POTENTIAL MECHANISMS OF METAL TRANSFER THROUGH TRANSPORTED OVERBURDEN WITHIN THE AUSTRALIAN REGOLITH: A REVIEW

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Irrespective of the technique employed (geophysical and/or geochemical), the depositional landforms or "transported regolith" dominated landforms remain the most difficult to explore in. With respect to applying surface geochemistry in these "cover" landforms, there is a worldwide move towards employing partial, selective and sequential leaches, gas analysis and biogeochemical surveys to delineate anomalies in depositional landforms. Some of these techniques have been in application for over 30 years but recent advances in analytical detection have increased their use. However, these techniques have found mixed success in identifying buried mineralization as opposed to only "anomalies", especially in Australia, because the particular mechanism(s) and their effectiveness in transferring metals associated with mineralization upwards through the often complex transported overburden is poorly understood. The lack of understanding of transfer mechanisms and its effectiveness thereby complicates and limits the interpretation of datasets, and precludes the discrimination of null from a negative result. To address the lack of understanding of various upward metal transfer mechanisms through transported regolith (as opposed to the well understood residual regolith), a review was conducted to evaluate the potential mechanisms effective in the Australian environment. In general, four dominant mechanisms with potential to transfer metals upwards through barren cover were identified, some covered by (Cameron *et al.* 2004): groundwater; gases; vegetation; and, bioturbation. Most of these categories have variants or sub-mechanisms, and may be influenced by microbial processes, and all are summarized below.

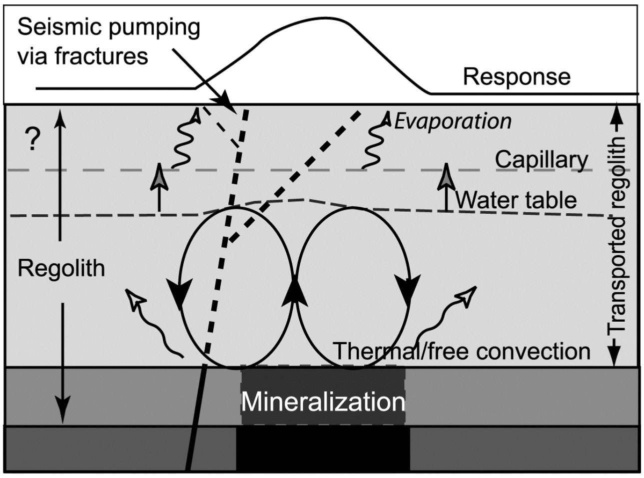

Figure 1: Some potential hydrogeochemical mechanisms for dispersion through transported regolith. The genesis and evolution of electrochemical processes within saturated transported cover are covered by Hamilton (2000).

GROUNDWATER

Groundwater in association with infiltrated water is the main agent of chemical weathering, and facilitates the dispersion of metals from the ore body (Figure 1). Flow directions, solution properties, aquifer heterogeneity, adsorption, complexation and inherent interactions and feedbacks between these processes influence the extent of lateral and vertical dispersion within the unconfined aquifer. Redox processes and formation of a possible stagnant zone at varying depths affect vertical migration and fractionation of specific elements (rare earths, Fe, Mn, V, As) at or within the fluctuating zone of the water table. Capillary forces at and above the water table can induce upward migration of solutes, with the rise being dependant on aquifer grain size and evaporation rates (Figure 1). Seismic or dilatancy pumping occurs in neo-tectonically active areas where faults and fractures act as conduits for upward transfer of mineralized groundwater (Cameron *et al.* 2002). Earth tremors promote compressional stresses along faults and force groundwaters upward, with possible surface discharge resulting in a near-surface anomaly. This mechanism is limited to low-rainfall and neo-tectonic areas that have regular seismic activity after overburden deposition. Free convection or buoyancy driven currents within the groundwater can arise due to density differences induced from point or diffuse heat sources. These can promote faster solute migration in a particular direction and the possible formation of irregular fronts of metal concentrations in groundwater. The oxidation of sulphides in an ore body is an exothermic reaction that produces heat and is capable of increasing groundwater temperatures and facilitating rapid increases of solute concentrations above ore bodies. The ability of convective flow to rapidly transfer solutes upwards up to the water table remains unexplored and has only been investigated via simulations and laboratory tests for point source contaminant transport. The formation of electrochemical cells around an oxidizing-reducing sulphide body within groundwater can provide excess

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cation concentrations at the oxidized upper edges of the sulphide body, and the proposed pattern of "rabbit ear" surface anomalies in regolith suggests it is a possible operation (Govett *et al.* 1984). A particularly relevant model positions the onset of redox anisotropy between the buried sulphide body (reducing) and water table (oxidizing) after the deposition of sediments. Self-potentials arise and are maintained due to reducing conditions at the sulphide body front and oxidizing conditions at the water table, leading to upward and outward migration of reduced species and their subsequent oxidation and formation of a reduced column above the ore body (Hamilton 2000). This voltaic cell model suggests a capability to rapidly transfer metals upwards through thick (30 m) saturated cover (Cameron *et al.* 2004). All the groundwater-supported transfer mechanisms are limited to the upward limit to which groundwater rises or the water table (and capillary fringe), except that of seismic pumping. In the Australian environment dominated by Mediterranean, Semi-arid, and Arid settings, groundwaters are commonly more than 5 m below surface except in lower, discharge-landform sites, and other, or additional, mechanisms are necessary to transfer metals from the water table upwards.

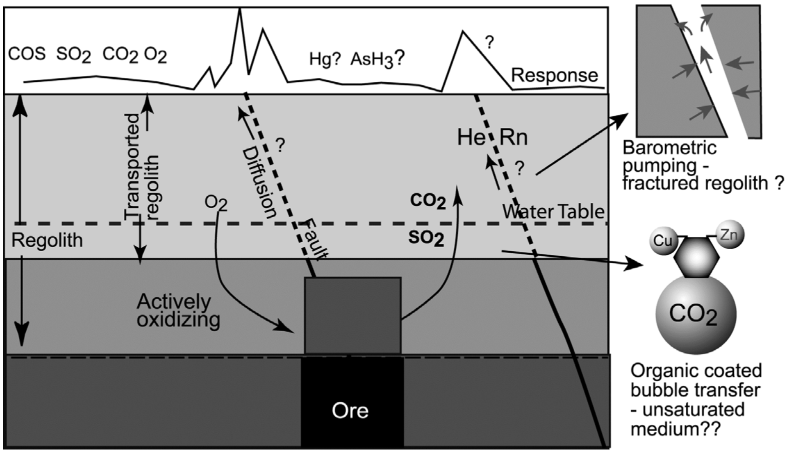

Figure 2: Illustration of potential gas based migration mechanisms through transported regolith.

GASES

Gases migrate via molecular diffusion, advection and gas streaming (Hale 2000). Diffusion and advection appear to be the main sources of rapid upward migration of ore-related gases (CO_2, SO_2, COS) and possibly of volatile metals. Diffusion of gases produced as a result of weathering of ore body (COS, CO_2, H_2S) as a potential mechanism is limited by the individual gas stability and tortuosity of the weathered, and often cemented regolith medium. Atmospheric pumping, the depression front set up by large barometric pressure change, causes rapid upward migration of air present in pores and conduits, and has the capability to transport volatile (I, Hg) and radiogenic elements from nuclear blasts (Cameron *et al.* 2004). Atmospheric pumping is restricted to fractured media (Figure 2), and whether it may operate in a connected heterogeneous sedimentary overburden needs testing. Gas streaming or bubble migration is the upward transfer of microscopic gas bubbles that form within the groundwater due to overpressure, and are then released from the water table. Specific metals (Cu, Zn, Pb, Hg, actinides) and ultra-fine particles (clays, oxides, bacteria) can attach to the surfaces of ascending gas bubbles (dominantly composed of CO_2), especially if the gas bubbles have an organic coating acquired from trace organics in groundwater (Figure 2). The bubbles can then be transported upwards to the near-surface environments, where pressure changes induce bubble instability and release metals. The stability of bubbles during their transfer from a saturated to an unsaturated medium is unclear. Furthermore, the fate of adsorbed particulate matter in a heterogeneous, but enclosed, medium such as weathered sedimentary material, is unproven. In any case most, if not all, studies of gas anomalies at the surface indicate rapid migration along conduits such as faults, fractures and shears, above which the gas anomalies are present, and this confirmation holds promise to at least accurately demarcate structural features, but so can geophysical techniques.

VEGETATION

Vegetation or plant physiological uptake of elements from the subsurface and their release to the surface via litter is a potential mechanism of rapid metal transfer. However, the ability of plants to tap water sources for their nutrient content is critical to the transfer mechanism, otherwise higher metal content plants merely indicate recycling of a soil anomaly. The potential of plant-assisted metal transfer from deeper groundwater comes from deuterium isotopic studies on facultative pheratophytes—plants having dimorphic roots systems with laterals and sinker or tap roots (vertical), the latter roots acquiring water and nutrients from deeper groundwater source, especially during summer (Pate *et al*. 1999). Recent work on plant-metal relationships in the Northern Yilgarn suggests plants do uptake ore-related metals from groundwater at depth. Additionally, hydraulic lift—redistribution of deeper water acquired by sinker roots to near surface soil horizons to be used by laterals (Caldwell *et al.* 1998)—is capable of rapid transfer of water and possibly metals within the overburden. Diurnal uptake and transfer of water groundwater to surface soil has been confirmed, but no data exist on ore metal transfer.

The depth of rooting is critical to the ability of vegetation in transferring water and possibly ore metals upwards. A global survey indicates that deep roots, especially sinkers, are ubiquitous with > 10 m depths regularly reached and confirmed in several climatic settings (Canadell *et al*. 1996). Plants are known to take up mineralization-associated elements that are essential micronutrients (Zn, Mo, Se) plus other ore metals (Au, Ni, Cu, Pb) and even potentially toxic metals such as As in significant concentrations (Meharg & Hartley-Whitaker 2002). Plant physiological processes biotransform specific metals within their tissues, thereby influencing the effectiveness of selective leaches and element mobility once the metals are released on the surface via litter. For example, Au absorbed by roots in the dissolved form can be converted into colloidal form within the plant tissues, and As and other elements are combined with phytochelatins to reduce toxicity. The subsequent release of these organo and colloidal species on the surface and their impact on partial or selective leaches needs further evaluation. Preliminary results point to the potential of phreatophytes and other specific plants to transfer metals from 10 m deep current or palaeo-groundwater tables (redox fronts) or capillary fringes, but identifying the species, the regolith and groundwater environments (perched or permanent, saline or fresh) under which plant transfer is operative requires extensive testing.

BIOTURBATION

Bioturbation within the biomantle is capable of moving huge amounts of soil material, and thereby bringing up anomalous material from depth to the surface. Ants, termites and earthworms are the main bioturbators in the Australian environment, but only ants and termites have the capacity to penetrate deeper into the transported regolith (> 1 m). These bioturbators, in combination with rainwash, are the primary cause of soil (and anomaly!) homogenization and lateral dispersion of surface anomalies over time. Although bioturbation on freshly deposited sediment begins within years, with 1 m penetration achieved randomly, it is the development and evolution of the biomantle across the depositional landform that needs to be considered for anomaly homogenization. The homogenization of the biomantle takes hundreds to thousands of years depending on the interplay between deposition rates on the particular landform (varies on different landforms and climate). Furthermore, unlike vegetation, barring a few exceptions from the Kalahari in Africa, the effectiveness of bioturbation decreases rapidly downwards, with activity mostly ceasing at a depth of 2 m.

MICROBES

The role of microbes in transferring metals upwards is restricted, but they affect most of the processes responsible for metal transfer. Microbial metabolism affects the kinetics of many hydrochemical processes, especially sulphide oxidation and other redox transfers (Edwards *et al*. 2000). Microbial metabolism can impact on gaseous migration of elements by generating methanogenic, CO_2 and sulphur gases, and by generating volatile metal species via biomethylation (As, Se, Sb, Mo). They can influence the efficiency of metal uptake by roots via redox reactions, symbiotic associations and organic secretions. Microbes participate in intracellular and extracellular formation of minerals (and Au particles) within the saturated zone and soil, and can influence the efficiency of partial and selective leaches (Figure 3). Microbial-induced biomethylation (with As, Sb, Se, Hg) can significantly affect the "loosely" bound metal fraction or the efficacy of selective or partial leaches. For example, recent studies demonstrate microbial role in biomethylation of commonly used pathfinders with some of the metal differentiating into volatiles (Craig *et al*. 2003), possibly followed by demethylation. Microbial roles need to be investigated to address the question of whether the results of selective leaches or gas analysis are dependant on microbial populations, their seasonal variations and soil conditions rather than transfer mechanisms. For example, Bajc (1998) in a comparison of different leaches at different times, found the repeatability of the results from leaches to be poor, and one reason for this poor repeatability could be seasonal variations in microbial metabolism induced biomethylation or other metal transformations.

NATURE OF COVER

The vital aspect that influences the operation of the diverse mechanisms responsible for upward metal migration is the nature of the transported overburden (pre- and post- weathering) and its depth, both factors in turn affected by time and landscape factors. Overburden weathering and formation of a concomitant water table within the overburden increases the possibility to transfer metals upwards via a combination of mechanisms such as vertical hydrogeochemical gradient and electrochemical effects, vegetation uptake and bioturbation, to form "incremental" anomalies over time. This has been shown to occur in deposits in Canada overlain by saturated 30 m thick glacial clay (Cameron *et al*. 2004) and at the Lancefield gold mine in Western Australia, where the oxidized orebody is overlain by sediments comprising 10-20 m of mottled Permian fluvio-glacial sediments, 3-8 m of mottled Tertiary palaeochannel clays, and 2 m of silicified colluvium (Anand *et al*. 2004). Alternatively, younger, fresh to slightly weathered sediments, even of shallow depth, will afford a much lesser opportunity for diverse mechanisms to operate, except gaseous diffusion and advection and possibly plant uptake, depending on porosity, anisotropy and hardness. However, specific partial leaches, gas measurements and electrochemical techniques work on the principle of a rapid migration mechanism even in recent, fresh cover, and therein lies the need to understand the rate, extent and overall effectiveness of the mechanism(s) to mobilize ore metals upwards under different transported cover settings, so surface geochemical techniques can be efficiently and predictively applied, or discarded.

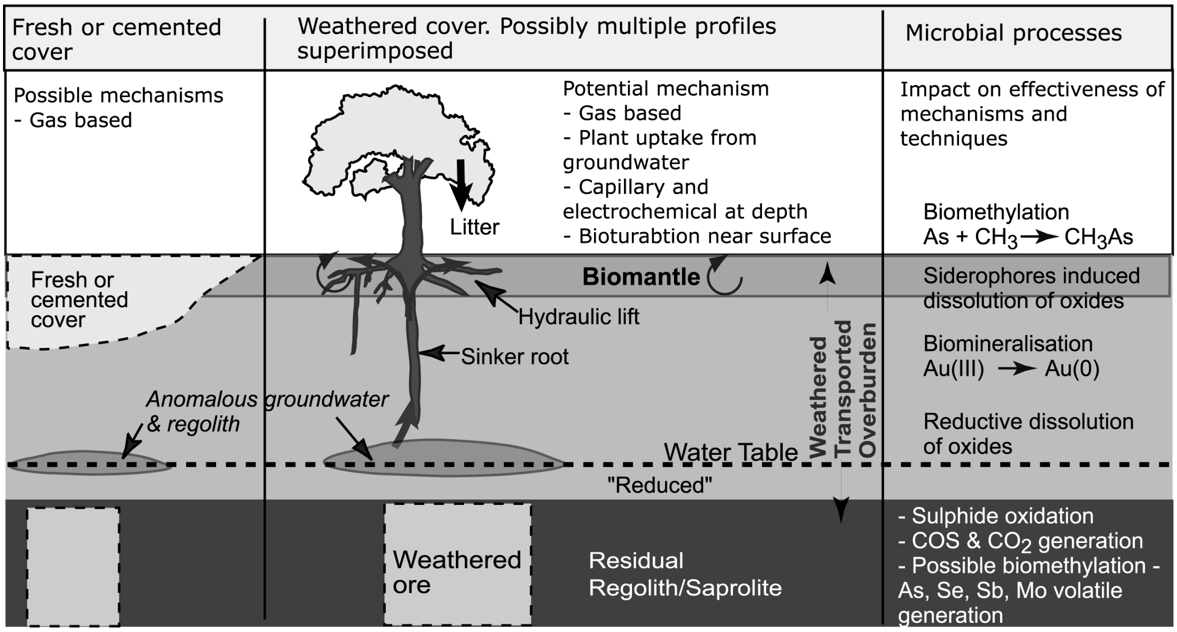

Figure 3: Illustration showing the operation of potential mechanisms depending on nature of cover (fresh or cemented as compared to deeply weathered with minimal cementation) and influences of microbial processes.

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