Gold Deposits in the Hot Spring Environment

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Abstract

There are currently fifteen gold deposits which exhibit evidence for an origin at or directly beneath the paleosurface. Ten of these deposits, containing a total of over seven million recoverable ounces of gold, are located in the western United States. All ten were discovered since 1978.

Hot spring gold deposits are silicified breccias and vein stockworks which contain microcrystalline quartz, minor adularia, several volume percent pyrite-marcasite and native gold. Unequivocal evidence for a hot spring origin includes silica sinter, deposited originally as amorphous silica in pools and terraces; hydrothermal eruption debris deposits which thicken and coarsen toward the vent; and geyserite, accretionary silica tumbled in the throats of geysers and periodically erupted onto the surface. A blanket of advanced argillic alteration, consisting of cristobalite-alunite-kaolinite, is superimposed, when present, on ore-bearing siliciclastic silification.

Hot spring gold deposits form at lower temperatures and are enriched in As, Ba, Hg, Sb and Tl relative to higher grade, precious metal bonanzas. A steep near-surface thermal gradient, steepened even more during periods of high fluid throughput, accounts for zoned enrichments from shallow Sb-Hg-Tl through precious metal ore into deep, low-level base metals and tungsten.

Hydrothermal eruptions are documented at all of the better grade (greater than 0.1 opt) hot spring gold deposits. Hydrothermal vent breccias contain episodically silicified fragments supported by a matrix of variably comminuted rock flour. Precious metal mineralization in the vent breccias and in peripheral fractured stockworks occurs in response to shallow boiling. Periods of high fluid discharge steepen the pressure gradient in a rising fluid column and lift the boiling level to within a few hundred meters of the surface. Flow rate, rather than temperature or dissolved carbon dioxide content, is the single most influential factor affecting level of boiling and consequent depth of precious metal mineralization.

Introduction

Precious metal orebodies which form at or directly beneath the paleosurface are collectively referred to as hot spring deposits. Members of the group share a variety of physical and chemical characteristics that distinguish them from, for example, bonanza or Carlin-type ore deposits. These common features are represented schematically in Figure 1.

There are currently fifteen gold deposits that exhibit geologic evidence for a near-surface origin. Table 1 provides a list of these deposits (current as of October 1986) and their announced reserve, the geologic evidence for a near-surface origin, the operating company, and the date of first production. Ten of the deposits are located in the western United States. All ten were discovered since 1978.

Many of the deposits listed in Table 1 contain siliceous sinter, deposited at the paleosurface by hot springs saturated with respect to amorphous silica. These orebodies provide graphic documentation of the geothermal connection championed by Don White (1955, 1967, 1981). Hot spring gold deposits are recognizable fossil analogues of active hot spring systems.

This is not to say that orebodies are currently forming in all or even in many active geothermal fields. Drilling of geothermal reservoirs around the world penetrated no
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Economically recoverable precious metal deposits in spite of over thirty years (1955-1985) of exploration and development. Most geothermal fields have been active for a period of time sufficient to deposit a precious metal orebody, and some, such as Steamboat Springs in Nevada, have been active for several million years.

Kennecott's gold discovery on Lihir Island in the western Pacific provides the first example of ore grade and tonnage developed in an active hot spring system. Other hot spring and bonanza-type precious metal deposits occur in or near recently active geothermal fields. Homestake's McLaughlin hot spring gold deposit in California occurs in a fossil portion of the Knoxville KGRA (Known Geothermal Resource Area). Sumitomo's Hishikari bonanza gold deposit in Japan (minimum 1.5 million tons of 2.35 opt gold) occurs in a fossil portion of the active Kirishima geothermal field.

The descriptive portion of this paper focuses on geologic and geochemical characteristics shared by hot spring gold deposits. A section on deposit genesis discusses the mechanics of shallow gold mineralization. A final section on exploration tools summarizes descriptive and genetic models in a form useful to the explorationist. Emphasis throughout is on why certain hot spring systems contain gold orebodies while others do not. This paper does not discuss hot spring silver deposits such as the DeLamar deposit in Idaho, nor does it discuss submarine hot spring systems such as those which may be responsible for precious metal mineralization in many massive sulfide deposits and in banded iron formations. Readers who wish to review the physical and chemical characteristics of active geothermal fields are referred to texts by Elder (1981) and Ellis and Mahon (1972) and to a comprehensive review paper by Henley and Ellis (1983).

Deposit Descriptions

Hot spring gold deposits contain geologic evidence for a near-surface origin. Such evidence may include silica sinter, deposited originally as amorphous silica in pools and terraces; hydrothermal eruption debris deposits which thicken and coarsen toward the vent;

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**ALTERATION**

- Late, advanced argillic alteration
- Silicified vein stockwork, grades outward through an argillic envelope into unaltered host rock
- Quartz-K feldspar replacements occupy hydrothermal conduits

**Schematic cross section**

- Steeply zoned Sb, Hg, and Tl
- Precious metal orebody contains Au, Ag, As, Hg, Sb, Tl, and minor base metals
- Base metals and W increase with local high grade precious metal vein intercepts

**MINERALIZATION**

*Scale*

- 100 meters
- no vertical exaggeration

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**Fig.1:** Schematic hot spring gold deposit: a vein stockwork surrounding single or multiple mineralized hydrothermal eruption vents.
### Table 1

**Hot Spring Gold Deposits**

<table>
<thead>
<tr>
<th>Deposit/Owners (First Production)</th>
<th>Size (Mt)</th>
<th>Grade (opt)</th>
<th>Evidence for a near surface origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>McLaughlin, California, Homestake Mining (1985)</td>
<td>22.0</td>
<td>0.16 Au</td>
<td>sinter and subaerial breccia</td>
</tr>
<tr>
<td>Wau, PNG, New Guinea Gold Fields (?)</td>
<td>3.5</td>
<td>0.09 Au</td>
<td>sinter and subaerial breccia</td>
</tr>
<tr>
<td>Lihir Island, PNG, Kennecott</td>
<td>10.0</td>
<td>0.3 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Paradise Peak, Nevada, FMC (1986)</td>
<td>10.0</td>
<td>0.14 Au</td>
<td>sinter (?)</td>
</tr>
<tr>
<td>Akeshi, Japan, Miyachi-Akeshi Mining (1932)</td>
<td>4.0</td>
<td>0.2 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Iwato, Japan, Miyachi-Akeshi Mining (1938)</td>
<td>5.0</td>
<td>0.12 Au</td>
<td>Sinter</td>
</tr>
<tr>
<td>Sleeper, Nevada, Amex (1986)</td>
<td>1.2</td>
<td>0.38 Au</td>
<td>sinter (?)</td>
</tr>
<tr>
<td>Kasuga, Japan, Nippon Mining (1932)</td>
<td>4.5</td>
<td>0.06 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Borealis, Nevada, Tenneco Minerals (1981)</td>
<td>2.3</td>
<td>0.11 Au</td>
<td>Alteration</td>
</tr>
<tr>
<td>Borealis, Jaime's Ridge, Cerro Duro, East Ridge</td>
<td>1.5, 0.3, 0.05, 0.5</td>
<td>0.12, 0.13, 0.08, 0.08</td>
<td>Au</td>
</tr>
<tr>
<td>Buckhorn, Nevada, Cominco American (1983)</td>
<td>5.1</td>
<td>0.045 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Hasbrouck Mtn., Nevada, Franco Nevada (1986)</td>
<td>7.7</td>
<td>0.036 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Sulfur, Nevada, Standard Slag (1984)</td>
<td>10.0</td>
<td>0.04 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Florida Canyon, Nevada, Pegasus</td>
<td>11.8</td>
<td>0.032 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Great Barrier Island, N.Z. (1892 - 1908)</td>
<td>0.017</td>
<td>2.44 Au</td>
<td>sinter</td>
</tr>
<tr>
<td>Hog Ranch, Nevada, Western Goldfields (1986)</td>
<td>4.5</td>
<td>0.086 Au</td>
<td>subaerial breccia</td>
</tr>
</tbody>
</table>
widespread alunite-kaolinite-cristobalite, a product of alteration by shallow, steam-heated acid sulfate fluids; and geysersite, accretionary silica tumbled in the throats of geysers and periodically erupted onto the surface.

Hot spring gold deposits are silicified breccias and vein stockworks which contain microcrystalline quartz, several volume percent pyrite plus marcasite, and native gold. Adularia occurs at vein margins and as replacements along hydrothermal conduits. Hydrothermal carbonate occurs beneath a mushroom-shaped core of sulfidic silicification; as late, cross-cutting veins, and as calcareous tufas deposited during the waning stages of hot spring activity. Argillization may be widespread, as at Borealis, or nearly absent, as at McLaughlin. A number of factors influence the strength and distribution of argillic alteration. These factors include composition of the host rock, depth of the groundwater table, depth of boiling, salinity, and the dissolved sulfur, oxygen (Eh) and hydrogen ion (pH) concentration of the hydrothermal fluid.

The oxidation state of geothermal fluids is buffered to low values at depth by equilibria involving pyrite and a divalent iron aluminum silicate such as chlorite or epidote (Giggenbach, 1980). A convecting geothermal fluid becomes more oxidized near the surface through boiling, mixing with shallow fluids and cooling. During boiling, reduced acid volatiles (H₂, H₂S, CH₄) are preferentially partitioned into the exsolving vapor (Drummond and Ohmoto, 1985). This vapor migrates upward, condenses in an oxidizing, near-surface environment, and generates the acid sulfate fluids responsible for blanket-like deposits of shallow argillic and advanced argillic alteration. A deep boiling level provides for prolonged exsolution of acid volatiles, deep precious metal mineralization and extensive near-surface acid alteration.

Deep geothermal fluids are buffered to near neutral pH by alteration equilibria involving feldspars, micas and clays. These mineral equilibria are in turn influenced by host rock composition, reservoir temperature, and salinity. Saline, high-temperature reservoirs are relatively acid in comparison to dilute, moderate-temperature reservoirs (Ellis, 1970). Gold solubility as a bisulfide complex is enhanced by reducing (pyrite-stable) Eh and neutral to slightly alkaline pH (Romberger, 1984). Dilute, moderate-temperature (200°-300° C) solutions are capable of dissolving, transporting, and precipitating more gold than saline, high-temperature solutions. The observation that volcanic-hosted geothermal reservoirs are dilute relative to sediment-hosted reservoirs accounts, at least in part, for the association of hot spring and bonanza precious metal deposits with volcanic rocks.

Dissolved carbon dioxide in the deep geothermal reservoir is also controlled by alteration mineral equilibria (Giggenbach, 1981). However, once boiling commences, carbon dioxide partitions into the vapor and fluid pH becomes a function of the buffered exchange between hydrogen ion, bicarbonate ion and dissolved carbon dioxide.

Dissolved carbon dioxide has a direct effect on the level of boiling in the reservoir (Sutton and McNabb, 1977) and the energy available to drive hydrothermal eruptions (Nelson and Giles, 1985). A gas-charged reservoir boils at a deeper level and has greater explosive potential than a gas-poor reservoir of a similar temperature.

Dissolved carbon dioxide content of the geothermal reservoir may significantly influence gold mineralization in the California Coast Ranges. Mercury deposits in the Coast Ranges are typically associated with widespread silica-carbonate alteration produced by a reaction between host serpentinites and carbon dioxide-charged geothermal fluids (Barnes et al., 1973). Reservoirs containing high dissolved carbon dioxide overcome the buffering effect of reactions with serpentinite, become somewhat acid, and are less capable of transporting gold. In the hot spring environment, these acid fluids produce widespread silica-carbonate alteration with associated cinnabar. Reservoirs containing less dissolved carbon dioxide (or more serpentinite) are more pH alkaline, are capable of dissolving more gold, and are capable of dissolving more silica. In the hot spring environment, these fluids deposit a core of gold-bearing sulfidic silicification. Manhattan (McLaughlin) and Wilbur Springs, the only two
Coast Range mercury deposits that are known to carry economically recoverable gold, each have a core of sulfidic silicification. Neutral to acid pH renders some reservoirs incapable of dissolving and transporting significant quantities of gold.

Bonham (1986) has proposed a classification of epithermal precious metal deposits based on sulfur content. High-sulfur gold deposits, with widespread argillic alteration and associated enargite mineralization, are distinguished from low-sulfur gold deposits, with associated quartz-adularia-carbonate alteration and lower base metals. This classification focuses attention on the role of dissolved sulfur and its influence on alteration and mineralization.

High-sulfur systems may develop when acid volatiles (CO₂, SO₂), exsolved from a magma, are dissolved in an overlying geothermal reservoir. Reservoir fluids would be driven toward low pH during such periods, producing deep argillic alteration. It may be that some geothermal reservoirs exhibit both high-sulfur and low-sulfur characteristics. A reservoir normally buffered to alkaline pH by geothermal mineral equilibria could occasionally be overwhelmed by the infusion of acid volatiles from an underlying magma.

Low-sulfur systems are capable of generating widespread argillic and advanced argillic alteration (e.g. Waiotapu thermal area, New Zealand). Deep boiling of a dilute, alkaline chloride fluid releases acid volatiles which condense in the near-surface environment to produce blanket-like deposits of cristobalite-aluminate-kaolinite (Henley and Ellis, 1983). Schoen, White and Hemley (1974) have suggested that similar blanket-like deposits of cristobalite-aluminate-kaolinite may form above the groundwater table by the activity of sulfur-oxidizing bacteria. These bacteria feed on H₂S exsolved from the underlying reservoir. The bacteria oxidize the sulfur which then condenses to form sulfuric acid (H₂SO₄). When such widespread advanced argillic alteration does occur at a hot spring gold deposit (e.g. Borealis, Paradise Peak), it is superimposed on an earlier episode of gold-bearing sulfidic silicification and overlies alteration (montmorillonite-pyrite) characteristic of a low-sulfur reservoir. Hot spring gold mineralization is associated with periods of high alkaline-chloride fluid discharge, construction of siliceous sinter terraces, shallow boiling, and sulfidic silicification.

Hot spring gold deposits are enriched in the same trace element geochemical suite (Au, Ag, As, Sb, Hg, Ba, Tl) recognized at Carlin-type gold deposits. However, as in Carlin-type systems, enrichment in this epithermal pathfinder suite does not guarantee a precious metal orebody. Geochemical data for representative rock suites from barren and mineralized hot spring systems is compiled in Table 2. The data indicate that barren hot spring systems (those with no associated precious metal mineralization) are often as anomalous as hot spring gold orebodies in all members of the epithermal pathfinder suite. Given enriched values in this suite, including anomalous precious metals, one can conclude that an epithermal process was active but not that the system has an associated orebody. Nonetheless, consistent anomalous values or a regular pattern of distribution, particularly for the precious metals, is encouraging. Also, mineralized hot spring systems often exhibit very steep geochemical zoning. Values for Hg, Sb and Tl drop one to two orders of magnitude over a vertical interval of only 20m at McLaughlin. Mercury (as cinnabar), antimony (as stibnite), and thallium (?) are zoned from thousands or tens of thousands of ppm in the near-surface to tens or hundreds of ppm at depth. As little as 20m of erosion would have been sufficient to remove the mercury deposit that brought Homestake’s exploration team to McLaughlin. Consistent anomalous values, a regular pattern of distribution (as opposed to spotty anomalies), and steep vertical zoning in the epithermal suite are all characteristic of hot spring gold deposits.

Deposit Genesis

Numerous authors have drawn schematic cross sections for hot spring gold deposits. Some examples include Saito and Sato (1978), Berger and Eimon (1982), Giles and Nelson
Table 2
Geochemistry of Barren and Mineralized Hot Spring Systems

Hot Spring Gold Deposits:

<table>
<thead>
<tr>
<th>Location</th>
<th>Au</th>
<th>Ag</th>
<th>As</th>
<th>Sb</th>
<th>Hg</th>
<th>Ba</th>
<th>Tl</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borealis, NV.</td>
<td>2.2</td>
<td>3.6</td>
<td>92.8</td>
<td>62.8</td>
<td>19.9</td>
<td>2000.0</td>
<td>nv</td>
<td>25</td>
</tr>
<tr>
<td>Buckhorn, NV.</td>
<td>1.7</td>
<td>25.4</td>
<td>179.0</td>
<td>14.3</td>
<td>21.2</td>
<td>nv</td>
<td>nv</td>
<td>36</td>
</tr>
<tr>
<td>Hasbrouck, NV.</td>
<td>1.3</td>
<td>17.9</td>
<td>66.6</td>
<td>44.0</td>
<td>0.6</td>
<td>800.0</td>
<td>1.7</td>
<td>12</td>
</tr>
<tr>
<td>McLaughlin, CA.</td>
<td>3.8</td>
<td>4.6</td>
<td>323.5</td>
<td>877.4</td>
<td>61.7</td>
<td>1343.7</td>
<td>17.3</td>
<td>163</td>
</tr>
<tr>
<td>Sulfur, NV.</td>
<td>0.5</td>
<td>24.6</td>
<td>148.4</td>
<td>75.5</td>
<td>7.6</td>
<td>525.0</td>
<td>16.7</td>
<td>94</td>
</tr>
</tbody>
</table>

Barren and Sub-economic Hot Spring Systems:

<table>
<thead>
<tr>
<th>Location</th>
<th>Au</th>
<th>Ag</th>
<th>As</th>
<th>Sb</th>
<th>Hg</th>
<th>Ba</th>
<th>Tl</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beowawe, NV.</td>
<td>0.1</td>
<td>1.0</td>
<td>65.8</td>
<td>11.3</td>
<td>1.3</td>
<td>837.3</td>
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<td>30</td>
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<tr>
<td>Hope Butte, OR.</td>
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<td>386.0</td>
<td>20.0</td>
<td>22.4</td>
<td>nv</td>
<td>nv</td>
<td>30</td>
</tr>
<tr>
<td>Idaho-Almaden, ID.</td>
<td>1.1</td>
<td>nv</td>
<td>245.5</td>
<td>29.3</td>
<td>121.8</td>
<td>nv</td>
<td>nv</td>
<td>84</td>
</tr>
<tr>
<td>Pyramid, NV.</td>
<td>0.5</td>
<td>14.6</td>
<td>34.6</td>
<td>23.0</td>
<td>3.1</td>
<td>241.2</td>
<td>2.75</td>
<td>26</td>
</tr>
</tbody>
</table>

*n = number of samples
nv = no analyses available

(1982), Silberman (1982), and Bonham (1986). The deposits upon which these cross sections are based are actually much more similar than the variety of cross sections would suggest. Differences are the natural result of emphasis by each author on features considered genetically significant. The main feature of Figure 1, emphasized because of its inferred genetic importance, is a hydrothermal eruption breccia.

It is useful to contrast hot spring-type deposits with the better known bonanza-type deposits (Fig. 2). Both types occur in fossil geothermal systems; both consist of mineralized breccias and vein stockworks; and both are usually, but not exclusively, hosted by volcanic rocks. Differences between the two deposit types are primarily related to depth of mineralization. Propylitic alteration, for instance, is widespread in bonanza deposits, but is weakly developed or absent in hot spring deposits. Argillic alteration may be widespread in the hot spring environment whereas, in eroded low-sulfur bonanza systems, it is restricted to "caps" of mixed phyllic and argillic alteration. Overall enrichment in members of the epithermal trace element suite also varies significantly. Hot spring deposits contain higher overall As, Sb, Hg and Tl. Bonanza deposits contain higher overall Cu, Pb, Zn plus occasionally high Se, Te, and Bi. Geochemical zoning is steep in hot spring orebodies. Bonanza orebodies also may be zoned toward deep base metals, but changes are less pronounced and occur over a vertical interval of hundreds rather than tens of meters. Representative hot spring, bonanza, and Carlin-type deposit geochemistry is presented in Table 3.
AU IN HOT SPRINGS ENVIRONMENT

Silicification is more pronounced in hot spring than in bonanza deposits due to the controlling influence of temperature on silica deposition. Five times as much silica will be precipitated from a boiling solution saturated with respect to silica over the interval 0-50 m than is precipitated by the same solution over a similar 50 m interval at a depth of 1500 m (Cathles, 1982). Mixing of deep reservoir solutions with shallow acid sulfate fluids can also contribute to silica precipitation.

Fluid inclusion studies of mineralized systems where the paleosurface is preserved yield homogenization temperatures which plot above the reference hydrostatic boiling curve. These data indicate an over-pressured geothermal fluid. A likely explanation for these over-pressures is provided by Donaldson (1968). Donaldson’s modeling of a convecting hydrothermal system shows that the pressure gradient in a rising column of fluid increases for a boiling system as a function of mass flow rate (Q) divided by permeability (k). High flow rates, characteristic of periods of high fluid discharge, are easily sufficient to account for the over-pressured fluid inclusion measurements reported from mineralized hot spring and bonanza epithermal systems. An important consequence of high vertical flow rate is a shallow boiling level. Donaldson’s modeling of a 260°C convecting fluid indicates that boiling level is raised from a hydrostatic level of 560 m to within 200 m of the surface during periods of high fluid discharge. Dissolved gas content has a relatively small effect on boiling level during periods of high fluid throughput (Fig. 3).

Hot spring gold mineralization is associated with periods of high fluid discharge, construction of thick sinter terraces, and associated shallow boiling. As flow rate increases, and as permeability is decreased by silicification, pressure in the upwelling fluid conduit increases.

Fig. 2: Schematic bonanza precious metal deposit: fissure veins and hangingwall stockworks stacked above a mineralized bonanza and porphyry intrusive.
Boiling is delayed to an increasingly shallow depth lifting precious metals and similarly complexed members of the epithermal suite to essentially grassroots levels. Steep geochemical zoning, characteristic of mineralized hot spring systems, is a direct response to the steepened thermal gradient imposed above an elevated boiling level. Alteration and mineralization are compressed against the paleosurface.

Table 3
Geochemistry of Epithermal Precious Metal Deposits

Hot Spring Gold Deposits:

<table>
<thead>
<tr>
<th>Location</th>
<th>Au</th>
<th>Ag</th>
<th>As</th>
<th>Sb</th>
<th>Hg</th>
<th>Ba</th>
<th>Tl</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borealis, NV.</td>
<td>2.2</td>
<td>3.6</td>
<td>92.8</td>
<td>62.8</td>
<td>19.9</td>
<td>2000.0</td>
<td>nv</td>
<td>25</td>
</tr>
<tr>
<td>Buckhorn, NV.</td>
<td>1.7</td>
<td>25.4</td>
<td>179.0</td>
<td>14.3</td>
<td>21.2</td>
<td>nv</td>
<td>nv</td>
<td>36</td>
</tr>
<tr>
<td>Hasbrouck, NV.</td>
<td>1.3</td>
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<td>66.6</td>
<td>44.0</td>
<td>0.6</td>
<td>800.0</td>
<td>1.7</td>
<td>12</td>
</tr>
<tr>
<td>McLaughlin, CA.</td>
<td>3.8</td>
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<td>323.5</td>
<td>877.4</td>
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<td>1343.7</td>
<td>17.3</td>
<td>163</td>
</tr>
<tr>
<td>Sulfur, NV.</td>
<td>0.5</td>
<td>24.6</td>
<td>148.4</td>
<td>75.5</td>
<td>7.6</td>
<td>525.0</td>
<td>16.7</td>
<td>94</td>
</tr>
</tbody>
</table>

Bonanza Precious Metal Deposits:

<table>
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<tr>
<th>Location</th>
<th>Au</th>
<th>Ag</th>
<th>As</th>
<th>Sb</th>
<th>Hg</th>
<th>Ba</th>
<th>Tl</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bodie, CA.</td>
<td>3.7</td>
<td>23.7</td>
<td>81.3</td>
<td>788.3</td>
<td>0.6</td>
<td>383.8</td>
<td>nv</td>
<td>9</td>
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<td>Comstock, NV.</td>
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<td>301.3</td>
<td>24.2</td>
<td>11.4</td>
<td>0.3</td>
<td>469.5</td>
<td>1.3</td>
<td>20</td>
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<td>Gooseberry, NV.</td>
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<td>510.9</td>
<td>19.3</td>
<td>29.3</td>
<td>0.2</td>
<td>213.9</td>
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<tr>
<td>Guanajuato, Mex.</td>
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<td>365.6</td>
<td>76.3</td>
<td>5.0</td>
<td>0.04</td>
<td>890.7</td>
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</tbody>
</table>

Carlin-type Gold Deposits

<table>
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<tr>
<th>Location</th>
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<th>As</th>
<th>Sb</th>
<th>Hg</th>
<th>Ba</th>
<th>Tl</th>
<th>n*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alligator Ridge, NV.</td>
<td>2.2</td>
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<td>419.0</td>
<td>136.0</td>
<td>2.0</td>
<td>2160.0</td>
<td>0.7</td>
<td>102</td>
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<tr>
<td>Carlin, NV.</td>
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<td>0.4</td>
<td>338.0</td>
<td>52.2</td>
<td>4.7</td>
<td>nv</td>
<td>nv</td>
<td>52</td>
</tr>
<tr>
<td>Cortez, NV.</td>
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<td>102.0</td>
<td>0.3</td>
<td>nv</td>
<td>2.2</td>
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</tr>
<tr>
<td>Getchell, NV.</td>
<td>9.3</td>
<td>0.8</td>
<td>2850.0</td>
<td>325.0</td>
<td>22.0</td>
<td>190.0</td>
<td>nv</td>
<td>181</td>
</tr>
<tr>
<td>Horse Canyon, NV.</td>
<td>0.4</td>
<td>0.3</td>
<td>194.0</td>
<td>65.7</td>
<td>nv</td>
<td>1190.0</td>
<td>nv</td>
<td>24</td>
</tr>
<tr>
<td>Jerritt Canyon, NV.</td>
<td>2.2</td>
<td>0.3</td>
<td>282.0</td>
<td>721.0</td>
<td>0.4</td>
<td>3960.0</td>
<td>0.3</td>
<td>86</td>
</tr>
<tr>
<td>Mercur, NV.</td>
<td>0.6</td>
<td>3.1</td>
<td>1590.9</td>
<td>112.9</td>
<td>7.8</td>
<td>2252.9</td>
<td>111.7</td>
<td>11</td>
</tr>
<tr>
<td>Pinson, NV.</td>
<td>4.2</td>
<td>0.2</td>
<td>594.0</td>
<td>36.1</td>
<td>10.3</td>
<td>nv</td>
<td>nv</td>
<td>28</td>
</tr>
<tr>
<td>Relief Canyon, NV.</td>
<td>1.0</td>
<td>7.9</td>
<td>274.0</td>
<td>125.0</td>
<td>nv</td>
<td>nv</td>
<td>nv</td>
<td>15</td>
</tr>
</tbody>
</table>

*n = number of samples
nv = no analyses available
Conduits for fluid discharge in hot spring systems are typically hydrothermal vent breccias. Higher grade hot spring gold deposits are characterized by multiple episodes of hydrothermal eruption, high fluid discharge, and shallow precious metal mineralization. Hydrothermal eruptions are discussed in detail by Hedenquist and Henley (1985) and by Nelson and Giles (1985). A schematic representation of episodic mineralization during the life of a hot spring system is shown in Figure 4. During periods of high fluid discharge, the rate \( Q/k \) may be thought of as being controlled by permeability: any increase in permeability results in an increase in flow rate maintaining \( Q/k \) at a constant high level. During periods of increasing or decreasing fluid discharge, the ratio of \( Q/k \) may be thought of as flow-rate controlled: any change in flow rate results in a change in \( Q/k \) since permeability is everywhere easily sufficient to handle available mass flow. Periods of high \( Q/k \) coincide with periods of high fluid discharge. High fluid discharge may in turn be driven by a contribution of heat and/or gases from an underlying magma. High fluid discharge might also be associated with earthquake activity through a phenomenon known as seismic pumping. Calculations by Sibson, Moore and Rankin (1975) show that a magnitude 6 earthquake could pump as much as \( 5 \times 10^9 \) liters of fluid, sufficient to deposit a vein of quartz measuring 1cm by 40m by 10km (\( 10^{10} \) grams of silica), given a 350°C reservoir initially saturated with respect to silica. Modification of these figures to lower temperatures and smaller volumes of fluid still provides a convincing mechanism for the generation of crustiform banding, common in both hot spring and bonanza precious metal deposits.

Hydrothermal eruption vents are permeable conduits for fluid discharge. A good example is provided by the Champagne Pool in the Waiotapu geothermal field of New Zealand. Surface fluid discharge at Waiotapu is focused through a hydrothermal eruption vent. Gold is adsorbed from solution on amorphous arsenide sols which periodically accumulate at the margin of the pool producing local high-grade precipitates. Similar gold-bearing precipitates are reported from sinters at Steamboat Springs, Yellowstone, and Beowawe in the United States and from sinters at Waimangu, Whaquawerawa and Broadlands in New Zealand.
Drilling in these areas for geothermal resources did not encounter significant subsurface precious metal mineralization. Confounding the problem, fourteen sinter samples with variable sulfide from the McLaughlin gold deposit contained no gold values higher than 0.04 ppm, except where cut by later veins and breccias. For epithermal deposits in general, local gold and silver anomalies are part of the epithermal suite and do not indicate a nearby ore reserve. For hot spring systems in particular, local gold and silver anomalies in sinter are the result of rapid pH changes in surface pools and the low temperature scavenging of metals by colloidal precipitates. A nearby ore reserve is not indicated. Indeed, even those sinters which are known to overlie several million ounces of hot spring gold mineralization are typically barren of precious metals.

Mineralization occurs episodically during the life of a hot spring system. Periodic intrusion of magma heats the geothermal reservoir. Higher reservoir temperature increases the cold water hydrostatic head, increases the rate of fluid discharge and lifts the boiling level towards the surface. An increase in gas content, possibly originating with a magma, would lower the boiling level in the geothermal reservoir thereby also increasing the cold water head. In zones of coincident seismic and hot spring activity, earthquakes periodically increase fluid discharge by seismic pumping. Episodic high fluid discharge, with associated high vertical flow rate through permeable hydrothermal vent breccias, lifts the boiling level towards the surface and causes hot spring gold mineralization.

Calculations by Nelson and Giles (1985) demonstrate that grades as high as 1 ppm gold can be precipitated over a 100-m interval from a solution containing 0.1 ppm gold during a 100-year period of high fluid discharge (assuming a discharge rate of 100 grams per square cm per year). Maximum gold solubilities in a dilute, alkaline geothermal fluid are on the order of

\[ \frac{Q}{k} \]

*Fig. 4: Development of a hot spring gold deposit during periods of high fluid discharge and associated shallow boiling. Boiling level fluctuates in response to variations in \( \frac{Q}{k} \), the ratio of mass flow rate to permeability.*
100 ppm (Seward, 1973). As fluid discharge disperses the heat added by a magma or the seismic pulse contributed by an earthquake, the boiling level will fall and the geothermal system will return to a pressure gradient approximating that which existed prior to the disturbance. Normal pressure gradients in a convecting hydrothermal system approximate the cold water hydrostatic head (Cathles, 1977).

The lifetime of the average hydrothermal system is over a million years (Silberman, 1983). A few hydrothermal systems (e.g. Steamboat Springs, Nevada) exhibit evidence for as much as three million years of at least intermittent hot spring activity. Coincident seismic activity could reasonably generate fault displacements of one millimeter per year. A million years of seismic activity would generate a total displacement of one km. This aggregate displacement would require between 1000 and 10,000 magnitude 6 earthquakes (Sibson, Moore and Rankin, 1975) each capable of driving an episode of seismic pumping and related hot spring gold mineralization. Periods of increased fluid discharge and, in particular, CO₂-rich fluid discharge are known to follow seismic activity (Barnes, Irwin and White, 1978; Sibson, Moore and Rankin, 1975; Tsuneishi and Nakamura, 1970). Whether or not hot spring gold mineralization is associated with each of these events will depend on factors such as the reservoir temperature, the depth of boiling, and the magnitude and depth of the seismic event.

A potentially mineralizing system requires a source of gold. A potentially mineralizing event requires a mechanism for removing gold from solution. Boiling, through its destabilizing effect on soluble gold thio-complexes, is a favored mechanism for precious metal precipitation. Boiling level will vary, over hundreds of meters, as a result of changing flow rate and, to a lesser extent, changing fluid temperature and dissolved gas content. Hot spring gold orebodies, deposited during periods of maximum fluid discharge, may overlie bonanza orebodies, deposited during periods of deeper boiling. Bonanza orebodies may, in turn, be stacked on several levels. Trace element enrichment, geochemical zoning, and alteration in bonanza and hot spring ore deposits reflect a fundamental control by flow rate on depth of mineralization.

**Exploration Tools**

The preceding discussion of hot spring gold deposit characteristics and genesis suggests a variety of features that are of potential use to the explorationist.

Hot spring gold deposits consist of multiple, mushroom-shaped orebodies, each of which narrows with depth into a structurally controlled hydrothermal conduit. Examples include the Borealis and Hog Ranch deposits in the U.S. and the Nansatsu deposits in Japan. Individual orebodies are typically less than 1 million tons, but aggregate deposit size is an order of magnitude greater. Multiple orebodies, each centered around an individual vent, may overlap, as at McLaughlin, to produce a larger deposit minable from a single open pit.

Alteration zoning consists of a core of mineralized sulfidic silicification surrounded by an argillically altered envelope which grades outward into unaltered host rock. Propylitic alteration is weak to absent. Sulfidic silicification extends to the paleosurface. The argillically altered rind may be as narrow as several meters. Widespread argillic alteration, particularly the advanced argillic assemblage cristobalite-alunite-kaolinite, is superimposed, if it is present at all, on gold-bearing sulfidic silicification. Gold grade may even increase in argillized rock as a result of acid leaching of the silicate rock matrix.

Hot spring systems which, throughout their lifespan, are characterized by widespread advanced argillic alteration and/or a sub-surface groundwater table make poor candidates for shallow gold mineralization. Hot spring gold deposits form in systems which have experienced episodic high fluid discharge. Episodic high fluid discharge is indicated by thick deposits (5-50 m) of siliceous sinter which form around a hydrothermal conduit. Sinters which
overlie hot spring gold deposits are typically chalcedonic, having inverted from amorphous silica. Opaline sinters or carbonate tufas may be preserved on top of chalcedonic silica or may be peripheral to the mineralized portion of the hot spring system. Chalcedony forms by inversion of opaline silica in a time- and temperature-dependent reaction accelerated by episodic discharge of hot fluids. Hot spring systems which are entirely opaline have low gold potential. Chalcedonic sinter, particularly in young hot spring systems, suggests repeated alteration and mineralization and associated higher gold potential.

Episodic activity may be indicated by crustiform banded veins, quartz stockworks, and evidence for hydrothermal eruptions. The best mineralization is, typically, in the area most likely to be covered by sinter (Fig. 1). However, hydrothermal eruption debris, interbedded with sinter, contains fragments of underlying mineralization. These deposits thicken and coarsen towards their vent(s). Hydrothermal vent breccias are locally matrix supported, contain episodically silicified fragments and lack evidence, such as fresh pumice fragments, for a direct contribution of magma. Once hydrothermal eruption vents are located (multiple eruptions are the rule), hot spring precious metal potential can be evaluated by drilling. Hydrothermal eruption vents contain the best grade mineralization in hot spring orebodies. Peripheral stockworks may contribute to the total reserve, but at a lower grade than the vent breccias.

High-temperature, gas-charged geothermal reservoirs are more explosive than lower-temperature, gas-poor geothermal reservoirs (Nelson and Giles, 1985) and are, therefore, more likely to generate hydrothermal eruptions. Magmas provide the heat source for gas-rich, high-temperature geothermal reservoirs in the western United States and around the circum-Pacific rim. Magmas are also capable of providing a sudden pulse of heat or gases during intrusion or through episodic devolatilization. Intrusion of magma may overwhelm the capacity of the geothermal reservoir to dissipate energy through normal convection and fluid discharge. The result is a hydrothermal eruption. Historic hydrothermal eruptions in active geothermal areas are all associated with periods of volcanic activity or magma emplacement. There is also evidence in hot spring gold deposits that hydrothermal eruptions follow a period of volcanic and hydrovolcanic activity. Deposits where this progression is documented include the Wau deposit, Papua New Guinea (Sillitoe, Baker and Brook, 1984) and the McLaughlin deposit, California (Lehrman, 1986).

Hot spring gold deposits contain several volume percent sulfide (mostly pyrite-marcasite). This is sufficient to generate an I.P. anomaly which, in mineralized systems, includes the orebody. The I.P. anomaly may coincide with, or may underlie, a zone of high resistivity. An overlying pile of siliceous sinter will produce a resistivity high.

Siliceous sinter may contain ore-grade gold precipitates, or as is more frequently the case, may be completely barren. Some hot spring systems with no associated precious metal reserve (e.g. Steamboat Springs, Nevada and Waiotapu, New Zealand) have ore-grade gold precipitates in sinter. Some hot spring gold orebodies (e.g. McLaughlin, California and Sulfur, Nevada) contain sinter with uniformly low or non-detectable gold. The presence or absence of precious metal enrichments in sinter does not reflect on the potential for a hot spring gold orebody.

Hot spring gold deposits contain anomalous Au, Ag, As, Sb, Hg, Ba, Tl, and occasionally W. Barren hot spring systems are anomalous in the same epithermal suite (Table 2). Consistent anomalous precious metals and/or a regular pattern of anomalies is, however, encouraging for hot spring gold potential. Steep zoning with a near-surface enrichment in Hg, Sb, Tl reflects the steep thermal gradient and shallow boiling level characteristic of mineralized hot spring systems.

K-feldspar is a common alteration product despite the low temperature of hot spring gold mineralization. K-feldspar (as adularia) occurs with quartz in vein stockworks and, deeper in the system, as replacements along hydrothermal fluid conduits. Deep K-feldspar
replacements have been mistaken for rhyolite at several epithermal gold orebodies. These deep replacements contain ore-grade gold and elevated base metals.

Hot spring gold deposits are being discovered in the western United States at a rate of one per year. The average deposit from Table 1 contains 5 million tons at a grade of 0.12 opt gold for a total reserve of 0.6 million ounces. New discoveries both in the western United States and around the circum-Pacific rim are likely to accelerate as exploration emphasis continues to focus on bulk mineable precious metal deposits of generally low unit recovery cost.

Acknowledgments

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Mine staffs and corporate owners for each of the orebodies listed in Tables 2 and 3 are thanked for providing access to and permission to sample their ore deposits.

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