EMPIRICAL INVESTIGATION OF AIRBORNE GAMMA-RAY IMAGES AS AN INDICATOR OF SOIL PROPERTIES - WAGGA WAGGA, NSW.

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ABSTRACT

The information content of airborne gamma-ray imagery is assessed by the empirical analysis of radioelement abundances and soil properties in soil samples. Interpretations are made within the context of geology, geomorphology and pedogenesis. Results suggest that gamma images are capable of mapping soil properties such as pH, composition/nutrients and texture but that gamma responses often a mixture of mineral, geomorphic and pedogenic processes. In areas of relative geomorphic inactivity, potassium maps leaching and acidity while thorium defines clay type and content. In general, mixing of effects including different element mobilities, preclude simple interpretation. Models for interpretation should involve subdividing the data into domains based on geomorphology and geology.

INTRODUCTION

This paper reports on significant findings from a pilot study examining the utility of airborne gamma-radiometric data as a rapid mapping tool for soils and land degradation (Bierwirth, 1996). Airborne gamma-spectrometry provides spatial images of the geochemistry of the top 30-45 cm of the rock/soil layer by measuring the abundance of gamma-rays produced by the radioactive decay of K, Th and U with only minor effects from vegetation.

In a certain landscape, the spatial distribution of K, U and Th and the decay products of U and Th will be a function of physical and chemical weathering processes - relating to primary minerals and the weathering patterns of these minerals influenced by the geomorphic status and climate of a region. Physical transport of minerals by wind, surface wash and alluvial processes accounts for much of the distribution of radioelements (Martz and de Jong ,1990).

Upon chemical breakdown of mineral components, most elements are known to be mobile (being either soluble or attached to colloids) depending on the chemical conditions which in turn may be a function of the mineralogy, age of the landscape and climatic factors. For example, as a result of hydrolysis, K^+ is released from k-feldspar and micas to be used in the formation of illite, adsorbed on to other clays or removed by fluid migration (Wedepohl,1969). Acid solutions will aid the release of K^+ by substituting H^+ in the early stages of weathering which may initially also increase pH (Wollast,1967). Airborne detected spatial patterns of K distribution will therefore depend on the mineralogy and age (ie weathering state) of soils.

Since airborne U and Th data are derived from gamma emissions due to decay products ^{214}Bi and ^{208}Tl respectively, it is important to understand mobility aspects of all the parents of these elements that have reasonably long half-lives. In the Uranium decay chain, isotopes of

Uranium and Radium are soluble under various chemical conditions (Langmuir, 1978). In general, most of the parent and decay isotopes are known to adsorb onto fine organic and mineral particles known as colloids depending on the chemical conditions (Wedepohl, 1969). Movement of these colloids by physical processes is therefore important in the mobility of most elements.

Data acquisition.

The Australian Geological Survey Organisation (AGSO) operates an aircraft which acquires gamma-ray data on a regional basis. To capture enough signal, an aircraft must fly at low altitude generally at a maximum of only 120 metres. The AGSO system also acquires elevation information.

The first Wagga Wagga data were acquired over a nine day period at the beginning of May, 1992 across the entire Wagga 1:100k sheet (see Figure 1 for location). A reading in each of four channels (see below) was collected every 70 metres along evenly spaced flight lines 400 metres apart. Significant overlap between sample points occurs due to the large 'footprint' - 50% of received gamma-rays emanate from an area of 180 metres in diameter. The line data are then interpolated to form a grid of values or image. The Wagga Wagga data was gridded to form 50 metre pixels. A second smaller airborne survey was acquired in early November, 1993 at 100 metres line spacing and gridded to a 50 metre pixel.

Prior to the creation of gamma-ray images, three important corrections are applied to the data: 1) background radiation correction, 2) terrain clearance height correction and 3) spectral stripping (Minty, 1988). After these corrections, four images are created (total count and abundance for potassium, uranium, thorium).

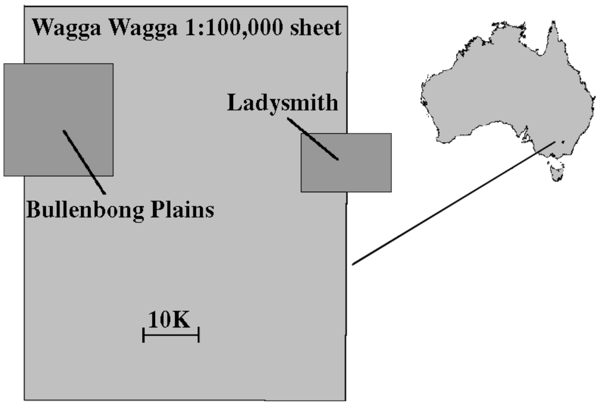

Figure 1. Location of study area

STUDY SITES AND GROUND SAMPLING

In order to study the effects of local geology and landforms on gamma-ray response, regional samples were analysed and two areas were chosen for detailed sampling and analysis. Locations of these areas are shown on Figure 1. The Ladysmith study site corresponds with the area of the second experimental airborne survey.

Ladysmith area (Ordovician Metasediment Hills)

The Ladysmith study area is approx. 7 x 15 km of rolling hills and comprises mostly one lithology. These are slightly metamorphosed shales and sandstones of marine origin. Minerals present are dominantly quartz, muscovite and illite. The latter two contain most of the K, U and Th present and the breakdown of these minerals controls the dispersion of radioelements. The area was analysed, both for soil properties and terrain attributes, as part of the Wagga Wagga study (Gessler and Ashton, in prep). A system of distributed soil cores (76 sites), each divided into horizons, and a 20 metre DEM were used to generate soil and terrain variables. Gamma-ray emitting elements in a subset of the soil samples (23 sites, 52 samples) were analysed in the laboratory using X-ray diffraction (XRF, U and Th) and Atomic Absorption (K) techniques. Ground gamma spectrometer measurements were also collected at the sample sites. Laboratory measured K in soil samples is referred to as 'sample K'.

Bullenbong Plains (Flat lands - alluvium)

The main aim of studying this area was to determine if gamma-ray data can be an significant mapping aid in the vast expanses of gentle, very low relief land requiring land resource survey in Australia. The area of detailed investigation is located some 25 km west of Wagga Wagga (see Figure 1). Lacking rock outcrop and current geomorphic activity, it is part of an old landscape. To investigate the image variations, four traverses were conducted which included ground spectrometer readings, bulk soil sampling to 30 cm depth and field soil tests.

RESULTS

Regional samples

Figure 2 shows regional A horizon sample results for K and pH measured in $CaCl_2$ solution. This shows only areas classified by Chen and McKane (1996) as piedmont terraces and sloping plains (pied) as well as lower footslopes of metasediments (pu), granites (fh) and inactive alluvial areas (ob). The observed relationship between sample K and pH is significant in that, for these residual landscapes, K images may directly indicate pH. This relationship can be used to create a surface soil pH map for parts of the landscape (Bierwirth, 1996).

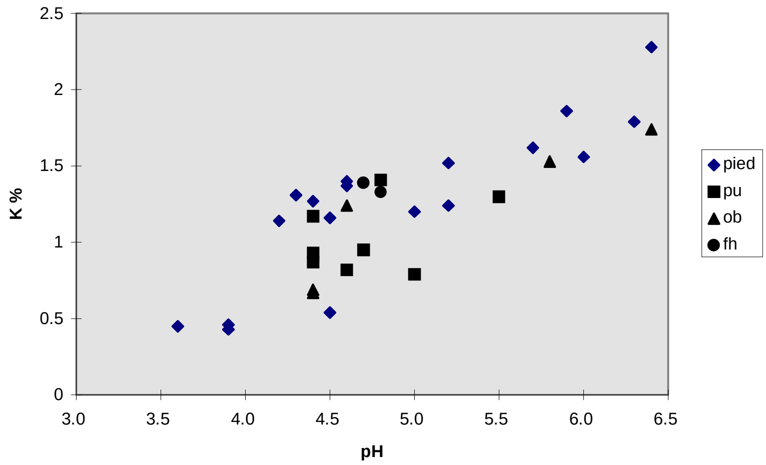

Figure 2. Acidity versus K in soil samples for residual landscape categories.

Regional samples also showed that in acid soils, high values of exchangeable Al were produced (Bierwirth, 1996). This means that K images can be used to indicate areas of Aluminium toxicity. Soils containing less than 1% K may be acid enough to produce near toxic levels of available Aluminium.

Ladysmith area

Figure 3 is a 3D perspective showing just potassium for part of the area draped over the digital elevation model (DEM), also derived from the airborne survey. At the tops of ridges soils are shallow and high levels of potassium and thorium relate to erosional dispersal of clays as the bedrock breaks up. Away from ridges, loss of elements is suggested. The question is; what are the mobility pathways? Do the elements move down profile or laterally either by surface erosion or subsurface redistribution?

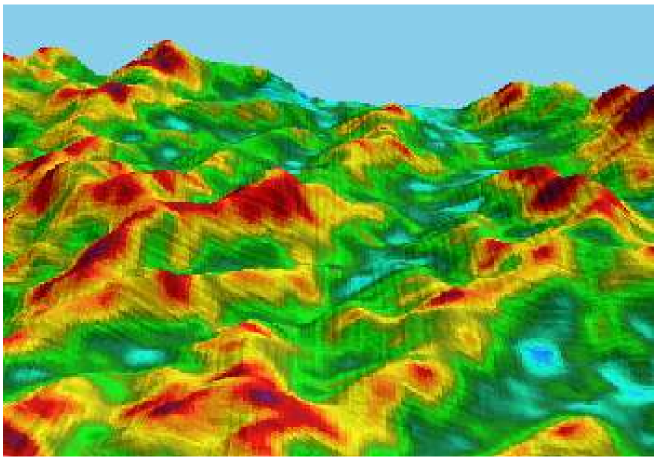

Figure 3. Perspective of Ladysmith area hills. Colour coded K concentration is draped on the DEM. K ranges from 0.9% (blue) to 3% (red). The scene is 3km across.

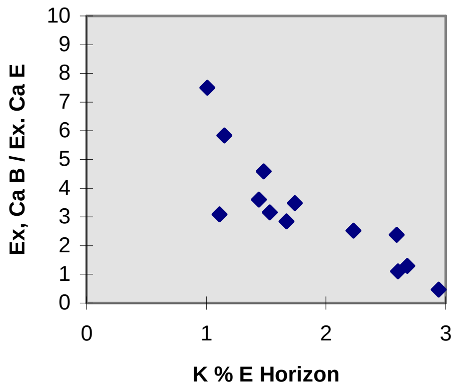

Figure 4(a). K in the E horizon v Calcium leaching

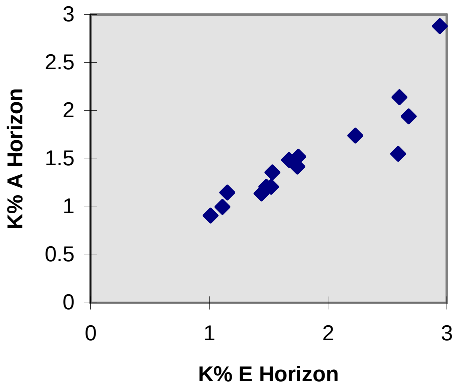

Figure 4(b). K in E versus A horizons

In the A and E (bleached A2) horizons, weak relationships were observed between CEC, which may indicate clay content, and sample K and Th contents (R ~ 0.5). This indicates that at least some of the distribution patterns of these elements may be due to clay dispersal.

However, in a geomorphic context clays would be expected to accumulate lower in the landscape which doesn't fit with the observed distributions of K and Th on the surface. To test for leaching as a K removal process, relative levels of exchangeable Calcium were examined in the E and upper B horizons - a high Ca (B)/Ca(E) ratio indicates more leaching. A strong correlation was observed between sample K and the ratio (Figure 4a). This suggests that areas with lower K in the E horizon have strongest leaching. Figure 4b shows that K concentrations between the E and A horizons are strongly correlated and a similar relationship exists with K in the B horizon (Bierwirth, 1996).

Bullenbong Plains

The gamma-radiometric images of K and Th for the area are shown in Figure 5. K, and Th images are uncorrelated apart from active alluvial floodplains in the north and south-west of the area. The thorium shows (middle left of area) what appears to be an older alluvial system. However the same feature is not discernible in the K image - this may be a result of K leaching which has been observed in both regional and Ladysmith samples. Both ground and airborne gamma-ray measurements of Th correlate with 'clay dispersion' which measures the proportion of clay that is easily dispersed in water after shaking (figure 6). The fact that a relationship exists with dispersion properties, and there is no good correlation between clay content and Th (Bierwirth, 1996), indicates that Th values are related to clay type. This agrees with tests in the field which show that low thorium areas in the image data relate to swelling and cracking clays, ie montmorillonite group clays. Conversely, higher thorium areas relate to greater proportions non-swelling clays such as kaolinite and illite.

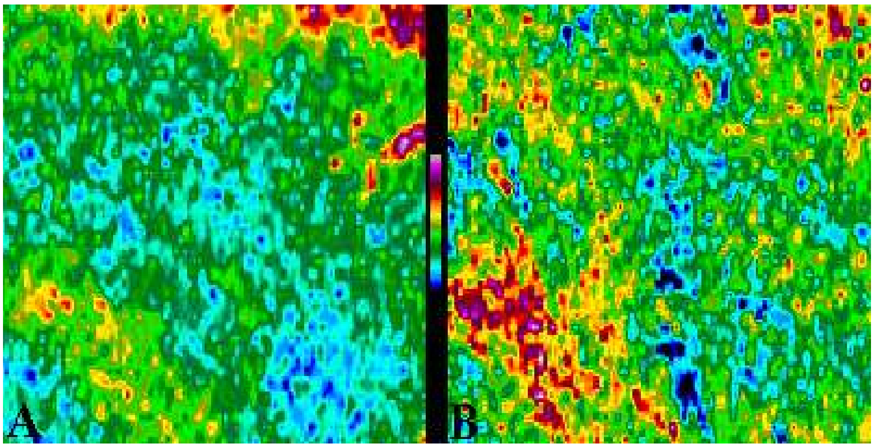

Figure 5 (a) Bullenbong plains, K concentration (0.9-2% = blue to red), (b) Th concentration (10-18 ppm = blue through to red)

The difference in Thorium gamma response between cracking and non-cracking clay soils is not conclusively a function of different source materials for the different phases of alluvial deposition. Ground readings for both U and Th were consistently lower on cracking clays than non-cracking areas. There is a possibility that radon gas release from cracks in the soil may be reducing the amounts of detectable daughter products in both the ^{232}Th and ^{238}U chains. XRF measurements in regional samples of Th isotopes compared with airborne measured ^{208}Tl support this theory (Bierwirth, 1996).

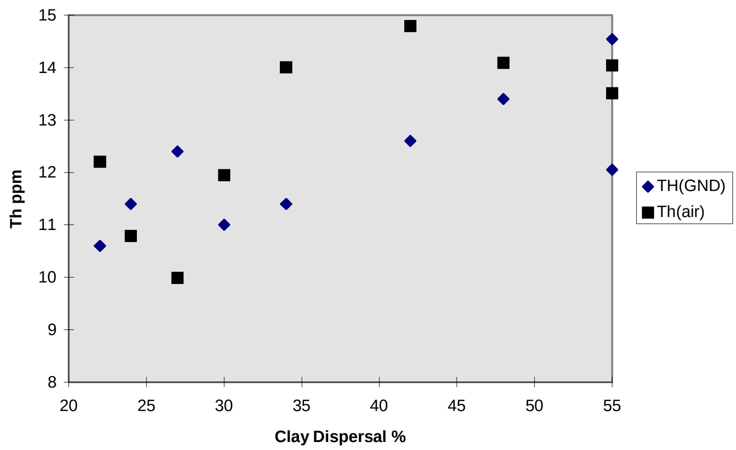

Figure 6. Soil clay dispersal versus airborne and ground measurements of Thorium

DISCUSSION

Ladysmith area

Results show that spatial distributions of K indicate leaching, and abundance in the A horizon reflects abundance in the E and B horizons. Where leaching is strongest, the whole profile is depleted in K whereas exch. Ca is depleted in the E horizon. This is likely because we are comparing total K, which slowly becomes available for leaching, with available Ca which leaches readily. Measuring K in the A horizon by airborne methods will indicate subsurface K and the extent of leaching and development of the E horizon. The fact that K and Th are depleted in zones of increased leaching indicates down-profile water movement is a dominant factor in the removal of these elements

Bullenbong Plains

In terms of sediment sources, the airborne gamma-ray data for the Bullenbong plains is particularly useful for understanding geomorphic history and determining soil types at the surface. High values of K (> 1.4%) and Th (>15 ppm) in the respective images (Figure 5) show areas of recent deposition associated with high levels of silt (Bierwirth, 1996). Away from the current floodplains, soils are much older and there is little correlation between Th and K data. This is because K is strongly influenced by leaching effects over time and Th is showing different phases of deposition and source materials. Intermediate thorium values (12.5 - 15 ppm) relate to an older phase of alluvial deposition with low silt and the clays are mainly non-smectites, ie illite and kaolinite. In some areas, Th values in this range also relate to the deposition of wind-blown clays or ‘parna’ (see middle right of image). Low thorium areas (< 12.5 ppm) represent the earliest phase of alluvials where the dominant clay is montmorillonite and seasonal cracking is common. Montmorillonite forms in conditions where excessive leaching is absent (Buckman and Brady, 1960) and this earliest phase of deposition probably relates to either a period of aridity or lake deposition of finer montmorillonite clays. The most recent deposition of silt is probably a result of increased erosion due to land clearing in the last 100 years.

General Findings

Results of this study generally indicate that the three elements mapped by airborne gamma spectrometry have both unique and similar modes of distribution around the landscape. Radioelement distribution patterns are often a complex mixture of effects that require sensible interpretation. The approach taken in analysing the elements separately was seen to be important in understanding these effects.

For areas with shallow soils on bedrock, gamma-ray signatures are variable and often high (with the exception of sandstones) and relate primarily to rock composition. These are generally areas of active erosion where fresh material is continually being exposed. As weathering proceeds, minerals breakdown and soils develop, there is often a loss of radioelements which are transported away attached to finer particles. In these geomorphically active areas gamma responses are a function of bedrock composition, the degree of weathering and soil thickness.

Away from actively eroding areas, there are large areas of residual to semi-residual slope colluvium and alluvium in the Wagga Wagga region. K, U and Th are distributed by adsorption onto and transport with clays and some K may be present within the clays. The level of adsorption depends on the type of clay. In relatively geomorphically inactive areas such as gentle slopes, pedogenesis and down-profile mobility of elements becomes important in understanding radiometric patterns. Importantly, after deposition, K dissolves over time and Th does not under normal ranges of acidity. This means that in residual areas, K can be used to assess acidity/leaching over time and Th can be used to assess clay content or clay type.

After subdividing into geomorphic and geological landscapes, the radiometrics can provide specific information about soil nutrients, texture and chemistry. Some of the soil properties that can be mapped are outlined below in the context of geomorphic and geologic categories:

Geomorphically inactive soils - Acidity/leaching and Al toxicity (low K), clay types (e.g. montmorillonite (low Th) versus illite, kaolinite (higher Th),
Shallow bedrock areas - extent of sandy colluvium shown by low K in sandstone areas, feldspar content in granite areas, illite content in metasediment areas (both high K)
Active alluvial areas - texture, silty top soils (high K and Th) can be separated easily on the Bullenbong Plains (alluvial)

Multichannel classification

This study has found that radiometric signatures require different interpretations for different areas (Bierwirth, 1996). For example:
- sedimentary clays in shallow soils over bedrock in metasediment areas have an identical signature to alluvial clays on parts of the Murrumbidgee floodplain;
- aeolian clay deposits and old alluvial deposits on the Bullenbong Plains are inseparable radiometrically;
- alluvial cracking clays have similar responses to colluvial soils derived from sandstone;
- high uranium responses in some areas due to groundwater effects cause similar soils to have completely different responses.

For this reason, wholesale classification of the multichannel data will produce a large number of assumed soil similarities that do not exist. In some areas, K and Th patterns are not correlated since they show different properties. For example, on the Bullenbong Plains, Th is showing clay types and K is showing the extent of leaching. Classification shows a confused mixture of the two effects. For classification to be useful, the data should first be divided into particular geomorphic or geological terrains. This should incorporate DEM modelling (Gessler et al. 1995) and might only involve a particular gamma element image. If one element best defines soil properties that define mappable soil units, then inclusion of other elements, in a mapping model, may degrade the model.

CONCLUSION.

Airborne gamma-radiometric data is a valuable tool for mapping soil types, soil properties and aspects of degradation. While not the complete answer, this data in combination with DEM's and traditional methods can improve both the speed and accuracy of soil surveying. In some cases, gamma chemical images can rapidly detect landscape properties - such as leaching, windblown materials, basin-fill colluvium, radon discharge and sediment provenance - that are not achievable by other remote sensing methods.

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