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# Mineral exploration in regolith-dominated terrains: Global considerations and challenges

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ABSTRACT

Mineral exploration through transported cover is becoming one of the fundamental challenges for the exploration industry in this century. The sharp increase in demand for commodities driven by a growing population and technology-based society is coupled with the decrease in world-class ore deposit discoveries in the last three decades. This is setting the stage for an unprecedented scenario, that is, ensuring that the market supply for critical metals (Ni, Co, Au, PGE, etc.) is satisfied. This situation is becoming the driving force for a restructuring of mineral exploration paradigms. New technologies and methodologies are being developed; and, as a consequence, regions that were considered to be unfavourable for ore deposit exploration are now being reconsidered. Among these areas are vast regions of Regolith-Dominated Terrains (RTD) with basement rock suites buried under thick transported cover and/or deeply weathered profiles.

This Special Issue presents several studies on mineral exploration in RTDs in Brazil, China and Australia, and addresses some of the issues that hinder exploration in these problematic terrains, in the hope of reaching a broad audience, and encouraging researchers from a wide spectrum of disciplines to contribute to this exciting and inspiring exercise.



## 1. Global considerations

Nearly 25% of the Earth's continental surface area is affected by tropical climatic conditions that result in intense chemical weathering (Fig. 1; Strakhov, 1967). This figure increases when considering regions which experienced these conditions in the past. These areas often display lateritic profiles that may reach considerable depths, up to >100 m (e.g., Anand and Paine, 2002; Bardossy and Aleva, 1990; Goudie, 2004; Thomas, 1994). Similar features are also observed in non-tropical areas, although they are not regionally extensive (Migoń and LidmarBergström, 2001). Deeply weathered regions commonly coincide with major geomorphological features such as cratons and shields, as well as continental lowlands and plateaus (Fig. 1; Taylor and Eggleton, 2001; Twidale and Campbell, 1995), which today are under arid climatic conditions in parts of Australia, Africa and China, and are blanketed by cover and/or dissected landscapes, down to depths of hundreds of metres (Fig. 1). These regions are commonly referred to as regolith-dominated terrains (RTDs). The geological understanding of these regions is problematic due to their lack of fresh bedrock outcrop and complex weathering histories. In fact many of these areas display weathered profiles, which have been developing for millions of years (e.g., Anand and Paine, 2002). Thus many of these regions correspond to ancient, stable and weathered landscapes, as is the case of several regions in Australia, where fossil Palaeogene landscapes (~65–25 Ma; Pillans, 2005 and references therein), and weathered profiles with residual clays dating back to the Late Palaeozoic (>250 Ma; Bird and Chivas, 1988) occur.

Understanding the processes of weathering, erosion and deposition that have formed the thick transported cover over these terrains requires a different approach than applied to their counterparts in recently glaciated and juvenile settings. This is due to the much longer time scales involved and the overprinting by successive weathering events under different climatic environments (Anand and Paine, 2002). These environments are widespread across many continents, but have been largely overlooked for mineral exploration due the risk and cost associated with their exploration. However, increasing mineral resource demand resulting from the exhaustion of world-class ore deposits, and a recent paucity of significant discoveries in the near surface (<50 m), is a compelling motivation to further explore RTDs. Also compelling is the development of new technologies and methodologies that are making mineral exploration in RTDs more economically feasible such as geophysics, and data integration platforms.

Mineral deposits are geochemical anomalies in the Earth's crust due to their local high concentration of one or a diverse suite of trace elements (Ni, Au, Co, Cr, Sc, REE, HFS, etc.), that may develop geochemical footprints. Such anomalies have enormous value when they are

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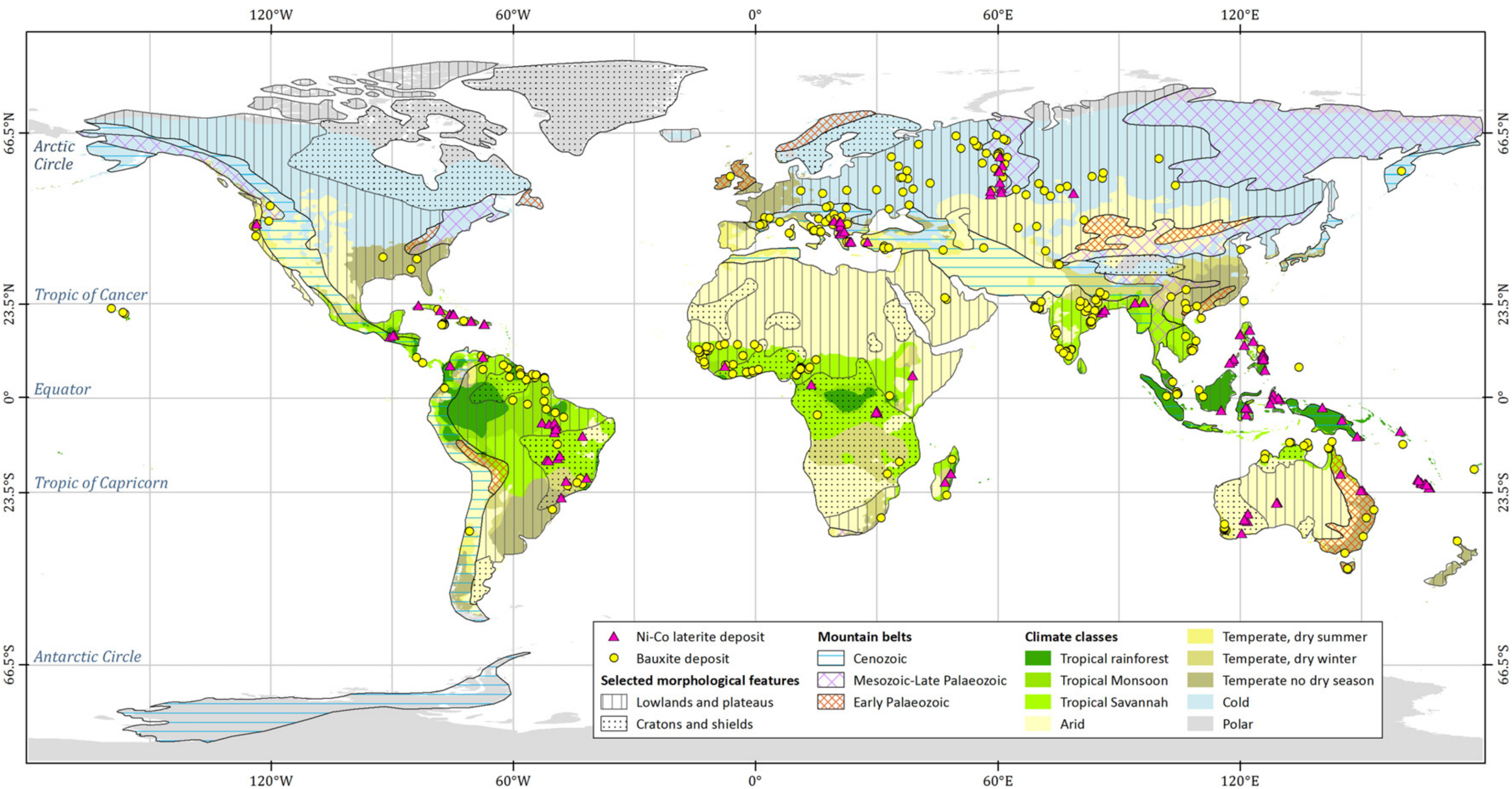


**Fig. 1.** Main climatic domains based on Köppen's classification and modified after Peel et al. (2007), with the location of the main Ni–Co laterite and bauxite deposits (Schulte and Foley, 2014; USGS, 2015), plotted over selected major morphological features (modified after Taylor and Eggleton, 2001).

discovered in deeply weathered regions as they act as a laboratory where geochemical tracers can be studied to understand the causes of the complex overprinting of weathering processes through time. This may be expressed by the mobility and/or fractionation of a wide variety of unusually high concentrations of trace elements emanating from the mineral deposit. Weathered mineralization leaves intense geochemical footprints that overwhelm the background levels of the same elements, and consequently are exceptional natural geochemical markers. These markers can be used to decode complex weathering processes, separating one weathering event from another, and thus linking them with the general landscape geochemistry. This is of key significance to understanding weathering processes throughout geological time, and enables us to articulate more efficient mineral exploration protocols to discover ore deposits under transported and in situ weathered cover.

There is a widespread assumption about deeply weathered profiles within the tropical climatologic zone (~23° north and south of the Equator; Fig. 1), that is, intense weathering is the aftermath of tectonic activity and sedimentary processes, which obliterates the primary geochemical signature of rocks at depth. However, such weathering profiles are now extensively distributed geographically throughout the continents in regions currently under diverse climatic conditions, spanning from Artic to Mediterranean climates (e.g., Ollier, 2010). A large number of commodities are extracted from ore deposits related to palaeoweathering profiles in these regions, such as Ni, Co, Al, Zn, and Cu (Fig. 1). Hence models dealing with supergene metal enrichment must take into account diverse climatic conditions (e.g., Zn, Cu, Ni laterites; bauxites; humid-tropical conditions versus Savannah; Cu supergene deposits in South America; e.g., Herrington et al., 2007).

Rates of weathering and resulting bulk compositional changes in the regolith have been widely studied (e.g., Anand and Paine, 2002; Thomas, 1994; White, 2003, and references therein; Goudie, 2004 and references therein). However, their relation to climatic models remains unclear, since weathering mass transfers in small catchment areas often display an important climatic component, whereas their continental counterparts do not (White, 2003 and references therein). In modern tropical regions such as Papua New Guinea, based on clay mineral types and abundance, weathering rates are reported to produce incipient weathering profiles at variable depths after 5000 years, whereas immature weathering requires 5000–20,000 years, and mature weathering >20,000 years, and reported profiles deeper than 10 m (Löffler, 1977 and references therein). This indicates that the formation of >10 m weathering profiles over large regions under specific climatic conditions can occur in very short time spans. This increases the likelihood of its preservation in the stratigraphic record since even active tectonic and erosional environments at regional scale rarely obliterate the complete weathering record (e.g., Ollier, 2010).

Weathered profiles are widespread in Europe, where they form blankets often >50 m thick, such as in the Scandinavian mountains, Fennoscandian Shield, British Isles, and the Central European belt of mid-mountains and uplands, which are all characterized by the abundance of Mesozoic and post-Mesozoic kaolinite-rich saprolite (Migoń and LidmarBergström, 2001). Olesen et al. (2013) reported that remnants of deeply weathered basement rocks of Norway occur along structurally defined zones of crustal weakness, where locally continuous saprolite layers are up to >100 m thickness. This is suggested to have had a substantial impact on the shaping of the topography of Norway, since erosion of the sedimentary succession does not seem sufficient to explain the observed immature Alpine-type topography (Brönner et al., 2014; Olesen et al., 2013). Evidence of Oligocene tropical weathering has been reported in the Dagshai Formation, in the Himalayan foreland in India (Srivastava et al., 2013). Extensive Mesozoic laterite and bauxite deposits are described from regions such as the Urals, which hosts the second largest Ni mineral resource in Russia (Mikhailov, 2000). Other lateritic zones important for Ni, Co and Al ore are spread throughout Greece and Turkey (Mediterranean), central China and eastern Australia, which lie outside of the contemporary tropical belt (Fig. 1; Schulte and Foley, 2014; U.S. Geological Survey, 2015).

Weathered horizons buried under sedimentary packages could be of substantial importance not only for mineral deposit exploration but also for petroleum exploration. The presence of fractured basement reservoirs has been reported within the hydrocarbon industry for decades and regarded previously as non-economic (Gutmanis, 2005). In many cases, these basement reservoirs underlie regional unconformities in an area of increased porosity and permeability associated with in situ palaeoweathering processes, which allowed the accumulation of petroleum by a variety of charging mechanisms and migration routes (e.g., fault-valving, seismic pumping and downward migration; Gutmanis, 2005 and references therein). The exploration for regolith packages beneath sedimentary sequences is thus also a target for petroleum exploration. A future target for research will be to study the weathering processes at a larger scale, which may include offshore environments for which information is limited, to better understand how weathering profiles may be generated and preserved in modern landscapes.

## 2. Insights on the challenge of mineral exploration through cover

### *2.1. Historical perspective and insights on metal dispersion through weathered cover*

In the first part of this Special Issue, Butt (2016–in this issue) presents a comprehensive overview of the development of regolith exploration geochemistry through time, specifically for tropical and subtropical environments. Butt (2016–in this issue) takes us from the earliest Neolithic times when people manufactured tools and utensils out of diverse rock types, to the times of the pioneering geochemical surveys in Africa (~1950–1970), and the development of the concept of landscape geochemistry. One of the key points drawn by Butt (2016–in this issue) is that the successful application of exploration geochemistry in RTDs requires an understanding of the evolution of that geochemistry as the landscape itself evolves.

Following up the historical perspective presented, Anand et al. (2016b–in this issue) present a review of the mechanisms capable of transferring metals through transported cover to the surface, through the phreatic and vadose zones. The authors discuss a wide spectrum of metal transport mechanisms in various regolith environments reported in the literature, from groundwater and bubble transport, to gaseous, electrochemical and biological diffusion transfers. An example of the latter is the "termitaria" data presented for which termites are described as a direct mechanism of element transport when making their nests. The combination of identifying the different mechanisms and the understanding of the geochemical evolution of the transported cover through time, are critical in exploration in RTDs.

### *2.2. Case studies: China, Brazil and Australia*

In the second part of this Special Issue several case studies are presented from three diverse regolith-dominated settings. In the first case, Xueqiu et al. (2016–in this issue) present several case studies discussing how surface geochemical exploration has played an important role in discovering new ore deposits in the ~4 million km$^2$ within basement rock under cover in China. In regions experiencing arid to semi-arid desert conditions, fine clay fraction horizons in soil are a good medium to sample in regional geochemical surveys to highlight geochemical anomalies related to sandstone-type U, Au and base metal deposits; whereas in laterites, instead, nanoparticles (1–100 nm) of Au and Cu were reported to migrate through the transported cover and were found on the fine fractions of soils containing clays (<0.05 mm), colloids, oxides and organic matter (Yueyang ore deposits at the Zijin Au–Cu–Ag field).

In the second case study Porto (2016–in this issue) examines an area in Brazil, located where the world-class Carajás Mineral Province is, to explore the lateritic gold deposit of Igarapé Bahia, which is buried by

~80 m of saprolite and latosol. Porto describes how routine soil sampling adopted in exploration campaigns in the Carajás region may be misleading, due to the transported nature of the latosol sampled. In addition, Porto (2016–in this issue) describes the effectiveness of lag sampling in the Amazon region, which has never been reported before.

The third case study presented by Anand (2016a–in this issue) is an overview of regolith-geochemical work in the Mt Isa region, Queensland, Australia. The region was subjected to erosion, deposition and weathering during the Mesozoic and Cenozoic, to form complex landscapes and regolith. The broad effects of this weathering history are recorded in the landforms and regolith, hence they form an appropriate framework for describing and interpreting the geochemical patterns. Anand (2016a–in this issue) evaluates different sample media in a wide variety of deposits representing diverse regolith environments. Geochemical dispersion processes and models are presented for each type of terrain regolith-landform mapping, regolith stratigraphy and origin of regolith materials are critical to understand, in order to correctly identify appropriate sample media; these elements play an important role in subsequent data interpretation.

### 2.3. Diverse exploration approaches through cover: the southeast Yilgarn Craton/Albany–Fraser Orogen margin

The last part of this Special Issue presents four distinct exploration methodologies used in mineral exploration in a specific area of Western Australia, which are envisioned to be combined in a unique integrated protocol for future research studies.

González-Álvarez et al. (2016a–in this issue) present a large-scale study on palaeolandscape in the Yilgarn Craton and the Albany–Fraser Orogen in the south of Western Australia. The authors describe a palaeolandscape influenced by transgression–regression sea level changes that resulted in the formation of a coastal landscape dominated by islands and estuarine zones, which were subsequently covered by other sediments. This geological history sets the regolith in this region apart from the adjacent fluvially-dominated Yilgarn Craton, which demonstrates the importance of understanding the evolution of landscapes in more accurately developing mineral exploration protocols in both regions.

Salama et al. (2016–in this issue) discusses the significance of weathering and regolith evolution at the Neale tenement, in the northeast Albany–Fraser Orogen margin. In this study the authors integrate landscape evolution with mineralogical and geochemical variations of the regolith and basement bedrock, to better characterize the relationship between the geochemistry of the basement and the cover. Salama et al. (2016–in this issue) debate that the residual weathering profile developed under warm and humid climatic conditions over sheared granitoids. The authors describe a residual Au anomaly in the lower ferruginous saprolite above a Au-bearing mafic intrusion with no expression at surface, and a Au anomaly in the transported cover. Their integrated study allowed them to discriminate the origin and importance of the geochemical anomalies present in the cover.

González-Álvarez et al. (2016b–in this issue) report on two case studies on airborne electromagnetic (AEM) conductivity models resulting in a complete 2D regolith model at the prospect scale (Neale tenement), assisting in the generation of a geochemical dispersion model for the area. In the second AEM exercise, the authors delineate the geometry of a palaeochannel saturated with hypersaline groundwater. AEM data, integrated and constrained in the geological context, is presented as one of the most promising tools to understand the architecture of the cover.

Satellite imaging and the use of hyperspectral technologies are presented by Laukamp et al. (2016–in this issue). The authors recommend the use of proximal and remote spectroscopic characterization of regolith as a tool for rapid characterization of the regolith units, as well as for mapping extensive areas. The authors describe this exercise over the same Neale tenement area as in Salama et al. (2016–in this issue) and González-Álvarez et al. (2016b–in this issue), to exemplify how diverse techniques contribute different aspects to the modelling of the regolith cover. The use of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data suggested the presence of three different major regolith landforms: erosional, depositional and relict. These were used to produce a regolith map of the area for transported and in situ regimes.

Whilst our understanding of how weathering complexity evolves through geological time progresses, and of how ore deposit footprints can be linked to landscape geochemistry changes, mineral exploration paradigms will shift. Tracking the geochemical footprint of a mineral system could be blocked or distorted by hundreds of metres of transported cover, which may indicate dozens or hundreds of millions of years of sedimentation and/or climatic changes, is a strategic challenge for mineral exploration in the 21st Century. To accomplish significant advances in this challenge demands a deep revision of the traditional approaches on deep weathering in Tropical and non-tropical areas as well as the articulation of truly cohesive and multidisciplinary mineral exploration models.

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