Relevance of Microorganisms for the Formation of and the Exploration for Gold Deposits in the Australian Regolith

BULLETIN

By Frank Reith*

INTRODUCTION

Numerous studies conducted with regolith materials from Australia, Brazil, and Papua New Guinea, have shown that gold is chemically mobilised, transported and precipitated in the weathering environment. However, the mechanisms of solubilisation, transport and precipitation are poorly understood. Microorganisms, ie bacteria, archaea (a group of related microorganisms distinct from bacteria) and fungi, are present in all terrestrial environments, such as soils, regolith materials and sediments to depths of up to several kilometres. They have been shaping their environment and thus the earth's lithosphere, hydrosphere and pedosphere for several billion years. Bacteria and archaea are known to affect cycling of many elements, such as H, C, P, S, V, Mn, Fe, Cr, Co, Cu, As, Se, Mo, Sn, Br, Bi, Te, Sb, W, and U, in the surficial environment.

Therefore, researchers have considered the possibility that microorganisms might influence the solubilisation, mobility and precipitation of gold in the supergene environment. In the 1960s and 70s test-tube experiments were conducted with bacteria to study the effect of auric, colloidal and native gold on various species. Several species of autotrophic (using CO_2 as carbon source) and heterotrophic (requiring an organic carbon source) bacteria have been shown to dissolve gold under oxidising and reducing conditions. Today, *thiobacilli* are commonly used in bioleaching operations to extract gold and other metals from sulfide ores. Bacteria and fungi have also been shown to selectively accumulate gold via adsorption onto their cell walls or absorption into the microbial cell itself. Both processes appear to play an important role in the precipitation of gold by microorganisms, and thus in the biomineralisation of gold, which as recent evidence suggests has led to the formation of some of the world largest gold deposits, such as the Witwatersrand paleo-placer deposit in South Africa. Colonies of gold encrusted microbial fossils have been identified on gold flakes and nuggets from placer deposits in the USA, Australia, Venezuela and South Africa. Based on morphological features, these microbial colonies have been described as *Pedomicrobium spp.* Studies in Belgium, China, Argentina and Mexico focussing on the usage of microorganisms as indicators for gold deposits have demonstrated an unambiguous correlation of *Bacillus cereus* spores with gold in top soils, which in turn can indicate the presence of buried gold deposits. *Bacillus cereus* spores could therefore be used as an indicator in exploration for gold deposits.

INVESTIGATION OF A MICROBIALLY MEDIATED GOLD CYCLE AT AUSTRALIAN SITES

Prior to the present study, no comprehensive investigation of a microbially mediated cycle of gold in the weathering environment has been carried out in Australia. The aim of this study was to assess the components of the biogeochemical cycle of gold shown in Figure 1 by linking field observation with geochemical and microbiological experiments. Three field areas were chosen:

1. Tomakin Park Gold Mine in temperate south eastern New South Wales; an arsenopyrite-quartz-vein-deposit embedded in Ordovician metasediments, gold in the deposit is finely disseminated ('invisible') within the arsenopyrite, overlying the deposit is a intact soil and weathering profile.
2. Peak Hill gold mine in central west New South Wales operated by Alkane Pty., an epithermal deposit in the semiarid region of New South Wales;
3. Two deposits in the Palmer River region in tropical North Queensland. The deposits here were a placer and an arsenopyrite-quartz-vein deposit imbedded in Ordovician metasediments geologically similar to the Tomakin Park Gold Mine.

Methods used in the study included total- and selective, sequential extractions, microcosm experiments (batch-type experiments incubated with live and dead microflorae), reactive transport (column) experiments, community structure analysis of the resident microflorae, isolation and adsorption experiments with microorganisms, and *Bacillus cereus* spore counts.

MOBILITY OF GOLD IN REGOLITH FROM EASTERN AUSTRALIA

Samples of regolith materials from the three field sites in different stages of weathering were subjected to a selective sequential leaching. Leaching solutions used in the experiments were (host phases or materials are given in brackets): MilliQ water (water soluble content of the material), ammonium acetate (exchangeable, clay and carbonate), sodium pyrophosphate (organics), hydroxylamine hydrochloride (Mn- and amorphous Fe-oxides), 4 M HCl (crystalline Fe-oxides), conc. aqua regia (residues).

The six materials tested from Tomakin Park and the Palmer River were unweathered, slightly and moderately weathered quartz, phyllite surrounding the vein, and two soil horizons; gold bearing iron-oxides and two soil horizons were tested from Peak Hill. The results showed that gold in the unweathered quartz was strongly bound within the arsenopyrite. However, in slightly and moderately weathered quartz an increasing proportion of the gold was associated with amorphous- and crystalline Fe-oxides indicating solubilization and re-adsorption of gold during the weathering of the host materials. In the soil horizon of all mines, gold was mostly associated with the exchangeable, clay- and carbonate-bound and the organic fractions. These results indicate that gold is solubilised and redistributed during the weathering and soil formation and in conclusion appears to be chemically mobile at the three field sites.

SOLUBILISATION OF GOLD BY THE RESIDENT MICROFLORA

Whether or not the solubilisation of gold in the weathering environment is a biotic or an abiotic process cannot be investigated by selective sequential extractions. To assess the influence of the natural microflora on the solubilisation, microcosm experiments with samples from the three sites were conducted. The microcosms with gold bearing soil or regolith materials were incubated field-fresh, (with a living microflora) vs. sterilised (with a dead microflora). Water logged soil and regolith microcosms were incubated under oxic and anoxic. Aliquots of the waters were taken over time (70-90 days) and analysed for gold. Field-fresh microcosms solubilisation of the gold occurred generally after 20-30 days of incubation. Up to 3 ppm of gold in solution was measured in experiments where gold had been added as gold pellets. In sterilized microcosms, very little or no gold was detected in the solution. In all field-fresh microcosms, gold was solubilised within 20-40 days, after 60 days no gold was measured in solution and gold appeared to have been re-adsorbed to the host materials indicating a change in the community structure in the microcosms over time. Community structure analysis confirmed these changes during the incubation time.

Different processes of microbial gold solubilisation are proposed for different environments. In soils with high contents of organic matter heterotrophic bacteria and fungi appear to dominate the gold dissolution by excreting amino acids, low molecular weight organic acids (LMWOAs), cyanide or organic sulfur compounds. These molecules were shown to have the ability to dissolve native gold and act as complexing agents for the resulting gold ions. In carbon-limited environments, such as arsenopyrite-quartz-gold-veins and other sulfide ores, iron and sulfur oxidizing bacteria, such as *thiobacilli,* appear to liberate gold by breaking down the sulfide minerals.

TRANSPORT AND MOBILITY OF GOLD IN A REGOLITH PROFILE

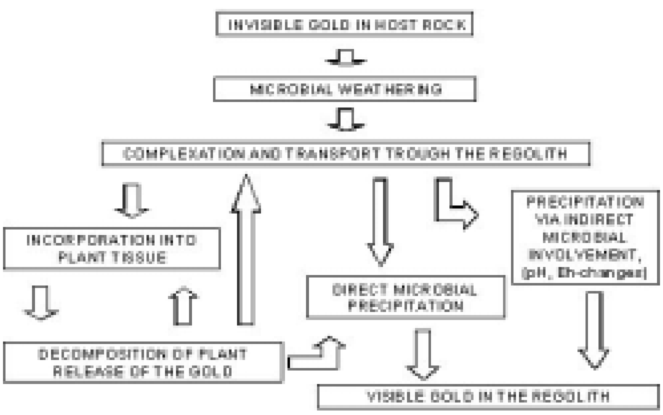


Figure 1: Flow chart showing biotic processes involved in the solubilisation, the transport and the precipitation of gold in the Australian regolith.

Advective transport by water movement in the vadose zone and absorption by plant roots are two processes, which appear to play an important role in the transport of gold in the surface environment. In recycle-reactor-column-experiments on soil samples from the Tomakin Mine simulating advective transport, up to 65 ppb of gold was liberated and transported within the first ten days of the experiment. However, the form in which gold is transported in this environment is not clear. Gold ions are unstable in aqueous solution because of their high redox-potential of 1.50 and 1.68 for Au^{3+} and Au^{1+} respectively. Therefore, the solution- and transport chemistry of gold must be that of complexed ions and colloids. In areas were organic ligands are not readily available inorganic ligands, such as chloride, sulfur-, bromide-, iodide- and hydroxo-species appear to form complexes with Au^{1+}- and Au^{3+}-ions. Iron- and sulfur-oxidizing bacteria form thiosulfate during the oxidation of metal sulfides, which forms stable complexes with gold. Cyanide is known to form stable complexes with gold and is commonly used in many leaching operations. *Chromobacterium violaceum* has been shown to dissolve gold via production and excretion of cyanide. As mentioned above, other heterotrophic bacteria excrete organic compounds, which dissolve and complex gold ions. Humic acids and fulvic acids also have also been shown to form stable complexes with gold or reduce gold ions to colloids.

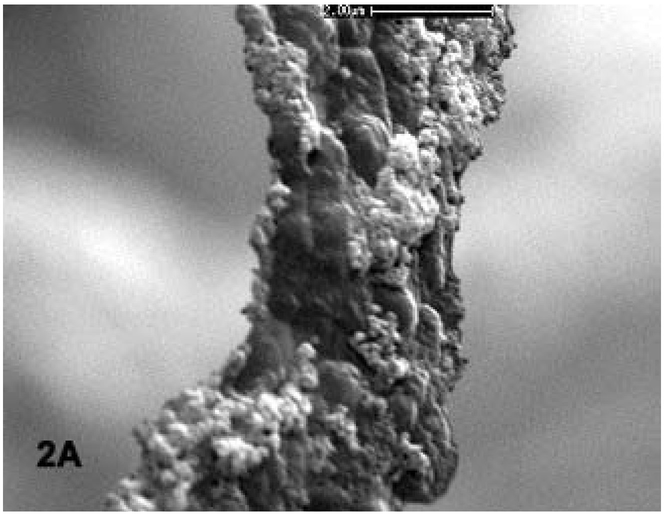
Plant leaves and leaf litter of various *Eucalypt* and *Acacia* species growing on top of the Peak Hill deposit displayed gold contents of up to 110 ppb, indicating that plants significantly contribute towards the transport of gold to the surface. Several plants species have been shown to accumulate gold in their cell tissue and release it into the surface environments with the death and decay of tissue.

PRECIPITATION OF GOLD BY MICROORGANISMS

In order to isolate bacteria and fungi, which might influence the precipitation of gold, microbial media containing Au^{3+} and colloidal gold were inoculated with soil samples from the Tomakin Park Gold Mine. In general, the growth of microbial colonies was found to be severely inhibited by the gold in the medium solution. However, several species of fungi and bacteria were able to grow in media with gold contents of up to 2 g L^{-1}. Some of the bacterial and fungal isolates were able to accumulate gold along their cell walls, as depicted in Figure 2A. Generally, the mass and rate of gold uptake was larger in fungi compared to bacteria, but the fungus generally died during the accumulation process.

Gold panned from the soil surrounding the gold deposits at Tomakin and Palmer River was analysed using SEM-EDS and found to be 99 per cent gold indicative of a secondary origin. Thus a process of gold precipitation and accumulation appears to exist in these soils. Gold encrusted microfossils of budding bacteria growing on gold flakes indicating a microbially mediated formation of nuggets were reported from the USA, Australia, Venezuela and Mexico. Areas of these samples panned in Tomakin and the Palmer River gold flakes were covered with similar microfossils, Figure 2B. In some areas, remnants of the cell structures were visible and in other areas carbonaceous matter possibly belonging to a recent biofilm was discovered, indicating that microorganisms are capable of mediating the accumulation of gold in the weathering environment. However, DNA-

Relevance of Microorganisms for the Formation of and the Exploration for Gold Deposits in the Australian Regolith



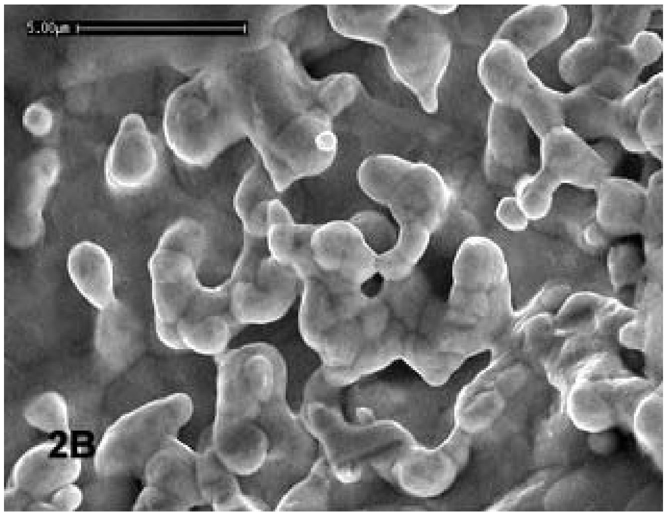


Figure 2A: Gold colloids precipitated along a fungal hyphae isolated from soil samples from the Tomakin Park Gold Mine.
Figure 2B: Fossilized colony of budding bacterial cells, possibly Pedomicrobium sp. australiensis, *on a gold flake panned from soil close to a gold mine in the Palmer River goldfields.*

staining of these microbes growing on the gold flakes will be undertaken to verify without doubt that the structures are microbial and to identify the species involved.

BACILLUS CEREUS SPORE COUNTS AS POTENTIAL EXPLORATION TOOL

In studies conducted outside of Australia, the common soil bacterium, *Bacillus cereus*, has been shown to act as a biogeochemical indicator for concealed mineralization. Top-soils were sampled along a 400 m traverse perpendicular to the main quartz-gold vein in Tomakin Park Gold Mine were analyzed for *Bacillus cereus* and 56 major and trace elements. *Bacillus cereus* spore counts were found to be up to ten times higher in soils where elevated concentrations of gold were measured. The results of this study strongly indicate that the increase in *Bacillus cereus* spores are linked to gold in Australian soils. However, it has not been determined whether or not gold directly exerts a toxic effect on *Bacillus cereus* causing increased spore formation or whether the increased spore counts are an effect of penicillin-resistant strains dominating in the metalliferous soils.

POTENTIAL BENEFIT OF THIS STUDY TO THE AUSTRALIAN MINERALS INDUSTRY

As exploration for new deposits appears to get increasingly harder, a comprehensive knowledge of all the processes influencing the behavior of gold in the environment is essential.

This study has shown that microorganisms contribute to the dispersion and the accumulation of gold in the environment, and thus in the formation of secondary gold deposits in the supergene environment. The experimental evidence collected provides the first field relevant analysis of the microbiological element in the behavior of gold in the Australian regolith, and thus lays the foundation for a further in-depth investigation of the subject.

It has also been demonstrated that the soil bacterium *Bacillus cereus* can be used as a direct indicator for gold exploration. Particularly, this biogeochemical exploration technique may be of use in Australia, where exploration is often undertaken in remote areas and results cannot be obtained on site, due to the complex analytical facilities required for trace element analysis. *Bacillus cereus* spore counts can easily be conducted in the field. *Bacillus cereus* pre-screening could be used to identify areas in place of a substantial part of laboratory-based quantitative analysis in gold exploration, and thus allow more cost-effective field sampling.

Microorganisms have been isolated that have been shown to accumulate large quantities of gold. This discovery could be modified to a biological second stage to the already operative bioleaching, and thus might contribute towards an even more environmentally friendly processing of gold ores.

ACKNOWLEDGMENTS

The author expresses sincere appreciation to: Peter Hancock for inviting me as a speaker to AusIMM Canberra and Central West NSW seminar series; B.N. Opdyke and D.C. McPhail for their supervision of this project; the Cooperative Research Centre for Landscape Environment and Mineral Exploration (CRC LEME) for funding and support of this project; Geoffrey Smith and the School for Biochemistry and Molecular Biology for the use of the laboratory facilities; Peter and Kinuyo Wyatt at Tomakin Park Gold Mine for the access to the property and help during my stay; the ANU Electron Microscopy unit for help with the SEM-EDS analysis.

* Frank Reith is a geomicrobiologist researching microbe-gold interactions with CRC LEME and currently completing a PhD at Department of Geology, ANU. ■