# SEDIMENT-HOSTED AU DEPOSITS
# (MODEL 26a; Berger, 1986)

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## SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Carlin-type deposits are epigenetic, large-tonnage, low-grade, sediment-hosted disseminated gold deposits. The deposits are known mainly in northern Nevada and northwestern Utah where they are arranged in clusters and belts. The deposits in this region are estimated to contain about 5,000 tonnes of gold, more than half of which (~3100 tonnes) is in the Carlin Trend. Approximately 1,000 tonnes of gold have been produced. Carlin-type gold deposits are one of the most important types currently being mined in the western United States.

Many aspects of this geoenvironmental model also apply to distal disseminated deposits as defined by Cox and Singer (1990), Doebrich and Theodore (in press), and Howe and others (1995).

### Deposit geology

Unoxidized refractory ore: Refractory ore consists of variably decalcified, dedolomitized, argillized, silicified, sulfidized, carbonaceous sedimentary rocks that contain disseminated iron, arsenic, antimony, mercury, and thallium sulfide minerals. Base-metal sulfide minerals are rare or absent in most deposits. Although pyrite, marcasite, orpiment, and realgar have high acid-generating capacity, they generally are present in small amounts (much less than 5 volume percent) and are usually disseminated in, or surrounded by, carbonate rocks with high acid-consuming capacity. Zones with 5-50 volume percent pyrite, marcasite, orpiment, or realgar are present in some deposits. Ore is refractory because much of the gold forms sub-micron grains in pyrite and marcasite and because carbon in the rock can extract gold from cyanide solutions.

Oxide ore: Natural weathering and oxidation of refractory ore cause formation of oxide ore (with low sulfide mineral and carbon contents) from which gold is recovered by cyanide heap leaching. Acid generating capacity of the surrounding carbonate rocks is low or nil, and their acid consuming capacity is high.

Jasperoid ore: Jasperoid ore is similar to refractory ore but is strongly silicified and usually lacks orpiment and realgar. Its acid-generating capacity is moderately high due to disseminated pyrite and marcasite and its acid-consuming capacity is low due to lack of carbonate minerals; however, jasperoids are usually surrounded by carbonate rocks with high acid-consuming capacity. Jasperoids are brittle and often highly fractured, which enhances permeability; in many places, they are weathered and oxidized to great depths, >300 m in a few instances, whereas surrounding rocks are generally oxidized to shallower depths. Some poorly developed jasperoid or partly silicified rocks have abundant, well-developed porosity in and near some of the largest Carlin-type systems in Nevada. Rocks adjacent to oxidized jasperoids are usually decalcified and argillized due to acid attack by supergene fluids.

### Examples

The following deposits are in Nevada, unless otherwise noted: Carlin, Cortez, Getchell, Gold Acres, Gold Quarry, Jerritt Canyon, Alligator Ridge, Post-Betze, Rain, Twin Creeks, Meikle, Mercur (Utah), Ratatotok (Indonesia?), and deposits in Guizhou and Guangxi Provinces (China ?).

### Spatially and (or) genetically related deposit types

Carlin-type deposits show no clear genetic relationship to other types of ore deposits. Locally, they may be present in the vicinity of volcanic-hosted precious metal deposits, epizonal pluton-related porphyry, skarn, manto, or vein deposits, syngenetic base-metal or barite deposits, or epithermal quartz-stibnite-barite veins.

### Potential environmental considerations

Relative to other mineral deposit types, sediment-hosted gold deposits have relatively low potential for associated environmental concerns, especially in light of their large size. Mining activity predominantly exploits oxidized ore with negligible acid generating and high acid consuming capacities. Refractory ore is processed in mills, and its waste is collected in closely monitored tailings ponds. Environmental mitigation commonly emphasizes isolation of sulfide-mineral-rich rocks (refractory ore stockpiles) with low acid consuming capacity from weathering and oxidation. Commonly, rocks with the greatest acid generation potential and highest base-metal concentrations are unrelated to the gold deposits and coincidentally are present in the mine area. Waste rock with high acid generating and low acid consuming capacities or high base-metal concentrations is isolated from weathering and oxidation and (or) mixed with or encased in calcareous waste rock.

Because natural ground water associated with these deposits can have elevated concentrations of Fe, Mn, As, Sb, Tl, Hg, Se, W, ± base metals, water produced from dewatering wells may require treatment to decrease concentrations of these elements, and to decrease abundances of suspended sediment. The large size and depth of some deposits requires dewatering large volumes of rock, on the order of 0.1 to 1.0 $km^3$ for some deposits or clusters of deposits. Substantial amounts of water, some of which is used to grow alfalfa in Nevada, are produced during mining. The temperature of ground water produced from some deposits is higher than ambient temperatures, which increases its metal transport capability.

In comparison to other deposit types, potential downstream and offsite environmental effects are of relatively limited magnitude and spatial extent; however, surface and groundwater may include elevated concentrations of one or more of the elements As, Sb, Tl, Hg, Se, W, ± base metals. Vegetation such as sagebrush and grasses may accumulate arsenic and other elements.

Dust generated by open pit mining refractory ore, which contains elevated concentrations of sulfur, arsenic, and other elements, may be transported downwind from the mine.

### Exploration geophysics

Satellite and airborne multispectral data are helpful in defining major lithologic boundaries, structural zones, and areas of hydrothermal alteration (Rowan and Wetlaufer, 1981; Kruse and others, 1988). Airborne magnetic and electromagnetic surveys can be used to delineate intrusive contacts, rock units and faults, and detect alteration (Grauch, 1988; Taylor, 1990; Grauch and Bankey, 1991; Hoover and others, 1991; Pierce and Hoover, 1991; Wojniak and Hoover, 1991).

### References

Joraleman (1951), Erickson and others (1964), Erickson and others (1966), Hausen and Kerr (1968), Wells and others (1969), Wells and Mullins (1973), Radtke and others (1980), Bagby and Berger (1985), Rye (1985), Bakken and Einaudi (1986), Romberger (1986), Tafuri (1987), Cunningham and others (1988), Holland and others (1988), Bakken and others (1989), Kuehn (1989), Berger and Bagby (1990), Ilchik (1990), Leventhal and Hofstra (1990), Massinter (1990), Nelson (1990), Hofstra and others (1991), Kuehn and Rose (1992), Arehart and others (1993a,b), Maher and others (1993), Christensen (1994), Albino (1994), Hofstra (1994), Turner and others (1994), and Doebrich and Theodore (in press).

## GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

### Deposit size

Deposits are small (100,000 metric tonnes) to large (200,000,000 metric tonnes). Grades range from 1 to 20 gm Au/t. Contained gold ranges from 1,500 Kg (50,000 oz) to 930,000 Kg (30,000,000 oz; Post-Betze, Nev).

### Host rocks

Calcareous or dolomitic sedimentary rocks are the dominant host rocks for this deposit type. Ore may also be hosted by siliceous sedimentary rocks or igneous rocks.

### Surrounding geologic terrane

Most deposits are hosted in Paleozoic and to a lesser extent Mesozoic miogeoclinal and eugeoclinal sedimentary rocks. Jurassic to Late Eocene calc-alkalic plutons and Eocene to Recent fluvial, lacustrine and volcanic rocks are present locally. Carlin-type deposits in Nevada and Utah are approximately coeval and cospatial with a late Eocene volcanic field, although a one-to-one spatial correspondence between the deposits and volcanic centers or plutons is absent.

### Wall-rock alteration

Refractory ore: Alteration associated with refractory ore reflects progressive reaction of moderately acidic $CO_2$- and $H_2S$-rich ore fluids (pH 4 to 5) with carbonate host rocks. Inner zone-- decalcified, ± dedolomitized, ± argillized, ± silicified, and sulfidized. Realgar and (or) orpiment are locally present. Narrow zones that consist predominantly of iron and (or) arsenic sulfide minerals are present in some deposits. Intermediate zone-- dolomite stable, 2m1 mica stable, partially to completely decalcified, sulfidized, ± realgar/orpiment. Outer zone-- calcite stable, sulfidized. Jasperoid: Silicification reflects combined effects of cooling and reaction with carbonate host rocks. Boundary with unaltered carbonate rocks is gradational but very abrupt. Jasperoids are above, below, beside, or within refractory ore zones.

Typical sulfide-mineral sulfur concentrations are <5 weight percent in refractory ore. Sulfidized and argillized intermediate to mafic igneous rocks have sulfide-mineral sulfur concentrations >10 weight percent and therefore have high acid generating and relatively low acid consuming capacities. Some deposits contain narrow zones with 10 to 50 volume percent realgar and (or) orpiment enclosed by decalcified rock that has high acid generating and low to moderate acid consuming capacities. Oxide ore is a product of supergene weathering of refractory ore and jasperoid and generally has sulfide mineral concentrations <1 volume percent.

### Nature of ore

Refractory ore: Most gold resides in trace-element-rich pyrite and marcasite as sub-micron blebs. Arsenic is the major trace element in pyrite and (or) marcasite followed in decreasing abundance by antimony, thallium, and mercury. Gold also resides in orpiment, realgar, and cinnabar, on the surface of clay minerals, in or on organic carbon, and in or on quartz.

Oxide ore: Gold is present as free gold, resides in iron oxide minerals or quartz, and is adsorbed on clay minerals.

### Deposit trace element geochemistry

These deposits exhibit a characteristic suite of trace elements, including silver, arsenic, antimony, mercury, thallium, and barium ± tungsten ± selenium, whose abundances are elevated.

### Ore and gangue mineralogy and zonation

Minerals listed in decreasing order of abundance. Acid-generating minerals underlined. Barite is present locally.

Inner refractory ore: Quartz, ± dolomite, 2m1 mica, pyrite, marcasite, orpiment, realgar, kaolinite, illite/smectite.

Outer refractory ore: Calcite, dolomite, quartz, 2m1 mica, pyrite, marcasite.

Oxide ore: Calcite, dolomite, quartz, 2m1 mica, limonite/goethite/hematite, kaolinite, illite/smectite, relict pyrite.

### Mineral characteristics

Pyrite/marcasite and arsenopyrite generally replace iron-bearing minerals and form disseminations in host rocks; they are generally fine grained and 1 mm to 1 micron in size. Late botryoidal pyrite/marcasite is present in some deposits. Most orpiment, realgar, stibnite, cinnabar, and barite are in open space along fractures and in breccias.

### Secondary mineralogy

Supergene minerals include travertine, goethite, limonite, hematite, alunite, kaolinite, stibiconite, scorodite, gypsum, celestite, and phosphate minerals. Small amounts of melanterite precipitate where ground water has evaporated from mine faces in open pits.

### Topography, physiography

In the Basin and Range Province of Nevada and Utah, sediment-hosted gold deposits are present at elevations between 3,000 and 1,200 m, from the crest of mountain ranges to valley margins; some are concealed by pediment gravels or alluvial valley fill. Jasperoids are resistant to erosion and commonly form bold outcrops. Because of alteration and the presence of sulfide minerals, refractory ore zones are generally more easily eroded than unaltered rocks.

### Hydrology

Jasperoids are usually fractured, and therefore highly permeable, and can focus flow of oxidized ground water to great depth. Decalcified refractory ore is usually porous and permeable; rocks within and above these zones are commonly fractured or brecciated due to volume losses associated with alteration. Faults and fractures also serve as conduits for ground water flow. Brittle siliceous rocks (chert, siltite, quartz arenite) are commonly fractured, permeable, and focus ground water flow. Karst cavities and breccias, that also focus ground water flow, are present in some deposits; karst may have developed at several times between the Paleozoic and Tertiary.

Position of the water table: Water table elevation relative to the deposits has a dramatic effect on the acid generating capacity of ore. For instance, the current water table at one deposit is at a depth of ~60 m. However, associated wall rock is oxidized to a depth of ~200 m, which suggests that the paleo-water table previously extended to much greater depth. Consequently, present-day ground water is neutral to alkaline and contains low trace metal abundances. Mining this ore has little impact on water quality because the rocks are already oxidized. In contrast, mining unoxidized ore associated with many sediment-hosted gold deposits entails significant potential for

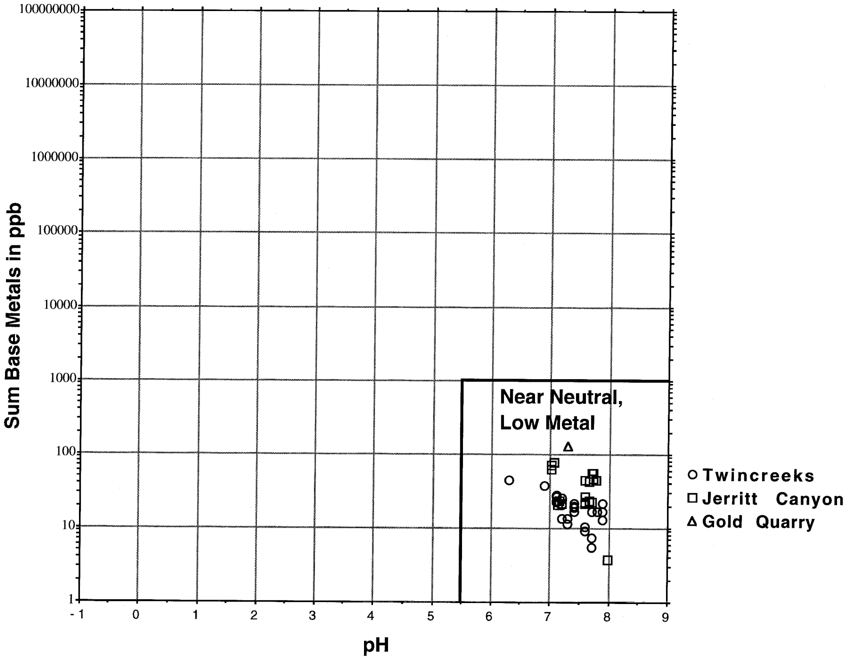

**Figure 1.** Ficklin plot (Ficklin and others, 1992) showing composition of natural ground water from Twin Creeks, Jerritt Canyon, and Gold Quarry, Nev., mines. All data plot within the "near neutral-low metal field."

environmental degradation. However, the overall potential for undesirable environmental impact associated with mining Carlin-type deposits is small compared to effects associated with other deposit types because these deposits have low base-metal contents and high host-rock, acid-consuming potential.

Deposits above the water table, but hosted by thick sequences of carbonaceous, pyritic, shaley eugeoclinal rocks are relatively unoxidized compared to those hosted by less carbonaceous, less pyritic calcareous miogeoclinal rocks. The eugeoclinal rocks apparently consume oxygen in descending ground water before the water table is reached.

Data for the Twin Creeks, Nev., deposit (Grimes and others, 1994; 1995) show that natural ground water, under reducing conditions below the water table, in refractory ore zones has the highest concentrations of arsenic, antimony, tungsten, manganese, iron and possibly thallium and selenium. These elements are concentrated in iron and manganese precipitates under oxidizing conditions at or above the water table.

### Mining and milling methods

Historic: Oxide ore was produced from open pit mines and processed by cyanide heap leach solutions that potentially may have leaked into ground water. Refractory ore was generally avoided or stockpiled.

Modern: Oxide and refractory ore are produced from open pit and underground mines; oxide ore is processed by cyanide heap leaching. Refractory ore is oxidized using one, or a combination, of the following methods: biologic oxidation, chlorination, pressure oxidation (autoclave), or roasting. Gold is subsequently stripped from the cyanide solutions using activated carbon.

## ENVIRONMENTAL SIGNATURES

### Drainage signatures

The U.S. Environmental Protection Agency (EPA) chronic criteria freshwater standards most likely to be exceeded are 5.2 μg/l cyanide, 190 μg/l arsenic, 5 μg/l selenium, 0.012 μg/l mercury, 30 μg/l antimony (proposed standard), and 40 μg/l thallium (proposed standard). Tungsten abundances are likely to be anomalous, although no freshwater standard has been defined. In some deposits, elevated base-metal concentrations may pose a problem. The standards for these elements are as follows: 0.12 μg/l silver, 12 μg/l copper, 3.2 μg/l lead, 110 μg/l zinc, 1.1 μg/l cadmium, 210 μg/l chromium[III], 11 μg/l chromium[VI], and 160 μg/l nickel).

Mine drainage data: More work is needed to obtain and synthesize available data.

Natural stream/spring drainage data: More work is needed to obtain and synthesize available data.

Natural ground water data: Chemical analyses of natural ground water from the Twin Creeks, Jerritt Canyon and Gold Quarry, Nev., mines are shown on figures 1-2. Using the classification scheme of Ficklin and others (1992),

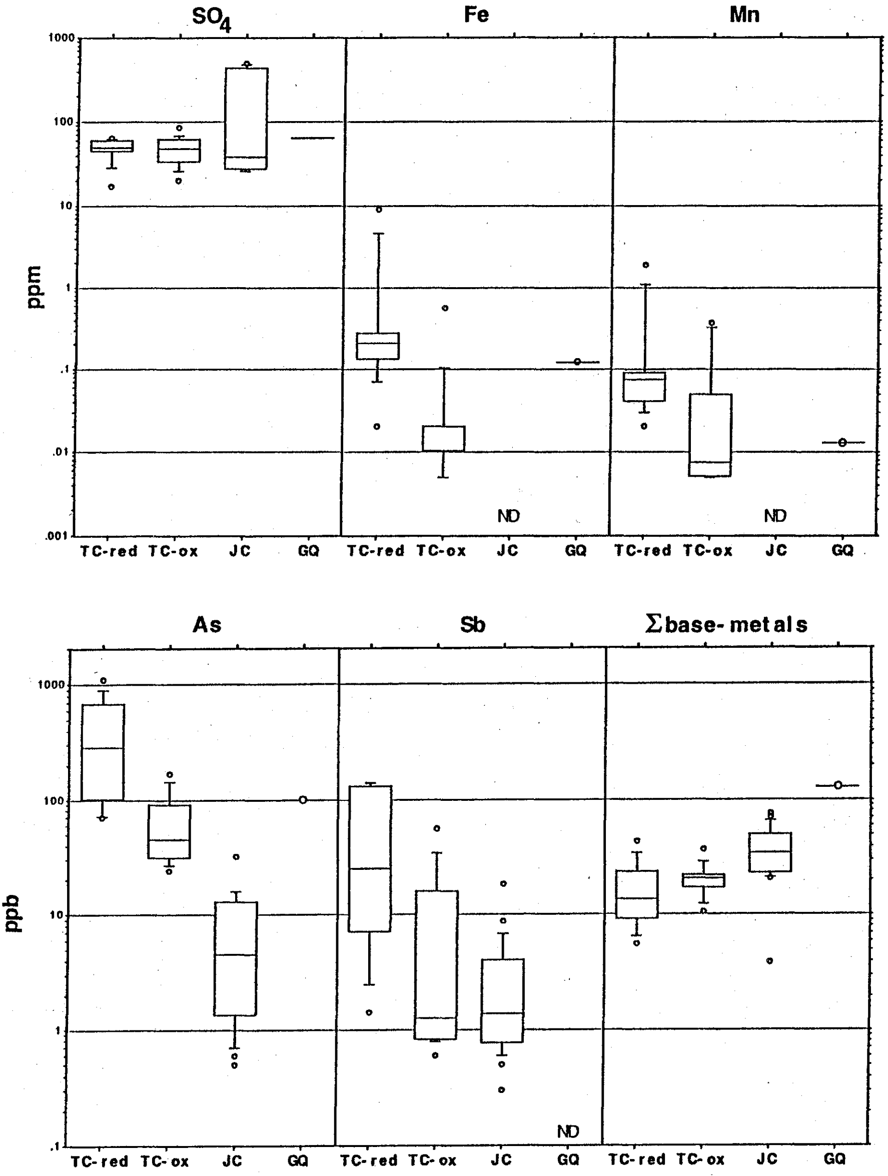

**Figure 2.** Bar and whisker plots showing percentile ranges of values for sulfate, iron, manganese, arsenic, antimony, and total base metals in natural ground water draining sediment-hosted gold deposits, Nev.; TC-red, Twin Creeks mine, reduced ground water; TC-ox, Twin Creeks mine, oxidized ground water; JC, Jerritt Canyon mine; GQ, Gold Quarry mine. The line in each box corresponds to the 50th percentile value. The top and bottom of each box correspond to the 75th and 25th percentile values, respectively. The whiskers extending from the top and bottom of each box correspond to values above and below the 90th and 10th percentile values.

all samples lie within the "near-neutral, low-metal field". Some samples have arsenic, antimony, selenium, or mercury concentrations that exceed EPA chronic criteria for fresh water. Concentrations of copper, lead, zinc, cadmium, nickel, and chromium are all below the EPA fresh water standard. Ground water samples from the Twin Creeks mine indicate anomalous concentrations of arsenic, antimony, tungsten (as much as 140 µg/l), iron, and manganese (Grimes and others, 1994, 1995). The highest concentrations are at sites where measured Eh indicates reducing conditions. Some elements are concentrated where alluvium is adjacent to the present-day water table. Ground water from Gold Quarry is similar to the more oxidized samples from Twin Creeks (Davis and others, in press) and contains elevated dissolved metal abundances, including 10 µg/l thallium, 59 µg/l selenium, and 0.4 µg/l mercury. Arsenic concentrations in drainage water associated with Jerritt Canyon are much lower than those at Twin Creeks due to more oxidizing conditions and rocks that contain lower abundances of realgar and orpiment (Al Hofstra, unpub. data, 1995).

### Metal mobility from solid mine wastes

More work is needed to obtain and synthesize available data.

### Soil, sediment signatures prior to mining

More work is needed to obtain and synthesize available data.
Soil: Some soil geochemical data are available for the Getchell (Erickson and others, 1964; Brooks and Berger, 1978); Dee (Bagby and others, 1985), and Preble (Lawrence, 1986), Nev., deposits.
Stream sediment: More work is needed to obtain and synthesize available data.
Plants: Data concerning the chemistry of sagebrush growing in the vicinity of Carlin-type deposits has been published by Stewart and others (1994).

### Potential environmental concerns associated with mineral processing

Heap leach and other cyanide processing solutions may contain copper, zinc, and silver complexes in addition to gold. Arsenic, cobalt, nickel, and iron may be present in low mg/l abundances in cyanide heap leach solutions. Thiocyanate ($SCN^-$) abundances are highest in ore that contains unoxidized sulfide minerals.

### Smelter signatures

Effluent from a few old smelters has contaminated down wind soil and vegetation. Modern operations do not involve smelting. Stack emissions from autoclaves, fluid bed roasters, chlorination circuits, etc. are monitored for compliance with federal, state, and local guidelines.

### Climate effects on environmental signatures

In the Basin and Range Province of Nevada and Utah, most sediment-hosted gold deposits are in semi-arid to arid climates, although deposits in alpine settings may receive 75 to 100 cm of yearly precipitation. In the dry season, evaporation leads to formation of acid salts that dissolve during storm events or the next wet season. Surrounding carbonate rocks neutralize acid water generated during storm events.

### Geoenvironmental geophysics

Ground magnetic and various electromagnetic methods may be used to map faults, fractures, and highly permeable altered zones that may serve as ground water conduits (Heran and Smith, 1984; Heran and McCafferty, 1986; Hoover and others, 1986; Hoekstra and others, 1989). Electrical resistivity methods can delineate hydrothermally altered areas and fault zones as resistivity lows and silicified rock as resistivity highs (Hallof, 1989; Hoekstra and others, 1989; Corbett, 1990). Electrical and seismic methods can be employed to determine depth to bedrock or locations of permeable and impermeable beds (Zohdy and others, 1974; Cooksley and Kendrick, 1990). Electrical methods also may be used to locate the present day water table and can delineate contaminated water plumes having significant electrical contrasts. Induced polarization surveys can be used to estimate sulfide mineral concentrations in refractory ore or in unmined or stockpiled mixed sulfide-oxide ore.

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