Association of mineral spectral signatures with gold and uranium mining and off-site impacts in a seasonal summer rainfall environment - the Witwatersrand Basin, South Africa

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ABSTRACT

Acid rock drainage (ARD) and tailings dust are hazards associated with gold and uranium mine residue deposits (MRDs) on the Witwatersrand basin, which is located on the Highveld of South Africa. Such hazards can impact negatively on human and environmental health, and consequently on sustainable land use. Our objective was to determine which remotely-sensed minerals are the most conservative signatures of different types of MRD (rock, sand or slime), emission pathways and land contamination. The Highveld is highly seasonal, with summer rainfall of 500-750mm and annual evapotranspiration (ET) of >2.5 times mean annual precipitation (MAP), which suggests that efflorescence minerals could be used to identify sources of acid generation and off-site impacts. Greater Johannesburg has experienced intensive historical mining, therefore sections with a diversity of substrata and land-uses were selected as representative study sites, i.e. a polygon of the East Rand and part of the Central Rand, and two 1km wide transects from the West to East Rand.

A Geographical Information System (GIS) was constructed using historical aerial photographs (1938, 1964 and 2003), spatial data (i.e. geology, hydrology, land use and MRD geotechnical features) and semi-quantitative thematic images of eight minerals, which we considered potential indicators of MRD emissions by different transport routes under Highveld conditions. We chose two primary minerals characteristic of gold-bearing tailings (pyrophyllite and chlorite), three secondary sulphate minerals with distinct precipitation chemistry and solubility (copiapite, jarosite and gypsum), two contrasting iron oxides (goethite and haematite), and a potential surrogate signature for uranium-bearing residues ('mincrust'). Thematic images were compiled for pyrophyllite, chlorite, copiapite, jarosite and mincrust from data acquired for the East and Central Rand polygon over two years (2002 and 2003) in two seasons (Austral spring and summer) by the TERRA satellite's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor, and for all eight minerals from hyper-spectral data, acquired for the West to East Rand airborne transects in August 2005 with a push-broom AISA-ES sensor. The airborne transects were replicated at 10,000 and 25,000 fagl in order to assess the influence of altitude on mineral detection and spatial extent. Ground-based data acquisition using an analytical spectral device (ASD) was undertaken simultaneously with sampling for chemical analysis during the airborne campaign and was conducted retrospectively for the ASTER imagery. The normalised difference vegetation index (NDVI) was derived from both the ASTER and hyper-spectral data, and was used to identify any masking effect of active vegetation.

Regression analysis was used to test agreements between ASTER or airborne data, mineral spectra from the USGS spectral library, and ground-truth data. Statistical significance was taken at the 5% level, with the Bonferoni adjustment used for multiple comparison tests. Seasonal impacts on mineral detection by ASTER were assessed using Friedman ANOVA and Wilcoxon matched pairs tests to examine differences in the spatial

extent of minerals, and McNemar tests for differences in the probability of detecting minerals. Associations between detected minerals and features (i.e. type of mine residue, spillage, land-uses and vegetation cover) were tested using chi-square (X^2) contingency tables with standardised (Pearson) residuals and odds ratios used to examine the lack of independence.

Overall, chlorite was found to be an unreliable indicator, whereas mincrust, jarosite, pyrophyllite and copiapite were reliably associated with mine residues, in that order, with mincrust the least masked by active vegetation. The most extensive detection of these four minerals was after a few dry days following the first spring rains. Distinct zonation of copiapite and jarosite, corresponding to substrate pH, was clearly visible on MRDs, whereas mincrust and pyrophyllite distributions were independent of pH. Gypsum was strongly associated with ARD-contaminated evaporative sinks on dolomitic substrata, including areas being irrigated with gypsiferous water. The iron oxides were associated with bare soils but could only be discriminated between at low altitude, with goethite detected at higher concentrations on ARD-contaminated than on uncontaminated soils. Pyrophyllite and copiapite were enriched on industrial and business lands, and appeared to be associated with tailings dust capture by large roofs; and, in the case of copiapite, oxidation. Jarosite and mincrust were reliable indicators of mining residues. Jarosite was consistently detected on MRDs and on some soils that had previously supported MRDs (`footprints'). Mincrust was consistently detected on both the former and also on spillages, reef weathering deposits in drainage lines, wetlands, waste rock used in construction, sand in golf course bunkers and old irrigated lands, which had been recently developed. These sites contained uranium in localised surface deposits or crusts at concentrations of 50 to 800 ppm. Mincrust was detected on some irrigated croplands with an odds ratio of 10 to 36 times greater than for rain-fed croplands, which suggests an aqueous/evaporative pathway from contaminated sources of irrigation. In conclusion, although a combination of pyrophyllite, copiapite, jarosite, mincrust, gypsum and goethite can be used to screen entire gold and uranium mining districts on the Highveld for mine residues and associated contamination, we found that jarosite was the most continuous signature of MRDs, whereas mincrust was a consistent surrogate indicator of off-site contamination on diverse substrata. Further assessment of mincrust mineralogy, speciation chemistry and stable isotope ratios is recommended to confirm the identity and origins of off-site uranium-bearing materials.

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