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THE AIRBORNE GAMMA-RAY SPECTROMETRIC RESPONSE OVER ARID AUSTRALIAN TERRANES

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ABSTRACT

Airborne gamma-ray spectrometric data are commonly used for lithological mapping. A good correlation between bedrock and the gamma-ray spectrometric data is found in exposed, unweathered, previously glaciated terranes such as occur in northern Europe and North America. In weathered terranes, the airborne gamma-ray spectrometric response is usually a complex combination of the response due to fresh bedrock, weathered bedrock and transported material.

Recent studies using airborne gamma-ray spectrometric data from arid and semi-arid areas of Australia are establishing new criteria for using these data to identify the weathered and transported material, and to identify the weathering processes. The methodology is important for the mapping of bedrock lithology in highly weathered areas, the assessment of geochemical survey data for mineral exploration, and for land-use and land-degradation studies.

INTRODUCTION

The airborne gamma-ray spectrometric method is a surface mapping method in which the response is dominated by radiation arising from the top 35 cm of earth material. In contrast with the aeromagnetic method, the airborne gamma-ray spectrometric response varies with the climate to which the area surveyed has been subjected. This is because a significant gamma-ray spectrometric response arises from weathered rocks and transported material, as well as from fresh bedrock. It is the geochemical properties of radioelements which govern the gamma ray signatures in different environments. The purpose of this paper is to present examples of airborne gamma-ray spectrometric data from arid areas in Australia, and to explain some characteristic features. The paper draws on reports of active research (e.g., Dickson and Scott, 1997; Wilford *et al.*, 1997) directed at defining the characteristics of the gamma-ray spectrometric response in Australian terranes. While each area has its own peculiar characteristics, many of the processes and airborne gamma-ray spectrometric signatures described in this paper may have relevance to the interpretation of gamma-ray spectrometric data in arid areas elsewhere in the world.

GAMMA-RAY SPECTROMETRIC RESPONSE IN ARID AREAS — PRINCIPLES

Minty (1997) and Minty *et al.* (1997) have recently reviewed the airborne gamma-ray spectrometric method. The conventional approach to the acquisition and processing of airborne gamma-ray spectrometric data is to monitor at least three energy windows for the measurement of gamma radiation due to potassium (K), uranium (U) and thorium (Th). Through suitable calibration and data processing, the observed counts can be converted to concentrations of the radioelements in the rocks and weathered and transported material below the airborne detector.

The K window monitors the 1.46 MeV gamma-rays emitted by ^{40}K. Since ^{40}K occurs as a fixed proportion of K in the natural environment, the gamma-ray flux from ^{40}K can be used to estimate the total amount of K present. U occurs naturally as the radioisotopes ^{238}U and ^{235}U, which give rise to radioactive decay series. Th occurs naturally as the radioisotope ^{232}Th which also gives rise to a radioactive decay series. Neither Th nor U emit gamma rays, and gamma-ray emissions from their radioactive daughter products are used to estimate their concentrations. Gamma-ray emissions from ^{214}Bi and ^{208}Tl are used to estimate the concentration of U and Th respectively. These estimates are based on the assumption of radioactive equilibrium in the U and Th decay series. While Th rarely occurs out of equilibrium in nature, disequilibrium in the U decay series is common. Estimates of U and Th concentrations are therefore usually reported as ‘equivalent uranium’ and ‘equivalent thorium’ as they are based on the assumption of equilibrium conditions in the source.

Gamma radiation is attenuated by material between the source and the detector. Absorption thus also occurs within the earth, with the result that the geochemical mapping utility of the airborne gamma-ray spectrometric method is limited to approximately the top 35 cm of the earth’s surface. Gamma rays emitted beneath deeper cover are absorbed by the earth. For typical source densities, over 98% of the radiation emanating from the earth’s surface originates in the top 35 cm of the earth’s crust.

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This has profound implications for the sources of airborne gamma-ray spectrometric anomalies. These sources group into three main types: unweathered bedrock; weathered bedrock; and transported material.

The gamma-ray spectrometric response of earth materials has been described by Darnley and Ford (1987), IAEA (1988), Dickson and Scott (1997), and Wilford *et al.* (1997). The following account is based on these sources. An extensive bibliography is given by Shives and Ford (1994).

Unweathered bedrock response

The gamma-ray spectrometric response of unweathered, exposed bedrock reflects the constituent concentrations of K, Th and U in the bedrock. Potassium is a common element comprising about 2% of the earth's crust. The main potassium response arises from potassic feldspars and micas. The percentage of K is generally high in acid felsic rocks and low in mafic rocks. Potassium does not occur in all mafic rocks. Uranium has an average concentration of about 2.5 ppm in the earth's crust. It occurs as U oxide and silicate minerals. Zircons frequently contain U. Uranium minerals tend to be present in pegmatites, syenites, carbonatites, granites and some shales. As with U, Th is a minor constituent of the earth's crust with a concentration of about 9 ppm. Thorium occurs in allanite, monazite, xenotime and zircon, and as trace amounts in other rock-forming minerals. Both U and Th are present as trace elements in the primary rock-forming minerals. Their concentrations in igneous rocks generally increase as the K and silica content of the rocks increase.

As U is more mobile under low temperature oxidising conditions than K or Th, rocks formed as a result of weathering processes reflect specific radioelement characteristics. Mature sediments such as quartzites tend to have elevated Th compositions whereas immature sediments such as arkoses, greywackes and shales have radioelement concentrations tending to correlate with the radioelement concentrations of their source rocks. Limestones may be relatively enriched in U.

Fresh unweathered bedrock is exposed at the surface in many areas of the northern hemisphere as a result of the planing of the land surface by glaciers during the last ice age. The only areas of Australia that have equivalent exposures of fresh bedrock are southern Tasmania and portions of the Australian Alps where Pleistocene glaciation also occurred.

Weathered bedrock response

Radioelements are released from bedrock lithological units during both chemical and physical weathering processes. The effects of chemical weathering depend primarily on groundwater characteristics such as acidity and salinity, since these parameters govern the extent to which radioelements are removed and reprecipitated. It is important to distinguish in situ weathered products, which replace the upper levels of the parent bedrock, from transported weathered products, which involve the mobilisation of the products of bedrock weathering. In situ and transported weathered materials have markedly different radiometric properties.

With in situ weathering, the host minerals of K are destroyed. The weathering results in K depletion through leaching. However, potassium may be incorporated into (or adsorbed by) any clay minerals that form. Clays may have elevated potassium values.

Uranium may form soluble minerals which may be leached from both bedrock and in situ weathering products. This process will decrease the U concentration of weathered material. Some U minerals are insoluble and therefore do not tend to migrate. Near-surface U may increase due to adsorption in clays and precipitation in association with iron oxides and carbonates.

Thorium compounds generally have low solubilities except in acid solutions. The major Th-bearing minerals (monazite and zircon) are stable during weathering. Any Th freed by the weathering process may accumulate in clays and in iron or titanium oxides.

Weathering in Australia is mainly dependent on rain and water flow, and extremes of heat and cold. Weathering rates vary according to topography, and it is possible for the same lithologic unit to have different expressions of weathering between its highest and lowest portions. Many areas of Australia have been exposed to erosion over considerable periods of geological time. This has resulted in the development of deep weathering profiles in many areas.

The term *regolith* is used in Australia to describe all weathered material above fresh bedrock. The weathering products vary from the surface to the fresh bedrock. Soil is commonly the uppermost part of a regolith profile. In areas where no transport of weathering products has occurred, soils provide the cover to weathered bedrock and the gamma-ray spectrometric response of such soils reflects the radioelement concentrations of the underlying bedrock. Soils often have a reduced radiometric response relative to the parent bedrock material due to leaching of radioelements during the soil formation process. Moisture in the soils may also reduce the response. Soils derived from granites and felsic volcanics have lower K countrates than their parent bedrock as a result of K leaching. It is only when some concentration mechanism occurs that soils show an increase in radioelement concentrations relative to the parent bedrock. Clays may have elevated K concentrations due to incorporation or adsorption of K by clay minerals. Increases in U and Th concentrations can occur during the weathering of intermediate, mafic, and ultramafic rocks. This is due to the incorporation of these elements into iron oxides and clays during the weathering process. While there is generally no predictable relationship between soil type and the underlying bedrock, constant relationships occur in particular areas. The use of the airborne gamma-ray spectrometric method as a soil mapping tool therefore requires a component of ground calibration.

Arid weathering in Australia produces a variety of chemically precipitated products that include calcretes, silcretes and laterites. Calcretes generally have low U although U can be precipitated from groundwaters to cause localised U accumulations in calcretes. Silcretes and iron-rich surface materials, such as laterites have elevated Th and U concentrations relative to bedrock. Potassium tends to be severely depleted in these units.

Transported material

The products of bedrock weathering undergo both chemical changes and mechanical sorting during transportation. Radioelements may be both concentrated and diluted during transport. Water, gravity and wind are the principal stimulants to transport in Australia. Topography, which in many instances is related to bedrock lithology, is often the principal control on the direction and speed of the transport.

The gamma-ray response of transported material is related to the source of the material. The response can thus be used to identify the provenance of the transported material and the distribution of the transported products. Sorting of material during transport will be dependent on grain size and density, and the radiometric response of the components of depositional systems will reflect this sorting. K may be transported in clay minerals in silts. U and Th may also be transported through adsorption onto clay minerals. Such radioelement concentrations can be used to map the fine-texture portions of the systems. Coarse-textured components will have a different response. For example, coarse-textured lithic fragments derived from granite bedrock will reflect the high K concentrations associated with granites. As noted by Wilford *et al.* (1997), the distribution of radioelements in active depositional systems is a dynamic process that includes leaching of K and removal of Th and U from clays. Current research seeks to refine methods for identifying the state of such systems on the basis of the radioelement distributions.

Soluble U may be transported in solution and precipitated when reducing conditions are encountered. Zircons and monazite are stable during transport. U and Th may be concentrated in heavy mineral deposits by wind and water action.

Extensive areas of Australia are covered with dune fields or have received dust mantles. These features have variable radioelement concentrations which depend on their provenance. Dust mantles and dunes blanket radioelement signatures of local soils and bedrock, and superimpose their own radioelement signatures on the local countryside.

GAMMA-RAY SPECTROMETRIC RESPONSE IN ARID AREAS—EXAMPLES

Figure 1 shows the locations of three surveys discussed in this paper, namely the Bendigo, Sir Samuel and Broken Hill surveys. These areas have been selected to contrast the gamma-ray spectrometric response between areas subjected to differing degrees of weathering and aridity.

The gamma-ray spectrometric data are shown in this paper as composite ternary images with K concentrations displayed in red, Th in green and U in blue. Areas of very low concentrations appear black and areas of high concentrations in all of the radioelements appear white. In the actual detailed analysis for each area, separate images for each radioelement were studied in addition to the ternary image.

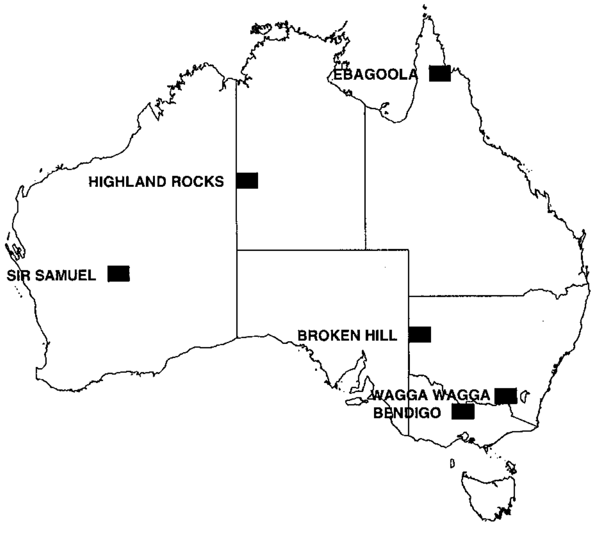

Figure 1: *Locality diagram showing the location of survey areas referred to in the text.*

Bendigo

The geology and physiology of the Bendigo 1:250 000 map sheet area (Figure 1), situated just north of the Australian Great Dividing Range of eastern and southeastern Australia, combine to provide several excellent illustrations of the gamma-ray spectrometric response of bedrock, weathered bedrock, and transported material in an area which is on the fringe of the extremely arid areas of Australia. Annual rainfall is 372 mm, which tends to be distributed throughout the year, and summer temperatures are frequently in the high 20°C range. Agriculture in the area consists of wheat, sheep grazing, dairy farming and irrigated orchards.

Simplified geology and a digital elevation image for the area are shown in Figures 2a and b. Basement, consisting primarily of tightly folded Ordovician, Devonian and Silurian siltstones, shales, sandstones and greywackes intruded by granites and various mafic rocks outcrops in the mountainous region to the south. Drainage is to the north towards the Murray River. The area between the bedrock outcrop and the Murray River consists of flat lying sediments of the Murray Basin, which overly the basement rocks with thicknesses up to a few hundred metres. The surface of the Murray Basin in the Bendigo area consists primarily of material eroded from the highlands to the south and east.

Slater and De Plater (1997) published a soil association map for the Nagambie 1:100 000 map sheet (the southeast sixth of the area illustrated in Figure 2) based on the interpretation of airborne gamma-ray spectrometric data. Field mapping was used in this pilot study to correlate soil identifications and gamma-ray response.

Figures 2c and d show aeromagnetic and ternary gamma-ray spectrometric images of the Bendigo sheet area. The geophysical data were acquired at 80 m height on east-west flight lines primarily 400 m apart. Data in the southwest of the study area was acquired with 200 m line spacing. Figure 2a shows the location of features referred to in the following discussion.

A Devonian granite (A) outcrops in the extreme southeast of the Bendigo area. The mapped outcrop of the granite corresponds to a topographic high, and a gravity low (gravity data not shown). The associated magnetic high is deceptive as it arises from a deeper magnetic body. The mapped outcrop of the granite corresponds to a classic area of high potassium activity. This response is due to a combination of fresh bedrock and in situ weathered bedrock. Slater and De Plater (1997) identify "shallow stony earths, duplex soils and granite bedrock" in this area. The area of high potassium concentration extends northward beyond the granite outcrop to an area where, on the basis of the gravity data, no granite is likely. This extension of the potassium anomaly (B) is obviously due to material eroded and transported as a sheet from the granite source. Slater and De Plater (1997) identify the source of this response as "sandy soils".

A Devonian granite outcropping in the southwest portion of the area (C) also results in the mapping of high radioelement concentrations. Material transported from this feature is confined to a distinct fan structure (D) which precisely defines the provenance of its contents.

A third granite (E) outcrops in the northwest corner of the area. The gamma-ray spectrometric anomaly associated with this granite extends over a much larger area than that covered by its outcrop. Soils developed above this feature reflect the radiometric character of the underlying granite bedrock whose extent is defined in the aeromagnetic data by a magnetic high due to a contact metamorphic aureole. The surface radiometric response may, however, be enhanced by erosional material from the topographically high portions of the granite.

A linear north-striking zone of mafic rocks with ophiolite affinities occurs in the centre of the area (F). As expected, both the outcrops of this unit and the soils derived from it (G) have negligible K response. Bedrock outcrops are relatively high in Th, and the soils derived from the mafic rocks are enriched in U. Other mafic units in the area (H and J) give similar responses.

The outcropping sediments and metasediments in the south of the study area show significant radiometric detail due to a combination of fresh bedrock and in situ weathered material. The gamma-ray spectrometric data provide greater detail on these units than the aeromagnetic data. The radiometric response of the sediments and metasediments is reflected in soils derived from bedrock north of the limits of the outcrops of these units in the area marked as K. In the northern half of the Bendigo area the gamma-ray response of these soil are overprinted by the gamma-ray response of transported material. This transported material completely obscures the response due to the various bedrock units visible in the aeromagnetic data. The transported sediments comprise a melange of detritus eroded from the mountains to the south, floodplains deposited by various river systems and aeolian sands blown from areas to the west. Several wind-blown lunette dunes are evident as crescent-shaped K highs (L, M, and N).

Sir Samuel

The Sir Samuel 1:250 000 map sheet (Figure 1) is located on the Yilgarn Archaean Craton of Western Australia over a region where the basement is comprised of granites, gneiss complexes and greenstone belts consisting of mafic and ultramafic rocks, banded iron formations and sediments. Rainfall is approximately 215 mm per year and tends to be concentrated in short periods during the summer. Summer temperatures are frequently in the high 30°C range. The bedrock in the area is poorly exposed and deeply weathered. The granitic areas are kaolinised to depths of tens of metres below ground surface. Oxidation of the mafic and ironstone units in the greenstone belts extends in places to depths of more than 50 m. Much of the weathered bedrock is covered either by aeolian sands or by silcretes and laterites. The Sir Samuel area provides a good example of the gamma-ray spectrometric response in a region of significant weathering. Wilford *et al.* (1997) used these data to assist in the mapping of the regolith in this area (Australian Geological Survey Organisation, 1995). The following account is based on these sources.

Figures 3a, b, c and d show a simplified regolith map, a digital elevation model, the aeromagnetic response, and a ternary gamma-ray spectrometric image of the area, respectively. The regolith map differentiates in situ regolith (A), transported regolith (B), and lacustrine sediments and calcrete (C). The geophysical data were acquired at 100 m height along east-west flight lines 400 m apart.

Greenstone belts are recognisable in the aeromagnetic data as broad areas of low (generally blue) magnetic intensity containing narrow, elongated, high-amplitude anomalies. The high amplitude magnetic

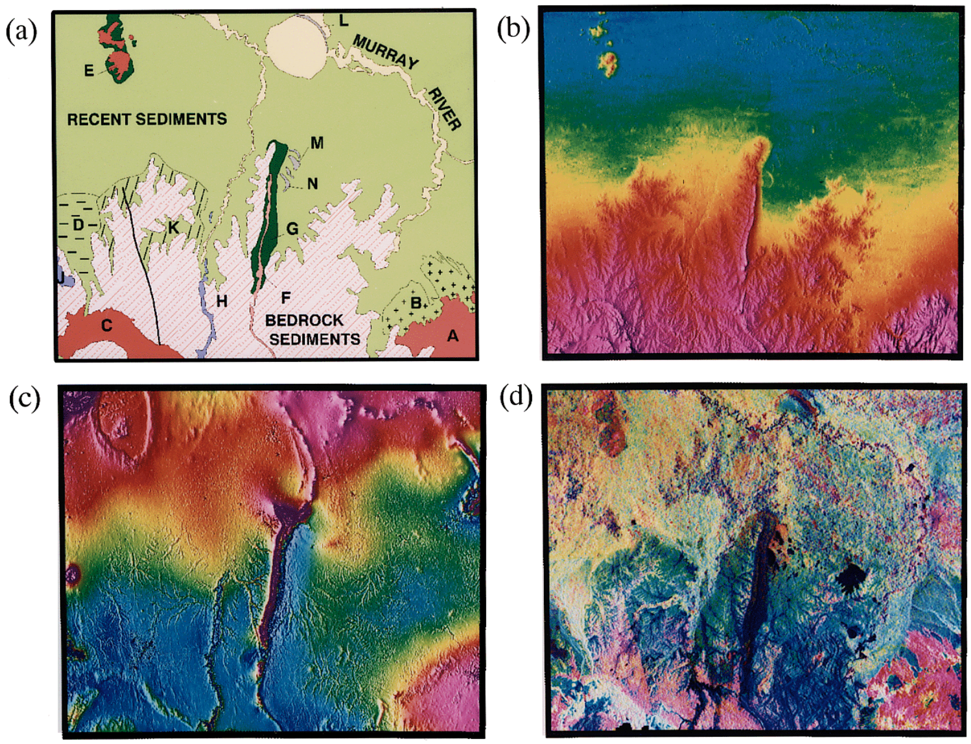

Figure 2: *Bendigo survey area showing (**a**) geology, (**b**) digital elevation model, (**c**) total magnetic intensity, and (**d**) ternary gamma-ray spectrometry images.*

anomalies are due are due to serpentinised ultramafics and iron formations within the greenstone belts. This greenstone component of the bedrock has few outcrops which are confined to small, low-amplitude linear ridges evident in the digital elevation data of Figure 3b. The outcrops associate with areas of low radioelement concentrations. This is due to the leaching of the radioelements through weathering, and also because the fresh bedrock in these areas consists of units likely to have low potassium concentrations.

Areas of granite and gneiss complexes have high K, Th and U responses where in situ weathering products are exposed at the surface. This response reflects the higher radioelement concentrations of the parent rocks.

A large proportion of the Sir Samuel sheet area is covered by sheetwash and sandplains. The gamma-ray spectrometric response of these areas varies according to the relative concentration of quartz and felspathic grains, with the areas of higher felspar concentration having higher potassium concentrations.

Silcretes in the area have green and blue hues reflecting higher Th and U concentrations. This is due to heavy mineral grains, such as zircons, within the silcretes, or concentrations of Th and U formed during the formation of the silcrete. Although laterites have similar Th and U concentrations to silcretes, the Th is preferentially concentrated by scavenging iron oxides. Laterites over greenstone units originally low in radioelements appear as black areas.

Various low-energy drainage systems are evident and the courses of many of these features are marked by intermittent salt lakes and carbonate deposition. The higher U concentration seen in these features is a result of the precipitation of U from percolating ground waters. The U would originally have been leached from granites. This process has produced a potentially economic U deposit at Yeelirrie on an adjacent 1:250 000 map sheet (Cameron, 1990).

In simplistic terms, the gamma-ray spectrometric response shown in the ternary image of Figure 3d can be classified as follows:

Red	K: regions associated with exposed granitic bedrock.
Green	Th: various ferruginous materials at the surface.
Blue	U: calcrete, calcareous sediments and soils.
Black to brown	Low in K, Th and U: duricrusts and exposed bedrock. These areas correspond to greenstones and some sand plains.
White to yellowish	High K, Th, U: geomorphically active areas with exposed weathered granite and sediments derived from granite.

Wilford *et al.* (1997) present a 3-D perspective view of the Sir Samuel gamma-ray spectrometric data draped over a digital elevation model. This type of presentation is useful for illustrating the relationship between weathering processes and topography.

Broken Hill

The Broken Hill area of western New South Wales (Figure 1) has an annual rainfall of 248 mm falling mainly in the winter and an average

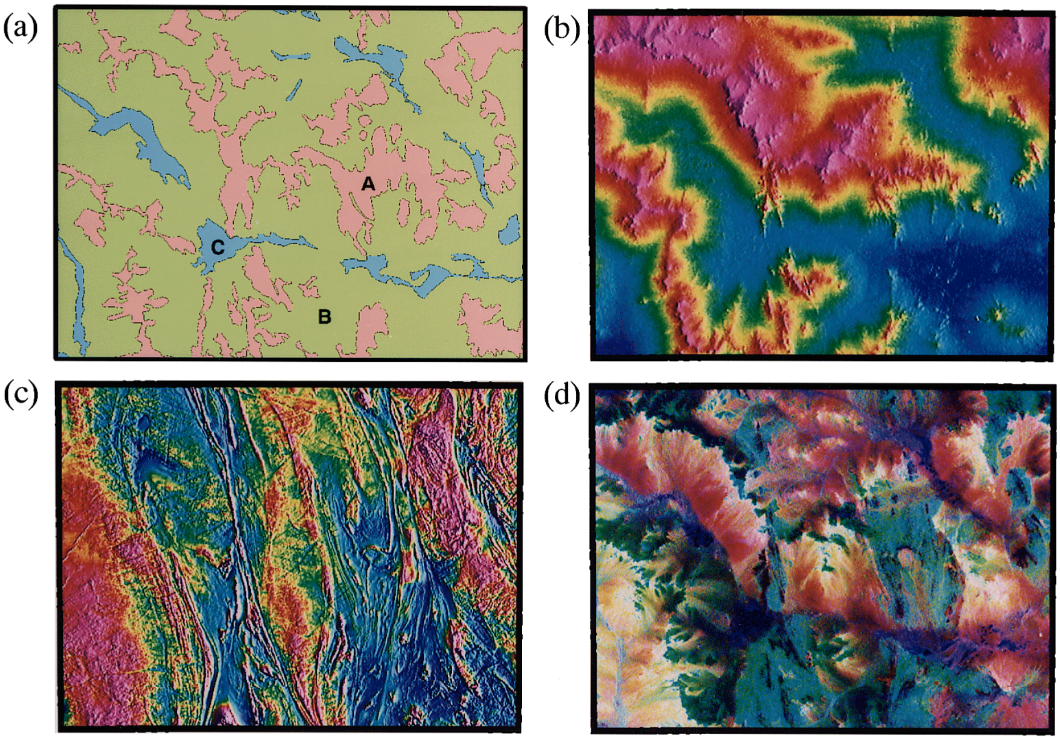

Figure 3: *Sir Samuel survey area showing (**a**) regolith, (**b**) digital elevation model, (**c**) total magnetic intensity, and (**d**) ternary gamma-ray spectrometry images.*

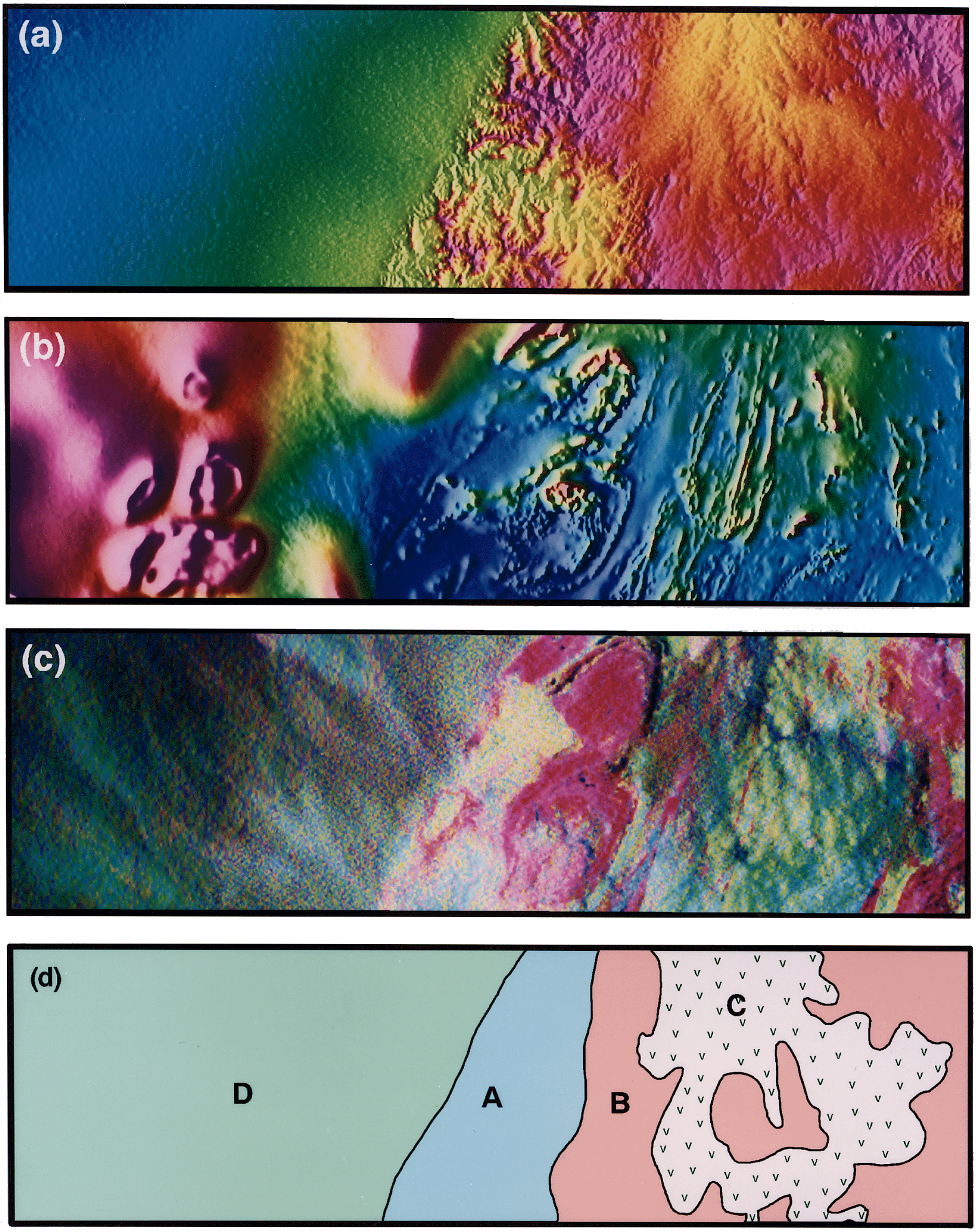

Figure 4: *Broken Hill survey area showing (**a**) regolith, (**b**) total magnetic intensity, (**c**) ternary gamma-ray spectrometry image, and (**d**) digital elevation model.*

summer temperature of approximately 30°C. The vegetation in the area consists of sparse scrub and grasslands. Minor sheep grazing occurs in the area. Mining is the principal economic base of the area (Stevens *et al.*, 1990), and centres on the major Broken Hill silver-lead-zinc deposit. The deposit is hosted by Proterozoic basement rocks. The Broken Hill area is an arid region containing significant proportions of relatively unweathered bedrock exposed at the surface. Haren *et al.* (1997) have commented on the gamma-ray spectrometric response of the area.

Figures 4a, b, c and d show a digital elevation model, total magnetic intensity image, ternary gamma-ray spectrometric image, and a regolith interpretation of the area, respectively. The geophysical data were acquired at 60 m height along east-west flight lines 100 m apart. The regolith interpretation is based on a map published by Gibson and Wilford (1996).

The survey area comprises intensely deformed, high-grade metamorphic Proterozoic basement with little or no surficial cover in the eastern half, and a down-faulted continuation of similar rocks under a cover of 200–300 m of flat-lying sediments in the western half. The precise line of the fault separating these two areas can be recognised by the change from shallow magnetic sources causing high frequency anomalies in the east to deeper magnetic sources causing broader magnetic anomalies in the west. This fault line is also marked by a scarp in the digital elevation data.

The western half of the area, corresponding to the area of sediment subcrop, is a flat plain. The eastern half of the area, corresponding to the area of outcropping and subcropping Proterozoic metamorphic rocks, has a higher average elevation and, as is evident in the digital elevation model, contains numerous ridges and low hills with reliefs of the order of a few tens of metres.

Most of the area is covered by a veneer of partly aeolian-derived sand and silt which has a very low radiometric response. This cover is thin in areas of high relief where the soil mineralogy correlates closely with the underlying bedrock lithology. Areas of low topographic relief generally have lower gamma-ray spectrometric response due to greater relative concentrations of the aeolian derived material.

Gibson and Wilford's (1996) interpretation of the regolith identified the following components (identified by letters on Figure 4d):

1. Moderately to slightly weathered rocks forming low hills of 90+ metres relief (A).

   Much of this area is underlain by an area of pegmatitic rocks producing high countrates.

2. Moderately to slightly weathered rocks forming low hills of 30–90 metres relief (B).

   Both areas *A* and *B* have little surficial cover and, since the bedrock is only slightly weathered, the gamma-ray spectrometric response reflects the bedrock lithologies. A striking feature of the Broken Hill area is that, despite the arid climate, the exposed bedrock remains relatively unweathered.

   Since high-grade temperature and pressure metamorphism do not markedly affect the radiometric properties of rocks, the gamma-ray spectrometric data from the Broken Hill area are a useful guide to geological mapping in an area where metamorphic processes have made the visual identification of lithologies difficult.

3. Broad low-relief drainage basins (C)

   Areas of topographic lows in the Broken Hill area contain alluvium and colluvium sediments as well as mateial with an aeolian origin. The topographic lows are separated by rises of slightly to moderately weathered bedrock. The transported material often has sufficient thickness that the gamma-ray spectrometric response of the bedrock is obscured. Generally high relief results in a greater proportion of bedrock derived material in the surficial deposits.

4. Alluvial sand silt and minor gravel (D)

   The flat plain in the west of the area has a surface coverage of aeolian material combined with alluvial sand silt and minor gravel. The gamma-ray spectrometric response of this area is characterised by the superposition of various erosional fans derived from the topographically elevated pegmatitic rocks to the east. These fans reflect the elevated radioelement concentrations of their pegmatitic sources.

CONCLUDING REMARKS

Examples of the airborne gamma-ray spectrometric response from three different climatic areas in Australia have been presented. Several other examples from Australia are to be found in the literature. Wilford *et al.* (1997) presented examples from the Wagga and Ebagoola areas (see Figure 1). The Wagga area is similar in many ways to the Bendigo sheet area discussed in this paper. The Ebagoola area has a warm monsoonal climate with distinct wet and dry seasons and open savannah vegetation. Maidment (1994) interpreted the gamma-ray spectrometric data for the Highland Rocks 1:250 000 map sheet (Figure 1). This is another example of a semi-desert area. The gamma-ray spectrometric response of the bedrock (high-grade metamorphic rocks) in the Highland Rocks area is almost completely obscured by the response of weathering products and transported material. This is similar to the Sir Samuel area, although aeolian material, including extensive dune systems with a distinct gamma-ray spectrometric response, is far more prevalent on the Highland Rocks area.

Airborne gamma-ray spectrometry is being increasingly used in Australia to assist geological mapping and for land use studies. Recent studies in Australia have indicated a wide range of relationships between the observed gamma-ray spectrometric response and the source material for different climatic areas. While these studies have begun to quantify these relationships, further research is required. In particular, the relationships between topography, weathering and radiometric response need to be further clarified. Additional studies are required to assess the relative effects of present day climates and previous weathering episodes on weathering profiles and the gamma-ray spectrometric response. An obvious feature of the results presented is that there is not always a clear correlation between gamma-ray spectrometric responses and present day climate.

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