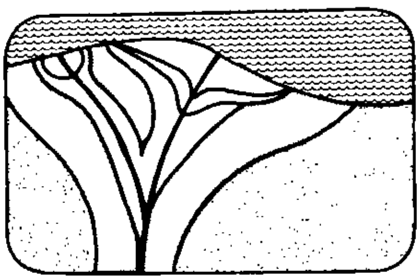

A Model for Bonanza Gold Deposits

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INTRODUCTION

Bonanza is a descriptive, semiquantitative and subjective term that has been used to describe deposits from which large quantities of precious metals have been recovered from relatively small high-grade orebodies. Such deposits were sought and mined by gold prospectors throughout historical times, and many present-day operating mines were developed on extensions of these high-grade discoveries into lower grade, but larger, disseminated deposits. Depending on the scale chosen, most structurally controlled deposits will have local concentrations of precious metals, which might be referred to as bonanza orebodies, where gold grades of hundreds of grams per tonne occur. However, these by themselves may not be economical because of the limited tonnage. Such concentrations occur in deposits in a wide variety of geologic environments from Archean greenstone terranes in Canada, southern Africa, and western Australia to Neogene volcanic environments of the southwestern Pacific. Because of their high grade, some of these bonanza ores may be quite spectacular in appearance, consisting of readily visible ribbons and coatings of native gold occupying open spaces in fractured and brecciated host rock. This tendency to the spectacular culminates in the widely acclaimed specimen gold recovered from the Mother Lode in California. This paper is concerned primarily with deposits hosted by, or spatially related to, Tertiary volcanic terranes of the western Cordillera of North and South America because other deposit types and host terranes are discussed elsewhere. However, to begin by putting things in perspective, these so-called bonanza deposits should be compared with the much larger disseminated deposits hosted by sedimentary and volcanic rocks. Even though these "bonanza" deposits locally contain high-grade ores, their total gold content is small when compared to the latter deposits.

Table 1 contains a list of districts in the western Cordillera that have produced or have reserves in excess of 30 tonnes of gold where the average grade exceeds 7 grams gold per tonne (g Au/t). The locations of these deposits are shown in Figure 1. Historically, the largest gold producer in the western Cordillera was the Comstock district of western Nevada, with 258 tonnes from approximately 17 million tonnes of ore (Buchanan, 1981). This same district produced in excess of 6220 tonnes of silver. The "Big Bonanza" orebody of the Comstock yielded 1.4 million tonnes of ore, averaging about 69 g Au/t and 1244 g Ag/t, and resulting in 93 tonnes of gold and 1866 tonnes of silver from one small orebody (Carrington, 1981). The El Indio-Tambo deposits of Chile have reported production and reserves totalling about 108 tonnes of gold and high-grade ores averaging, about 200 g Au/t (Siddeley and Araneda, 1986). The Sleeper deposit in northwestern Nevada has yielded some spectacular ore on a hand specimen scale, up to several thousand grams gold per tonne. During exploration drilling, grades of 28 g Au/t were obtained from intercepts of more than 100 m. In total, the Sleeper ore body contains nearly 3.5 million tonnes of ore averaging 7.5 g Au/t, for a gold content of more than 26 tonnes (Wood, 1988). The discovery of the Wood orebody has increased the total gold reserves to more than 79 tonnes (Nash *et al.*, 1991). One of the largest gold mines in the western hemisphere is the Homestake Mine in Lead, South Dakota, having produced more than 1000 tonnes of gold from approximately 120 million tonnes of ore for an average grade of about 8.9 g Au/t (Nelson, 1986). The ore is hosted by a metamorphosed Archean iron formation and, while visible gold is locally present, the deposit has not been commonly referred to as a bonanza deposit.

In the western Cordillera, some of the largest deposits in terms of contained gold are those hosted by carbonate sedimentary rocks. At the north end of the Carlin trend in northeastern Nevada, Barrick Goldstrike Mines, Inc. reports that their portion of the Post property alone contains nearly 500 tonnes of gold in 149 million tonnes of ore, for an average grade of about 3.4 g Au/t. Within this deposit is a high-grade core containing about one million tonnes of ore, with a grade of about 34 g Au/t (Bettles, 1989). This could be referred to as a bonanza orebody using a broad definition of the term. The other "half" of the ore deposit lies on Newmont Gold Company property. The Gold Quarry sedimentary rock-host disseminated deposit along the same trend contains about 218 tonnes of gold in 134 million tonnes of ore, averaging 1.7 g Au/t (Rota, 1988). The Carlin Mine, itself, produced more than 124 tonnes of gold from 16.8 million tonnes, averaging about 9.3 g Au/t (Cuffney *et al.*, 1988). Finally, the Round Mountain deposit of central Nevada is presently the largest gold deposit hosted by volcanic rocks in the western Cordillera. Published reserves at the end of 1985 were 160 million tonnes of 1.34 g Au/t, or 212 tonnes of gold. Previously, 21 tonnes of gold had been recovered from the present mine, and 17 tonnes from lode and placer deposits, resulting in total production plus reserves of about 249 tonnes of gold (Sander, 1988). Additional exploration at the property has extended the reserves, so the total system may contain 311 tonnes of gold. Some of the lode deposits were high grade although very small. From 1918 to 1925, grades averaged slightly more than 34 g Au/t, and in 1921–1922, 5400 tonnes of ore were mined, with an average grade of nearly 103 g Au/t (Tingley and Berger, 1985).

The production records above serve to emphasize two important points concerning gold deposits that have been referred to as "bonanzas". First, even though high grades are locally common and spectacular specimen gold has been recovered, these deposits are relatively small in production when compared to large low-grade disseminated deposits. A second implied point is that gold grades are highly variable within deposits containing bonanza orebodies. These two factors lead to the conclusion that bonanza deposits represent a chance concentration of gold within a much larger mineralizing system produced by the focussing of the mineralizing solutions along principal structurally imposed channels. The amount of

Table 1 Tonnes of gold contained or produced by selected bonanza gold districts and their grades.

District	Tonnes	Avg. Grade (g/t)	Reference
Comstock	258	15	Buchanan (1981)
Tonopah	56	7	Bonham and Garside (1979)
Goldfields	130	31	Ruetz (1987)
Sleeper	79	7.5	Nash *et al.* (1991)
Bodie-Aurora	93	60	Buchanan (1981); Osborne (1987); Herrara (1988)
Tayoltita	218	12	Smith *et al.* (1982)
El Indio	108	12	Siddeley and Araneda (1986)

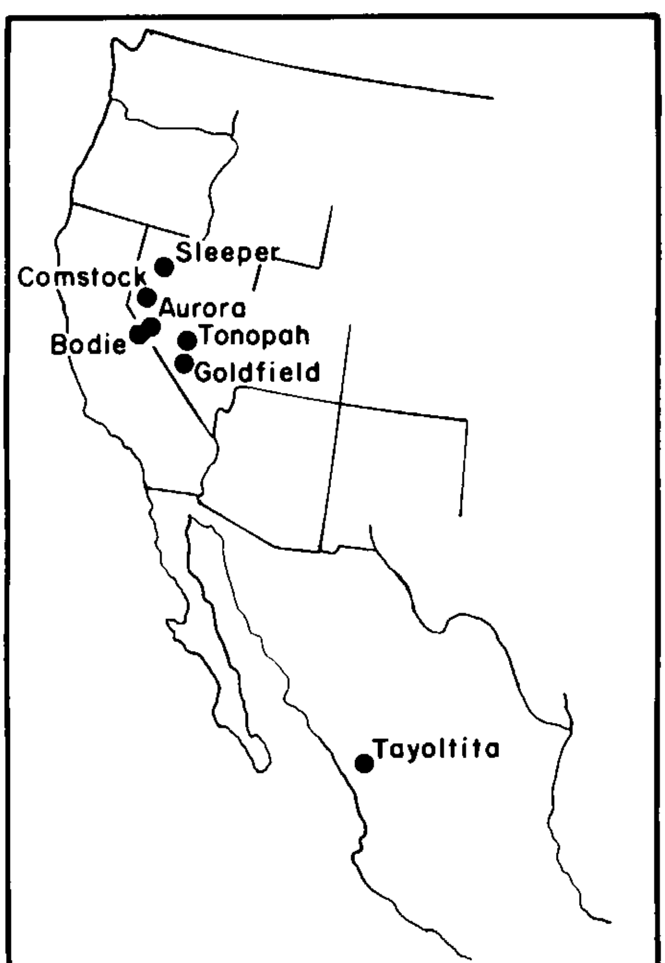
gold occurring in some disseminated deposits suggests that undiscovered lower grade deposits still exist in the vicinity of many "bonanza" deposits, or that permeability relationships have resulted in the dispersion of much gold into subeconomic haloes. An example of how much gold can be dispersed in a single hydrothermal system is the Bingham Canyon copper deposits of northern Utah. By 1972, nearly 467 tonnes of gold had been produced, mainly as a by-product from 1.1 billion tonnes of copper ore. The average grade was about 0.206 g Au/t (James, 1978). At that time, published reserves amounted to about 1.6 billion tonnes of ore (Gilmour, 1982), so assuming the gold grades do not change, more than 930 tonnes of recoverable gold may exist in this one porphyry deposit and the geologic resource may exceed 1000 tonnes. If only a small amount of this gold had been focussed into a favourable structural environment, a significant bonanza gold deposit might have been formed.

EXISTING MODELS

Buchanan (1981) developed a general model for structurally controlled precious metal deposits based on characteristics of 60 occurrences. Berger (1982) and Berger and Eimon (1982) also developed a conceptual model for the origin of epithermal deposits, emphasizing their geochemical attributes. These and other studies (Henley and Ellis, 1983; Berger and Bethke, 1985) emphasized the similarities between these deposits and present-day geothermal systems, and assumed that groundwater was important in their origin. Based on fluid inclusion studies and the inferred connection with geothermal systems, many of these previous models involved boiling of the hydrothermal mineralizing solution in a relatively open geochemical system as an important control on precious metal deposition. Foley (1984), Hayba *et al.* (1985), and Heald *et al.* (1987) assembled geologic, mineralogic and geochemical data for volcanic rock-hosted precious metal deposits that are useful in defining the environment of deposition. Nelson and Giles (1985) and Nelson (1988) developed a genetic model for breccia-hosted hydrothermal gold deposits, emphasizing the importance of brecciation in the localization of the ores.

Romberger (1988b) suggested that there may be little difference in the geochemical processes responsible for disseminated and vein gold deposits. A detailed inspection of the former indicates that the ores are strongly fracture controlled. The main difference between the two deposit types may be that the flow of the mineralizing solutions is responding to different styles of structural ground preparation. Argillaceous sedimentary rocks will yield or fracture at depth along several closely spaced planes of limited extent, while siliceous volcanic rocks emplaced at or near the surface will undergo brittle fracturing to produce open through-going fractures and breccia zones. These would result in the focussing of large volumes of solution required to transport the abundant metals typical of bonanza orebodies along a few well-developed channels. However, as will be discussed more fully below, the volume of mineralizing solution may not be as important as the length of time during which physicochemical gradients, responsible for gold deposition, exist within the favourable structural zone.

Recently, Bonham (1988) and Henley (1991) presented comprehensive reviews of genetic models for volcanic rock-hosted precious metal deposits. Bonham divided these into three types: low-sulphur and high-sulphur systems, equivalent to the adularia-sericite and acid-sulphate types, respectively, of Heald *et al.* (1987), and an alkalic type where the ores may contain significant amounts of telluride minerals and be associated with alkalic volcanic rocks. It will be



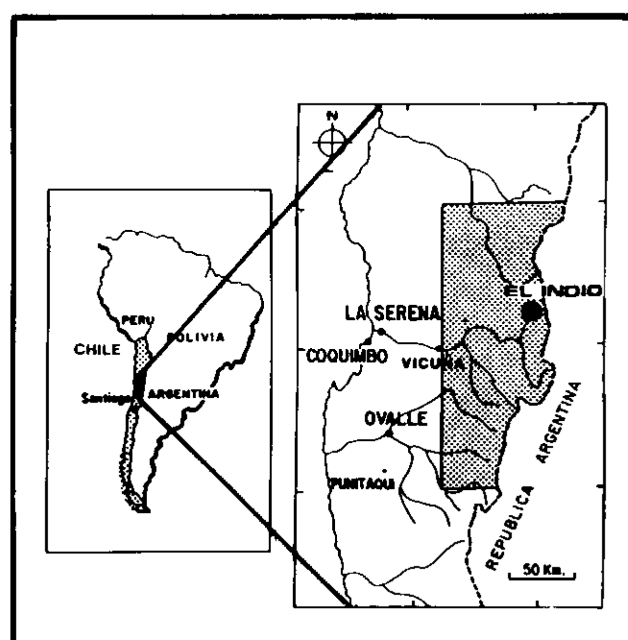


Figure 1 *Location of districts and deposits listed in Table 1.*

difficult at this time to improve upon these existing models in terms of the lithologic and structural setting and the overall physical processes involved. However, there is the opportunity to incorporate the best features of these models with geochemical, fluid flow, and mass transport concepts to explain the exceptionally high grades observed locally in these deposits.

GEOLOGY

A few selected deposits have been chosen to illustrate the features exhibited by high-grade concentrations of gold. However, the choice here is, for the most part, subjective, and the difference between these and other vein deposits not discussed may be only a matter of scale. Table 1 summarizes the precious metal production and grades of a few deposits or districts that may be considered bonanzas. Some of these are discussed below. These deposits have had a significant proportion of the total production come from one or more high-grade bodies or veins. For example, of the total gold and silver produced from 18 million tonnes of ore in the Comstock district, more than 30% of the gold and silver came from one orebody containing 1.4 million tonnes, or less than 8% of the total. In contrast, at Round Mountain less than 11 tonnes of gold came from the high-grade lode deposits compared with the total contained gold in the disseminated ores of more than 231 tonnes.

Comstock District

The centre of the Comstock district is Virginia City, Nevada, about 32 km southeast of Reno. The geology of the district has been summarized most recently by Hudson (1986), Vikre *et al.* (1988), Vikre (1989a) and Brake (1989). The district lies on the southeast flank of the Virginia Range, which is a horst block uplifted during the development of Basin and Range topography. The oldest rocks in the immediate area are Mesozoic metasedimentary and metavolcanic rocks intruded by granodiorite and granite of the same age. Unconformably overlying the Mesozoic rocks is a sequence of silicic ash flow tuffs which have ages between 20 Ma and 28 Ma. All these rocks are unconformably overlain in turn by up to 1000 m of Miocene andesitic flows, flow breccias, lahars and lacustrine sedimentary rocks. Except in proximity to major faults, the attitudes of all Miocene extrusive volcanic and associated sedimentary rocks are subhorizontal. Based on the regional distribution of the volcanic rocks, attitudes, and thicknesses, it appears that the source of the flows was in the Virginia City area.

The Miocene history of volcanism and associated mineralization in the Comstock district is very complex. There are three principal parts to the volcanic stratigraphy. The Alta Formation consists of andesitic flows, flow breccias, mud flow breccias, and lacustrine sedimentary rocks. This formation has an age from 14 Ma to 20 Ma and is the principal ore host, although veins cut all older lithologies. The overlying Kate Peak Formation has lithologies similar to the Alta Formation and an age in the range of 12–14 Ma. The Mount Davidson Granodiorite, with a radiometric age of about 15 Ma (Vikre *et al.*, 1988) intrudes the Alta Formation in the western part of the mineralized district. Other volcanic units occur throughout the district, but are volumetrically less important than these three units.

Most of the ore bodies in the Comstock district are localized along the Comstock fault and related fractures. The Comstock fault is a north-northeast striking, east-dipping normal fault that can be traced along strike for more than 10 km. Its average dip is about 45°; however, near the present surface, it steepens and locally is overturned. At its southern end, the Comstock fault is joined by the Silver City fault that strikes southeasterly and dips to the east. The footwall rocks of the Comstock fault consist mostly of Miocene volcanic units, although in the Virginia City area the footwall is the Mount Davidson granodiorite and, at its extreme southern end, Mesozoic metasedimentary and metavolcanic rocks form the footwall. The hanging wall consists of Miocene volcanic units along most of its length. Premineralization dip-slip displacement is estimated at 400-430 m (Hudson, 1986; Vikre *et al.*, 1988). Vikre *et al.* (1988) estimate about 200 m of post-mineralization displacement. Subparallel vertical subsidiary fractures that originate at the main fault plane occur in the hanging wall of the Comstock fault. Although orebodies may occur on either the main Comstock structure or these hanging wall fractures, the well-known Big Bonanza occupied one of the latter. Vikre (1989a) presented a north-south longitudinal profile along the Comstock fault suggesting that most of the orebodies are restricted in vertical extent and occur at specific elevations within 500-540 m of the present surface.

The orebodies in the Comstock district consist of stockworks containing multiple stages of quartz and sulphides with minor amounts of adularia, sericite, chlorite, albite and late-stage calcite. The ore minerals are galena, sphalerite, chalcopyrite, gold, argentite, polybasite, stephanite, pyrargyrite and proustite. At shallow depths, the wallrocks adjacent to the veins in the stockworks have been altered to various proportions of quartz, pyrite, sericite, montmorillonite and kaolinite. At depth, chlorite is an important alteration mineral along with quartz. The bonanza nature of some orebodies is a function of the greater density and larger size of the veins in the stockworks together with the increase in the proportion of ore minerals in the latter. Repeated fracturing of silicified wallrocks and veins, accompanied by multiple invasions by hydrothermal mineralizing solutions, resulted in the local development of continuous zones of sulphides to the point where the stockwork nature of the orebodies was often obliterated.

Oxygen and hydrogen isotopic studies by Taylor (1973) and Vikre (1989a) suggest that meteoric water dominated the hydrothermal mineralizing system at Comstock, although the data allow for a small contribution of magmatic water as well. Vikre (1989a) reported fluid inclusion geothermometry results indicating a maximum temperature for ore formation at about 300°C. The bonanza ores were deposited at temperatures of about 250°-275°C. Salinities were 2-6 weight percent (wt.%) NaCl equivalent. Brake (1989) reported fluid inclusion homogenization temperatures for one of the stockwork ore bodies of 260°-270°C and salinities of about 1 wt.% NaCl equivalent. No evidence was found to suggest the mineralizing solutions boiled, and Brake (1989) attributed ore deposition to the mixing of solutions of contrasting composition. Vikre (1989a) also concluded that more than one fluid was involved in mineralization at Comstock, based on the spread of hydrogen isotope values.

Tonopah District

The Tonopah district is centred at the town of the same name at the southern end of the San Antonio Mountains, 330 km northwest of Las Vegas, Nevada. From 1900 to 1957, the district produced more than 56 tonnes of gold and 5412 tonnes of silver, from approximately 8 million tonnes of ore (Bonham and Garside, 1979). Grade figures for bonanza ore bodies are not readily available. However, in the early years of mining, values in excess of $100 per tonne were common. During 1903, the ore averaged 82 g Au/t and 9120 g Ag/t and had a value of about $230 per tonne. Bastin and Laney (1918) reported assays as high as 1645 g Au/t from high-grade ore samples.

The geology and mineral deposits of the district have been described by Nolan (1935), Bonham and Garside (1974, 1979), and Fahley (1981). The mineralization occurs in quartz veins hosted by Tertiary volcanic rocks ranging in composition from andesite to rhyolite. The main ore host is the Miocene Mizpah Formation that consists of approximately 700 m of porphyritic andesite and trachyandesite flows and breccias, interbedded volcaniclastic sedimentary rocks, and minor dacite intrusions. This formation overlies the oldest Tertiary unit in the district which is the Oligocene Tonopah Formation, consisting of approximately 300 m of ash flow tuffs and rhyolite domes and flows. Volcanic units stratigraphically above the Mizpah Formation are younger than the precious metal veins. These are, in ascending order: the Fraction Tuff, consisting of rhyolite ash flow tuff, tuff breccia, and minor volcaniclastic units; the Heller Tuff, a quartz latite ash flow tuff; and the Siebert Formation, consisting of volcaniclastic siltstone, sandstone, and conglomerate. These formations are intruded by the Odie and Brougher rhyolites in the form of plugs, dykes and domes.

Age determinations by Silberman *et al.* (1978) have shown that the mineralization at Tonopah is an integral part of a sequence of closely spaced volcanic and hydrothermal events that spanned approximately 4 m.y. The Mizpah Formation has an age of 20.4 ± 0.6 Ma, while the Odie and Brougher rhyolites have ages of 16.5 ± 0.5 and 16.2 ± 0.4 Ma, respectively. The age of the veins is 19.1 ± 0.4 Ma (Silberman *et al.*, 1978).

The rocks at Tonopah have been affected by at least four episodes of normal faulting, resulting in a complex system of fault blocks that has produced a regional tilting of the volcanic units to the west of about 45° (Fahley, 1981). Most of the mineralized veins are associated with the Tonopah fault, a northwest-striking normal fault with variable low dips to the northeast and southwest. The estimated displacement along the Tonopah fault is 1000 m (Nolan, 1935). This fault has been intruded locally by pre-mineralization rhyolite and rhyolite breccia dykes. In the fault hanging wall are numerous fractures and faults of small displacement that join the Tonopah fault at low angles. Veins in these hanging wall fractures are consistently of a higher grade than those occupying the Tonopah fault itself. In the latter, vein widths in excess of 12 m occur, whereas veins in the hanging wall fractures seldom reach 3 m.

The orebodies at Tonopah occurred in an east-west elongated dome-shaped zone with an average thickness of about 200 m. The boundaries of this zone cut across lithologic contacts and faults. The veins consist predominantly of quartz, and formed by both open-space filling and by replacement of wall rocks adjacent to fractures. Fahley (1981) described three stages of mineralization: an early barren stage consisting of quartz, sericite, adularia and pyrite; a silver stage consisting of quartz, base metal sulphides, gold, adularia, sericite, pyrite, argentite, pyrargyrite and polybasite; and a late barren stage consisting of quartz, calcite and barite. The base metal sulphides occurring in the main ore stage are chalcopyrite, sphalerite and galena. Immediately adjacent to the veins, the wall rocks have been altered to a mixture of quartz, sericite and adularia. This grades outward into an argillic alteration consisting of kaolinite, montmorillonite and sericite, and then into propylitic alteration consisting of chlorite, pyrite, calcite and albitic plagioclase (Bonham and Garside, 1979; Fahley, 1981).

Fluid inclusion thermometric studies by Fahley (1981) suggest that the silver stage mineralization occurred between 290°C and 240°C from solutions with salinities between 1 and 3 wt.% NaCl equivalent. Variable liquid to vapour ratios in inclusions from veins in the hanging wall fractures, together with textures in the ores and gangue, suggest that the mineralizing fluids periodically boiled. Fahley (1981) estimated that veins formed at depths of 325-650 m. Based on oxygen isotopic studies on vein material, Taylor (1973) concluded that the hydrothermal alteration and ore deposition were produced by heated and compositionally evolved meteoric waters, and that water:rock ratios were greater than two. The isotopic studies support the model of Nolan (1935) that the hydrothermal system was driven by an intrusion at depth centrally located below the apex of the dome-shaped ore zone. The Tonopah fault served as a major conduit for the ascending solutions, which were deflected into the hanging wall fractures where boiling and mineralization occurred. Fahley (1981) recognized the coincidence between a broad zone of boiling in the hanging wall fractures and the ore shell, and attributed deposition to chemical changes occurring in the solution that resulted from boiling.

Goldfields District

In the Goldfields district about 40 km south of Tonopah, Nevada, gold was discovered in 1902 and production reached its peak in 1910. Mining operations were sporadic after 1918, and up to 1951, when historic operations ceased, the district had produced 130 tonnes of gold, 45 tonnes of silver, and 16,870 tonnes of copper from 4.2 million tonnes of ore, for an average grade of about 31 g Au/t (Ruetz, 1987). Mining activities in the 1980s have concentrated on recovering low-grade oxidized ores, containing less than 3 g Au/t, from areas adjacent to old lode workings.

The geology of the Goldfields district has been described by Ashley (1974, 1979) and Ruetz (1987). Geochemical studies on the ores have been carried out by Taylor (1973), Bruha and Noble (1983), and Vikre (1989b). Heald *et al.* (1987) classified the district as an acid-sulphate epithermal type hosted by volcanic rocks. The host rocks for the ores consist of Oligocene to Miocene andesitic to dacitic flows, tuffs, breccias and intrusive rocks. The basement in the Goldfields region consists of Jurassic quartz monzonite intruded into Ordovician black siliceous shales. The oldest Tertiary volcanic rocks have ages of 30-31 Ma and consist of quartz latite to rhyolite flows and tuffs. During this period of eruption, doming and fracturing resulted in a circular feature that resembles a caldera approximately 5 km in diameter bounded by concentric normal faults (Ashley, 1974). However, the true nature of this structural feature has been obscured by later volcanism. Unconformably overlying the early volcanic rocks is the 600 m-thick Milltown Andesite that consists of trachyandesite and rhyodacite flows and tuffs with minor amounts of basalt and quartz latite; this formation has an age of 20-22 Ma. Intruding these rocks along the concentric fracture system is a series of porphyritic rhyodacite flow-domes with ages slightly younger than the Milltown Andesite (Ashley, 1974). One of these intrusive-extrusive bodies serves as the host for much of the ore in the main part of the Goldfields district. The youngest volcanic units are late Miocene to Pliocene siliceous tuffs, volcaniclastic sedimentary rocks, and basalt flows that all postdate alteration and mineralization.

The ores occur as veins that occupy concentric fractures related to the caldera-like feature. Approximately 95% of the ore was recovered from a relatively small 2 km^2 area along the western rim. However, the area of alteration covers approximately 50 km^2 and goes well beyond this main productive area. Both alteration and ore have ages of 20-22 Ma and therefore are coincident with, but slightly younger than, the Milltown Andesite and flow-dome complexes. Alteration of the host rocks is pervasive and consists of quartz, kaolinite and alunite. The veins consist of a zone of intense silicification that contains small amounts of alunite, kaolinite, pyrite and trace diaspore and pyrophyllite. The bonanza orebodies occur as discontinuous pipe-like lenses within these intensely silicified zones. Adjacent to these veins is an envelope of quartz, alunite, kaolinite, sericite, pyrite and locally opal that grades outward into an argillic alteration consisting of variable proportions of montmorillonite and illite.

The Goldfields ores are well known for their bonanza character. The main district contained as many as 15 bonanza gold orebodies averaging about 100,000 tonnes with grades of 35-170 g Au/t. The richest ore, from the Mohawk mine, contained 15,000-20,000 g Au/t, or 1.5-2%. (Ashley, 1974). One bonanza orebody in this same mine contained more than 11,000 tonnes of ore averaging 685 g Au/t, and would be worth close to $90 million at today's gold prices. The ores consist of pyrite, marcasite, famatinite, tetrahedrite-tennantite, bismuthinite, goldfieldite ($Cu_6Sb_2(S,Te)_9$), native gold, and gold and silver tellurides as massive fine-grained bonanza pods within veins, and fine-grained disseminations in quartz. Crustiform textures in veins and breccias are also common. A crude paragenesis, given by Ruetz (1987), consists of early quartz, kaolinite and alunite followed and overlapped by pyrite and marcasite, then copper sulphides and sulphosalts, then bismuthinite, goldfieldite and tellurides, and finally, late native gold. Thermometric studies on fluid inclusions suggest the temperature of formation was between 250°C and 290°C (Bruha and Noble, 1983). Taylor (1973) and Ashley (1979) concluded, on the basis of oxygen and hydrogen isotopic data, that the mineralizing solutions were dominated by meteoric water.

Vikre (1989b) reported six separate stages of mineralization in the Sandstorm Kendall Ledge area approximately 2 km north of the main Goldfields district: 1) replacement quartz; 2) barite and sulphides (barite has not been reported from the main producing zone to the south); 3) quartz, pyrite, and barite; 4) quartz, barite, and kaolinite breccia; 5) vuggy quartz; and 6) lateral replacement quartz. Even though these veins are not within the main productive part of the district, they probably resulted from the same series of mineralizing events that produced the bonanza ores of the Goldfields area. Gold occurs as inclusions in famatinite, luzonite and barite in stage 2 and in barite and quartz in stage 4. Vikre (1989b) reported fluid inclusion homogenization temperatures in quartz and barite from 292°C to 100°C and salinities of 0.2-7.9 wt.% NaCl equivalent. Based on fluid isotopic compositions and salinities, Vikre (1989b) concluded that the mineralizing solutions contained contributions from pre-Miocene formation water, meteoric water, and magmatic water.

Sleeper Deposit

The Sleeper deposit is located approximately 45 km northwest of Winnemucca in northwestern Nevada on the east side of Desert Valley at the base of the Slumbering Hills. The geology, mineralogy and geochemistry of the deposit have been discussed previously by Wood (1988), Saunders *et al.* (1988), Saunders (1990) and Nash *et al.* (1991). The oldest rocks in the area consist of Mesozoic slates, phyllites and quartzites intruded by a granodiorite to monzonite Cretaceous stock. Unconformably overlying the Mesozoic rocks is a series of Tertiary volcanic rocks that can be divided roughly into three sequences based on origin and composition. The lower sequence consists of basaltic and andesitic flows and related dykes, andesitic to dacitic tuffs, and volcaniclastic sedimentary units capped by a basalt, dated at 16.1 Ma. The upper sequence consists of peralkaline rhyolite ash-flow tuffs, welded tuffs, and air-fall tuffs erupted from the McDermitt caldera system, 55 km to the north, between 15 and 16 Ma (Rytuba and McKee, 1984). A locally derived sequence of rhyolite porphyry dykes, domes and flows serves as the main ore host in the Sleeper deposit. Approximately 30 m of clay and silt, deposited during Pleistocene Lake Lahontan time, concealed the deposit.

The structure in the vicinity of the Sleeper deposit is very complex and consists of multiple sets of northwest- to northeast-striking, steep west-dipping faults of primarily normal displacement. Displacements along these faults are generally only a few metres. The present structure is dominated by north- to northeast-trending, west-dipping range-front normal faults related to Basin and Range development that separate the Slumbering Hills from the Desert Valley to the west. Some of these faults consist of zones 20 m wide with displacements of up to 100 m. These faults, and another set of northwest-striking normal faults, have broken the host rhyolites into a mosaic of blocks, resulting in both west- and east-dipping volcanic units.These two fault sets are post ore and therefore have also segmented the mineralized structures. The major Basin and Range faults have resulted in the deposit being down-dropped between 300 m and 600 m to the west (Nash *et al.*, 1991). The ore-bearing veins developed in west-dipping tensional fractures, with little displacement, that are subparallel to the range-front faults.

There are two distinct types of mineralization in the Sleeper deposit: high-grade relatively continuous banded quartz-gold-silver veins, and low-grade stockworks and breccia zones containing silver with small amounts of gold. The veins have a silver to gold ratio of less than one and carry most of the gold values in the deposit. They occur in a zone about 1200 m long and 450 m wide and are mineralized over a vertical extent of at least 500 m. The largest vein mined so far is the Sleeper Main Vein that has a strike length of nearly 1000 m and varies in width from <1 m to >5 m. It has been followed down dip for ~500 m. Bonanza zones within this vein average about 300 g Au/t. However, 6 m intercepts in drill holes have yielded more than 6000 g Au/t. Smaller, less extensive and lower grade veins occur parallel to the Sleeper Vein and as hanging wall splits off this main vein. The veins can be divided into three stages (Nash *et al.*, 1991), the first of which consists of multiple continuous bands of quartz, adularia, gold and electrum with minor amounts of carbonate and barite, and very small amounts of late argentite, miargyrite, tetrahedrite, silver selenides and tellurides, pyrite and rutile. This banded vein material locally is brecciated and cemented by second-stage quartz, electrum, silver selenides, sphalerite and fine-grained pyrite. The last stage is represented by veinlets and bands of coarse stibnite and quartz.

Breccia and stockwork ore occurs between closely spaced veins and in the hanging walls of major veins in intensely silicified rhyolite porphyry. This ore has silver to gold ratios from 6 to 10, and contains much more sulphide, up to 10%, than the veins. The breccias are fragment supported and are cemented by quartz and sulphides. Veinlets in the stockworks are generally only a few millimetres wide and contain quartz and sulphide. The relative timing of the main veins and breccia ore is equivocal. Nash *et al.* (1991) interpret the breccia ore to be related to an early pervasive silicification event. However, Utterback (unpublished) suggests the vein structures served as feeder systems to the breccias and stockworks.

The most common alteration observed at Sleeper is silicification. Pre-ore silica-pyrite alteration has affected large areas in the vicinity of the deposit. This has been superimposed by several stages and types of ore-stage silicification that range from intense replacement of rhyolite porphyry adjacent to veins and in breccias, to massive fracture fillings of opal spatially related to main stage veins. Late-stage opal occurring with alunite, kaolinite and jarosite, occupies post-ore fractures. Hypogene argillic alteration occurs in zones peripheral to early silicification and is usually barren. A sericite-pyrite-quartz assemblage occurs adjacent to adularia-bearing gold veins where it grades outward into kaolinite-bearing argillized silicified rock. Post-ore acid leaching has resulted in sponge-like material consisting of nearly all silica with all other constituents removed. Supergene alteration has resulted in the oxidation and local redistribution of gold in the upper parts of the Sleeper deposit.

Saunders (1990) and Nash *et al.* (1991) suggest the deeper portions of the Sleeper deposit may be similar to other epithermal systems hosted by volcanic rocks. However, based on textures, the abundance of opal, and the occurrence of gold and silica in nearly monomineralic bands, Saunders (1990) suggested that the silica and gold may in part have been transported into the upper parts of the deposit as colloidal species. Even though this may not be a unique occurrence, it does not generally fit into the physicochemical model proposed below. Rather, it represents non-equilibrium events probably superimposed on an epithermal system that are the result of rapid changes in the solution chemistry at depth. However, the finely banded textures of gold and silica imply that at the final site of deposition conditions were actually quite subdued.

Bodie-Aurora

The Bodie and Aurora districts are about 12 km apart and lie in the Bodie Hills, a northeast-trending topographic high that straddles the California-Nevada border just north of the Mono Lake depression. The rocks underlying the Bodie Hills consist of volcanic lithologies, mainly andesites, ranging in age from 15.4 Ma to 0.24 Ma, unconformably overlying Mesozoic granitic and metamorphic basement.

The geology and mineral deposits of the Bodie district have been described by Silberman (1985), Silberman and Berger (1985), and Herrera (1988). The deposits occur in the center of the Bodie Hills, where veins are hosted by 7.8-13.3 Ma andesitic to dacitic flows, tuffs, breccias and intrusive equivalents. In the main bonanza zone, the veins are spatially related to a small andesitic to dacitic intrusion. The veins range in width from <1 m to 30 m, and occupy north- to northeast-trending steeply dipping fractures. Crustiform textures, cross-cutting relationships, and multiple stages of brecciation indicate that ore deposition was a result of multiple hydrothermal events that occurred between 8.0 Ma and 7.1 Ma. Average ore grades in the bonanza veins were about 60 g Au/t and 100 g Ag/t. These veins consist mostly of quartz with smaller amounts of adularia, purite, argentite, sphalerite, native gold and native silver. Gold enrichment occurs in veins to a depth of about 200 m, below which base metal and silver sulphides and sulphosalts become more important. Near the surface and at shallow depths, silicification and fracture-controlled potassic alteration are overprinted and surrounded by argillization, resulting in a quartz-adularia-illite assemblage adjacent to veins. This assemblage is typical of the main bonanza veins. Peripheral to the productive area and at greater depths, the volcanic rocks have been pervasively propylitized. Based on fluid inclusion studies, temperatures of ore deposition and solution salinity were 215°-245°C and <0.5 wt.% NaCl equivalent, respectively. Such a solution would boil at a depth of about 400 m (Haas, 1971). Herrera (1988) documented the occurrence of sinters and explosion breccias in proximity to the veins, and concluded that ore deposition at Bodie occurred in a paleogeothermal center similar to many present-day hot spring systems. This suggests that the present-day surface is not too far below the paleosurface at the time of ore formation, and that the latter occurred at a rather shallow level, perhaps at or less than the depth of boiling.

The geology and mineral deposits of the Aurora district have been described by Osborne (1987) and Dorff (1988). The host rocks consist of andesite agglomerates and flows, dated at 13.5-15.4 Ma, overlying Mesozoic basement. Altered rhyolite domes, dated at 11.0 Ma, occur in the vicinity of the mineralized veins, the latter having an age of about 10.3 Ma. Bonanza orebodies developed where movement along major intersecting northeast- and north-trending steeply dipping fractures produced dilation zones within the faults. The resultant veins are 1-12 m wide within an ore-bearing horizon that extends from the present surface to a depth of about 150 m. Fragments of wallrock andesite occur in the veins, and veinlets and stockworks extend into brecciated andesite. Some of this stockwork material may be very high grade, locally as high as 500 g Au/t, with ore shoots averaging 60 g Au/t. Productive veins consist of massive fine-grained multiple-banded quartz and adularia with variable amounts of chlorite, pyrite, calcite, electrum, acanthite, naumannite (Ag_2Se), barite and bromargyrite (AgBr), the latter probably a product of supergene oxidation. At shallow levels, the veins are bounded by a quartz-illite-montmorillonite alteration halo that locally may contain adularia or kaolinite. This grades outward into a propylitic assemblage containing the assemblage albite-quartz-illite-chlorite-montmorillonite-calcite. At deeper levels, quartz-albite-adularia-illite grades outward to quartz-albite-adularia-chlorite ± pyrite. A few homogenization temperatures from ore-stage quartz yield an average of 240°-250°C (Osborne, 1987).

Tayoltita, Mexico

The Tayoltita silver-gold deposit is located 150 km west of the city of Durango in west-central Mexico. The geology and geochemistry of the deposit have been discussed by Smith *et al.* (1982), and the following summary is taken from their paper. Even though the deposit is primarily a silver producer, it has also yielded significant amounts of gold from relatively high-grade veins (Table 1). Regionally, the host rocks belong to the Sierra Madre Occidental volcanic pile, consisting of more than 3000 m of andesitic to rhyolitic flows and ash flow tuffs. These are intruded by coeval igneous rocks that are part of the large composite granite to granodiorite Sinaloa batholith that ranges in age from 100 to 45 Ma. The basement consists of Cretaceous and early Tertiary sedimentary, volcanic, and intrusive rocks. The earlier volcanic series is overlain by more than 2500 m of post-ore rhyolite, latite, dacite and andesite lavas and ignimbrites and related volcaniclastic rocks, ranging in age from 32 Ma to 23 Ma.

Locally, the ore deposits are spatially and genetically related to the 45 Ma andesitic Candelaria stock, and veins occur within the stock and in an adjacent, 750 m-thick andesite. At the time of mineralization, the host lavas were essentially horizontal, and ore deposition occurred along a 600 m-thick favourable horizon parallel to the untilted volcanic units. However, post-ore normal faulting has resulted in the tilting of all rocks about 35° to the east. Veins range in width from < 1 m to > 25 m, occupy east- to northeast-trending fractures, and occur as complex braided systems of cymoid loops. The veins are banded and crustified. Open-space filling is the most common mode of ore deposition. Replacement of wall rock and early vein stages also occurs. The mineralization can be divided into three stages, and the most abundant mineral in all three is quartz. Base and precious metals occur in all three stages also. However, stage two contains the bulk of the economic mineralization and the bonanza orebodies. The latter consist of pyrite, base metal sulphides, silver sulphide and sulphosalts, and electrum in a gangue of quartz, chlorite, adularia and manganese silicates. Major quartz introduction during stage three followed a period of brecciation of the earlier veins, resulting in the dilution of grades produced during stage two. Hydrothermal alteration consists of pervasive propylitization and chloritization of the andesitic volcanic rocks superimposed by zoned assemblages related to vein development. Silicification occurring close to the veins grades outward into chloritized and epidotized rocks, and finally, into the propylitized rocks. Locally, quartz-sericite-pyrite alteration occurs adjacent to some of the veins.

The grade of ore averages more than 600 g Ag/t and 12 g Au/t. The highest grades occur at vein intersections and in cymoid loops that appear to have served as major through-going channels for the upward-migration of the mineralizing solutions. The highest grades were found in the Arana vein, from which more than one million tonnes of ore were produced, averaging 785 g Ag/t and 15 g Au/t. Small high-grade pods, ranging in width from 0.1 m to 25 m, and averaging 3 m, occurred within the quartz veins. Geochemical studies by Smith *et al.* (1982) yielded fluid inclusion homogenization temperatures for stages two and three of 250°-310°C, and salinity values of 2-10 wt. % NaCl equivalent. Based on the evidence for boiling in stage three, together with temperature and salinity values, they estimated the depth to the top of the horizon of deposition to be about 400 m. In addition, oxygen isotopic studies for stages two and three suggest the mineralizing solutions were dominated by meteoric water.

El Indio, Chile

The El Indio and adjacent Tambo gold deposits are located 470 km north of Santiago and 180 km east of La Serena in the Chilean Andes Mountains at an elevation between 4000 m and 4400 m. The following summary of the geology of the deposits has been taken from Walthier *et al.* (1985) and Siddeley and Araneda (1986). The deposits are hosted by fractured and altered dacite porphyry that was emplaced at 10.7 Ma during a long and complex history of Tertiary volcanism along the northern Chilean Andean mountain chain. The basement in the area consists of upper Paleozoic to Triassic granitic to granodiorite batholiths, schists and sedimentary rocks overlain by Jurassic and Cretaceous andesitic volcanic rocks. Two periods of volcanism, between 27 Ma and 16 Ma, and between 16 Ma and 11 Ma, resulted in the overlying extensive andesitic to basaltic lavas, agglomerates and subvolcanic intrusions that constitute the Andean chain. The mineral deposits are associated with locally erupted rhyolitic to dacitic pyroclastic rocks of age 11.4-8.2 Ma. The age of the mineralization is about 8.6 Ma.

At El Indio, the ore is structurally controlled by two steep subparallel northeast-striking, northwest-dipping faults and cymoid loops that developed between these bounding structures. Two vein types occur: massive enargite-pyrite veins that are concentrated within the cymoid loops, and superimposed quartz-gold veins occurring within the bounding fault zones. Although the bulk of the ore occurs as the massive sulphide veins, the high-grade bonanza ores occur within the quartz-gold veins. The grades in the former are 6-12% Cu, 4-10 g Au/t, and 60-120 g Ag/t. The highest-grade vein is the Indio Sur 3500 that follows the Inca Sur fault, the southern northeast-trending bounding fracture zone. This vein is about 200 m long, 0.5-6 m wide, extends to a depth of at least 270 m, and has a steep rake to the northeast. It is zoned outward from a central high-grade core 50 m long and 0.5-2 m wide, averaging

250 g Au/t, surrounded by a lower grade quartz-gold ore averaging about 16 g Au/t. Individual lenses within the bonanza core exceed 1000 g Au/t. This vein alone will produce about 40 tonnes of gold. The bonanza ore averages about 110 g Ag/t and 3.7% Cu, although there appears to be an increase in copper content with depth. Other less productive bonanza veins occur within both the north- and south-bounding fault zones.

In the primary ores, gold occurs mostly in the native state as fine, less than 30 μm, particles. Minor to trace amounts of gold and silver tellurides occur in the quartz-gold veins. Silver occurs in the native state, in tetrahedrite-tennantite and as stromeyerite in the massive sulphide veins, and as tellurides in the quartz-gold veins. The most important copper mineral in all ores is enargite; however, small amounts of chalcopyrite, tetrahedrite-tennantite, famatinite, covellite and other sulphides and sulphosalts also occur. With depth, enargite appears to give way to chalcopyrite, tetrahedrite-tennantite, and other copper antimony sulphosalts. Gangue consists mostly of multiple stages of quartz and pyrite, and very small amounts of sphalerite and galena. The most important alteration associated with the veins is silicification. This grades outward into pervasive argillic alteration of the dacite porphyry host rocks, resulting in the conversion of feldspar to kaolinite, sericite, pyrophyllite and montmorillonite. Propylitic alteration is found in the underlying andesite and appears to be due to a widespread event not necessarily related to ore deposition. Late hypogene sulphate alteration has resulted in the formation of widespread deposits of alunite, jarosite, and barite and local alunite-native sulphur sinters. The large volume of sulphate, sulphide, and native sulphur present in the vicinity of the El Indio deposits suggested to Siddeley and Araneda (1986) that the hydrothermal system responsible for ore deposition was very high in sulphur.

Summary

The deposits described above serve as examples of bonanza deposits where unusually high concentrations of gold were locally deposited in structurally favourable zones. The geologic and geochemical characteristics exhibited by these deposits are strikingly similar to those observed in any number of lower grade volcanic rock-hosted precious metal deposits around the world. Therefore, the bonanza deposits do not represent a geologically or geochemically distinct type, but belong to a group where the principal distinguishing characteristic is that they produced a large tonnage of gold from a relatively small amount of ore.

THE MODEL

Two main conditions are required to form a high-grade bonanza gold deposit. The first is a well-developed fracture system of sufficient extent in time and space to allow large volumes of mineralizing solution to pass through. The second is the existence of physicochemical gradients, relatively well fixed in space and superimposed on the favourable structural zone, that will promote the efficient precipitation of metals over a significant length of time. The only differences between these bonanza orebodies and less spectacular vein and disseminated ores of lesser grade are the rate and duration of fluid flow, the degree to which the solutions have been focussed along a few well-developed channels, and the steepness of the physicochemical gradients (such as temperature and sulphur activity) responsible for the concentration of gold. Favourable structural environments will form in felsic volcanic rocks undergoing tensional stress at or near the surface because of their tendency toward brittle fracture. The result will be open, through-going and upward-branching fractures, rather than the stockworks formed in less competent lithologies or at greater depths. Fracture permeability in such shallow crustal environments will be perpetuated and enhanced by episodic hydrothermal brecciation (Nelson and Giles, 1985). Crustiform and banded textures in many bonanza ores attest to the long period of time that these systems were open.

An important characteristic of bonanza deposits that places physicochemical constraints on their conditions of formation is the large-scale introduction of silica as both silicification of host rocks and quartz gangue in the veins and breccias. Large volumes of rock have been converted to up to 90% silica, accompanied by small amounts of aluminosilicate alteration minerals and sulphides. This silicification is an important ground preparation event whereby the resultant competent rock enhances the tendency for brittle fracturing that is required for maintaining the open fractures for the deposition of bonanza quantities of gold. According to Fournier (1985), in low-pressure shallow environments typical of epithermal deposits, the only plausible mechanism for the precipitation of silica is temperature decrease. However, sparse thermometric data suggest that temperature gradients within the environment of bonanza deposit formation are no more than about 25°C at any particular time (Vikre, 1989a). In systems where phase separation, or boiling, occurs, significant amounts of silica will be deposited because of the decrease in the mass fraction of liquid water (Cline *et al.*, 1987). However, during some geochemical studies on fluid inclusions from bonanza deposits (Brake, 1989), no evidence is found for a separate vapour phase being present at the time of trapping.

Based on a summary of geochemical data gathered from bonanza deposits, the mineralizing solutions had temperatures between 250°C and 300°C and salinities of 3 wt.% NaCl equivalent or less. The solutions evolved from deep circulating meteoric water heated by magmas at depth, although in some high-sulphur systems some of the water may have a magmatic origin. The sulphur content of the solutions was probably between 100 and 1000 parts per million (ppm) and was reduced so that H_2S was the dominant sulphur species. The source of at least some, if not all, the sulphide was the disproportion of magmatic SO_2 (Stoffregen, 1987; Rye *et al.*, 1989). Because of the common association of gold with pyrite, the solutions had to be of a composition that was in equilibrium with this mineral. The pH of the solutions was probably within the range of one unit on either side of neutrality, although diverse alteration assemblages suggest the pH may have varied significantly. The occurrence of sulphates in some deposits suggests oxygen fugacity conditions were probably close to the sulphide-sulphate boundary. The solutions were saturated with silica and transported between 1 and 10 parts per billion (ppb) gold (Brown, 1986; Romberger, 1990). Bonanza orebodies usually occur as high-grade zones within larger lower grade deposits. Therefore, they probably do not result from solutions with significantly higher amounts of gold than those responsible for the mineral deposit as a whole. More likely, bonanza orebodies form as a result of greater fluid flow through a favourable structural zone and/or more efficient precipitation of gold along steeper physicochemical gradients.

Using the average temperature and composition postulated for the hydrothermal solutions responsible for the formation of bonanza deposits, along with the associated mineral assemblages, it is possible to determine the physicochemical conditions under which the ores were deposited. Given these, it is possible to predict the mechanisms for gold deposition. Figure 2 shows the solubility of gold as a function of temperature and oxygen fugacity at pH 5 in solutions containing 3 wt.% NaCl and 320 ppm sulphur (0.01 molal) superimposed on the stability relationships for iron sulphide and oxide minerals. The conditions under which the activities of sulphate and H_2S are equal are shown as a light dot-dashed curve. To the lower right of this boundary, H_2S will predominate and the solutions will be reduced, whereas to the upper left, sulphate predominates and solutions will be oxidized. The stippled area represents the physicochemical composition of the postulated average mineralizing solutions. The gold bisulphide solubility contours, shown as heavy solid lines, indicate that the maximum solubility of gold occurs along the sulphate-H_2S boundary within the field of stability of pyrite. Note that if gold concentrations of between 1 and 10 ppb are typical for mineralizing solutions, these solutions may be undersaturated in gold. However, the contours in the oxidized region show a steep solubility surface where the solubility decreases rapidly with decreasing temperature. The solubility of gold decreases about five orders of magnitude over a 25°C decrease in temperature, which is equivalent to an increase in oxygen fugacity of about one order of magnitude.

The grades of gold formed as a result of cooling of a silica-saturated hydrothermal solution are constrained by the amount of silica precipitated. Shown in Figure 2 is the solubility of silica as a function of temperature, using the data of Fournier (1985). In the temperature range between 250°C and 300°C, a 25° drop would result in the deposition of about 100 ppm silica if the solution is saturated with respect to quartz. The same temperature change will result in the nearly complete precipitation of gold from solution. If the hydrothermal solution starts out with about 2 ppb Au, 20 grams of gold will be deposited for each tonne of silica precipitated over this 25° decrease. Assuming 25% silica is added to the rock during the formation of an ore deposit, the grades will be limited to 5 g Au/t of ore if cooling is the only mechanism for deposition. High permeabilities typical of intensely brecciated rock or open fractures would allow more silica to be introduced, thus allowing higher gold grades. Also, higher initial gold concentrations in solution will have the same effect. If 50% silica is added, or the mineralizing solution contained 4 ppb Au, grades could reach 10 g Au/t.

Many bonanza deposits locally contain grades of at least 100 g Au/t, and some reach 1000 g Au/t. It is unlikely that the solutions contain more than about 10 ppb Au (Brown, 1986). Therefore, although cooling can explain the deposition of quartz and some gold, it is apparent that some other process must be occurring to result in the deposition of these large amounts of gold. Romberger (1988a) reviewed the mechanisms of gold precipitation, and suggested that oxidation and decrease in H_2S activity were important. Boiling and solution mixing are among the processes occurring in hydrothermal systems that result in these changes. Large amounts of banded adularia, ±calcite, with quartz, suggest that boiling has occurred in many systems. Only a one or two order of magnitude increase in oxygen fugacity is required to precipitate nearly all the gold in solution. A loss of half the H_2S in solution, either by oxidation or by boiling, can result in the deposition of two-thirds of the gold if the solution is saturated with respect to gold. Drummond and Ohmoto (1985) concluded that the decrease in H_2S activity was more efficient than oxidation in precipitating gold in a boiling hydrothermal system. An additional process that will result in the decrease in H_2S activity is the deposition of sulphides that precipitate as a result of either cooling or pH increase. Gold is associated with sulphides in many epithermal deposits, most commonly pyrite. However, there does not appear to be a direct relationship between the abundance of sulphides and gold grade in bonanza deposits. In fact, the highest grades commonly occur in quartz veins containing only minor sulphides.

Gold will be most readily deposited from solution by one or more of the mechanisms of oxidation, decrease in temperature, and decrease in H_2S activity. These physicochemical changes will be brought about by boiling of the hydrothermal transporting solution or mixing of the latter with shallow, cooler, more oxygenated ground waters. In order to get bonanza grade deposits, these processes must occur in a structurally confined environment, and the gradients in the above physicochemical parameters must be steep enough to efficiently precipitate the gold over a long time period. Figure 3 is a schematic diagram showing the structural geometry of a bonanza system that is recharged from below along well-defined channels. The model assumes that boiling and/or solution mixing will occur within a restricted zone of brecciated or otherwise fractured host rock. The selected parameters for the recharging solution are 250°C, 3 wt.% NaCl, and silica saturated. Such a solution will boil at a depth of approximately 450 m under hydrostatic conditions (Haas, 1971). In most systems, the depth of boiling will vary, depending on the rate of recharge, dissolved gas content, and the depth to the water table.

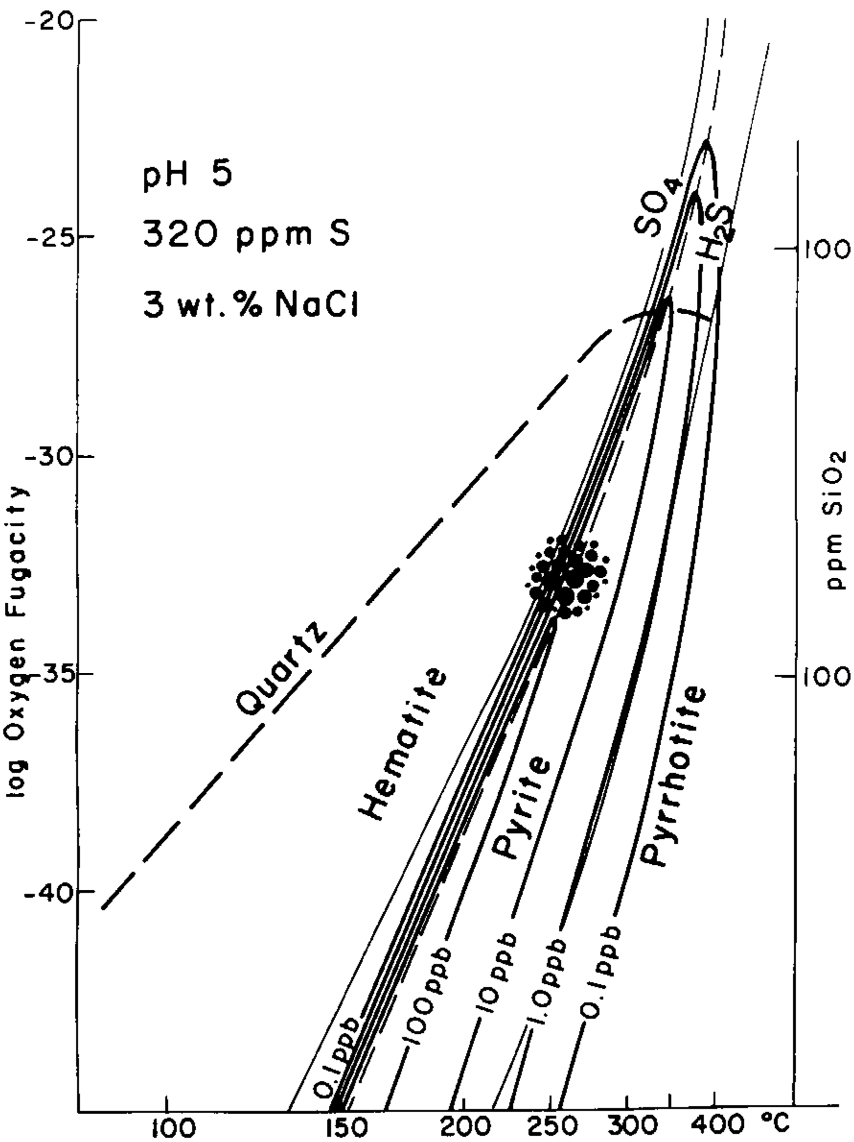


Figure 2 *Aqueous solubility of gold and silica as a function of temperature and oxygen activity at pH 5 in solutions containing 320 ppm sulphur (0.01 molal) and 3 wt.% NaCl (0.5 molal). Heavy solid lines are for gold bisulfide complexes calculated from the data of Shenberger and Barnes (1989) and heavy dashed line is for quartz solubility from Fournier (1985). The boundary between the aqueous sulphate and sulphide fields is shown as a fine dashed line. Fine solid lines show the boundaries between iron oxides and sulfides.*

In addition, the system will periodically seal itself by silica deposition, so the solution will experience confining pressures greater than hydrostatic at times, resulting in the variation in the depth of boiling. However, in order to create a bonanza orebody, conditions must be such that this depth of boiling is kept relatively constant if boiling is the primary cause for deposition, suggesting a sustained period of hydrostatic pressure had existed. This implies that in a boiling system, the major structures within a deposit in which hydrostatic pressure in open spaces is maintained for an extended length of time will most likely be the sites for bonanza ores to form. Oxygenated near-surface ground water may recharge into the site of deposition along subsidiary hanging wall fracture zones, provided the overall hydrologic system allows for discharge along major fractures, as shown. Mixing of these near-surface waters with the rising mineral transporting solutions will have the same effect as boiling on temperature, oxygen fugacity, and H_2S activity. The inset on the diagram shows the change in these parameters, as well as gold and silica concentration at the site of deposition.

Bonanza ore zones in many gold deposits contain on the order of 50-100 g Au/t. Assuming a gold content in the transporting solution of about 2 ppb, 32×10^6 L would be required to introduce 75 g Au into each tonne of host rock. To form a one million tonne orebody of this grade would require 32×10^{12} L of solution to discharge through the zone of deposition, if nearly all the dissolved gold is deposited. Silberman (1985) estimated that for precious metal vein deposits, hydrothermal activity lasts for periods of 0.5-1.5 m.y. Selecting an average value of approximately one million years results in an annual discharge through the bonanza host structures of approximately 32×10^6 L per year, or just more than 1 $L \cdot s^{-1}$. This is a low discharge rate, and much less than those for active hot spring systems in which gold has been found to precipitate. For example, White (1968) estimated the discharge for Steamboat Springs, Nevada to be approximately 70 $L \cdot s^{-1}$. The Champagne Pool at Waiotapu, New Zealand has an estimated discharge of 10 $L \cdot s^{-1}$, and the discharge of the entire Waiotapu field is about 440 $L \cdot s^{-1}$ (Henley, 1985).

Bonanza ore zones constitute only a small portion of the total ore deposit, and conditions for bonanza ore formation may occur for only a short time within the total life of the hydrothermal system. If this period of time is as brief as 100,000 years, discharge rates would be about 10 $L \cdot s^{-1}$. In addition, crustiform textures and banded ores suggest mineral precipitation is episodic, so it can be assumed that discharge rates will be variable as well. These low flow rates do suggest that the length of time during which mineralizing solutions flow through a favourable structural zone, and the efficiency of precipitation mechanisms, controlled by physicochemical gradients, are more important than the actual fluid discharge, or the concentration of gold in solution, in controlling the formation of bonanza orebodies.

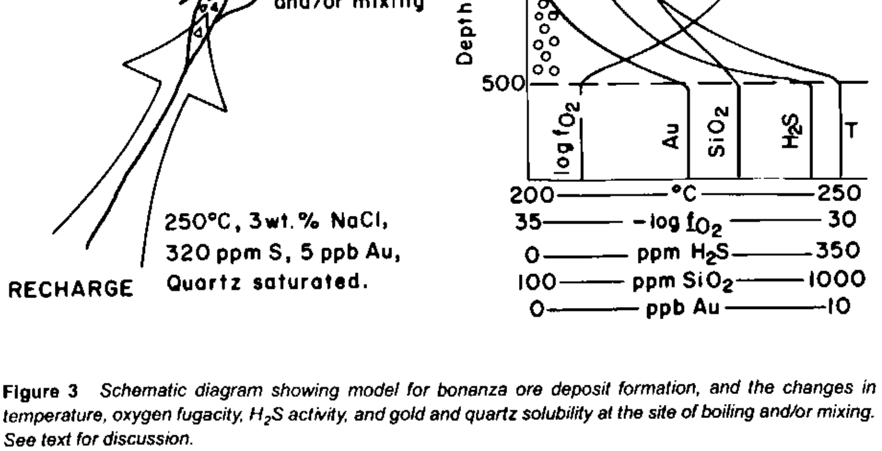


Figure 3 *Schematic diagram showing model for bonanza ore deposit formation, and the changes in temperature, oxygen fugacity, H_2S activity, and gold and quartz solubility at the site of boiling and/or mixing. See text for discussion.*

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