

Can geophysics and geochemistry combine to detect mineralisation under transported cover?

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SUMMARY

The oxidation of Fe-containing sulfide mineralization can lead to the development of natural galvanic cells that are characterized by a reduced acid chimney above the mineralization itself and pH-redox controlled chemical haloes surrounding the chimney. Such chimneys may extend through overlying transported regolith cover of varying thicknesses and composition, altering regolith mineralogy (changes to clays, loss of carbonates), element distribution patterns and geophysical characteristics such as electrical conductivity (EC). This paper compares EM and geochemical profiles in transported regolith over porphyry style Au-Mo-Cu mineralization at Mandamah (NSW) and MVT style Pb-Zn mineralization at Pitchi (Iran).

At Mandamah, mineralisation is buried under 30 m of residual regolith and a further 50 m of re-weathered alluvium. Mineralised zones that intersect the base of weathering are characterized by low EM and EC in the upper 6 m of the transported regolith profile. This can be related to changes in clay mineralogy and the destruction of carbonates caused by an acid chimney that formed during a “prograde” phase of regolith development. These patterns are also variably reflected in soil pH and the distribution of selectively-extracted Ca, Mg, S, Ba and REE in the upper part of the transported regolith profile, but generally not in the elements of economic interest (Au, Cu or Mo). At Pitch carbonate-hosted Pb-Zn mineralisation is covered by 80 m of barren dolomitic sedimentary rocks and a thin layer of alluvium and colluvium. There is an increase in the EM and EC as well as Na and S in the transported regolith above mineralisation and adjacent low EC values, but again no detectable patterns in the main ore-related metals. The combined geochemical and (EM) geophysical approach provides a new approach to exploration in areas with economically prospective geology but where mineralization is buried by various forms of cover including transported regolith.

Key words: Electrical conductivity, EM, geochemical dispersion, cover.

INTRODUCTION

Many regions of the world are dominated by areas of transported regolith cover. Such cover can restrict the vertical migration of ions from oxidising mineral deposits by mass transfer processes such as diffusion or advection, and the development of geochemical anomalies at surface. The cover can also significantly interfere with magnetic and electromagnetic geophysical mapping methods commonly employed in exploration for primary sulfide ore bodies (Cohen *et al.*, 2010). The rewards for development of reliable techniques for detecting subtle dispersion haloes the may develop in transported cover is the gain of large tracts of territory with high mineral potential which have been previously under-explored.

Various studies have, however, demonstrated that secondary geochemical dispersion haloes and mineralogical changes do develop within even substantial thicknesses of transported regolith cover, but which may not be detectable just by examining variations in the concentration of the elements of economic interest (Mann *et al.*, 1998; Smee, 1998; Kelley *et al.*, 2003). One mechanism proposed is enhanced ion migration due to electrochemical gradients and vertical H⁺ flux emanating from oxidising sulfide bodies (Govett, 1976; Smee, 1983; Hamilton, 1998; Heberlein and Samson, 2010). Whereas most studies have focussed on the geochemical patterns that develop at surface, such acidic chimneys developing in regolith above oxidising sulfide deposits will also change the original regolith mineralogy, including loss of carbonates and changes to clays at surface (Smee, 1983, Mokhtari *et al.*, 2009a; Cohen *et al.*, 2010) including cation exchange capacity and soil ionic conductivity (Govett, 1974). This, in turn, should be reflected in changes to the geophysical characteristics of the transported regolith such as the EM response.

Whereas ground conductivity measurements have been employed extensively by soil scientists to map soil salinity for agricultural purposes (Triantafilis *et al.*, 2001; Huang *et al.*, 2015), and boundaries of structures within regolith and between regolith and bedrock (Kriege, 2004), it has not been used specifically to detect the effects related to dispersion from oxidising sulfides. This paper compares shallow EM patterns and geochemical trends in transported regolith profiles above the Mandamah porphyry Au-Cu-Mo prospect in central NSW and the Pitchi Mississippi Valley Type Pb-Zn deposit at Irankuh, Iran.

CASE STUDY 1 – MANDAMAH PORPHYRY AU-CU-MO (REVISITED)

The sub-economic porphyry Cu-Au-Mo Mandamah deposit (~0.3% Cu) is hosted by altered andesitic Siluro-Ordovician Gidginbung Volcanics. The deposit is overlain by 30 m of *in-situ* (residual) regolith and 50 m of alluvium. The upper 70 cm of the profile contains discontinuous carbonate-rich zones, overlying silts that are acidic (pH <5) and containing Fe-rich mottling. Elevated Cu values (above 80 ppm) in the saprock are generally restricted to the zone directly overlying the mineralisation (Figure 1). There is substantial lateral dispersion in the overlying saprolite and the base of the transported cover. The upper 20 m of transported cover contains a few weakly elevated Cu values above and to the west of the underlying mineralisation. Total and selective geochemical extraction patterns displayed no indication of elevated values for the key commodities in the underlying mineralization (Cu, Mo and Au) but loss of Ca, REE and other carbonate-hosted elements above mineralisation (Dalrymple *et al.*, 2005; Mokhtari *et al.*, 2009a).

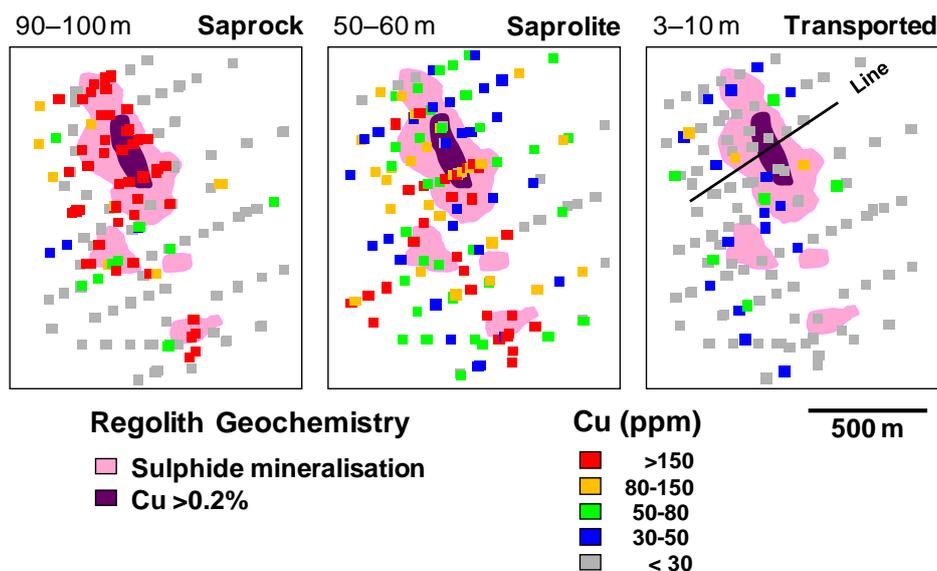


Figure 1: Location of deeply buried sulphide mineralisation (defined using a 0.2% Cu cut-off in bedrock) and spatial variation in Cu contents of various intervals of residual and transported regolith at Mandamah.

Various soil physical and geochemical parameters were measured on regolith profiles collected from a series of pits and 1.8 m cores at 10 m spacing along a number of traverses over the projected zone of mineralisation. At each site, the shallow EM response was measured using a Geonix frequency-domain EM38 unit that provides around 1.5 m penetration depending on dipole orientation. The cores and trench faces were sampled at 20 cm intervals down to a depth of 1.8 m. The samples were disaggregated, sieved to <180 µm and analysed for EC and pH on a 1:5 soil:water slurry, methylene blue cation exchange capacity (CEC), as well as a range of aqua regia-extractable element concentrations by ICP-MS at Acme Laboratories (now Bureau Veritas), Canada.

Along the line indicated in Figure 1, the EM data display a zone of low conductivity above the eastern (and high grade) section of buried mineralization where the mineralization extends above the base of weathering (Figure 2). It should be noted that mineralization is defined by the Cu values and need not necessarily correspond with the distribution of other sulfides such as pyrite. Chemical analysis of the regolith shows electrical conductivity to be a function of CEC and the spatially correlated with aqua regia-extractable Na. Calcium displays strong depletion within the low conductivity zone, but elevated values to the sides (and this is consistent with the “rabbit ears” patterns that characterize the electrochemical dispersion models (Govett *et al.*, 1987). The alkaline pH zone does not, however, correspond with elevated contents of pedogenic carbonates.

Despite a high regolith pH, the acid neutralizing capacity of the low-conductivity/low-Ca zone is significantly less than zones of similar pH away from mineralization (over the background) but which have higher Ca values. In a regolith evolution model developed for Mandamah (Mokhtari *et al.*, 2009a,b), the alteration of clays and loss of Ca from the upper parts of the transported part of the profile occurred during a “prograde” phase under elevated water tables and subsequent increase in Na following the transition to more arid conditions and inactivation of the chimney that resulted in low mobility for exchangeable ions and conductivity low over mineralization.

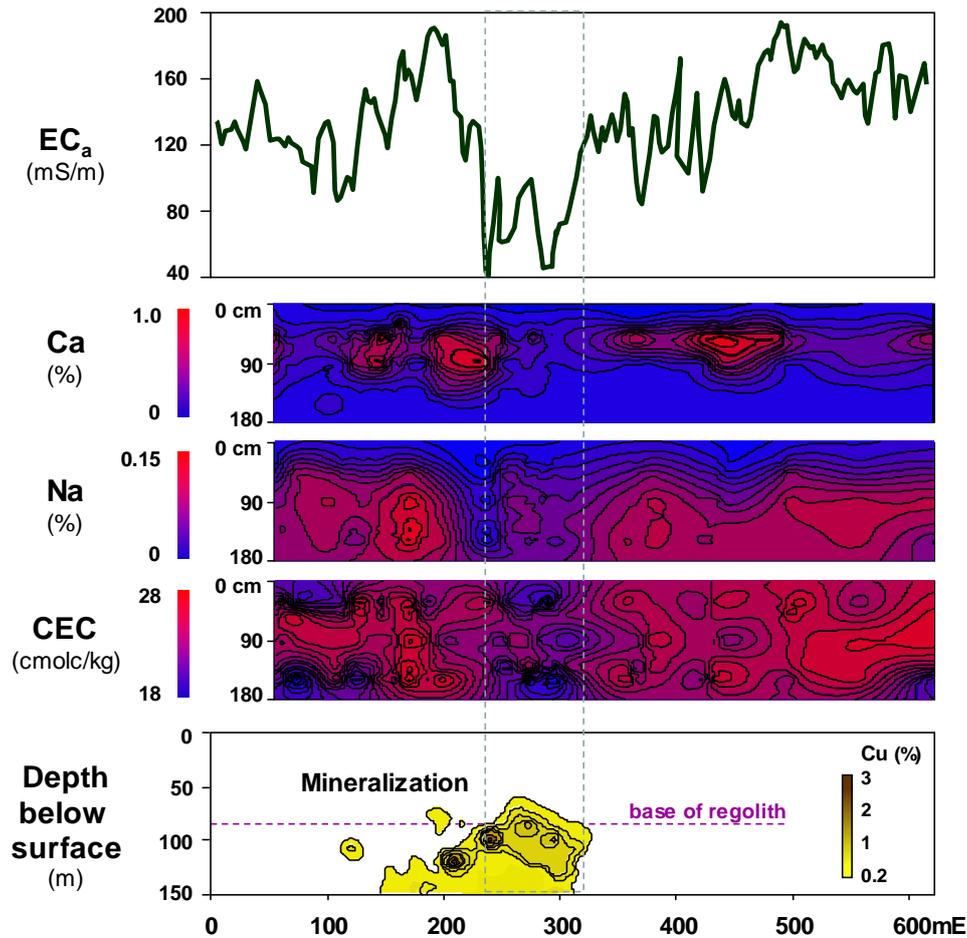


Figure 2: Comparison between EM response (EM38 in horizontal mode), Ca, Na and CEC in upper transported regolith across mineralisation at Mandamah (after Mokhtari *et al.*, 2009b).

CASE STUDY 2 – PITCHI MVT DEPOSIT, PITCHI

The MVT-style Pitchi Pb-Zn mineralisation is buried under alluvium and colluvium that varies in depth from 1 m to the southern of the mineralisation up to 10 m to the north. Mineralisation is further buried under ~65m of barren dolomite. As with Mandamah, the shallow EM response was measured using a Geonics EM38 device. Measurements were conducted on three profiles to the east of the main pit (Figure 3). Profile A was subsequently trenched and 201 regolith samples collected from the upper 0.5-3 m of the profile (depending on transported regolith depth). These samples were sieved to <180 μ m and splits analysed for EC and pH on a 1:5 soil:water slurry, as well as a range of aqua regia-extractable element concentrations by ICP-MS at Actlabs, Canada. Results of inferred EC measurements (based on the EM data) along the three profiles are plotted in Figure 4. The geochemical analyses from Profile A trench were interpolated by inverse distance weighting (IDW) and profiles for selected variables are also shown in Figure 4.

Although the EM response is somewhat erratic, there is a distinct EC_a low above the projected southern side of the mineralisation on all profiles, and peak EC values above the centre of mineralisation in Profiles A and C. The low EC values on the northern ends of the profiles are not associated with known underlying mineralisation. The measured EC values and pH of the soils increase substantially over the projected blind ore, and matches the patterns for Na and S (implying most of the conductivity to be associated with Na^+ and SO_4^{2-} , the latter possibly derived from oxidising sulfides). As in the case of Mandamah, the elements of economic interest related to the primary mineralisation (Pb and Zn) display no distribution patterns in the transported regolith that can be related to underlying mineralisation. Calcium does display depletion in the regolith at ~120 cm depth above mineralisation, but otherwise does not display the same depletion patterns that were observed at Mandamah. Despite high S (as sulfate), Ba is relatively depleted in the regolith over the projected mineralisation.

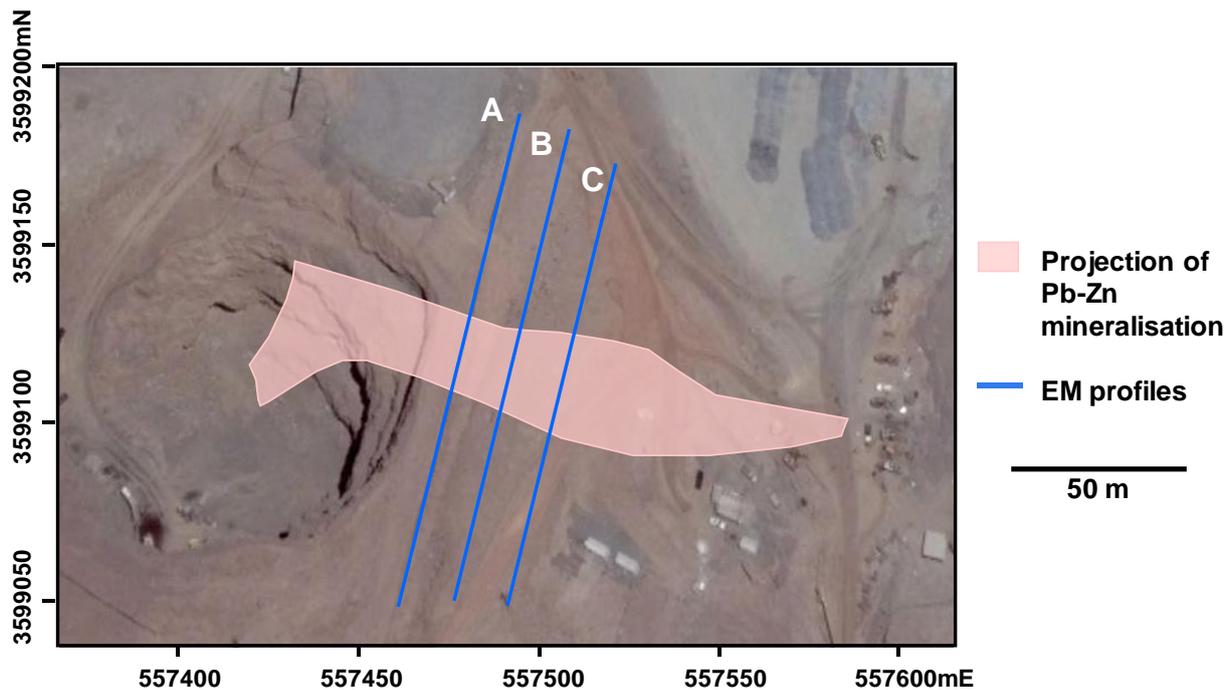


Figure 3: Aerial map of the Pitchi mine site with projection to surface of the buried Pitchi Pb-Zn mineralisation and three EM profiles.

CONCLUSIONS

Despite difference in deposit type and the nature of the transported regolith cover, both Mandamah and Pitchi are characterised by the lack of discernible geochemical signals related to commodity elements in the upper part of the regolith. Both deposits are characterised by patterns in shallow regolith EC (as reflected in both EM measurements and direct EC measurements on regolith samples) that can be spatially related to mineralisation. Both deposits display Ca and Ba depletion in the transported regolith over mineralisation. At Pitchi there is significantly elevated Na and S, as well as high EC values in the regolith, but the opposite pattern at Mandamah.

Work continues on developing a regolith evolution model for Pitchi, however, at both deposits the geophysical and geochemical patterns are consistent with the development in the current or previous weathering cycles of an acid reduced chimney within transported regolith cover above oxidising sulfidic mineralisation.

These studies indicate the potential use of shallow EM methods in detection of dispersion halos above deeply buried mineralization in transported regolith cover, in combination with measurement of various soil chemical parameters and regolith mapping.

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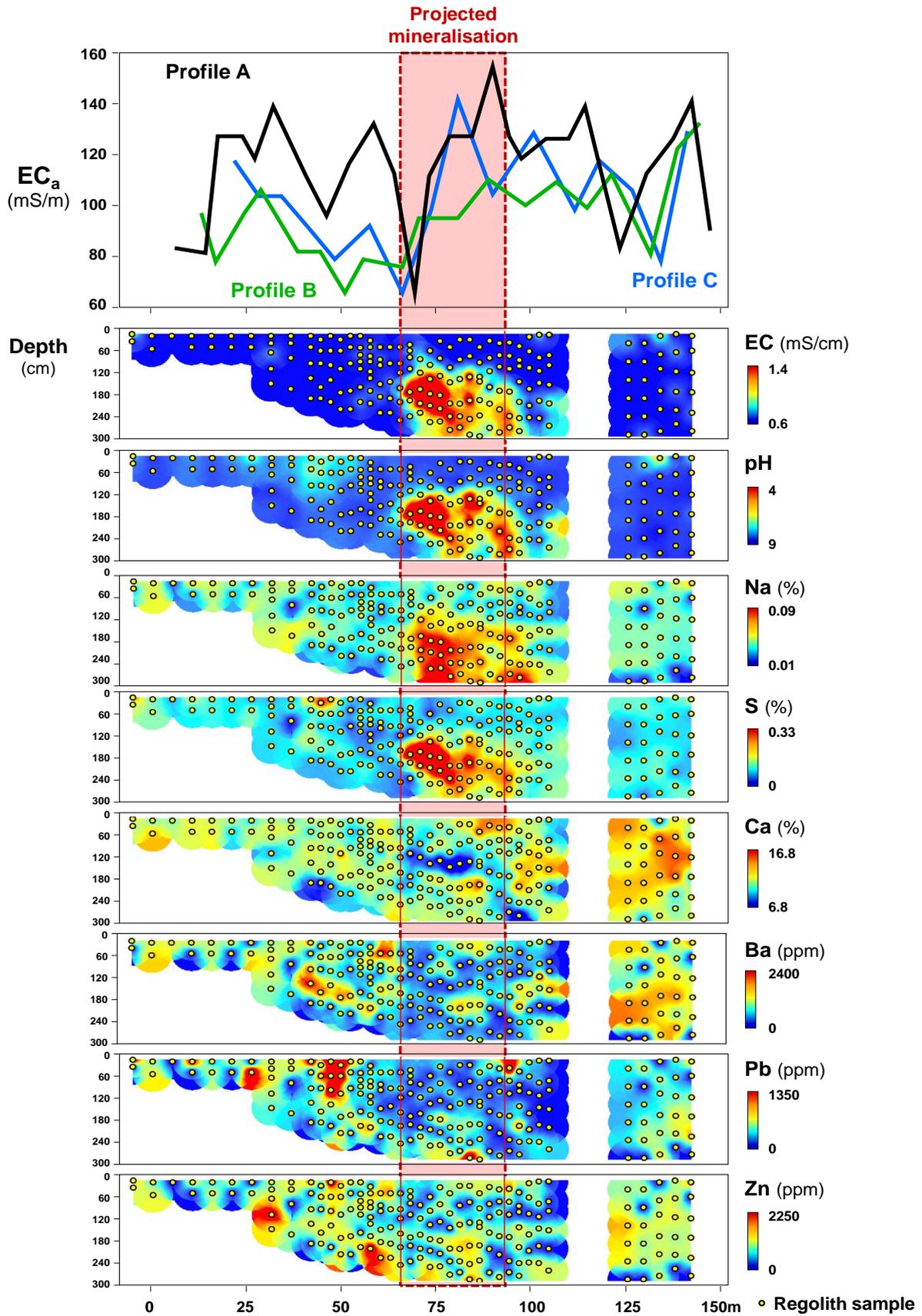


Figure 4: Comparison between EM response (EM38 in vertical mode) for profiles A, B and C and IDW-interpolated profiles of EC, pH and selected elements in regolith profiles from trench along profile A over the Pitchi blind Pb-Zn mineralisation.

REFERENCES

- Cohen, D.R., Kelley, D.L., Anand, R.R. and Coker, W.B., 2010**, Major Advances in Exploration Geochemistry 1998–2007: Geochemistry: Exploration Environment Analysis, 10, 3–16.
- Dalrymple, I.J., Cohen, D.R. and Gatehouse, S.G., 2005**, Optimisation of partial extraction chemistry for buffered acetate and hydroxylamine leaches: Geochemistry: Exploration, Environment, Analysis, 5, 279–285.
- Govett, G.J.S., 1974**, Soil conductivities: Assessment of an electrogeochemical exploration technique: Geochemical Exploration 1974, Association of Exploration Geochemists, 101–118.
- Govett, G.J.S. and Atherden, P.R., 1987**, Electrogeochemical patterns in surface soils: Detection of blind mineralization beneath exotic cover, Thalanga, Queensland, Australia: Journal of Geochemical Exploration, 28, 201–218.
- Govett, G.J.S., 1976**, Detection of deeply buried and blind sulphide deposits by measurement of H⁺ and conductivity of closely spaced surface soil samples: Journal of Geochemical Exploration, 6, 359–82.
- Hamilton, S.M., 1998**, Electrochemical mass-transport in overburden: a new model to account for the formation of selective leach geochemical anomalies in glacial terrain: Journal of Geochemical Exploration, 63, 155–172.
- Heberlein, D.R. and Samson H., 2010**, Comparative study of partial and selective extractions of soils over blind porphyry copper-gold mineralization at Kwanika and Mount Milligan, central British Columbia (NTS 093N/01./19): fieldwork, soil conductivity and pH results. Geoscience BC Summary of Activities 2009, Geoscience BC Report, 11–24.
- Huang, J., Mokhtari, A.R., Cohen, D.R., Monteiro Santos, F.A. and Triantafyllis, J., 2015**, Modelling soil salinity across a gilgai landscape by inversion of EM38 and EM31 data: European Journal of Soil Science, 66, 951–960.
- Kriege, R., 2004**, Determination of interfaces within the regolith using near-surface geophysical and petrographic methods at the Whirling Dervish gold project, Western Australia: I.C. Roach (ed.), Regolith 2004. CRCLEME, Perth.
- Mann, A.W., Birrell, R.D., Fedikow, M.A.F. and De Souza, H.A.F., 2005**, Vertical ionic migration: mechanisms, soil anomalies, and sampling depth for mineral exploration: Geochemistry - Exploration, Environment, Analysis, 5, 201–210.
- Mokhtari, A.R., Cohen, D.R. and Gatehouse S.G., 2009a**, Geochemical effects of deeply buried Cu–Au mineralization on transported regolith in an arid terrain: Geochemistry - Exploration, Environment, Analysis, 9, 227–236.
- Mokhtari, A.R., Cohen, D.R. and Gatehouse S.G., 2009b**, Geophysical support for geochemistry in detecting deeply buried mineralization: a case study from Mandamah, Australia: Explore, 145.
- Smee, B.W., 1983**, Laboratory and field evidence in support of the electrogeochemically enhanced migration of ions through glaciolacustrine sediment: Journal of Geochemical Exploration, 19, 277–304.
- Smee, B.W., 1998**, A new theory to explain the formation of soil geochemical responses over deeply covered gold mineralization in arid environments: Journal of Geochemical Exploration, 61, 149–72.
- Triantafyllis, J., Odeh, I.O.A. and McBratney, A.B., 2001**, Five geostatistical models to predict soil salinity from electromagnetic induction data across irrigated cotton: Soil Science Society of America Journal, 65, 869–878.