with a small proportion magmatic fluid (Dilles et al., 1995).

“Propylitic”-actinolite alteration

At Ann-Mason and elsewhere in the Yerington district, there is widespread “propylitic”-actinolite alteration that is intermediate in depth (~2.5–4.5 km depth) between deep-level sodic-calcic alteration and the high-level, chlorite-rich alteration described below. Such alteration types are proposed here (see Dilles and Einaudi, 1992) to be caused by sedimentary brines but at a lower temperature (~300°C) than the deeper sodic-calcic alteration. Propylitic-actinolite alteration is characterized by addition of actinolite, epidote, chlorite, minor calcite, hematite, sulfide, and magnetite in mafic mineral sites, and by weak alteration of plagioclase to epidote, fine-grained white micas and clays, and minor K feldspar. Veins are dominated by epidote along fractures similar to deeper sodic-calcic assemblages. Locally, at the Easter prospect in the MacArthur area, magnetite-apatite-chalcopyrite veins form in the upper parts of the propylitic-actinolite zone. In the interpretation here, the propylitic-actinolite zones represent alteration by sedimentary brines following complex flow paths, for example into the batholith laterally or downward as input into the sodic-calcic alteration zone, or possibly upward parallel to the magmatic fluids as the outflow zones for sodic-calcic alteration fluids. Temporal constraints on propylitic-actinolite alteration are minimal, but the alteration affects all Yerington batholith units as well as the Artesia Lake Volcanics and hence could be lengthy. An alternative interpretation is that propylitic alteration represents the outflow zone for rising and outward-spread magmatic fluids. We do not support this hypothesis because the sodic-calcic alteration zone commonly lies in an intermediate position between K silicate and propylitic-actinolite alteration; flow paths of magmatic fluids are mapped as near vertical; and the magmatic fluid signature of sulfide and acids is weak in the propylitic-actinolitic zone.

Magnetite-hematite lodes and chloride-rich alteration

In the upper part of the Yerington batholith hydrothermal system and its contact aureole, there is abundant silicate alteration and iron-oxide mineralization that is not clearly linked to magmatic-hydrothermal fluids. In many cases, these zones contain few porphyry dikes and those that are present contain little sulfide or hydrothermal biotite or sericite. In the Artesia Lake Volcanics, uppermost exposures of the McLeod Hill quartz monzodiorite, and base of the Fulstone Spring Volcanics, several Fe oxide-Cu-Au vein or lode systems are associated with broadly distributed wall rock alteration to chlorite, hematite, and local sercite, K feldspar, and
magnetite (and relict feldspar). Lodes exposed in the Artesia Lake Volcanics at the Buckskin mine, southern Buckskin Range (Gibson, 1987), are similar to those in the McLeod Hill Quartz Monzodiorite at Bluejay Hill, 5 km east of Yerington. In both cases, lodes are up to 15 m wide and consist of wall rock replaced by mixtures of quartz, hematite, chlorite, and minor sericite, pyrite, chalcopyrite, tourmaline, and traces of sphalerite, galena, and gold. At Bluejay Hill the lode systems can be traced downward about 1 km into zones of chlorite and quartz veins associated with epidote, magnetite, and sulfide veins with propylitic-actinolite and local sodic-calcic alteration. In the southwest part of the Ann-Mason area, veins with quartz, biotite, chlorite, magnetite, and hematite also pass downward over ~1 km into epidote vein zones with propylitic-actinolite alteration. Veins at the Buckskin mine (Gibson, 1987) and southwest Ann-Mason both contain hypersaline (halite-bearing) fluid inclusions similar to those found in deeper sodic-calcic veins (Dilles and Einaudi, 1992).

In the uppermost part of the Artesia Lake Volcanics, base of the Fulstone Spring Volcanics, and in porphyry dikes cutting the top of the Artesia in the central Buckskin, wall rock is widely altered to chlorite, sericite, quartz, and hematite with relict feldspar. Veins of specular hematite and quartz with minor pyrite and chalcopyrite have distinct inner sericitic alteration envelopes and are enclosed in rock altered to chlorite-sericite-hematite ± albite ± K feldspar (Lipske and Dilles, 2000). These veins postdate advanced argillic alteration in the area.

At the Minnesota Iron mine in northern Buckskin Range and in Lyon Fe-Cu-Au deposit in the Pumpkin Hollow area 10 km southeast of Yerington (ca. 2 and 100 Mt Fe contained in ores, respectively; Dilles and Proffett, 1995) iron oxides replaced earlier calc-silicate hornfels, minor Cu skarn, and marble. The ores consist of massive and vein-filling magnetite ± hematite ± chalcopyrite ± pyrite with associated silicate alteration minerals such as chlorite, actinolite, talc, serpentine, quartz (and calcite). These latter minerals locally replaced and destroyed early, high-temperature anhydrous calc-silicate minerals that include garnet and pyroxene. Similarly, in the Ludvig area, small volumes of quartz-calcite-hematite-magnetite with local actinolite, chlorite, talc and minor apatite replace early andradite- and salite pyroxene-skarn (Harris and Einaudi, 1982; Einaudi, 2000).

The Fe oxide Cu-An association in both the lodes in the batholith and the replacement deposits in the contact aureole have similar associations and likely a common parentage. These deposits are dominated by addition of Fe oxide minerals and low-temperature silicate alteration without important sulfur addition or hydrolytic alteration (clay, sericite). The deposits formed at least in part later than skarn and advanced argillic porphyry alteration (Figs. 4, 5). The deposits also lie above or outboard from zones of strong sodic-calcic alteration where Fe, K, and Cu were removed from the Yerington batholith (Figs. 2, 4; Carten, 1987; Dilles et al., 1995), and form along northwest-southeast striking structural pathways for fluid flow. In the model proposed here, these Fe oxide deposits are formed where deep sodic-calcic fluids moved upward and outward from the center of the Yerington batholith along permeable fracture zones, cooled, reacted with wall rocks, and saturated in hematite and magnetite (Fig. 4).

Surficial-Derived Fluids

The role of dilute surficial ground water or meteoric water at Yerington is not clear, but isotopic evidence and hydrothermal alteration patterns (Dilles et al., 1992; Dilles and Einaudi, 1992) suggest a minimal role. Dilute ground water may have been important in the subvolcanic environment dominated by sericite, chlorite, clay and local K feldspar-bearing assemblages. However, this weak acid and alkaline metasomatism may have been caused by ground water with moderate salinity that had formed in the Jurassic subaerial to evaporitic environment (Barton, 1998). The young event emplacement of the Shamrock was also accompanied by sodic-calcic alteration, which argues that sedimentary brines continued to dominate at depth (Battles and Barton, 1995).

Conclusions: Time-Space Evolution of Hydrothermal Flow

Figure 5 is a simplified cross section through the Yerington batholith that illustrates time-space evolution of the hydrothermal fluid flow, alteration, and ore deposition. In frame A, early equigranular intrusions created hornfels and endoskarn in the contact aureole. These fluids were dominated by sedimentary brines with lesser magmatic fluids.

In frame B, following intrusion of the Luhr Hill granite, crystallization led to aqueous fluid saturation, hydrofracturing, early porphyry intrusion, and upward movement of magmatic hydrothermal fluids to form deep K silicate alteration with Cu-Fe sulfide mineralization and shallow sericitic and advanced argillic alteration in the subvolcanic environment. Fracturing allowed sedimentary brines to move into the batholith, be heated, and cause sodic-calcic and propylitic-actinolite alteration flanking the K silicate alteration zones.

In frame C, the process in B was repeated multiple times in succession accompanying emplacement of a successive series of granite porphyry dikes (shown here schematically as one event). Most Cu-Fe sulfide and K silicate alteration, as well as late molybdenite, formed in this time interval along the porphyry dikes, as did andradite garnet skarn with Cu sulfide in the contact aureole. The subvolcanic environment was dominated by sericite and advanced argillic alteration waning in time to sericitic alteration only. Sodic-calcic and more distal propylitic-actinolite alteration increased with time as more sedimentary brine circulated through the batholith. As this fluid circulated upward through the top of the batholith and outward into the upper part of the contact aureole, early Fe oxide-Cu-An lode deposits began to form associated with chloride-rich hydrothermal alteration.

In frame D, young porphyries related to the Luhr Hill granite were emplaced together with hydrothermal fluids that produced pyrite-rich and Cu sulfide-poor mineralization and abundant sericite in the porphyry Cu(Mo) center. Continued circulation of sedimentary brines produced flanking sodic-calcic and more proximal albrite-rich alteration. Discharge of these brines led to a peak in the amount of Fe oxide Cu-An mineralization and associated hydrous silicate alteration (chlorite, etc.) in the contact aureole and subvolcanic zone, where it is superimposed on the earlier skarn zones and both sericitic and advanced argillic alteration zones, respectively.
Fig. 5. Simplified cross-sectional diagram of the Yerington batholith and its contact aureole, illustrating hydrothermal alteration at five successive times during magmatic evolution (cf. Fig. 4). Geology and features based on Figure 2 and references therein. Note that addition of Fe oxide deposits in the contact aureole in frame D is schematic, and is based on the geology of the Lyon (Pumpkin Hollow) part of the contact aureole, not the Ludwig segment.
In frame E, porphyries possibly related either to the Lahr Hill granite or to a new magma at depth were emplaced together with extrusive lavas and pyroclastic rocks that form the base of the Fulstone Spring Volcanics. Weak chlorite-hematite-calcite (with relict feldspar) alteration dominates the shallow environment and may be age-equivalent to late, deep propylitic-actinolite or possibly sodic-calcic alteration. Hematite-magnetite-copper-iron sulfide-gold veins are sparse in the shallow environment. Hydrothermal fluids are dominated by low-temperature, sedimentary brines with little magmatic input.

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