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Application of airborne gamma-ray spectrometry in soil/regolith mapping and applied geomorphology

J.R. Wilford[1] P.N. Bierwirth[1] & M.A. Craig[1]

Gamma-ray spectrometric surveys are an important source of information for soil, regolith and geomorphological studies, as demonstrated by the interpretation of airborne surveys in Western Australia, central New South Wales and north Queensland. Gamma-rays emitted from the ground surface relate to the primary mineralogy and geochemistry of the bedrock, and the secondary weathered materials. Weathering modifies the distribution and concentration of radioelements from the original bedrock source. Once the radioelement response of bedrock and weathered materials is understood, the gamma-ray data can provide information on geomorphic processes and soil/regolith properties, including their mineralogy, texture, chemistry and style of weathering. This information can contribute significantly to an understanding of the weathering and geomorphic history of a region and, therefore, has the potential to be used in developing more effective land-management strategies and refining geochemical models in support of mineral exploration. Gamma-ray imagery is enhanced when combined with Landsat TM bands and digital elevation models (DEM). This synergy enables geochemical information derived from the gamma-ray data to be interpreted within a geomorphic framework. Draping gamma-ray images over DEMs as 3D landscape perspective views aids interpretation and allows the interpreter to visualise complex relationships between the gamma-ray response and landform features.

Introduction

Gamma-ray spectrometry

Airborne gamma-ray spectrometry is a passive remote-sensing technique. Gamma-rays are a form of high-energy short-wavelength electromagnetic radiation. They have no mass or electronic charge and are emitted at different energy levels or peaks that correspond to radioactive decay of particular radioisotopes. The relative abundance or concentration of these radioelements in soil and bedrock is estimated from the intensity of their emittance peaks. Airborne gamma-ray spectrometry measures the abundance of potassium (K), thorium (Th) and uranium (U) in rocks and weathered materials by detecting gamma-rays emitted from the natural isotopic radioactive decay of these elements. Measured K directly corresponds to the isotopic decay peak for ^{40}K. ^{40}K emits gamma-rays as it decays to ^{40}Ar. Measuring Th and U concentrations is more complex, since ^{232}Th and ^{238}U decay through a series of daughter nuclides until they reach stable Pb isotopes. Distinct emission peaks associated with ^{208}Tl and ^{214}Bi, are used to calculate the abundance of Th and U, respectively (Minty 1997). Consequently, U and Th are usually expressed in equivalent parts per million (eU and eTh), which indicates that their concentrations are inferred from daughter elements in their decay chain, whereas, because of its higher crustal abundance, K is typically expressed as a percentage (K%).

However, the estimation of U and Th in this manner assumes that the daughter products in the Th and U decay series are in equilibrium. In some cases the measured isotopes in the U and Th decay series (i.e. ^{208}Tl and ^{214}Bi) may not perfectly quantify the parent elements, because of disequilibrium in the decay chain. Disequilibrium occurs when one or more of the daughter products in the decay chain is removed or concentrated. For example, in some salt lakes and groundwater discharge sites, high eU and eTh values may be due to the accumulation of radium isotopes that are mobile in acid saline solutions (Dickson 1985). Disequilibrium should, therefore, be considered when interpreting gamma-ray data, particularly when correlating rock or regolith sample geochemistry with airborne gamma-ray responses.

The source of gamma-rays—bedrock vs regolith

Ninety per cent of gamma-rays emanate from the top 30–45 cm of dry rock or soil (Gregory & Horwood 1961). The intensity of gamma-rays emitted from the surface relates to the mineralogy and geochemistry of the bedrock and the nature of weathering. K has an estimated crustal abundance of 2.5 per cent. It occurs mainly in primary rock-forming minerals, such as K-feldspar and micas. The percentage of K is generally high in acid-felsic rocks and low in mafic rocks. In contrast, U and Th are relatively rare with an estimated crustal average of 3 ppm and 12 ppm, respectively. U is found at much higher levels in pegmatites, syenites, carbonatites, radioactive granites

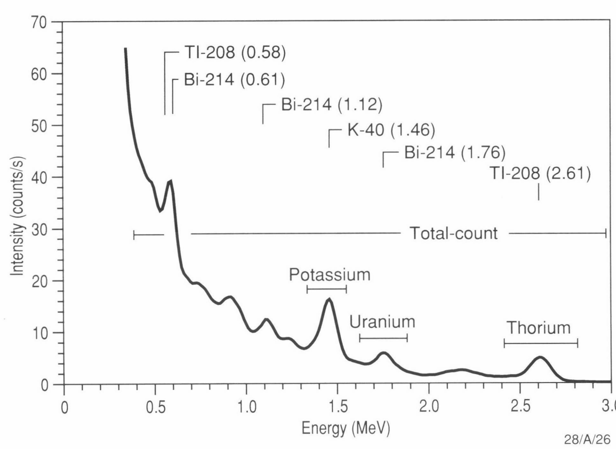


Figure 1. Airborne gamma-ray spectrum and position of potassium, thorium, uranium and total-count windows (modified from Foote 1968).

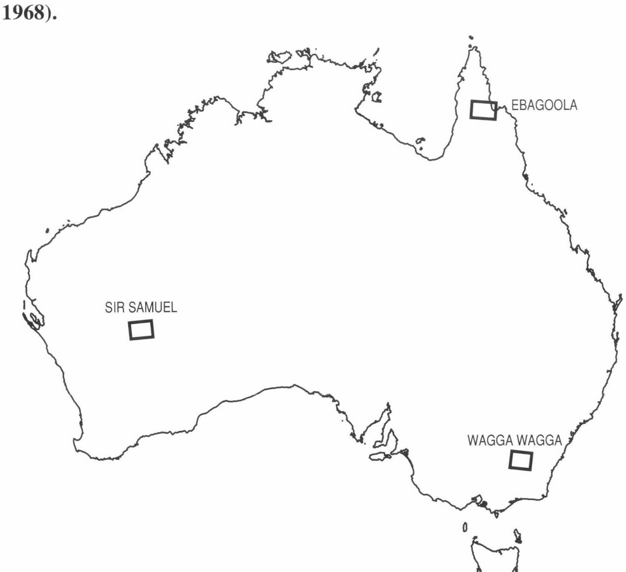


Figure 2. Location of the Ebagoola, Wagga Wagga and Sir Samuel study areas.

1 Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601, Australia

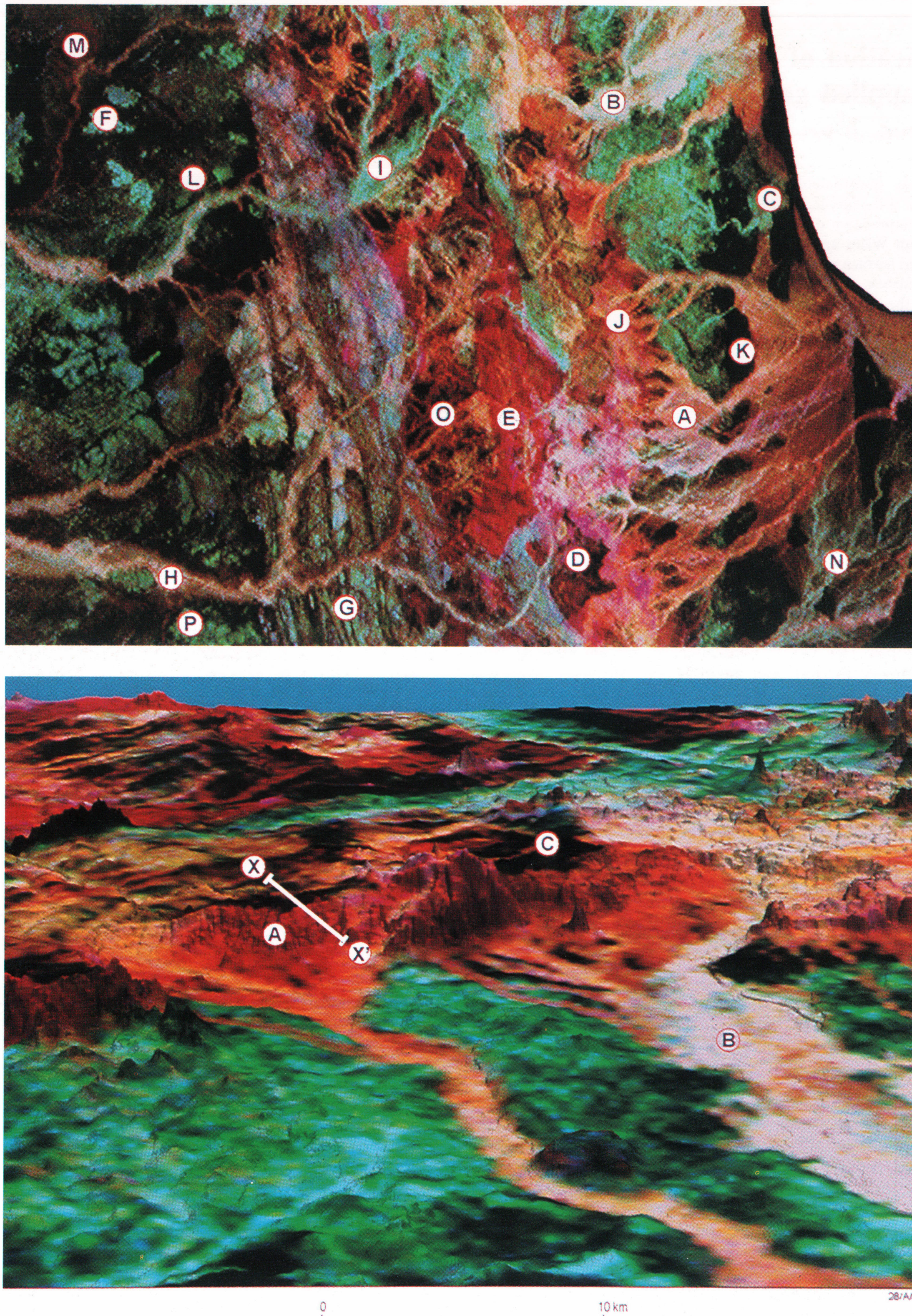
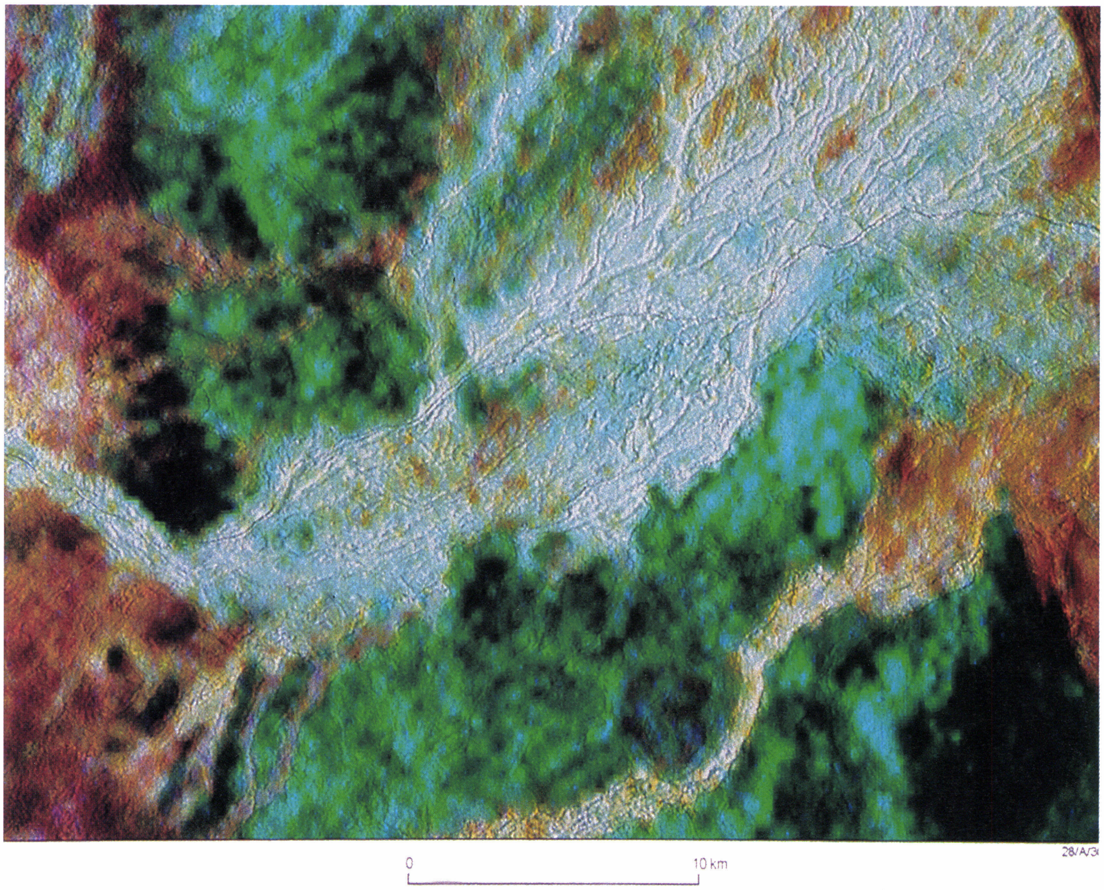


Figure 3. (a—above, upper) Three-band gamma-ray spectrometric image (K red, eTh green and eU blue) over the Ebagoola 1:250 000 map sheet area. A, alluvial sediments derived from granitic rocks; B, alluvial sediments derived from granitic and metamorphic rocks; C, alluvial sediments derived from metamorphic rocks; D, in-situ weathered residual quartz sands (sandy earths); E, lithosols over weathered granite (S-type); F. bauxitic and ferruginous plateaus; G, quartzite ridges; H, floodplain sediments; I, alluvial terrace sediments; J, eroding edge of the Great Escarpment; K, residual quartz sands over Mesozoic sandstones; L, lithosols over weathered siltstone; M, potassic and montmorillonite clays; N, former river channels; O, lithosols over weathered granite (I-type); and P, Fe duricrust. (b—above, lower) 3D perspective view of part of the Ebagoola gamma-ray image draped over a digital elevation model (DEM). The view is looking towards the southwest with Princess Charlotte Bay in the foreground. Features include active erosional edge of the Great Escarpment exposing granitic saprolite (A), active alluvial fan and floodplain sediments derived from the escarpment (B), and deep residual siliceous soils (C). For description of X–X[1] transect, refer to Figure 9. (c—opposite page) Landsat TM band 5 combined with RGB gamma-ray image over the northeastern corner of the Ebagoola 1:250 000 map sheet area. The Landsat image was edge-enhanced before being added to the gamma-ray imagery.



and some black shales. U and Th are found as traces in primary rock-forming minerals (e.g. feldspars), but are most common in accessory and resistate minerals (zircons, sphene, monazite, allanite, xenotime). The concentration of U and Th in igneous rocks generally increases with rock acidity (i.e. rocks with higher silica content).

During chemical and physical weathering, radioelements within rocks are released, redistributed and incorporated into the regolith* (including in-situ weathered and transported materials). In many cases, the radioelement characteristics of regolith materials differ markedly from their underlying source rocks. This is due to textural and geochemical reorganisation within the weathering profile. For example, some intensely weathered regolith materials typically show depletion of K, owing to leaching, and elevated U and Th values associated with clays and/or iron oxides in the upper part of the weathering profile (Koons et al. 1980; Dickson & Scott 1997).

* Regolith—a term used to describe all weathered material above fresh bedrock. Soil is interpreted as the uppermost part of a regolith profile. Regolith is used here to include soils and weathered rock (saprolite).

Attenuation of gamma-rays by water and vegetation

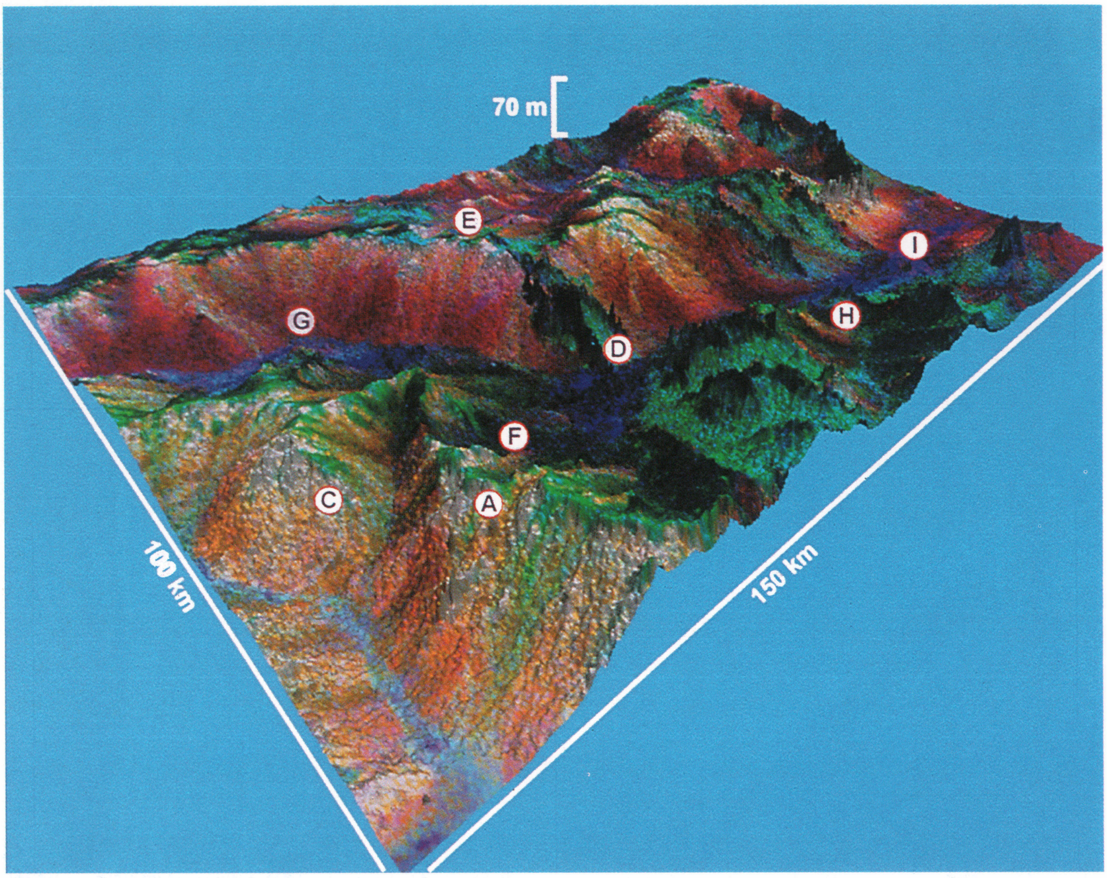
Water, as soil moisture or held within plant tissue, attenuates gamma-rays. However, the effects of soil moisture on gamma-ray emittance are complex. Gamma-ray intensity can increase or decrease, depending on soil moisture conditions (Minty 1997) —generally, a 20 per cent increase in soil moisture will result in a 20 per cent reduction of gamma-rays emitted at the soil surface. To avoid emittance variation due to changing soil moisture conditions, ground sampling and airborne measurements are best made when the ground is dry. Studies in the northern hemisphere have shown that the distribution of snow water equivalent cover can be mapped based on water-attenuation coefficients and repeated airborne measurements (Loijens & Grasty 1973; Carroll & Vose 1984).

Vegetation can attenuate gamma-rays reaching the aircraft, depending on the density of the cover. Gamma-rays are attenuated when the vegetation is dense and contains high volumes of woody material and water held in the tree canopy. However, in Australia, where vegetation consists mostly of open forest, woodlands, shrubs and heath lands, gamma-rays emanating from the soil or bedrock are largely unaffected by the vegetation cover. Even in well-vegetated country over parts of north Queensland, gamma-ray surveys effectively 'see through' the vegetation cover to map soil and bedrock types (Wilford 1992). Vegetation had little or no effects in the interpretation of airborne gamma-ray surveys for soil mapping in central New South Wales (Bierwirth 1996). Areas of dense vegetation (i.e. rainforest and pine forest) have the effect of subduing the gamma-ray response. In tropical environments, wetness indices derived from processed Landsat TM imagery have been used to correct airborne gamma-ray data for water and vegetation attenuation effects (Lavreau & Fernandez-Alonso 1991).

Plant tissue contains negligible traces of Th and U and, as a result, has little effect on the gamma-ray response. However, other studies show that the uptake of K by plants can contribute up to 15 per cent of the signal reaching the aircraft (Kogan et al. 1969). The effects of vegetation, both in terms of attenuation and contributions to the gamma-ray response, should, therefore, be considered when interpreting survey data.

Application of gamma-ray surveys to geological and regolith mapping

Airborne gamma-ray spectrometry has been used mainly as a tool for mineral exploration in locating U deposits and in lithological mapping (Darnley & Grasty 1971; Foote & Humphrey 1976; Galbraith & Saunders 1983; Tucker et al. 1984; Duval 1990; Graham & Bonham-Carter 1993). Although there has been some use of gamma-ray data for mapping



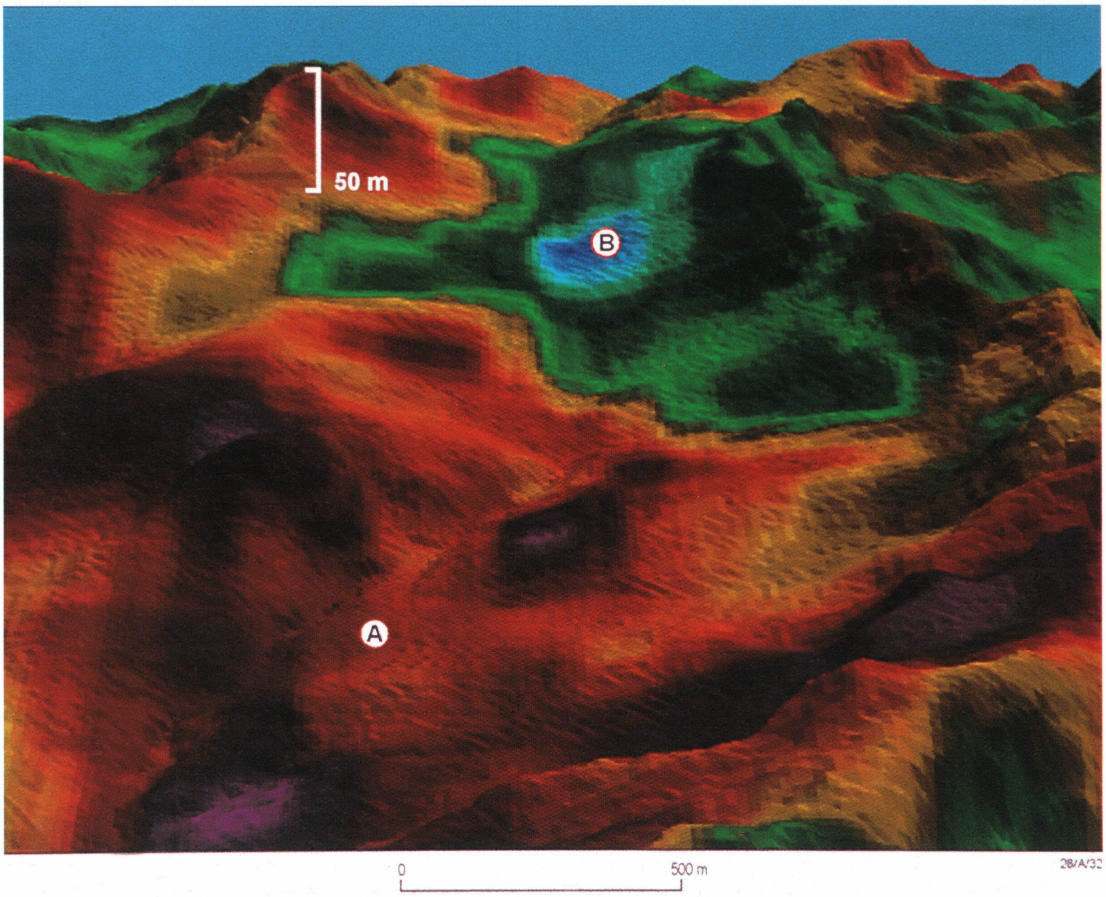
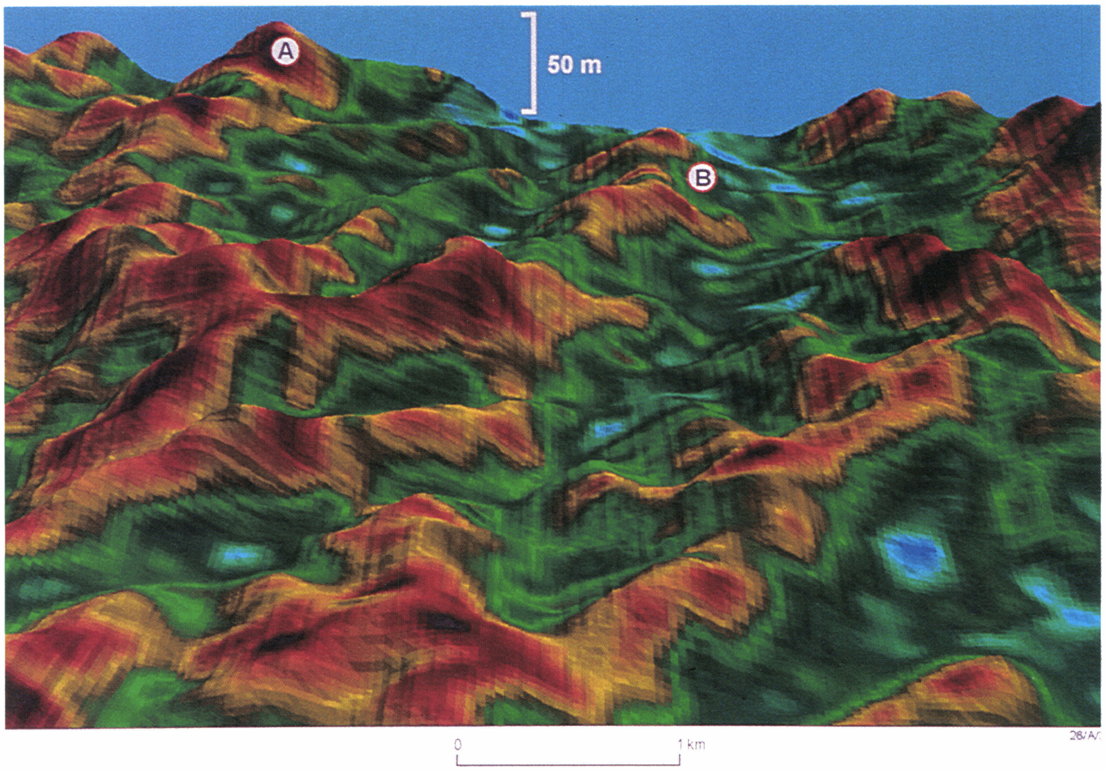
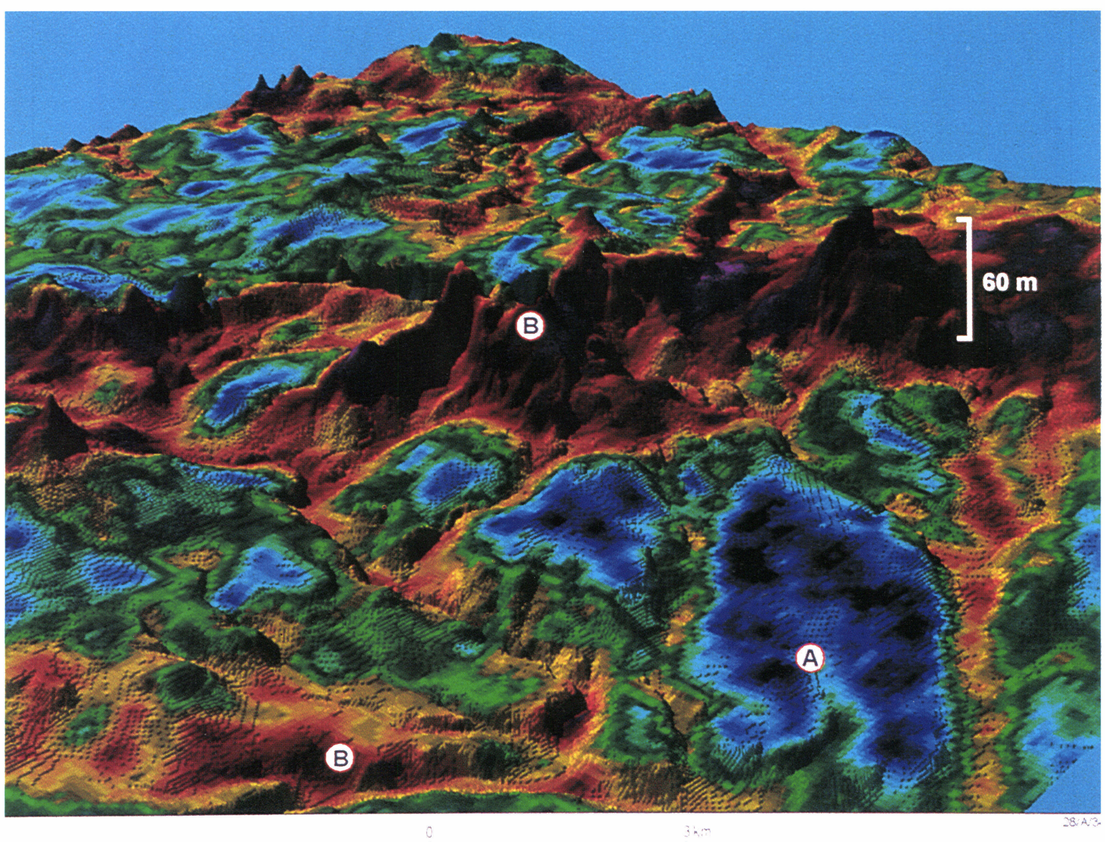


Figure 4. (a—top left) 3D perspective view of the Sir Samuel gamma-ray image draped over a digital elevation model (DEM). A variety of regolith materials can be distinguished and placed within a landscape context, including: A, silcrete forming a breakaway; B, ferricrete; C, granitic saprolite; D, ferricrete developed over greenstone rocks; E, aeolian sands derived from granitic source rocks; F, well-worked aeolian sands; G, sheet-flow fans derived from granite; H, Fe gravel lags; I, valley calcretes; (Image processing by M. Richardson, AGSO). (b—bottom left) 3D perspective of the K channel from the Wagga Wagga area draped over an elevation model.





Partially weathered granites (A) are distinguished by their high K values, corresponding to K-feldspars and K-mica. Perched basins (B), consisting of highly weathered colluvial sands are distinguished by a low K response, owing to leaching of K from the weathering profile. (c—top right) 3D perspective of the K channel from the Wagga Wagga area draped over an elevation model (from Bierwirth 1996) . High potassium values over ridge tops (A, lithosols) and low values in the adjacent valleys (B, colluvial clayey earths) reflect soil catenas developed over weathered metasediments. The colluvial soils have developed on inactive footslopes where the K has been leached during pedogenesis. As the thickness of colluvium increases, the imaged K signal decreases, as a result of leaching and burial of the underlying bedrock. (d—bottom right) 3D perspective of the K channel from part of the Ebagoola area draped over an elevation model. Deeply weathered siliceous sands (A) over hill crests are distinguished by their low K values and are separated from (B) thinner soils forming on steeper slopes and along river channels which have incised into the bedrock, by higher K values. These soils form an extensive catena over granitic bedrock.

regolith types (Schwarzer et al. 1972), the main application of airborne surveys to date has been in geological mapping, which have been driven primarily by the interests of the mineral industry. As a result, gamma-ray responses of rock material are generally well understood. However, the response and distribution of radioelements in weathered materials is less well known. More recently, there has been a growing interest in, and use of, gamma-ray data in regolith and geomorphological studies (Dickson & Scott 1990; McDonald & Pettifer 1992; Wilford 1992; Cook et al. 1996). This paper discusses how airborne gamma-ray data can be used to map regolith materials and contribute to our understanding of geomorphic processes in the landscape.

High-resolution (100–400 m line spacing) airborne spectrometric data used in this study were acquired by the Australian Geological Survey Organisation (AGSO) as part of the National Geoscience Mapping Accord (NGMA) and the National Environmental Geoscience Mapping Accord (NEGMA) projects. These initiatives are producing a new generation of geological and environmental maps over strategically important areas of Australia. Airborne spectrometric data are a key contribution to the generation of these maps. Gamma-ray imagery together with other data sets, including Landsat TM, colour photography, and digital elevation models (DEMs), is being used to develop more effective and quicker geological and regolith mapping tools. The objective of this paper is to:

- briefly discuss processing and integration techniques to enhance airborne gamma-ray data for interpretation, and
- assess the use of airborne gamma-ray data for regolith mapping and application in applied geomorphology.

This evaluation of gamma-ray data for regolith mapping and applied geomorphology is based on three airborne surveys from different parts of Australia with diverse weathering and geomorphic settings.

Data acquisition and processing

Flight-line spacing for the airborne surveys was mainly 400 m, with one smaller area flown at 100 m spacing. Gamma-ray measurements were recorded at 70 m intervals along the flight-lines from a height of 100 m. The detector on the aircraft consists of sodium iodide (NaI) crystals. When subject to gamma-rays, the crystals emit visible light or 'scintillations', which are converted to a measurable electrical pulse (Grasty 1976). Four channels were measured, including total count, K, eTh and eU. These channels record gamma radiation in the following energy windows; 0.4–3.0 MeV for total count, 1.37–1.57 MeV for K, 2.41–2.81 MeV for eTh, and 1.66–1.86 MeV for eU. The total-count window measures a broad range of gamma-ray radiation, including the three windows used to measure K, eU and eTh (Fig. 1). Data collected in these channels are corrected for background cosmic and atmospheric radiation, variations in flight elevation and Compton scattering. A comprehensive description of the processing and correction procedures for airborne gamma-ray survey data is given by Minty (1997).

Data resolution and display

The resolution of airborne gamma-ray data depends on the flying height of the aircraft and the flight-line spacing of the survey. Low flying height and closely spaced flight-lines increase data resolution. As a general rule, surveys flown at 1.5 km, 400 m and 100 m line spacing are useful for 1:250 000, 1:100 000 and 1:50 000 mapping scales, respectively. Although survey data are flight-line intensive, with much higher sampling density along flight-lines than between flight-lines, much of this resolution is lost, owing to the unfocussed nature of gamma radiation. For example, 60 per cent of the radiation recorded by the spectrometer from a height of 100 m represents gamma-rays emitted from an area of about 120 m radius on the ground. Therefore, significant overlap between sample points along flight-lines occurs because of the large gamma-ray 'footprint' or field of view (Hansen 1992).

Gamma-rays are measured in counts per second for each radioelement. Most survey data are now calibrated into per cent K and parts per million (ppm) for Th and U. Gamma-ray data are displayed as images, flight-line profiles or contours. Image displays are the most widely used for interpretation, particularly for mapping, where spatial continuity is essential. Spatial patterns and textures are more difficult to interpret from contour and flight-line maps. Imaged data can also be readily enhanced, manipulated and integrated with other data sets, using geographic information systems (GIS) and image-processing software. However, interpretation based on flight-line profiles should not be overlooked, since they can show subtle changes in gamma radiation not seen in imaged renditions which have been smoothed to help interpolation between flight lines (Wilford 1992).

All gamma-ray data used in this study were gridded to either 50 or 80 m pixels, depending on the flight-line spacing of the survey, and geometrically corrected to the Australian Map Grid (AMG) before being displayed as images and integrated with other data sets.

Noise removal

The imagery often shows varying degrees of striping and/or background noise, particularly in the eU channel. Several techniques can be used to remove this noise, including conventional levelling using crossover ties, interchannel correlation methods, and micro-levelling procedures. These techniques are discussed by Minty (1997). In addition several image-processing and filtering procedures are available for reducing noise and improving image interpretability. These are outlined below:

Principle component analysis (PCA). This procedure statistically finds orthogonal axes of variance within the data (Richards 1986) and represents them as images. The first axis (PC1) maps material whose surface variance dominates the data. Progressive PC axes show less dominant variations and the last commonly shows and isolates the noise. Noise can then be removed from the data by rotating the PC axes, excluding the last noisy axis, back to the original channels.

Filtering. One way of reducing the visual effects of speckling in the image is to replace erroneous pixel values with the average value of surrounding pixels. This is done by applying moving box filters (Richards 1986). Spurious elongate artefacts in the imagery, often caused by poor height correction, can be removed by applying a rectangular box filter to each gridded channel.

PCA was deemed the most effective technique for removing noise in the channel data, since, unlike filtering, it maintains the spectral integrity of the data and does not involve spatial averaging or data degradation.

Image enhancement and integration

Pseudo-colour single-channel images and three-band composite images, with K in red, eTh in green and eU in blue, were found to be the most effective enhancement for distinguishing soil/regolith materials. Histogram stretching and band ratioing of the channels (eU/eTh, eU/K, eTh/K) were used to maximise contrast and highlight subtle features in the data. Single-channel and three-channel composite renditions preserve the integrity of the data, allowing relative concentrations of K, eTh and eU to be directly correlated with the geochemistry of soil/regolith materials.

Although clustered image displays, using unsupervised classification procedures, have been used successfully to highlight differences and similarities between geological units and gamma-ray responses (Graham & Bonham-Carter 1993), similar techniques proved inadequate for separating regolith materials. Unsupervised classification algorithms were found to produce effective colour separation, but were difficult to interpret, owing to mixing of the gamma-ray channels. In addition, subtle gamma-ray responses and textural features were lost in classifying the data into similar spectral groups. Integration of the gamma-ray data with other complementary data sets was found to be the most effective enhancement technique.

Interpretation based on pseudo-coloured composite band and ratio images is further enhanced when combined with Landsat TM and digital elevation models (DEMs). Band 5 of Landsat TM was chosen to combine with gamma-ray imagery because it maximises landform features and subdues vegetation differences, which may be confusing in interpretation. A high band pass filter was used to enhance the high-frequency information in the TM band before adding it back to the gamma-ray image. The filtered image has the advantage of highlighting landform and structural edges, while removing areas of continuous tone which would otherwise distort the spectral characteristic of the gamma-ray image when the data sets are combined. The combined image (Fig. 3c) enables geochemical information derived from the gamma-ray responses to be interpreted within a geomorphic framework. The higher spatial resolution of the TM data also tends to sharpen the otherwise fuzzy gamma-ray image. In addition, adding back the high-frequency component of the total-count channel to the K, eTh and eU images was found to highlight edges associated with lithological and regolith boundaries.

Digital elevation models (DEMs) provide information on important geomorphic variables, including elevation, slope, aspect, convexity and relief. The accuracy of these variables largely depends on the spatial resolution of the DEM. The

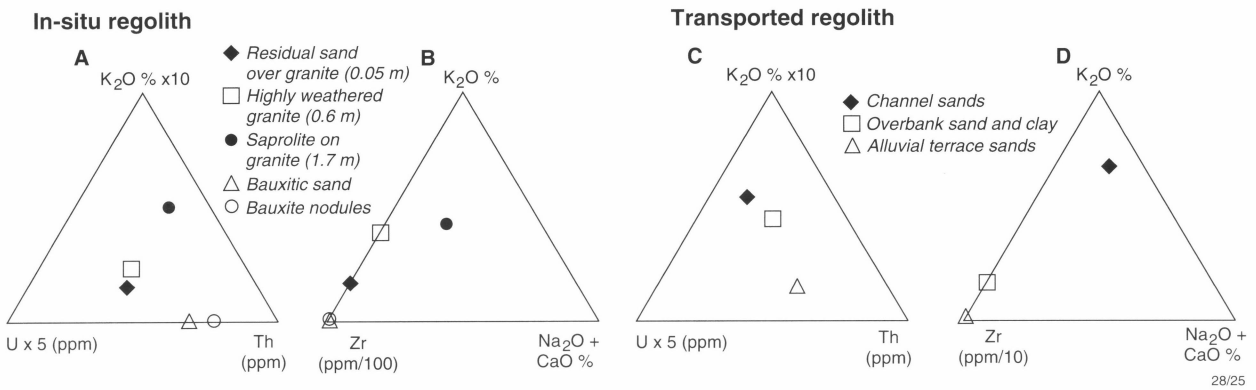


Figure 5. Ternary diagrams showing regolith geochemistry for K_2O, Th, U, Zr and Na_2O + CaO. A and B relate to in-situ weathering profiles on granite and bauxitic material. C and D relate to river channel, overbank and alluvial terrace sediments.

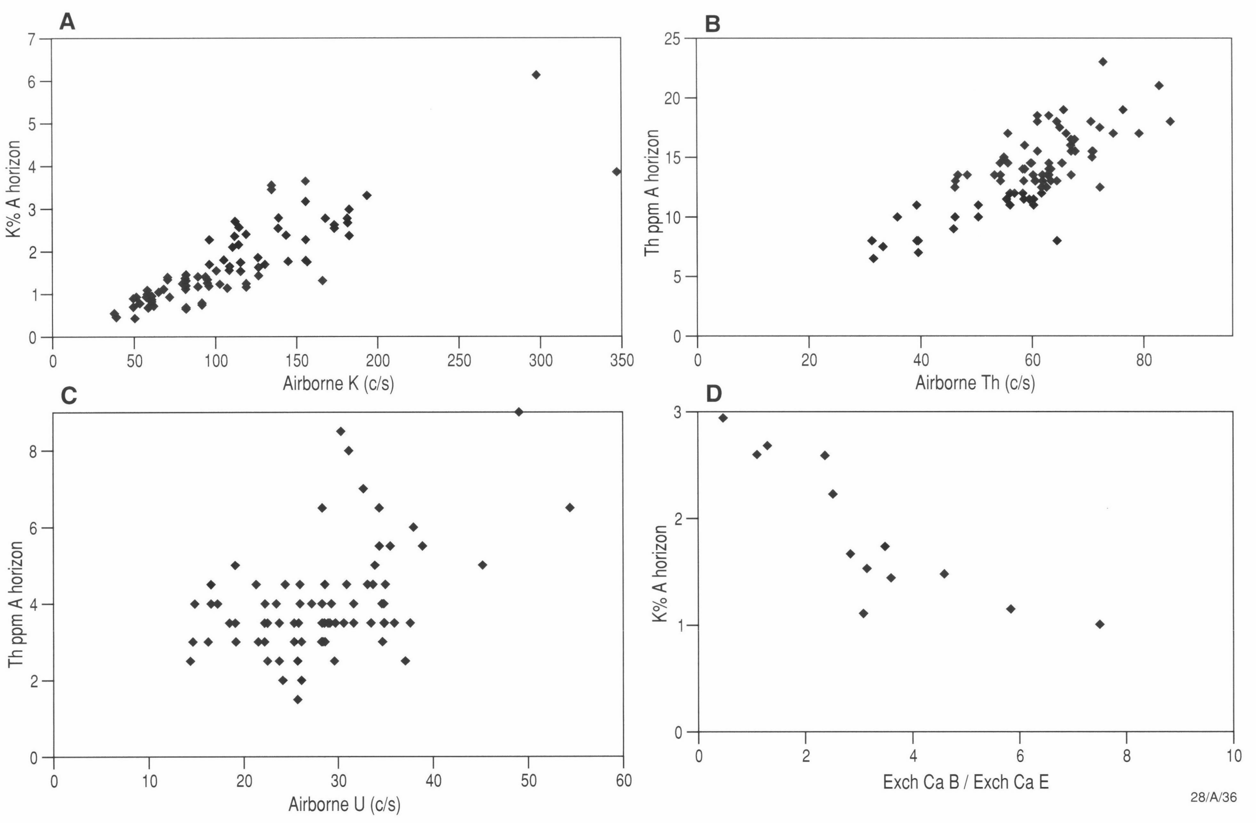


Figure 6. Scatter plots (a,b,c) showing the correlation between measured soil K, Th and U against aerial K, eTh and eU concentration over part of the Wagga Wagga region (from Bierwirth 1996). Evidence of leaching is shown in plot d, where site analyses of K in the upper A horizon are plotted against the ratio of exchangeable calcium in the upper B versus the bleached A2 (E Horizon).

variables have a controlling influence on geomorphic processes and distribution of soil/regolith materials. DEMs can be combined with the gamma-ray data as shaded relief images or as 3D perspective views, where the gamma-ray images are draped over the elevation model (Figs 3b, 4a–d). These displays facilitate the visualisation of complex relationships between the gamma-ray response and terrain morphology attributes.

Colour space transformations and pixel adding techniques are used to combine Landsat TM, DEM and gamma-ray images. Colour space manipulation is available on most image-processing platforms and is a common technique for merging multisensor data (e.g. Conradsen & Nilsson 1984; Welch & Ehlers 1987). Colour space transformations work by converting data sets into intensity, hue and saturation (IHS) components of colour. Once in IHS colour space, each of the colour parameters can be exchanged with other registered data sets before being converted back to the original RGB colour space coordinates for display. The IHS technique is used to combine Landsat TM band 5, artificial sun-angle illuminated DEM and total-count images with the K, Th and U channels by substituting these images as the intensity component of the gamma-ray channels. The result is an image which effectively shows the colours (or hue) of the gamma-ray data with the intensity of the colour modulated by either the Landsat, DEM or total-count image Figs 3c, 4a–d. The IHS technique, however, was found to distort to varying degrees the spectral characteristics of the original gamma-ray image. Another technique, which avoids this distortion problem, is a simple addition of proportions of each data set pixel-by-pixel. This method allows complete control over the percentage of each pixel added from each data set to the combined image (Wilford 1992).

Study areas

The study areas include the Ebagoola 1:250 000, Wagga Wagga 1:100 000 and Sir Samuel 1:250 000 map sheets (Fig. 2). Airborne gamma-ray surveys within these three areas provide a representative selection of different regolith materials, from deep chemical weathering and saprolite formation in Sir Samuel and parts of the Ebagoola region to generally less-weathered landscapes in Wagga Wagga study area. A summary of the climate, vegetation and geology of each area is given below.

Ebagoola

The Ebagoola study area has a warm monsoonal climate with distinct dry and wet seasons. Average annual rainfall is 1117 mm with 95 per cent falling in the wet season between November and April (Wagner 1989). Vegetation is mainly eucalyptus, open woodlands and forests. Land use is restricted to broad-scale cattle grazing, owing to the prolonged dry season. The geology of the Ebagoola study area can be divided into three main rock groups, comprising a central zone of Palaeozoic granites (granodiorite, muscovite–biotite and alkali-feldspar granites) and folded metamorphic rocks (phyllite, schist and gneiss) with gently dipping Mesozoic sediments (sandstones and siltstones) to the west and east (Blewett & Trail 1995).

Wagga Wagga

The Wagga Wagga study area has a temperate climate with average annual rainfall of 530 mm. Agricultural land use consists of wheat cropping, sheep grazing and dairy farming. Dryland salinity is an environmental problem in the area, owing to rising water tables caused by deforestation of the natural vegetation. The geology consists of Silurian granites intruding metamorphosed Ordovician slates and quartzites (Raymond 1992). In places, these rocks are unconformably overlain by Devonian sandstone. Large areas of Cainozoic alluvium and colluvium occur in valleys, floodplains and downslope from adjacent hills.

Sir Samuel

The Sir Samuel 1:250 000 area is semi-arid to arid with a mean annual rainfall of approximately 215 mm (Bunting & Williams 1979). Vegetation consists largely of mulga, blue bush, spinifex, mallee shrub and scattered trees (*Eucalyptus* spp.). Land use consists of broad-scale pastoral activities and mining. Rocks in the area are Archaean and include greenstone belts, consisting of metamorphosed sediments, volcanics and intrusives (Bunting & Williams 1979). The greenstone belts are separated by large areas of granite, including granodiorite, tonalite, monzonite and adamellite. These rocks are generally either exposed and deeply weathered (typically kaolinised to tens of metres below the surface) or covered by transported sediment.

Results—case studies

Interpretations of the three airborne surveys are firstly described in terms of gamma-ray response associated with in-situ and transported regolith material in the landscape. Then, selected examples from the surveys are used to illustrate how gamma-ray data can map areas of groundwater discharge and recharge and soil/regolith catenas and be used to assess weathering maturity and geomorphic processes in the landscape. Most of the examples are drawn from the Ebagoola study area. A comprehensive description and analysis of the airborne survey over the Wagga Wagga study area is given by Bierwirth (1996). The Wagga Wagga study involved a large number of ground spectrometer measurements, soil samples and XRF analyses. Interpretations in Ebagoola are based on limited laboratory and field spectrometric measurements, geochemical sampling and detailed field mapping (regolith). Major and minor elements for soil/regolith samples were determined using X-ray fluorescence (XRF); whereas X-ray diffraction (XRD) was used to identify minerals and clays. High specific gravity mineral concentrates were determined for some samples, using heavy liquids. Interpretation over the Sir Samuel area was largely based on field relationships and correlations with published regolith-landform maps (Craig & Churchward 1995).

Gamma-ray responses of in-situ soils/regolith

The gamma-ray responses of in-situ weathered regolith can be grouped according to the rock types being weathered. Where bedrock crops out or where soil/regolith materials are thin, the gamma-ray response directly relates to the primary rock minerals and geochemistry and, in places, secondary minerals associated with mineralisation (e.g. potassic alteration).

Regolith associated with metamorphic rocks

Regolith materials over metamorphic rocks in the Ebagoola study area are variable in nature and shallow. The variation reflects the lithological heterogeneity of the bedrock and landforms with moderate to high relief (>30 m). Areas of high relief are being actively eroded and regolith development is minimal, consisting mainly of lithosols overlying slightly weathered bedrock. The gamma-ray response from the partly weathered materials is essentially equivalent to the original bedrock response. Therefore, gamma-ray response over these landforms is directly related to bedrock geochemistry. Scree and lithosols on quartzite ridges have relatively high U values and are likely to reflect accessory resistant minerals, such as zircons, within the quartzites (area G, Fig. 3a) (Blewett & Trail 1995). Clayey earths on subdued topography between the quartzite ridges have formed by the weathering of schistose and phyllitic parent material. These soils are distinguished by moderately high K, eTh and eU values. The K element in the soils relates to potassic clays (illite) and micas. Th and U elements are likely to be associated with clays, Fe oxides and

Table 1. X-ray fluorescence (XRF), X-ray diffraction (XRD) and heavy-mineral separation for selected regolith samples over the Ebagoola area.

SAMPLE	SiO_2%	Al_2O_3%	FeO %	MgO %	CaO %	Na_2O %	K_2O %	Th ppm	U ppm	Zr ppm	XRD and heavy liquid separation
Bauxite nodules	55.24	27.26	4.83	0.07	0	0	0.03	41	2.5	869	*Kaolinite and quartz major, goethite and amorphous iron, zircons and rutile as trace*
Bauxitic sand	68.58	16.34	3.83	0.08	0.02	0	0.03	28	2.5	1243	*Quartz major, kaolinite, goethite and amorphous iron, zircon common - rutile as trace*
Clayey earth on schist	59.54	18.12	9.21	0.54	0.03	0.82	3.58	25	5.5	161	*Mica and kaolinite major, montmorillonite mixed layered clay and quartz trace*
Residual sand on sandstone	93.4	2.28	0.47	0.02	0.01	0	0.11	9	1.5	347	*Quartz major, amorphous iron - zircon and rutile as trace*
Residual sand on granite	92.53	3.74	0.98	0.03	0	0.01	0.51	13	4.5	204	*Quartz major, trace of amorphous iron, zircon and rutile*
Weathered saprolite	62.49	20.31	2.28	0.47	0	0.03	1.28	2.1	1.5	119	*Quartz major, minor kaolinite and K-feldspar*
Structured saprolite	65.92	16.38	4.73	0.81	0.23	1.03	2.41	17	3	262	*Quartz, kaolinite and K-feldspar major*
Shallow yellow earth on siltstone	61	7.4	24.19	0.03	0.04	0.01	0.09	9	2.5	208	*Quartz and kaolinite major, goethite and amorphous iron and zircon trace*
River channel sands	79.97	10.29	0.42	0.07	0.4	1.2	4.83	14	2	90	*Quartz major, K-feldspar, minor kaolinite and mixed layered clays*
Overbank - sand and clay	88.91	5.52	0.24	0.03	0.05	0.24	2.93	19	3.5	186	*Quartz major, minor K-feldspar, minor kaolinite and mixed layered clays*
Older alluvial terrace sands	95.59	1.22	0.31	0	0.02	0	0.46	16	5.5	399	*Quartz major - mica and zircon trace*

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lithic fragments in the weathering profiles (Table 1).

In the Wagga Wagga study area, gamma-ray response varies over hilly landforms of metasedimentary rocks, according to soil depth and degree of leaching. On ridge tops, soils are very shallow with relatively fresh bedrock fragments exposed at the surface. These shallow soils are distinguished by their high K response (Fig. 4c), which corresponds to K-mica and illite associated with weathered rock fragments and minor clays. Soils downslope from the ridges are deeper and are distinguished by low K response. Soil–landform relationships of these soils are discussed later under the heading ***Soil/regolith catenas***.

Regolith associated with granitic rocks

Weathering profiles are developed on granitic bedrock in each study area. In Ebagoola, regolith on gently undulating rises consists of deep uniformly textured residual yellow to yellowish-orange massive sandy earths over granitic saprolite. These soils are low in all radioelements and appear black in the imagery (area D, Fig. 3a). They consist mostly of quartz sand that accumulated preferentially as other, more soluble, minerals were removed from the top of the weathering profile, either in solution or as fine grains. Apart from quartz, there are minor amounts of mica and kaolinite, and traces of resistate minerals, such as rutile and zircon (Table 1). Thinner sandy earth soils with a poorly developed quartz sand horizon are separated from the deeper residual soils by their higher K response. The gamma-ray response of these thinner soils reflects the chemical composition and mineralogy of the underlying granite, in particular the abundance of K-feldspar and mica in the near surface. S and I-type granites can be distinguished in areas of thin regolith cover by their gamma-ray response. S-type granite has generally higher K and eTh values

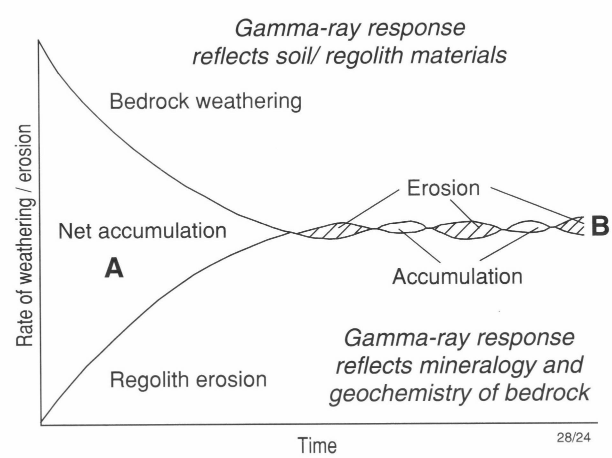


Figure 7. Diagrammatic representation of factors which affect the denudation balance in landscapes. Regolith or soil thickness at any one site will depend on the relative rates of regolith accumulation and erosion. A, weathering rates higher than erosion rates, resulting in regolith development; B, weathering and erosion rates are similar, resulting in thin permanently youthful regolith. In areas of active erosion, gamma-ray responses are likely to reflect geochemistry and mineralogy of the bedrock, whereas in areas of accumulation, the response is modified by pedogenesis (Figure modified from Crozier 1986)

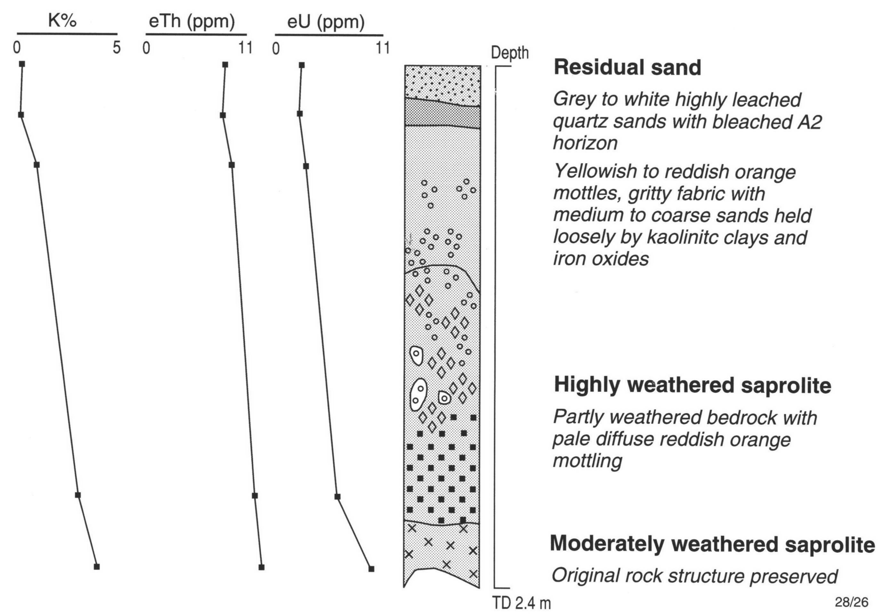


Figure 8. Highly leached, residual sandy weathering profile developed on granite in north Queensland (Ebagoola). K% and ppm equivalents of eTh and eU down the profile are measured by laboratory spectrometer.

than I-type granite (areas E & O, Fig. 3a).

In the Sir Samuel area, the gamma-ray response over granitic terrain varies, reflecting the degree of weathering and surface reworking by either aeolian or fluvial processes. Granitic saprolite is exposed in the Sir Samuel and Wagga Wagga study areas in areas of active erosion over hilly terrain. Here, the saprolite is distinguished by high K, eTh and eU responses, which reflect parent rock geochemistry and mineralogy. The freshest exposures in the Sir Samuel region are usually immediately downslope from breakaways (area C, Fig. 4a). Soil over the saprolite is typically thin with rock fragments at or near the surface. Geochemical analyses indicate that K is associated with K-feldspar in the coarse sand and gravel fraction of the soil (area A, Fig. 4a), whereas eTh and eU are likely to be associated with clays and lithic fragments.

Regolith associated with sedimentary rocks

In Ebagoola, regolith profiles developed on Mesozoic sandstone and siltstone consist, respectively, of deep, sandy red-yellow earths over highly weathered mottled bedrock, and shallower yellow earths over moderately weathered bedrock. The sandy earths give a low gamma-ray response for each radioelement (appear black in area K, Fig. 3a), owing largely to the accumulation of quartz sand, which is radioactively barren. The shallower, finer textured soils developed on siltstone give a higher eTh and eU response (area L, Fig. 3a), which reflects the geochemistry of the underlying bedrock. Gilgai or swelling clay soils (area M, Fig. 3a) developed on Mesozoic or more recent sediments are distinguished by higher K values, which are likely to be due to the presence of potassic clays (illite) and the absorption of K ions within the lattice of swelling clays (montmorillonite). In the Wagga Wagga area, low K, Th and U values characterise the gamma-ray response over weathered sandstone, reflecting the lack of radionuclides in the sandstone and abundance of silica sand, which is radioactively barren.

Ferruginous and siliceous duricrusts

Exposures in the Sir Samuel study area are generally poor and deeply weathered. In many places, saprolite is either covered by aeolian sands (see ***Gamma-ray response of transported soil/regolith***), cemented, or capped by silcrete and various ferruginous materials, including massive Fe duricrusts, ferricrete, ferruginous saprolite and iron-rich gravel lags. Typically, the radioelement characteristics of these weathered materials bear little resemblance to those of the underlying rocks. Silcrete and ferruginous crusts commonly form breakaways (area A, Fig. 4a) or mantles over undulating slopes and hill tops. Silcrete appears green and blue (area A, Fig. 4a), which indicates the lack of K and presence of Th and U. The high eTh and eU values are likely to relate to heavy-mineral grains (e.g. zircon) in the silcrete, or contamination by Th and U-rich groundwater during silcrete formation. Ferruginous material also appears green and blue, but typically has higher Th than silcrete. The high Th is likely to be associated with Fe oxides. However, some Fe duricrusts, particularly those developed over greenstone, are radiometrically barren (appear black in area D, Fig. 4a), which reflects the lack of the radioelements in the bedrock from which the Fe oxides have been sourced. In Ebagoola, unconsolidated ferruginous sands and, in places, cemented pisolitic Fe duricrusts are distinguished by their high Th values (areas P, Fig. 3a), which are likely to be due to Th associated with resistate minerals (e.g. zircon) and scavenging of Th by Fe oxides.

Gamma-ray response of transported soil/regolith

The gamma-ray response of transported regolith can be broadly divided and described in terms of alluvial, colluvial and aeolian material.

Alluvial material

Alluvial material includes sediment deposited by channel and overbank stream flow. In the Ebagoola study area, gamma-ray response is effective for mapping the distribution and provenance of alluvial sediment. River channel and alluvial fan sediments derived from granitic and metamorphic rocks are distinguished by high K, eTh and eU (area B, Fig. 3a). Sediment derived from metamorphic rocks is distinguished by low K and high eTh and eU, reflecting chemistry of the source rocks (area C, Fig. 3a). Sediment derived from granitic rocks is distinguished by high K and moderate to high eTh and eU (area A, Fig. 3a). In places, floodplain sediments are separated into channel and overbank deposits on the basis of their gamma-ray response. Channel sands are recognised by their

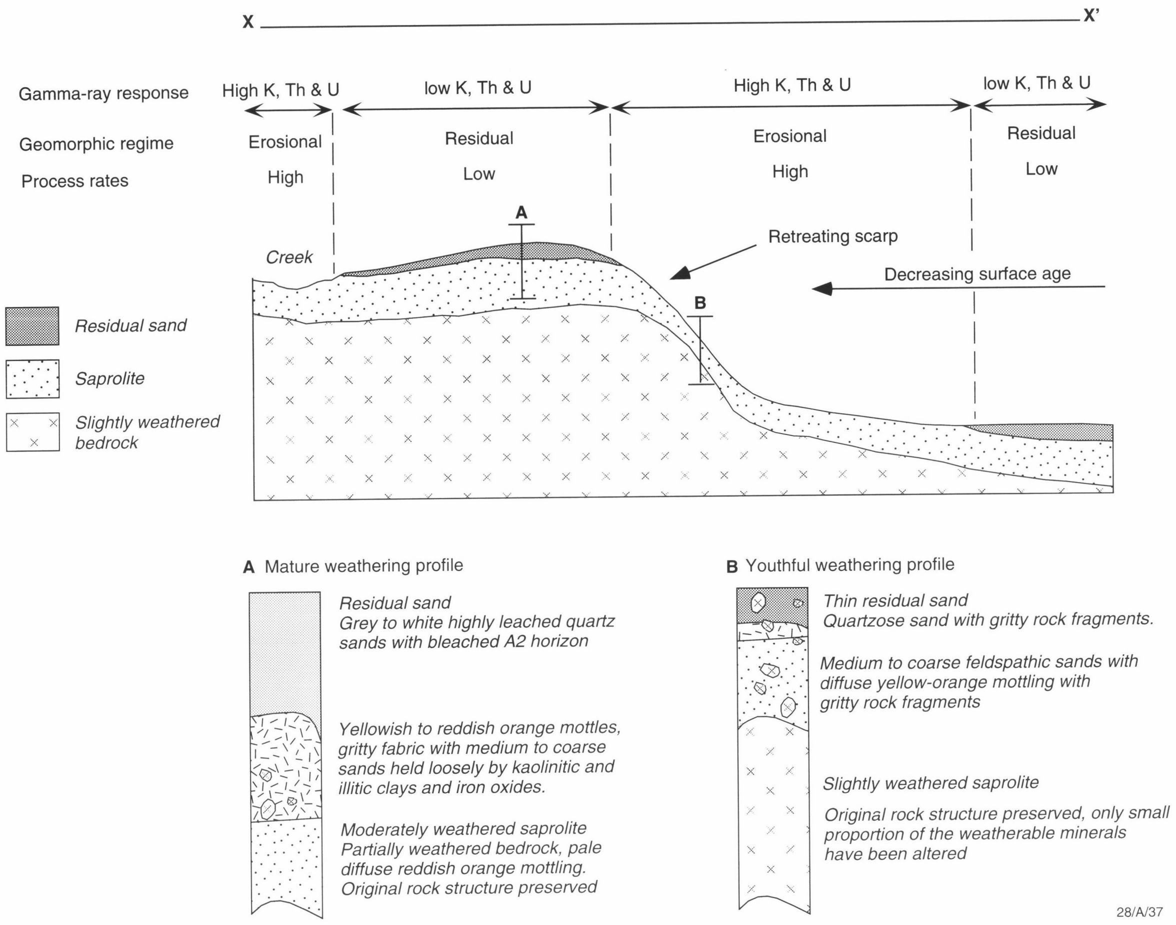


Figure 9. Relationship between gamma-ray response, soil/regolith type and geomorphic processes over the Great Escarpment in Ebagoola. Location of X–X[1] transect on the gamma-ray image shown on Figure 3b.

high K values and correspond to coarse-textured sediment rich in K-feldspar and mica. In contrast, soils developed on alluvial overbank sediment have lower K and relative high eTh and eU responses. Increased abundance of zircon in the overbank deposits (Table 1) may relate to higher eTh and eU responses. Adsorption of U and Th onto clay in the finer textured overbank sediment is also likely to contribute to higher eU and eTh responses. Differences in K concentration between channel and overbank sediment and implications for weathering development and depositional rates are discussed later under ***Weathering development and relative geomorphic activity***.

In the Wagga Wagga study area, river channel sediment derived from granitic bedrock is distinguished by high K values and relates to coarse-textured alluvial soils and sediment containing significant amounts of primary K-feldspar. Finer textured alluvial soils, where K and eTh are associated with clays, give a distinctive signature for floodplain sediment. Textural and possible age differences in the floodplain sediment can be distinguished on the basis of gamma-ray response. Variation in K and Th concentration is used to map areas of alkaline cracking clay, alluvial deposits of various ages and other non-cracking soils. Cracking clay and gilgai are indicated by low eTh response. This may be due to deposition of montmorillonite-rich clay with lower Th during a more arid period. More recent channels with greater amounts of illite and kaolinite clays have a higher Th response. Relatively more recent alluvial deposits are distinguished by elevated K and Th, which correlate with the amount of silt and clay particles in the sediment. Both K and Th are known to adsorb onto clay particles (Wedepohl 1969) and some K may be present in the silt and clay. This means that alluvial areas can be identified by radiometric signature and in some areas it may be used to predict surface grain size.

In the Sir Samuel study area, sediment derived from granitic sources is distinguished by high K, eTh and eU. However, many major river systems are delineated by a high eU response. The high eU may be associated with radium isotopes deposited from groundwater and saline lakes or U precipitated in calcrete, which tends to accumulate along valley floors.

Colluvial material

In the Wagga Wagga study area, active colluvial deposits derived from granitic rocks are distinguished by a high K response, associated with K-feldspars. They are separated from less active older deposits, which have low K signatures, owing to removal of soluble K-feldspar minerals from the weathering profile (Fig. 4b). The older colluvial deposits consist mostly of quartz sand within a clay matrix. The colluvial footslopes act as conduits for groundwater flow, with saline seepages occurring in creeks at the base of the footslopes. Highly weathered colluvial soils derived from the weathering metasedimentary rocks are also characterised by low K values. Detailed sampling of soil properties and radioelement concentrations (Bierwirth et al. 1996) indicate that loss of K on the colluvial footslopes is largely a result of leaching. Figure 6d, shows a leaching index (the ratio of exchangeable calcium in the upper B horizon versus the bleached A2 horizon) related to K in the A horizon of colluvial soils. As expected, K concentration in the soil inversely relates to degree of leaching. The same relationships were observed with K in the A2 and B horizons. Elsewhere, other studies have found that adsorption on clays and downslope surface transport dominate radioelement patterns (Martz & de Jong 1990). Soil chemistry and

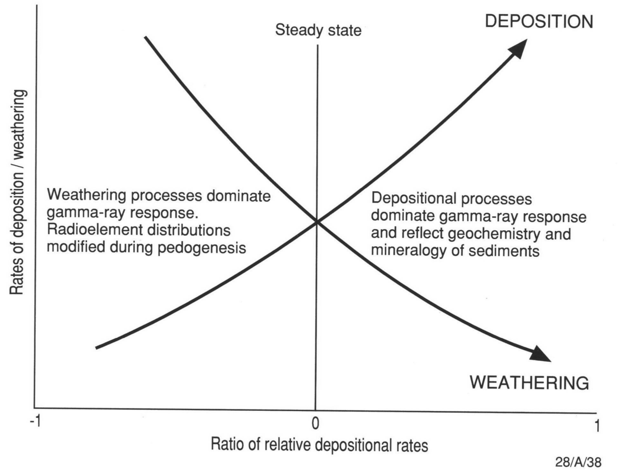


Figure 10. Relationship between gamma-ray response to relative rates of weathering and deposition. The steady state is where depositional and weathering processes have equal influence on the radioelement characteristics of the sediment.

radioelement concentrations (Fig. 6a, b) indicate that, despite the relatively coarse resolution of the airborne data (approx 100 m pixels), there is a good correlation between soil and airborne K and eTh measurements. This suggests that certain field site attributes or soil relationships based on geochemical trends (e.g. degree of leaching) can be extrapolated using gamma-ray signatures. Airborne eU values, however, are poorly correlated with soil measurements (Fig. 6c). In the Sir Samuel region, active colluvial fans derived from granitic rocks show high K responses, reflecting the abundance of coarse K-feldspar grains (area G Fig. 4a). Less active colluvial fans typically have subdued K response.

Aeolian material

A large proportion of the Sir Samuel study area is covered by sandplain or aeolian reworked sheet-flow fans, which consist of hummocky dunes and sand sheets. Well-worked quartzose aeolian sand is characterised by low radioelement response (black hues, area F, Fig. 4a) and can be separated from feldspathic sand, which has a high K signature. The feldspathic sand is sourced from and found adjacent to weathered granite.

Extensive areas of the Riverine Plain, including parts of Wagga Wagga study area, are covered by wind blown parna. Parna consists of clay and silt-size aggregates and was deposited during drier periods in the Quaternary (Butler 1956). Areas interpreted as parna on field sample data (Bierwirth 1996) are associated with high eTh response. However, since parna and older alluvial deposits have similar gamma-ray signatures, they are not easily separated. Further complications arise where the parna is weathered to various degrees or partly mixed with other material, as a result of bioturbation and fluvial reworking. Isolating the Th response associated with parna material is difficult and depends largely on the background radioelement patterns.

Groundwater recharge and discharge

In the Ebagoola and Wagga Wagga study areas, highly porous quartzose soils, developed in situ over granite, are readily distinguished from heavy-textured soils, which typically exhibit much higher K and/or Th/U responses (areas D & M, Fig. 3a). The sandy soils are potential groundwater recharge zones. Discharge zones sometimes have observable gamma-ray signatures. Salt lakes and freshwater springs often concentrate U series elements (Dickson et al. 1987), including dissolved Ra and sometimes U itself. In the Wagga Wagga study area, no evidence has been found for soil accumulation of Ra or U. However, evidence suggests that airborne eU anomalies associated with discharge sites (Bierwirth 1996) could be due to radon gas exsolving from groundwater.

Soil/regolith catenas

Catenas describe a sequence of soils developed from similar parent material, but having different characteristics, owing to variation in slope and drainage. Catenas are recognised on gamma-ray imagery over granitic rocks in the Ebagoola study area and shaly lithology in the Wagga Wagga study area. In Ebagoola, they consist of deep uniformly textured sandy (quartzose) earths, which grade at depth into highly weathered saprolite, and shallow sandy earths and red-yellow podzolic soils, which grade at depth into moderately to slightly weathered saprolite. The distribution of these regolith types reflects different rates of erosion and accumulation on different slopes. Uniformly textured soils occur over flat hill tops and are characterised by low K, Th and U values (area A, Fig. 4d), whereas shallower soils are associated with steeper slopes (area B, Fig. 4d) and are distinguished by their high K response. In the Wagga Wagga study area, the hill tops have thin and poorly developed soils, which consist largely of lithosols. Downslope and adjacent to these hills, the soils are deeper and finer textured, and have formed on colluvium derived from weathered sediments upslope. These soils form a catena over many square kilometres of terrain underlain by Ordovician metasediments and are easily mapped using the K channel draped over a DEM. High K values delineate areas of thin soil cover and low values correspond to deeper colluvial soils (Fig. 4c).

Weathering development and relative geomorphic activity

Bedrock-dominated landforms

The development of a weathering profile in bedrock-dominated landforms depends on the balance between the rate of bedrock weathering and the rate at which weathered material is removed (Fig. 7). The most stable parts of a landscape are where the rate of weathering exceeds the rate of erosion. Deep weathering profiles develop and are preserved in stable areas with low relief and where rates of erosion are relatively low.

Stable landscapes in the Ebagoola study area tend to have either low values for K, eTh and eU, which correlate with residual quartz sand, or low K and relatively high eTh and eU, associated with accumulation of oxides and resistate minerals. Strongly leached aluminous and ferruginous bauxitic soils developed on highly weathered Tertiary plateaus are delineated by low Th and U gamma-ray values (area F, Fig. 3a). A representative bauxite profile from top to bottom comprises a residual sandy (quartz) A horizon (10–70 cm), a zone of unconsolidated bauxitic/iron pisolites and nodules supported in a sandy matrix (1.2+ m), and a pallid zone, consisting mainly of kaolinitic clay with very little iron. The top of the profile is very low in soluble cations and consists mainly of iron and aluminium oxides, kaolinite, quartz and resistant minerals (Table 1). Soil geochemistry of bauxitic sand and nodules has shown them to be relatively high in Th, U and Zr, and low in K, Na and Ca (Fig. 5a,b). Low K has resulted from either intense leaching of K-bearing minerals in the weathering profile or low initial K concentration in the underlying bedrock. High Th and U are likely to correspond to the surface concentration of resistate minerals (e.g. zircon up to 1200 ppm, Table 1) and scavenging by Fe oxides.

In the Ebagoola study area depletion of K over granitic landforms, owing to leaching, is used to separate completely weathered saprolite on stable landforms from thinner, partly weathered saprolite on steeper, actively eroding slopes (Wilford 1995). Geochemical and radionuclide trends down the completely weathered profile are shown in Figure 8. This profile type has developed on stable landforms with low mean slopes and comprises residual sand overlying highly weathered mottled saprolite and structured saprolite. Residual sand forms from deep chemical weathering, resulting in the loss of soluble mineral constituents (K_2O, CaO, Na_2O) and concentration of resistant quartz and accessory minerals, such as zircon and monazite, in the upper part of the weathering profile (Fig. 5a,b). Residual quartz sand without accessory minerals is low in K, eTh and eU, and appears black in the image (area D, Fig. 3a; area C, Fig. 3b). In contrast, thinner, partly weathered profiles that form on steeper, actively eroding slopes are distinguished by their higher K response, reflecting the presence of alkali-feldspar and mica derived from the partly weathered granite. Conversely, on stable landforms, where weathering exceeds erosion, K decreases in concentration as K-bearing minerals are progressively leached from the weathering profile. These relationships are clearly illustrated in a 3D perspective view (Fig. 3b), where the edge of a major erosional scarp separates an area with high geomorphic activity and youthful weathering profiles from one with low geomorphic activity and mature weathering profiles. An explanation of the relationships between gamma-ray response, soil/regolith type and geomorphic processes in relation to the perspective image (Fig. 3b) is shown diagrammatically in Figure 9. Denudation balance in landscapes (or the relative rates of regolith formation versus rates of erosion) can be determined using airborne surveys. 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 (Fig. 7).

However, not all low K or high Th and U values in the gamma-ray image are associated with highly weathered substrates, because different bedrock types can give similar responses. Interpreting the degree of weathering and inferring process rates from gamma-ray responses requires an understanding of the radioelement characteristics of bedrock and weathered material. Therefore, care should be taken when using such relationships, because other regions may differ, depending on their bedrock type and weathering history.

Depositional landforms

Gamma-ray imagery can be used to show the degree of weathering and relative depositional activity in fluvial environments. Recently deposited channel sand sourced from mixed granitic and metamorphic provinces has high K, eTh and eU values (white hues, area B, Fig. 3a,b). The radioelement response from this sand closely reflects the chemistry of the bedrock from which it was derived. This suggests that erosion, transportation and deposition of the sediment is relatively rapid, with little time for weathering to modify the radioelement composition of the original bedrock source.

In contrast, older perched alluvial terrace and overbank sediments, also derived from granitic and metamorphic rocks, have lower K and relatively higher eTh and eU values (blue/green hues, area I, Fig. 3a). These differences probably reflect textural and compositional differences between the coarser channel sand and finer overbank sediment, and modification of the radioelements by pedogenesis and leaching. Compared with the channel sediment, the overbank and terrace sediments show relatively lower concentrations of readily soluble mineral constituents (CaO, NaO, K_2O; Fig. 5c,d) and a increase in resistant minerals, such as zircon. Of the soluble mineral constituents, K is detectable by airborne spectrometry and the low K concentration in the terrace sediment is likely to partly relate to surface leaching of K. The low K concentration may indicate a less active depositional regime with sufficient time for weathering to modify the distribution and/or concentration of radioelements in the sediment before deposition. Similar associations have been used in the Ebagoola study area (Wilford 1992) to distinguish palaeochannels and former river channels on the preferential loss of K and relative concentration of resistate minerals, indicated by higher eTh and eU responses (area N, Fig. 3a).

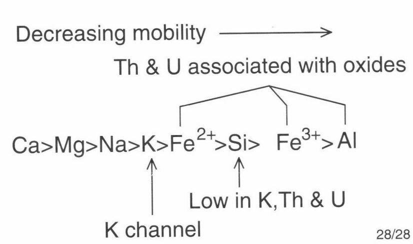
The gamma-ray response in active depositional regimes is likely to reflect the geochemistry and mineralogy of the bedrock from which sediment is derived, whereas the gamma-ray response in less active depositional systems is likely to reflect weathering processes. This is only true, however, where the concentration of radioelements in sediment is responsive to weathering processes (Fig. 10).

Discussion

Gamma-ray response over the three study areas shows broad correlation with rock units. However, variation within units corresponds mainly to the regolith, including in-situ and transported material. The source of gamma-rays emanating from the ground surface can be described as primary or secondary. Primary sources relate to the geochemistry and mineralogy of bedrock; secondary sources, to modification of radioelement distribution by weathering and pedogenesis. The latter is complex: some of the factors affecting the gamma-ray response over a single lithology are shown in Figure 11.

During weathering, radioelements are released from primary mineral constituents and incorporated into clay, iron oxides, groundwater and organic matter. K is geochemically mobile and soluble under most weathering conditions. During weathering it is lost from primary minerals, such as K-feldspar and mica, in solution and/or adsorbed onto clay minerals, such as illite, montmorillonite and, to a lesser, extent kaolinite. U and Th are typically much less mobile than K. U is leached and released from soluble minerals under oxidising conditions and precipitates in reducing conditions (Hansen 1992). Surface concentrations of eU can be associated with resistate minerals such as zircon and monazite, clay or ^{226}Ra exsolved from groundwater. Th can be highly mobile when combined with organic complexes in groundwater and soils (Dickson 1991). Th is also associated with resistate minerals and tends to be concentrated in residual regolith profiles. Both U and Th released during weathering are readily adsorbed onto clay minerals and are co-precipitated with Fe oxides in soils (Dickson & Scott 1990).

Although these secondary sources of gamma-rays relate to a variety of different materials and processes, some general trends do emerge. Typically, Th and U are associated with silt/clay fractions and sesquioxides in soils and tend to concentrate in highly weathered profiles relative to K. K is typically high in slightly weathered regolith (depending on bedrock composition) and low in highly weathered regolith, owing to leaching. The relative mobility of major mineral constituents released during weathering and their gamma-ray response are shown in the sequence below.



The sequence is generalised and ordering may change with to environmental conditions. As primary minerals weather, cations (e.g. K^+ Na^+ Ca^{+2}) are either incorporated into clay minerals (i.e. smectite & illite) or lost in solution. Further weathering leads to the development of kaolinitic clays and accumulation of silica, iron and aluminium oxides. The lack

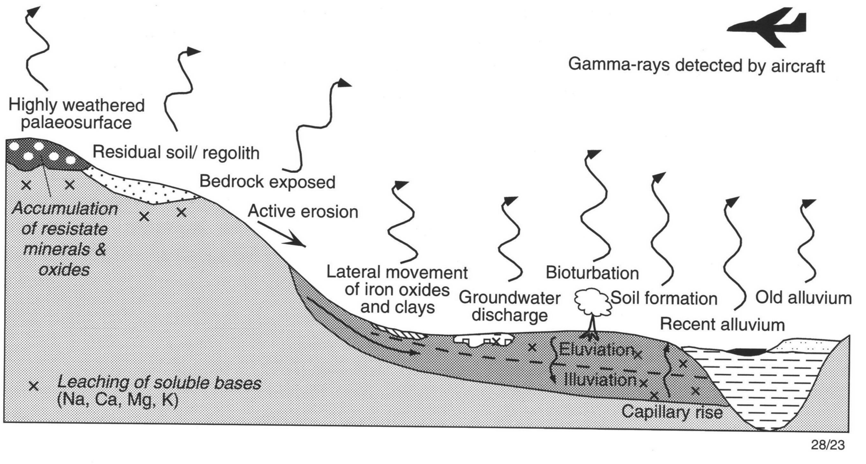


Figure 11. Diagrammatic sketch of factors affecting gamma-ray response over the same bedrock type. Gamma-rays will reflect the primary mineralogy and geochemistry of the bedrock, the nature of secondary weathering materials, groundwater dynamics and geomorphic processes in the landscape. Pedogenesis is important in modifying the distribution of radioelements at the surface.

of radioelements in quartz can be used in places to indirectly map highly siliceous soils.

The K channel and K/eTh & K/eU ratio channels can be used in places to assess the degree to which the source materials of regolith are weathered or leached—since K response is associated with easily weathered minerals, whereas Th and U are typically associated with residual clay, oxides and accessory minerals (previous weathering sequence diagram). For example, high and low K/eTh & K/eU ratio values over potassic rocks in the Ebagoola study area are likely to be associated with slightly weathered and highly leached soils, respectively. These highly leached soils also have a very low exchangeable cations and organic matter content (Isbell & Gillman 1973) and high porosity and permeability. In places, highly leached low-relief landforms in the Ebagoola study area, delineated by low K response, correlate well with moderately acidic soils (Biggs & Philip 1995). These acid soils are likely to have developed through the removal of basic cations and replacement by acidic ions (H^+ or Al^{+3}) during weathering. Studies from Wagga Wagga (Bierwirth 1996) indicate that in some areas airborne K images can be used to map soil acidity. Soil samples in stable landforms (i.e. areas where pedogenic processes dominate) showed a positive correlation between K and pH. This highlights the potential use of airborne surveys in indirectly mapping and assessing the nutrient status, pH and water-holding capacity of certain soils. Gamma-ray surveys have the potential to extend certain soil or regolith site-attribute information spatially and map it as continuous variables across the landscape. Airborne measurements record total concentration of radioelements at the surface and, therefore, measured K does not equate to exchangeable K in soils or availability to plants.

General geochemical trends in surface regolith samples were reflected in the airborne measurements. K and, to a lesser extent, Th correlated reasonably well with aerial measurements. However, U soil measurements generally correlate poorly with estimated aerial concentration. This poor correlation is largely due to the occurrence of radon, a decay product in the U decay chain and not the parent U. The lack of correlation may also be explained by the low count rates and high noise content of the U channel in the airborne data. Correlations are likely to be highest over homogenous regolith material and where Th and U are in equilibrium with their radioactive daughter isotopes.

The gamma-ray response of regolith material from each of the study areas varied according to differences in lithology, weathering and geomorphic history. Radioelement response over actively eroding landforms is likely to be closely correlated to bedrock geochemistry and mineralogy. However, in more stable landforms, where regolith materials are accumulating, weathering can result in radioelement response showing a marked disparity from the underlying bedrock signatures. If the gamma-ray responses of the bedrock and regolith are known, then areas of regolith accumulation associated with low geomorphic process rates can be separated from bedrock areas associated with relatively high process rates. These relationships can then be used to assess the denudation balance in the landscapes or the relative rates of regolith formation and erosion.

The relative depositional activity of alluvial sediments and the provenance from which the sediments are derived can be distinguished. Active depositional environments have similar gamma-ray signatures to their source rocks, indicating relatively rapid erosion, transportation and deposition, with minimal modification by weathering. Gamma-ray responses in less-active depositional environments often differ from their source rock responses, owing to removal of radionuclides by pedogenic processes. This information has the potential to be used in improving the interpretation of stream-sediment geochemistry for mineral exploration.

Gamma-ray data provide complementary geochemical information for land-system mapping, which, to date, has been largely based on interpretation of aerial photographs. The land-system approach uses landforms as a surrogate for mapping soil and regolith types. In many cases, the gamma-ray data can be used to extend or further subdivide landscape units, particularly in areas of poor landform expression. Modelling gamma-ray data with ancillary data sets has been used successfully in predicting soil/regolith attributes (Wilford & Butrovski 1996; Gessler, P.E. 1996). In addition, vegetation often has little effect on the gamma-ray response, unlike surface scanners such as SPOT and Landsat TM, where vegetation patterns can have a confusing effect in identifying soil and regolith boundaries. However, a limitation of airborne gamma-ray spectrometry for detailed terrain evaluation compared with SPOT, Landsat and, in particular, aerial photography is its comparatively poor spatial resolution. For example, over 20 per cent of the gamma-ray signal will be derived from a ground radius of greater than 300 m for a survey flown at a height of 100 m (Minty 1997). For this reason, the interpretability of gamma-ray imagery is enhanced by combining it with data sets of higher spatial resolution. Integrating gamma-ray imagery with Landsat TM and digital elevation models enables the distribution of radioelements to be interpreted in a landscape context. The integrated images allow for accurate geographic positioning and, as such, are useful for field interpretation. Three-dimensional perspective views allow the gamma-ray response relating to regolith, catenas and geomorphic processes to be visualised and separated from lithological responses.

Conclusions

A gamma-ray image is a geochemical map showing the distribution of radioelements K, eTh and eU in rocks and regolith. Gamma-ray response from regolith material relates to present-day and past weathering and geomorphic processes in the landscape. Once the gamma-ray response and relationships between bedrock and regolith are understood, gamma-ray data can provide information on regolith properties, including mineralogy and chemistry. From this, inferences can be made about the style of weathering, degree of leaching, pH, texture, nutrient status, and thickness of regolith material, and relative geomorphic process rates. Gamma-ray data often provide a more direct remote-sensing tool for soil mapping than surface scanners (e.g. Landsat), which rely on vegetation surrogates to map soil types.

In areas of bedrock terrain, gamma-ray response correlates broadly with major geological units. Variation within these units can correspond to lithological variation and different styles of in-situ weathering, which reflect underlying lithology, time and geomorphic processes. Gamma-ray response from transported sediment will reflect the bedrock source, texture and style of weathering, which is, in part, controlled by the rates of erosion, transport and deposition in the catchment. Radiometric models developed to explain relationships between gamma-ray response and regolith material in one region may not be transferable to another, because of differences in bedrock lithology, geochemical environment and weathering history. In bedrock terrains, gamma-ray relationships and responses are often specific to major lithological types and, therefore, interpretation is best made within these major groups. Similarly, interpretation in depositional landforms is best made within major river catchments, since relationships between gamma-ray response and regolith material are likely to change with the type of lithology being eroded and the rate of erosion within catchments.

There are limitations in using airborne gamma-ray data. Not all regolith types can be distinguished by their gamma-ray response. Different regoliths can have similar responses, whereas other materials are radioactively barren with no distinguishable gamma-ray signature. Variation in the intensity of the gamma-ray signal, reflecting changes in soil moisture, is likely to be difficult to separate from regolith response. Furthermore, small-scale surface features, particularly, those located between flight lines, are likely to be undetected, because of the relatively poor spatial resolution of the survey data. Gamma-ray data should, therefore, not be used in isolation in any comprehensive terrain analysis or evaluation, but together with all other available information.

However, despite these limitations, airborne gamma-ray surveys provide information on surface geochemistry, distribution of common primary and secondary minerals, different styles of weathering and geomorphic processes in the landscape. Airborne gamma-ray data are, therefore, invaluable for mapping regolith (including soils) and in mineral exploration. The significance of airborne gamma-surveys for regolith mapping is likely to increase as we improve our understanding of the behaviour and distribution of radioelements in weathering profiles. Airborne gamma-ray data can assist in land-degradation and salinity studies by delineating areas of active erosion and areas of groundwater discharge and recharge. The use of airborne gamma-ray surveys in mineral exploration will be more effective when the responses due to weathering and geomorphic processes are understood, allowing subtle variations in lithology or changes through mineralisation to be resolved.

Airborne gamma-ray data have the potential to complement and accelerate presently used land-system approaches for mapping regolith and soils. The effectiveness of using gamma-ray data for mapping regolith will increase when they are combined and modelled with other complementary data sets, particularly terrain attributes, such as slope and relief.

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