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Review

# A review of metal transfer mechanisms through transported cover with emphasis on the vadose zone within the Australian regolith

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ABSTRACT

There is a growing trend to try to make surface geochemistry effective for exploring areas of transported cover using sensitive techniques such as partial extractions of soil and gas analysis. However, these techniques have had mixed success in delineating buried ore bodies, because the particular mechanisms and their effectiveness in transferring ore-related metals upwards through transported cover are poorly understood. This precludes discriminating null results (a potentially ineffective technique) from negative results (no mineralization). A review of mechanisms capable of transferring metals through barren transported cover to the surface identified those well documented and others not well studied but nonetheless promising. The mechanisms are classified according to two main processes: phreatic process involving groundwater flow, convection, dilatancy, bubbles, diffusion and electromigration; and vadose processes involving capillary migration, gaseous transport and biological transfer. Microbial metabolism affects the kinetics of many hydrochemical processes, especially sulfide oxidation and other redox transfers, and also impacts, negatively and positively, on the generation of gases throughout the entire cover sequence. Phreatic mechanisms require groundwater to transfer solutes and are most effective. These have the most predictive capability where there are shallow water tables. In the Australian landscape, groundwater occurs commonly more than 5 m below surface except in lower, discharge landform sites, and therefore other mechanisms (biological, capillary, gaseous), are necessary to transfer metals up from the water table. Thus, much of the emphasis in this paper is on vadose processes. An integrated approach is necessary, combining different mechanisms with the nature and evolution of the transported cover and climatic settings. Regions and landforms of highly weathered transported cover with current or past water tables residing within the cover and long-standing vegetation will favor combined mechanisms such as electrochemical, plant uptake, capillarity, and bioturbation. Fresh, relatively unweathered and thick (>30 m) transported cover may prove the most unlikely to develop surface geochemical anomalies. Gas (e.g. $CO_2$, $H_2S$) mechanisms may work, provided that sufficient gases are generated from the oxidation of ore to produce a surface signature.

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## 1. Introduction

As discoveries of world-class mineral deposits continue to decline, increased attention is being focused on geochemical exploration methods specifically designed for terrains with significant transported cover (Kelley et al., 2004). Transported cover here refers to material of exotic or redistributed origin such as alluvium, colluvium, glacial, lacustrine, marine and aeolian material that blankets fresh or weathered bedrock. Exploration is difficult and expensive in these areas. Surface soil sampling has tremendous advantages for mineral exploration, and where effective, low-cost programs can be conducted in areas of transported cover, covering large areas and quickly eliminating barren ground. More expensive techniques, such as drilling, can then be concentrated in areas with higher probabilities of success. Aside from the expensive option of pattern drilling through transported cover, a number of geochemical techniques may be used, the main gas or vapor, biogeochemical and groundwater sampling, being partial extractions, and electrochemical techniques (Goldberg et al., 1997; Wang et al., 1997; Gray et al., 1999; Hale, 2000; Putikov and Wen, 2000; Gray, 2001; Cameron et al., 2004; Mann et al., 2005; Kelley et al., 2006; Anand et al., 2007; Klusman, 2009; Cohen et al., 2010; Cao et al., 2010; Lintern et al., 2013; Noble et al., 2013; Morris, 2013; Anand et al., 2014). Over the last two decades, one of the most common geochemical approaches has been to use partial extraction geochemistry to assist detection of weak geochemical dispersion haloes by chemically targeting the regolith components that are thought to host these haloes (Cameron et al., 2004). Partial extraction techniques rely on the premise that ore-associated elements are being actively transported upwards through the transported cover and occur in a labile, readily extractable form (Mann et al., 2005). However, what such mechanisms may be, and whether they occur (or have occurred) to any significant extent is unclear. Furthermore, active soil-forming processes may also involve labile elements, unrelated to mineralization, that will also be dissolved by these extractants, resulting in mixed data, potentially producing false anomalies. Poor understanding of the mechanisms of metal transfer precludes discriminating null results (ineffective technique) from negative results (no mineralization). This has limited the use and credibility of these techniques (Cohen et al., 1998; Gray et al., 1999; Butt et al., 2000a; Mokhtari et al., 2009; Anand et al., 2014).

Although false anomalies are common, the critical question is whether a lack of anomalous surface geochemical response can be interpreted as unmineralized bedrock below. An example of the value of understanding of whether metal signatures from mineralization are transferred upwards to the surface is illustrated in Fig. 1. Gold from the underlying mineralization has dispersed into the overlying older and intensely weathered transported cover, but not within the thinner, but less weathered near surface cover and soils, and subsequently surface geochemical sampling provided a null result (Fig. 1; Radford and Burton, 1999). The example highlights the lack of predictive capability of the surface geochemical technique because understanding how metals are transferred upwards through different cover and environmental settings is lacking. In comparison, the understanding of geochemical dispersion processes in residual regolith is well established with proven successes in Australian regolith settings (Butt et al., 2000a; Anand, 2000; Smith et al., 2000; Anand and Butt, 2010).

This paper reviews the potential mechanisms by which metals may transfer from the ore body upwards and laterally through unmineralized transported cover, with an emphasis on application to the Australian regolith. Where there appears a linkage between the operation of different mechanisms and the effectiveness of surface geochemical techniques, the paper alludes to the linkage. The diverse mechanisms and their underlying processes, cover a multitude of scientific disciplines.

## 2. The mechanisms

The mechanisms capable of transferring metals upwards can be grouped into two main categories based on whether they are within the saturated groundwater zone (phreatic zone) or above this saturated zone (vadose zone) (Fig. 2). This distinction is important for a dry continent like Australia because the water table across the semi-arid and arid regions is deep and therefore the unsaturated zone mechanisms are ultimately critical to upward transfer of metals to surface. Previous reviews (Cameron et al., 2004; Kelley et al., 2006) of metal transfer mechanisms have concentrated on the phreatic zone. Although most of the mechanisms described below have in the past been postulated to contribute to upward transfer of metals through transported cover, some have, as yet, not been proposed to achieve the same result (Aspandiar et al., 2006). Movement of ions and particles through transported cover is upwards against gravity, and therefore a medium (water, gas, mineral particles) and force (concentration, electrical, temperature or pressure gradients) are necessary to cause the upward transfer by diffusion or advection. The major transfer mechanisms categorized according to the main processes are summarized in Table 1 and Fig. 2.

The above mechanisms, if effective, can cause a direct and/or an indirect anomaly at the surface (Smee, 2003). In a direct anomaly, the target metals (metals associated with mineralization) are transferred to the surface. An indirect anomaly at the surface arises in response to another stimulus associated with the ore body. For example, the excess $H^+$ and $Fe^{2+}$ from sulfide weathering may diffuse to the surface and cause a detectable chemical change in the soil that implies buried sulfides.