AIRBORNE GAMMA-RAY SPECTROMETRY

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1. METHOD

Airborne gamma-ray spectrometry (AGRS) measures the abundance of Potassium (K), Thorium (eTh) and Uranium (eU) in rocks and weathered materials by detecting gamma-rays emitted due to the natural radioelement decay of these elements.

Potassium abundance is measured directly as gamma-rays are emitted when ^{40}K decays to Argon. Uranium and Thorium cannot be measured directly. Daughter nuclides generated during the decay of parent elements are measured, and the abundance of parent elements is inferred. Distinct emission peaks associated with ^{208}Tl and ^{214}Bi are used to calculate the concentration of Th and U (Figure 1). Therefore, U and Th are expressed in equivalent parts per million (eU and eTh).

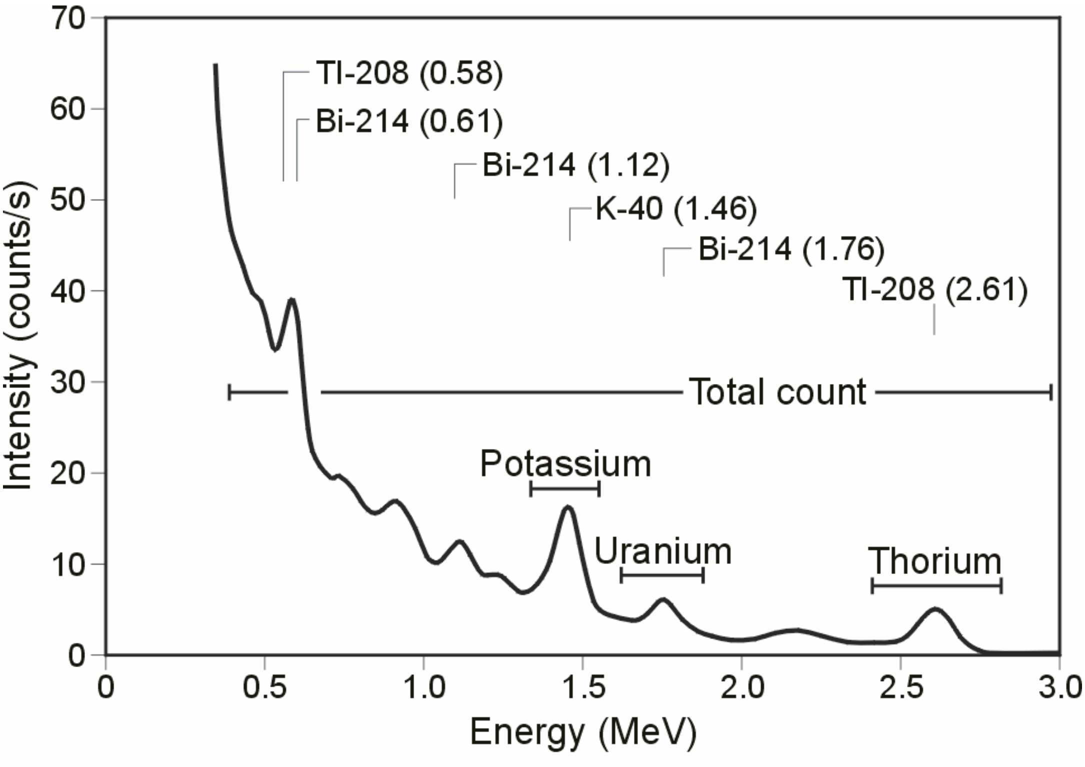

Figure 1. Gamma-ray spectrum showing the position of the K, Th, U and total count windows.

2. DATA COLLECTION AND SOURCE

Airborne gamma-ray data is collected by either helicopter or aeroplane, typically between 60 to 100 metres flying height above the surface. Sodium-iodide scintillation crystals on the aircraft measure gamma-rays emanating from the surface. Photomultiplier tubes attached to the scintillation crystals record and amplify the gamma-ray induced signal (Minty, 1997). The spatial resolution of gamma-ray data largely depends on the line spacing of the airborne survey. Flight line spacing is usually a compromise between data resolution and acquisition costs. Regional airborne geophysical surveys are

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typically flown at 400 or 200 metre line spacing, whereas detailed surveys are usually between 50 to 100 metres.

Gamma rays emanate from the top 30 cm of dry rock and soil (Minty, 1997). Potassium has a crustal abundance of 2.3 % and occurs in many rock-forming minerals such as K-feldspars, micas and as clays like illite. Uranium and Th are much less common compared with K, with an estimated crustal average of 3 ppm and 12 ppm, respectively. Uranium is associated with pegmatites, syenites, radioactive granites, some black shales and many accessory minerals. Thorium is most common in accessory and resistate minerals such as zircon, sphene, apatite, xenotime, monazite and epidote. Typical concentration of radioelements in Australian rocks and soils are given in Table 1. Vegetation, unless thick, generally has little effect on the gamma-ray response. Spectrometric surveys therefore have an advantage over other remotely sensed data such as Landsat and SPOT which can be difficult to interpret due to fire scarring and vegetation masking of soil and regolith materials (Wilford, 1992).

3. PROCESSING AND INTEPRETATION

Airborne gamma-ray survey datasets are typically displayed as images. Individual radioelements are displayed as pseudocoloured images or combined as false colour composites with K in red, eTh in green and eU in blue. White and black hues in the image correspond to high and low abundances, respectively, of all three of the radioelements. Mixtures of K, eU and eTh appear as magenta and yellow hues, respectively. Gamma-ray images are usually expressed as percent K and parts per million for eTh and eU. Images can be contrast stretched or ratioed (eg. K/eTh) to highlight subtle variations in the data. Before images are generated from the flightline profiles, several corrections are applied to the data (eg. to remove noise). These corrections are not discussed here but are described at length by Minty (1997).

Gamma-ray images can be readily integrated and manipulated with other datasets using geographic information systems and image processing systems. Combining gamma-ray images with SPOT or Landsat TM using additive or HIS colour space transforms (Wilford, et al., 1997) is particularly useful for adding terrain attributes and locational information for image interpretation. Digital elevation models can be combined with gamma-ray data as shaded relief images or as 2.5D perspective. Supervised and unsupervised classification techniques can be used to cluster radioelement responses into similar spectral groups for separating major lithological units.

4. APPLICATIONS FOR REGOLITH AND SOIL MAPPING

Gamma-rays emitted from the surface will relate to the mineralogy and geochemistry of the bedrock and weathered materials (eg. soils, saprolite, alluvial and colluvial sediments). Weathering modifies the distribution and concentration of radioelements compared to the original bedrock. Understanding the bedrock and regolith responses has proven invaluable for not only mapping regolith materials but also understanding geomorphic processes (Wilford, et al., 1997). Fortunately, from a regolith perspective K, Th and U behave quite differently from one another during bedrock weathering and pedogenesis. As a general rule, K concentration decreases with increasing weathering. This is because K is highly soluble under most weathering environments and is rapidly leached from a regolith profile. An exception to this is where K is incorporated into potassic clays such as illite. In contrast U and Th are associated with resistate minerals and are scavenged by iron oxides in the weathering profile. Therefore U and Th concentration tends to either stay the same or are preferentially increased in regolith materials as other more soluble minerals are lost in solution. These relationships are summarised in Figure 2.

Table 1. Radioelement content of Australian rocks and soils. Measured K, Th and U values (averaged value in brackets) for various rock types (modified from Dickson and Scott, 1997).

Rock type	Rock			Soil		
	K %	U ppm	Th ppm	K %	U ppm	Th ppm
Intrusives						
granitoids	0.3 - 4.5 (2.4)	0.4 - 7.8 (3.3)	2.3 - 45 (16)	0.4 - 3.9 (2.1)	0.5 - 7.8 (2.7)	2 - 37 (13)
gneissic rock	2.4 - 3.8 (2.4)	2.1 - 3.6 (2.5)	18 - 55 (15)	0.7 - 1.9 (1.3)	1.6 - 3.8 (2.2)	6 - 19 (12)
pegmatite	2.6 - 5.5 (3.7)	0.3 - 1 (0.7)	0.3 - 9.6 (2)			
aplites	0.6 - 4 (2.4)	1 - 8 (3.3)	3 - 20 (7)			
quartz-feldspar porphyry	1 - 5 (2.9)	1.3 - 2.9 (1.7)	6 - 14 (13)			
intermediate intrusives	0.7 - 5.6 (2.7)	0.1 - 1.2 (0.8)	0.8 - 6.1 (2.4)	0.7 - 3.4 (1.6)	1.5 - 2.3 (1.9)	2.9 - 8.4 (5.6)
mafic intrusives	0.1 - 0.8 (0.4)	0.0 - 1.1 (0.3)	0.0 - 3.1 (1.2)			
Extrusives						
felsic volcanics	2.0 - 4.4 (3.7)	1.4 - 13 (2.4)	13 - 28 (17)	1.8 - 3.2 (2.4)	1.3 - 2.4 (2.1)	10 - 18 (13)
intermediate volcanics	1.8 - 4.1 (2.7)	0.9 - 5.6 (2.3)	1.5 - 15 (9)	1.0 - 2.7 (1.9)	1.2 - 3.6 (2.1)	4 - 17 (10)
low-K andesites	0.7 - 0.9 (0.8)	1.0 - 2.5 (1.6)	3 - 8 (5)	0.8 - 1.5 (1.1)	1.2 - 1.5 (1.3)	4 - 6 (5)
mafic volcanics	0.3 - 1.3 (0.9)	0.3 - 1.3 (0.7)	2.0 - 5.0 (3.0)	0.2 - 1.4 (0.7)	0.6 - 2.5 (1.6)	3.3 - 13 (7.9)
ultramafic volcanics	0.2 - 0.9 (0.4)	0.3 - 0.9 (0.6)	0.0 - 4.0 (1.2)	0.6	2.0	6
Sedimentary rocks						
Archaean shales	0.4 - 1.6 (0.9)	0.3 - 1.3 (0.9)	1 - 5 (2.7)	0.8	1.2	3
other shales	0.1 - 4.0 (2.6)	1.6 - 3.8 (2.6)	10 - 55 (19)	0.7 - 3.0 (1.5)	1.2 - 5 (2.3)	6 - 19 (13)
arenites	0.0 - 5.5 (1.8)	0.7 - 5.1 (2.3)	4 - 22 (12)	0.1 - 2.4 (1.3)	1.2 - 4.4 (2.1)	7 - 18 (11)
carbonates	0.0 - 0.5 (0.2)	0.4 - 2.9 (1.6)	0 - 2.9 (1.4)			

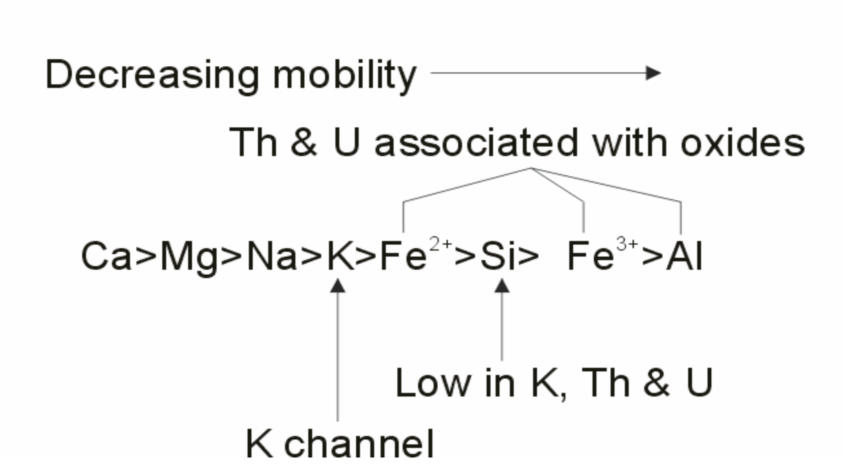

Figure 2. Element weathering and gamma-ray response (Wilford, et al., 1997).

Highly weathered landscapes in parts of Cape York Peninsula have either low abundance of K, eTh and eU (eg. quartzose sands) or low K and high eTh and eU associated with the accumulation of oxides and resistate minerals at or near the surface (Wilford, 1992). For example, highly leached aluminous and ferruginous bauxitic soils around the Weipa region are identified on the gamma-ray imagery by their low K and elevated eTh and eU values. This is reflecting soils with very low exchangeable cations and high content of iron and aluminium oxides and resistate minerals (eg. Zircons).

Gamma-ray spectrometry imagery can be used to separate areas of high geomorphic activity with shallow regolith from stable surfaces that are less geomorphically active and that have deeper and more highly weathered regolith (Wilford, 1992). Gamma-ray response over an actively eroding landscape is likely to reflect the mineralogy and geochemistry of the bedrock, whereas that over stable landforms is likely to reflect soil/regolith materials (Figure 3).

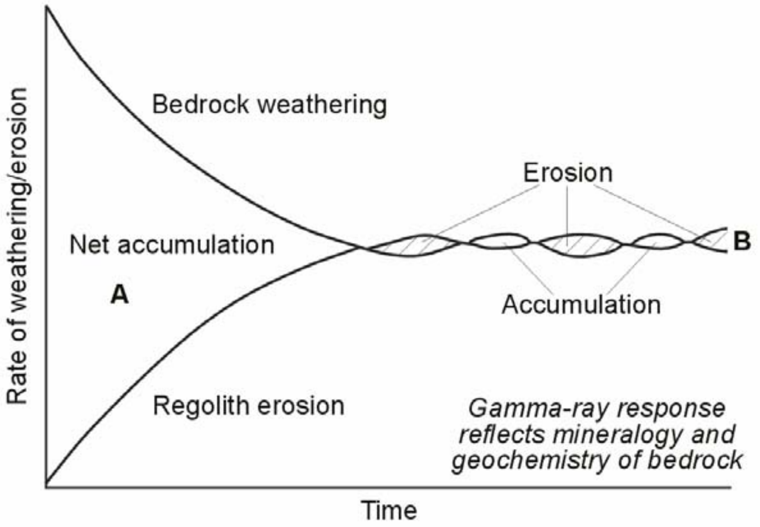

Figure 3. Relationship between gamma-ray response and denudation balance in landscapes. A - areas of active erosion (eg. where erosion rates are higher than rates of weathering) the gamma-ray response will reflect bedrock geochemistry. B – area where the rates of weathering are higher than the erosion rates the gamma-ray response will reflect regolith and soil geochemistry.

Draping the gamma-ray image over a digital elevation model as a perspective view is an excellent way of understanding geomorphic relationships and separating bedrock and regolith gamma-ray responses (Figure 4). An integrated approach using gamma-ray spectrometrics and digital elevation models was used to identify large-scale erosional and depositional processes within river catchments (Pickup and Marks, 1999).

Mapping catenas using airborne gamma-ray imagery is a good illustration of the relationship between geomorphic process and gamma-ray response. Catenas are recognised on gamma-ray imagery over granitic landforms in Cape York (Wilford, et al., 1997) and on shaly lithologies in the Wagga Wagga area in NSW (Bierwirth, 1996). In both cases the upper slopes have thin soils, with deeper soils and regolith on the lower slopes. The gamma-ray response of the upper slopes is dominated by bedrock chemistry whereas the gamma-ray response over the lower slopes has reduced K concentration due to weathering.

Gamma-ray images can be used to separate depositional regolith materials derived from different sources, or of different ages. In some landforms, potassium concentration can be used as a gauge of the degree of surface weathering, where depleted Potassium (K) is associated which leaching (eg. the development of podzolic soils where soluble cation are leached from the upper part of the soil profile). Bierwirth (1996) demonstrated the use of gamma-ray images for mapping soil properties in the Wagga region NSW in southeastern Australia. Interpreted images over the Wagga Wagga region provided information about soil nutrients, texture and chemistry. Ratios of K and Th have been used to separate different regolith materials from bedrock signatures in the Yilgarn Craton of Western Australia (Dauth, 1997), demonstrating that low K/Th ratio values generally related to highly weathered and ferruginous saprolite.

Gamma-ray imagery forms one of several datasets used for mapping regolith materials. Combining radioelement (K, eTh, eU and Total count) bands with ratio bands from Landsat TM (eg. clay and Fe) will improve the separability of regolith materials, based on their radioelement and reflective signatures.

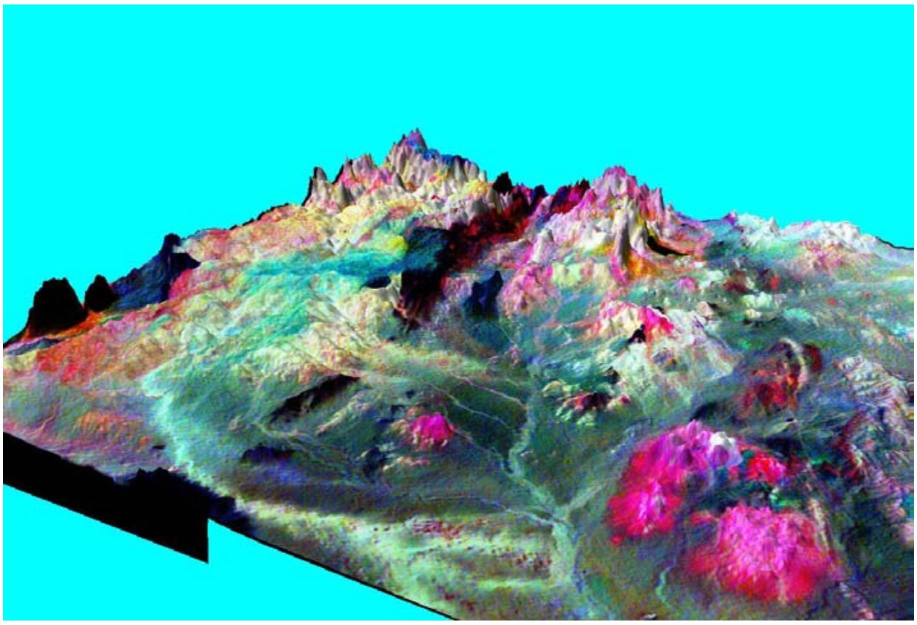

Figure 4. 3D landscape perspective and gamma-ray image over part of the Cootamundra 1:250 000 map sheet. Combined gamma-ray spectrometic images with DEM as 3D perspective views enable the visualisation of complex relationships between the gamma-ray response and terrain morphology attributes.

5. APPLICATION FOR MINERAL EXPLORATION

In addition to mapping the regolith, airborne gamma-ray spectrometric surveys show increasing potential to detect alteration associated with mineralisation (Dickson and Scott, 1997). Mineralising processes can change the abundance of one or several of the radioelements (eg. potassic alteration) compared to the surrounding host bedrock. Changes in radioelement concentration can either relate to primary mineralisation event(s) or to secondary processes. For example hydrothermal alteration may result in the rock being more susceptible to weathering. The higher degree of weathering may produce a distinctive gamma-ray response compared with the surrounding bedrock.

Residual analysis techniques can be used to identify subtle variation in radioelement abundance that may relate to localised mineralisation processes. Residual analysis involves calculating background K, eTh and eU values and then subtracting these values from the original image. For example regolith and geological units can be used to determine mean or average radioelement values for each unit. These average values are then subtracted from the original radioelement images to highlight values either higher or lower than the predicted regolith/bedrock response. This approach was used to identify elevated potassic values associated with quartz-illite-kaolinite-pyrite alteration in the Temora-Barmedman area, NSW (Lawrie, et al., 1998). Dickson, et al. (1996) has used a more sophisticated technique to develop predictive models of K, eTh and eU distribution in prospective rock units. Predictive abundance maps (generated using correlations with Landsat TM and DEM derived attributes) are compared with the original radioelement images to highlight subtle changes that may relate to mineralisation.

6. COSTS AND LIMITATIONS

Costs for acquiring airborne gamma-ray data is approximately $8.00 per line km. The cost to fly a 1:250 000 map sheet at 400 m line spacing would therefore be about $400,000. This includes all processing and also magnetic data. Not all regolith materials have a unique gamma-ray signature, therefore gamma-ray data for regolith mapping is best used together with other datasets including Landsat TM, airphotographs and digital elevation models. Gamma rays emanate from the top 20-30 cm and are therefore recording the radioelement characteristics of the ‘A’ or upper ‘B’ horizon of soils or bedrock. Relating gamma-ray responses to regolith properties at depth may be misleading.

Estimating U and Th using their daughter isotopes assumes equilibrium in the decay chain. However disequilibrium can occur and should be considered when interpreting their abundances. For example, U anomalies can be caused by the accumulation of radium (^{226}Ra) in ground waters (Giblin and Dickson, 1984).

The behaviour of radioelements during weathering will depend on the initial bedrock composition or chemistry. For example, weathered felsic rocks usually show a loss of K whereas weathered basic or ultramafic rocks are barren in all three radioelements, and as a consequence will be a poor surrogate for mapping the degree of surface weathering. The same radioelement response can relate to different materials depending largely on the bedrock chemistry and mineralogy. For example highly weathered residual quartz sands developed on granitic saprolite can have the same radioelement signature as exposed fresh ultramafic bedrock. For this reason it is best to interpret the gamma-ray response within major lithological-geochemical groups (eg. sandstones, granite, basalt).

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