Mapping porosity and density changes in soil and regolith from 256-channel radiometric data

Kirsty Beckett
CRC LEME Curtin University of Technology,
Kent Street, Bentley, Western Australia
kirsty.beckett@riotinto.com

Rio Tinto Iron Ore
152-158 St George's Tce, Perth, Western Australia

SUMMARY

Gamma ray emissions at 1120 keV and 1764 keV produced from ^{214}Bi (uranium-238 decay series daughter product) are emitted during the same decay reaction with the same probability of emission during decay. Thus, as uranium concentration varies, the ratio of 1120 keV to 1764 keV should remain stable. However, the lower 1120 keV energy is more susceptible to backscattering and normal Compton scatter than the stronger 1764 keV energy, where the probability for scatter to occur is correlated to the density and thickness of the absorber. In natural settings, soil and/or bedrock acts as an absorber. Consequently, as density or thickness of the soil and/or bedrock increases, the probability of scatter increases. Thus changes in the 1120 keV to 1764 keV ratio may indicate changes in soil thickness and/or density. By processing standard 256-channel radiometric data with multispectral processing techniques, ^{214}Bi 1120 keV gamma rays can be isolated in addition to standard ^{214}Bi 1764 keV. This case study illustrates how the spatial variability of 1120 keV to 1764 keV ratios highlight and map changes in soil thickness and/or density.

Key words: radiometrics, soil, regolith.

INTRODUCTION

In the 1940s, scientists began to examine natural background radioactivity in geology, vegetation, and soil (Marsden and Watson-Munro, 1944; Sizou and Hoogteijling, 1947; Trener and Scaramucci, 1948). Natural radionuclides were observed to originate from bedrock geology. Subjected to local landform processes and under different environmental conditions, radioactivity was observed to change; a function of the physical and chemical mobility of natural radionuclides. In soil and regolith, the processes controlling radioactivity changes were attributed to (after Talibudeen, 1964), in order of importance:

1. particle size distribution from erosion/deposition processes;
2. leaching;
3. frequency and intensity of wet and dry localised cycles;
4. Eh/pH conditions;
5. organic matter content; and
6. sesquioxide and carbonate content.

These initial studies into natural radioactivity and radionuclides utilised geochemical analysis. This highly specialised analytical method was relatively slow and expensive. With the development of Geiger-Muller counters, then later scintillometers, radioactivity could be rapidly measured by laypersons, accelerating the number of baseline studies of natural radioactivity in geology, vegetation, and soil conducted (Kiss *et al.*, 1988). Subsequently, inventories of radioactive response were established. Then, as improvements in scintillation technologies enabled specific radioelements to be identified, studies comparing scintillation results with standard geochemical techniques were spawned (de Lange, 1959; Purvis and Buckmeier, 1969), including evaluations of airborne counting and scintillation systems (Darnley and Feet, 1968; Darnley and Grasty, 1971).

In the last decade, arguably the most significant advance in the study of radioactivity with NaI spectrometry has been a reduction in the acquisition costs of high spatial resolution, sample intervals between 5 m and 50 m a part, 256-channel gamma ray NaI spectrometry (radiometric) surveys. This cost reduction has enabled radiometrics to become an economical mapping tool for small, low profit projects such as soil mapping.

This paper contributes to the development of radiometric techniques as soil and regolith mapping tools by examining soil characteristics and radiometric response using non-standard radiometric processing and interpretation methods. By modifying the manner through which 256-channel radiometric data is processed, this paper demonstrates that it is possible to isolate gamma ray energies whose physical relationships can be used to map soil and regolith characteristics; specifically changes in porosity and/or density. With high spatial resolution data, these characteristics can be interpreted to map soil or regolith processes.

The standard processing methodology for 256-channel radiometric data (IAEA, 2003) was developed to calculate the equivalent ground concentration of parent radionuclides potassium-40, thorium-232, and uranium-238. Thus historically, mapping studies using radiometric data (eg Wilford, 1992; Bierwirth, 1996; Cook *et al.*, 1996; Wilford *et al.*, 1997) have focused on the contribution and distribution of these radioelements in order to interpret soil or regolith units.

However, the 256-channel gamma ray energy signature recorded at each sample location during a survey contains more information than just that used to calculate radioelement concentrations. As described above, the physical and chemical environment surrounding a radioactive source can change the way the source and its decay products behave in the environment, changing its radioactivity. The physical location of the source in the soil profile, the soil moisture content, soil density and many other factors influence the gamma ray emission response detected at the surface. Changes to the gamma ray emissions of energies within the detection range of the system are recorded in the 256-channel response. By mapping individual gamma ray emissions spatially, the patterns or spatial variability can be used to map changes to soil and regolith properties.

Within the uranium-235 decay series, decaying ^{214}Bi emits 1764 keV and 1120 keV gamma rays simultaneously with equal probability. Thus, without interference, the ratio of detected 1120 keV to 1764 keV should remain constant even as the count rate changes. However, the lower 1120 keV energy is more susceptible to backscattering and normal Compton scatter than the stronger 1764 keV energy (Adams and Dams, 1970). The probability for scatter to occur is correlated to the density and thickness of the absorber such that, as the thickness and/or density of the absorber increase the probability of scattering increases, and the ratio of 1120 keV to1764 keV gamma rays changes.

In natural settings when surveying over soil or regolith, the absorber is the overlying soil or regolith located between the gamma emission source in the soil, regolith, or bedrock and the detector. Consequently, as the density or thickness of the soil or regolith increases the probability of scatter increases and fewer 1120 keV energy gamma rays are likely to be detected. Thus changes in the ratio of 1120 keV to1764 keV gamma rays should represent changes in the soil/regolith density or thickness. Presented spatially, areas with similar soil/regolith thickness or density above the source should produce clusters of similar 1120 keV to1764 keV ratios. Boundaries between the clusters can be used to map changing soil/regolith properties.

METHOD AND RESULTS

A multispectral processing technique developed to isolate peak gamma ray energies from standard 256-channel NaI spectrometry data (Beckett, 2004) was employed to extract 1764 keV and 1120 keV gamma rays from a high resolution (25 m sample spacing), 256-channel NaI radiometric data acquired over paddocks and wheat fields in Elashgin, Western Australia. Gamma ray counts for the 1764 keV and 1120 keV channels were subsequently gridded and a greyscale image of the ratio of the gridded 1764 keV and 1120 keV count rates was produced. The resulting greyscale image of the 1120 keV to1764 keV ratio is henceforth referred to as a uranium ratio image.

The Elashgin survey area was previously mapped (Cooper *et al.*, 2001) using standard soil mapping techniques integrated with an interpretation of standard processed, regional-scale radiometric data. The soil information produced from the Cooper *et al.* (2001) study was used as the control data set, against which interpretations of the uranium ratio images (Figures 1 to 3) were compared.

Figure 1 shows an area 500 m by 500 m wide over two regionally significant soil types: valley clay – a clay loam soil and valley duplex – a sandy loam over clay soil. Pore space within the top 40 cm (the approximate penetration range of gamma rays in soil) of the valley clay is significantly lower than in the equivalent depth of the valley duplex soil (Cooper *et al.*, 2001). As a result, the valley clay soil is more susceptible to waterlogging. The changing porosity within the top 40 cm should alter the 1120 keV to1764 keV ratio, reducing the 1120 keV count rate over the denser, lower porosity soil unit. This porosity change is borne out in the Figure 1 uranium ratio image by differing shades of grey: medium grey in the north-west corner representing the medium porosity in the sandy loam over clay soil, dark grey in the north-east corner over the valley clay (clay loam) soil, and light grey over the sandier loamy sand over clay soil.

However, a change in the uranium ratio does not necessarily dictate a change in soil type. In Figure 2, the 500 m by 500 m area covers a single soil unit – sandy loam over clay. As the depth of the sandy loam soil horizon increases the average density of the soil within the top 40 cm changes. The porosity change is reflected in the Figure 2 uranium ratio image by the lighter grey shades over the deeper, higher porosity, sand cover over clay in the north-west corner and relatively darker grey shading of the shallower sandy loam cover over clay in the south-east corner. For this Elashgin area, this increase in sand cover marks the edge of a palaeochannel that preferentially conveys saline groundwater through the area.

In other locations, depth variations in the sand horizon may have other implications. For example, controls on root depth penetration, soil water holding capacity, or soil waterlogging potential. Similar uranium ratio response within the same soil unit as identified in Figure 2 could also be indicative of soil degradation. Dispersed clay that clogs pore spaces, degrading the soil will increase the density of the top soil cover. The degraded soil will exhibit darker shades of grey, lower 1120 keV to 1764 keV ratio, in the uranium ratio image when compared with the same, healthy soil type.

Delineating the edge of subcrop or outcrop in standard radiometric imagery from rocky soil can be difficult where both outcrop and soil express the same or a graduated radiometric response. However, there is a notable difference in the density of the top 40 cm of outcrop compared to 40 cm of rocky soil. In Figure 3, the solid granite outcrop produces strong 1764 keV response from the top 40 cm of the outcrop, while the rock density scatters a significant proportion of the 1120 keV energies. Fractured rock in the soil surrounding the outcrop produces a similar 1764 keV response to that of the outcrop. However, within the rocky soil there is less scatter of the lower energy 1120 keV gamma rays through the top 40 cm of soil as a result of the fracturing, soil porosity and overall density decrease in the rocky soil compared to the solid rock. The density decrease in the rocky soil enables more 1120 keV energy gamma rays to reach the detector. The result, as illustrated in the Figure 3 uranium ratio image, is darker grey shades over the outcrop and lighter grey shades over the rocky soil. The boundary between the outcrop and the rocky soil is easily interpreted to define the extent of solid rock within the top 40 cm soil profile.

CONCLUSIONS

The spectrometry information acquired during a standard 256-channel NaI radiometric survey can be used to produce more than maps of radioelements potassium, thorium, and uranium. By using non-standard processing methods, this paper demonstrated through the use of ^{214}Bi gamma ray emissions 1120 keV and 1764 keV how the physical properties of gamma rays and their interaction with the local environment was used to map thickness and/or density changes in soil/regolith.

Gamma ray emissions with 1120 keV energy released during the decay of ^{214}Bi (uranium-238 decay series daughter product) are more susceptible to backscattering and normal Compton scatter than the stronger 1764 keV energy emitted during the same decay event. The ratio of 1120 keV to 1764 keV, presented as a greyscale image, highlighted locations where the density of overlying sediments in the top 40 cm changed. When this information was interpreted with an understanding of regional soil types, 1120 keV to 1764 keV (uranium) ratio imagery was interpreted to map changes in soil waterlogging susceptibility, palaeochannel formation, potential limitations on root depth penetration, soil water holding capacity, and potential soil degradation.

While this paper pertains specifically to ^{214}Bi gamma ray emissions and the soil properties they can help to resolve, other soil properties and environmental conditions can be delineated by examining the relationships of other separable gamma ray energies from the standard 256-channel NaI spectrum. For example, the physical and spatial relationships between ^{228}Ac peaks around 960 keV and 1620 keV and ^{208}Tl 2614 keV from the thorium-232 decay series have the potential to identify locations where decay daughter product ^{228}Th is separated from ^{232}Th within the local soil horizons (top 40 cm of soil). This relationship can be used to identify and map changes in soil chemistry or water movement.

ACKNOWLEDGMENTS

This work was supported by the Co-operative Research Centre for Landscape, Environment and Mineral Exploration (CRC LEME), the Co-operative Research Centre for Plant Based Solutions to Dryland Salinity, and Curtin University of Technology, Bentley, Western Australia.

REFERENCES

Adams, F., and R. Dams, 1970, Applied gamma-ray spectrometry: Pergamon Press.

Beckett, K., 2004, Airborne observations on the correlation between uranium and thorium radioelement channels in Western Australia Airborne Radiometric Surveys, *in* I. C. Roach, ed. Regolith 2004: Cooperative Research Centre for Landscape, Environment and Mineral Exploration (CRC LEME), 29–31.

Bierwirth, P., 1996, Investigation of airborne gamma-ray images as a rapid mapping tool for soil and land degradation, Wagga Wagga, NSW, Record 1996/22: Australian Geological Survey Organisation.

Cook, S. E., R. J. Corner, P. R. Groves, and G. J. Grealish, 1996b, Use of airborne gamma-radiometric data for soil mapping: Australian Journal of Soil Research; **34**, 183–194.

Cooper, S., N. Crossely, D. Cummins, G. Drysdale, R. Denham, P. Galloway, T. Lacey, H. Lauk, J. Smith, and J. Wayland, 2001, Elashgin focus catchment report: Department of Agriculture and Food, Government of Western Australia.

Darnley, A. G. and M. Fleet, 1968, Evaluation of airborne gamma-ray spectrometry in the Bancroft and Elliott Lake areas of Ontario, Canada: Proceedings of the fifth International Symposium on Remote Sensing Environment, Expanded Abstracts, 833-853.

Darnley, A. G. and R. L. Grasty, 1971, Mapping from the air by gamma-ray spectrometry, *in* R. W. Boyle, ed., Geochemical Exploration: Canadian Institute of Mining and Metallurgy, **11**, 485-500.

de Lange, P. W., 1959, The radiometric analysis of naturally leached uranium and thorium ore samples: Comparison of different methods: Journal of the South African Institute of Mining and Metallurgy, **60**, 640-656.

IAEA, 2003, Guidelines for radioelement mapping using gamma ray spectrometry data, technical report series, no. 1363: International Atomic Energy Agency.

Kiss, J. J., E. De Jong, and J. R. Bettany, 1988, The distribution of natural radionuclides in native soils of southern Saskatchewan: Canadian Journal of Environmental Quality, **17**, 437-445.

Marsden, E., and C. Watson-Munro, 1944, Radioactivity of New Zealand soils and rocks: New Zealand Journal of Science and Technology, **26B**, 99–114.

Purvis, A. E. and F. J. Buckmeier, 1969, Comparison of airborne spectral gamma radiation data with field verification measurements: Proceedings of the sixth International Symposium on Remote Sensing Environment, Expanded Abstracts, 553-564.

Sizou, G. J., and P. J. Hoogteijling, 1947, Radioactivity and granular composition of soil: Physica, **13**, 517-528.

Trener, G. B., and M. A. Scaramucci, 1948, Soil radioactivity of the surrounding Merano and of Lurisia (Cuneo): Ricerca Scientifica, **18**, 756-760.

Talibudeen, O., 1964, Natural radioactivity in soils: Soils and Fertilizers, **27**, 347-359.

Wilford, J. R., 1992, Regolith mapping using integrated Landsat TM imagery and high resolution gamma-ray spectrometric imagery – Cape York Peninsula, Record 1992/78: Bureau of Mineral Resources.

Wilford, J. R., P. N. Bierwirth, and M. A. Craig, 1997, Application of airborne gamma-ray spectrometry in soil/regolith mapping and applied geomorphology: AGSO Journal of Australian Geology and Geophysics, **17,** 201-216.

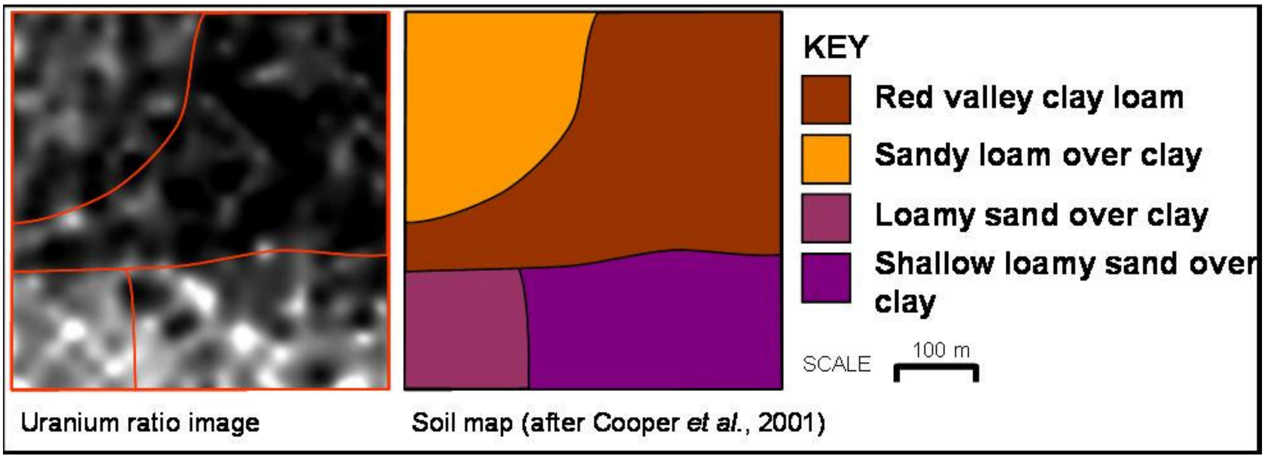

Figure 1. In the top 40 cm, loamy sand exhibits higher porosity than sandy loam, which in turn has more pore space than clay loam soil. The decreasing soil pore space increases the soil density, reducing the detected 1120 keV gamma ray energy count with respect to 1764 keV energies. As a result, the shade of grey within the uranium ratio image becomes darker with decreasing porosity.

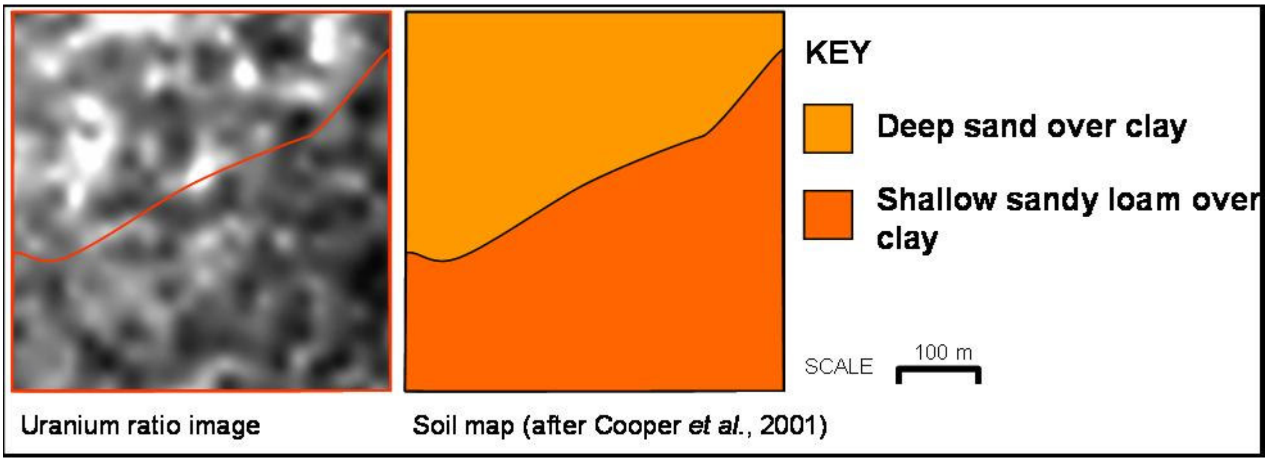

Figure 2. The increase in the uranium ratio response in the north-west corner highlights the increasing depth of sand cover over clay at the edge of a palaeochannel in this duplex soil unit.

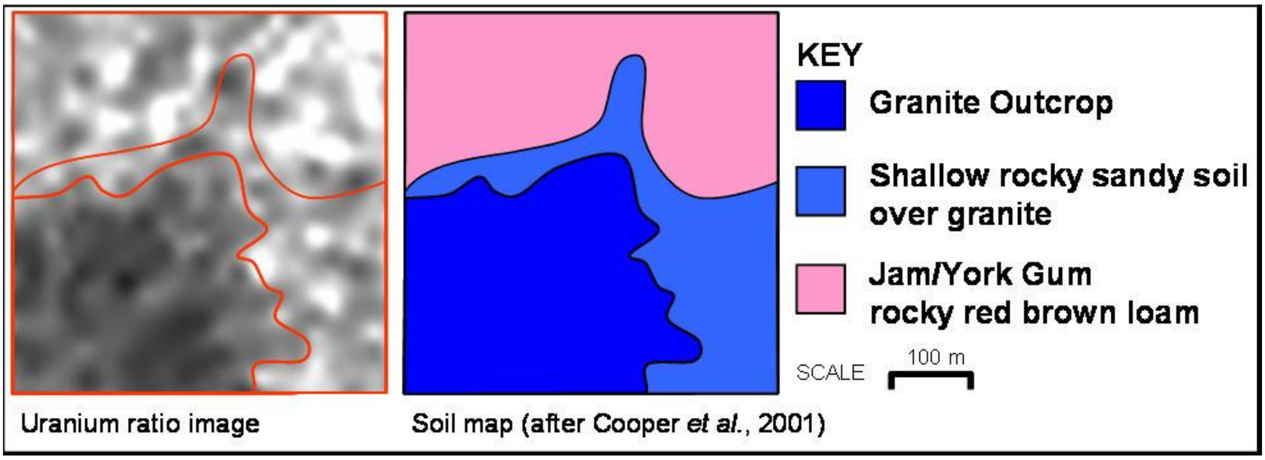

Figure 3: The boundary between granite outcrop and rocky granitic soil is easily delineated within the uranium ratio image due to the relative density differences and decrease in the 1120 keV to 1764 keV energy from the outcrop.