

## Bacteria gold interactions

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An *Acidithiobacillus thiooxidans* culture and a sulphate reducing bacterial (SRB) consortium, isolated from the Witwatersrand Basin, RSA were able to precipitate gold from  $\text{Au}(\text{S}_2\text{O}_3)_2^{3-}$ . In chemical control experiments, gold was not precipitated under similar experimental conditions and duration.

Growth of *A. thiooxidans* on media containing thiosulfate and gold thiosulfate decreased the pH of the culture medium from pH 5.4 to 1.9 and increased the Eh from 0.3 to between 0.5-0.6 Volts. The gold was stable in the bacterial systems until sulfur oxidation was complete, then the bacteria precipitated fine-grained colloidal gold (5-10 nm) inside the bacterial cells and  $\mu\text{m}$ -scale crystalline gold in the bulk fluid phase.

After gold thiosulfate was added to stationary phase SRB cultures (pH 7.4-8.0), the Eh decreased from approx. 0 down to -0.2 Volts and the gold precipitated intracellularly as nm-scale colloids (Fig. 1A) and extracellularly as nm-scale colloids within the FeS(s),  $\mu\text{m}$ -scale spherical aggregates of gold and  $\mu\text{m}$ -scale, octahedral gold (Fig. 1B).

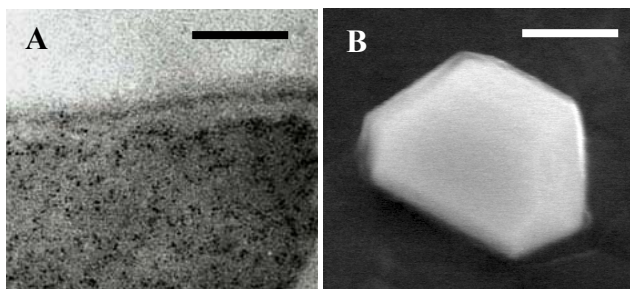


Fig. 1 – An ultrathin section TEM micrograph of colloidal gold within a SRB (A) and a SEM micrograph of octahedral gold within the fluid phase of the culture (B). Bars = 50 nm and 200 nm, respectively.

## Carbon, and gold-only deposits

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The association of carbon with gold deposits extends to graphite, carbonaceous material in black slate,  $\text{CO}_2$ -bearing fluid, carbonate minerals, migrated hydrocarbons, methane and coal. Of the 'gold-only' deposits (i.e. accounting for over 80 percent of the World's gold, and being deposits with gold as the prime economic mineral, and with low base metals), those without an apparent link to carbon species are rare. The source of the carbon includes that within original gold host rocks, and carbon introduced to the mineralizing domain as an essential component of the gold-bearing fluid.

Fluid inclusions associated with gold-only deposits in greenschist facies domains are highly distinctive amongst all ore forming fluids. They are of low salinity, elevated temperature, and mixed  $\text{H}_2\text{O}$ - $\text{CO}_2$  composition. The limited range of  $\text{H}_2\text{O}$ - $\text{CO}_2$  ratios around 3:1 is explained by mineral buffering during metamorphic devolatilization to produce the auriferous fluids. The role of the  $\text{CO}_2$  in auriferous fluids is not to complex with gold, but to buffer the fluid acidity to maintain pH within a range that favors gold transport as a reduced sulfur complex (Phillips and Evans, 2004).

Host rocks to gold deposits contain variable proportions of carbon in what are essentially coal seams (e.g. Owl Creek mine, Canada), black slates (e.g. Bendigo, Victoria), and migrated hydrocarbons (e.g. Carbon Leader reef in Witwatersrand goldfields; Carlin gold province). This carbon plays a role in fluid reduction and gold precipitation.

The result of fluid-wallrock interaction during gold formation includes carbonate minerals defining an alteration halo around many larger gold-only deposits that can be kilometers in scale. Several carbonate species can be present in single alteration haloes including calcite, ankerite, dolomite, magnesite and siderite, and there are multiple controls on the carbonate mineral species including host rock composition, degree of carbonation, and level of sulfidation. In mafic rocks, mild carbonation converts amphiboles to chlorite and calcite, and then progressive alteration breaks down the chlorite to stabilize ankerite. Higher levels of sulfur activity near mineralization may lead to pyrite growth, and the ankerite may give way to dolomite. Extreme variation of ankerite-dolomite composition over a few centimetres ( $\text{Fe}/(\text{Fe}+\text{Mg})$  from 0.02 to 0.43) reflects sulfur activity gradients adjacent to mineralization. Where the host rocks are ultramafic, rather than mafic, the dominant carbonate is likely to be magnesite. Siderite is common in iron-formations.

In gold deposits close to carbonaceous rocks, such as black shales, the fluid inclusions typically contain methane and  $\text{CO}_2$ , and this is attributed to local rock interaction rather than a separate methane-bearing fluid.

### Reference

Phillips G.N. and Evans K.A., (2004) Role of  $\text{CO}_2$  in the formation of gold deposits. *Nature* **429**, 860-863.

## Carbonaceous matter and gold in Carlin deposits: How intimate was the relationship?

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Gold deposits in the Great Basin of Nevada are characterised by the presence of carbonaceous material in and around the orebodies. Some previous workers have generally considered hydrocarbon generation and emplacement to predate ore formation by >100 Myr (e.g Kuehn & Rose, 1992). Others suggests that oil is at least locally syn-mineralisation (Hulen & Collister, 1999

The presence of live oil during the Tertiary is attested to by the occurrence of commercially-exploited oil in Tertiary reservoirs (Scott et al., 1987), and by the Basin and Range age of the faults creating the traps in both the Blackburn and Bacon Flat-Grant Canyon oilfields. In the latter case, Tertiary rocks also form the top seal to the reservoir.

Geochemical and petrographic data from the Jerritt Canyon and Screamer deposits clearly reveal that hydrocarbon was mobile and active at the time of ore formation. Analyses of country rocks surrounding ore reveal that organic carbon-rich domains are also associated with enrichments in Mo, V, Ni, U & Zn, and that there is a spatial relationship between these elements and ore. In situ organic matter is present adjacent to mineralisation together with migrated hydrocarbon in both host rocks and veins, and appears to have formed coevally with ore-stage minerals including kaolinite and realgar. Compositional zonation of the hydrocarbon (principally S and As) unambiguously points to its reactivity at ore stage, as do complexities in the reflectivity of the bitumens now preserved.

These observations extend to major areas of mineralisation the evidence for syn-mineralisation hydrocarbon mobility.

### References

- Hulen, J.B. and Collister, J. W. (1999) *Econ. Geol.* **94**, 1029-1050.  
Kuehn, C. A. and Rose, A. W. (1992) *Econ. Geol.* **87**, 1697-1721.  
Scott, C., Chamberlain, A. K., Aymard, W.H. and Perry, J. (1987), *Oil & Gas J.* **85/33**, 54-57.

## Discovery and significance of gold-rich bitumen in the Rodeo Deposit, northern Carlin Trend, Nevada

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Laser ablation ICP-MS analyses reveal that bitumen in the Upper Zone of the Rodeo deposit contains up to 100 ppm Au, 0.7% V, and ca. 0.1% (Ni, As, Hg, Cu). This represents a previously unrecognized type of Au mineralization in the world's third largest Au producing district. Recent studies of the Rodeo deposit have shown that the deposit contains both Devonian sedimentary exhalative (sedex) Au and Eocene Carlin type mineralization. Sedex Au ore with up to 68 g/t Au is stratabound in the Devonian Upper Mud Member (UM) of the Popovich Fm. The UM is a carbonaceous mudstone that regionally contains 5-15% TOC. Burial diagenesis with emplacement of the Roberts Mountain Allochthon in early Mississippian time caused these carbonaceous ores to generate petroleum. Petroleum, now bitumen, occurs as veins that cut the sedex mineralization. The bitumen contains grains of cinnabar, pyrite, base metal sulfides and native Au (<1 µm).

Line scans across bitumen grains reveal two distributions of Au. A heterogeneous Au signal with discrete Au spikes indicates, as observed petrographically, the inclusions of native Au. A homogeneous signal suggests that Au and related elements are chemically bound in the bitumen. Au and related trace elements show no enrichment on outer margins of bitumen grains. This along with (1) the distinct chemical signature, (2) paragenetic relationships that constrain Au-rich bitumen to a Mississippian age, (3) the absence of hydrothermal alteration, and (4) the lack of Au in bitumen from high-grade Carlin ore outside the UM all suggests that metal enrichments are not the result of Carlin hydrothermal fluids.

Together these relationships suggest that Au and associated metals were remobilized and transported from sedex mineralization in petroleum as organo-metallic compounds during oil generation and migration. The Au concentration in bitumen in rocks containing up to 15 % TOC, suggest that substantial amounts of sedex Au were remobilized during petroleum formation and that a significant proportion of the Au mined from the Rodeo resides in bitumen. These observations demonstrate a new environment and mechanism of Au transport with significant implications for Au metallogeny.

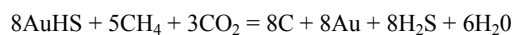
## Methane in Carlin-type gold deposit fluid inclusions

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We measured methane and other major volatiles in fluid inclusions in bulk from the Lone Tree, Getchell, Twin Creeks, and Pipeline Carlin-type gold deposits in Nevada by quadrupole mass spectrometry. Ore-stage fluids are characterized by CO<sub>2</sub>/CH<sub>4</sub> ratios that typically are < 10. Fluid inclusion methane concentrations generally are between 0.1 and 0.5 mol.%; other gaseous species show much wider ranges in composition. Also associated with gold mineralizing fluids are concentrations of H<sub>2</sub>S at or above amount that would be in equilibrium with pyrite-magnetite, and N<sub>2</sub>/Ar ratios > air. Methane strongly partitions into a vapour phase, but we can find no evidence that measurement of high methane concentrations is a consequence of bulk analysis of inclusion material bearing trapped vapour.

We can see no reason why methane is required for the transport of gold. High N<sub>2</sub>/Ar ratios indicate a magmatic volatile component in the fluids, but it is hard to explain the methane source as magmatic. It could be that methane is accidental to gold ore fluids and a consequence of the environment of gold ore fluid formation rich in carbonaceous rocks. High concentrations of methane lower the oxidation state of gold ore fluids to the point that pyrrhotite is stable. Methane could be important kinetically in the oxidation-reduction couple required for gold deposition when gold is complexed with bisulfide. A possible reaction is:



which also explains the common occurrence of small amounts of carbon in gold ores. Methane-rich fluids can explain deposition of carbon that is common in greenstone-hosted and Carlin-type ore deposits.

Conversely, methane might be important in the deposition of gold. Gold solubility reactions that include methane, like that above, indicate that an increase in methane fugacity will act to precipitate gold. A possible scenario for gold ore formation is addition of methane to gold ore solutions by interaction with carbonaceous metasediments and volcanics.

We conclude that methane is a common but enigmatic constituent of Carlin-type gold ore fluids, and can explain the occurrence of carbon in gold ores. Its occurrence may be accidental, or methane may be a critical factor in the deposition of gold.